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Antenna Selection and Deployment Strategies for Indoor Wireless Communication Systems

by

Alex H. C. Wong

Abstract

Effective antenna selection and deployment strategies are important for reducing co-channel interference in indoor wireless systems. Low-cost solutions are essential, and strategies that utilise simple antennas (such as directional patches) are advantageous from this perspective. However, performance is always an issue and the improvements achievable through clever antenna deployment need to be quantified. In this thesis, an experimental investigation of indoor propagation comparing the performance of directional antennas and multiple-element arrays (MEAs) with omni-directional antennas is reported. Estimation of the performance of a direct sequence code division multiple access (DS-CDMA) system operating in a variety of deployment scenarios allows the identification of a range of performance-limiting factors and the optimal deployment strategies.

It is shown that the orientation of single-element directional antennas can significantly impact on system performance compared to omni-directional antennas in traditional systems. The deployment of MEAs with an active diversity combining scheme can further improve system performance by more than one order of magnitude. From the perspective of system planning, the choice of antenna selection and deployment options depends on the current and future demand for system performance and the financial resources available. An evolutionary path has been proposed to provide a smooth transition from conventional (low-cost) to high-performance (high-cost) antenna systems as demand dictates.

Other performance-limiting factors in indoor wireless systems include the physical environment and external interference. It is also shown that electromagnetically-opaque obstacles in the environment can amplify the effectiveness of the antenna deployment by acting as physical zone boundaries that restrict interference. External interference has been shown to cause a significant degradation to the performance of an indoor system when the carrier-to-external-interference ratio (CEIR) is below 30 dB. This performance degradation can be minimised by appropriate antenna deployment, although the optimum antenna orientations depends on the strength of the external interference.
Acknowledgements

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Without the endless jokes and comfort from the members of the Radio Systems Group, the sometimes tedious work and intense pressure both academically and emotionally would not be bearable. Thanks to David Yuen for his Lord of the Rings analogy, envisioning the PhD programme as a journey of life experience instead of focusing on the end result. Special thanks to Mark Twiname for his technical support and assistance in the construction of the measurement systems.

I would also like to extend my sincere thank you to The University of Auckland for granting me a Doctoral Scholarship, providing me with the necessary financial assistance in completing my degree.

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<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>AMPS</td>
<td>Advanced Mobile Phone System</td>
</tr>
<tr>
<td>AWGN</td>
<td>additive white Gaussian noise</td>
</tr>
<tr>
<td>BER</td>
<td>bit-error-rate</td>
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<tr>
<td>BPSK</td>
<td>binary phase-shift keying</td>
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<tr>
<td>CDF</td>
<td>cumulative distribution function</td>
</tr>
<tr>
<td>CDMA</td>
<td>code division multiple access</td>
</tr>
<tr>
<td>CEIR</td>
<td>carrier-to-external-interference ratio</td>
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<tr>
<td>CIR</td>
<td>carrier-to-interference ratio</td>
</tr>
<tr>
<td>CNR</td>
<td>carrier-to-noise ratio</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>carrier-sense multiple access with collision avoidance</td>
</tr>
<tr>
<td>CSMA/CD</td>
<td>carrier-sense multiple access with collision detection</td>
</tr>
<tr>
<td>CTS</td>
<td>Clear to Send</td>
</tr>
<tr>
<td>CW</td>
<td>continuous-wave</td>
</tr>
<tr>
<td>DAMPS</td>
<td>digital advanced mobile phone system</td>
</tr>
<tr>
<td>DCOM</td>
<td>distributed component object model</td>
</tr>
<tr>
<td>DS</td>
<td>direct sum</td>
</tr>
<tr>
<td>DS-CDMA</td>
<td>direct sequence code division multiple access</td>
</tr>
<tr>
<td>DSMA</td>
<td>direct sequence multiple access</td>
</tr>
<tr>
<td>EDGE</td>
<td>Enhanced Data Rates for GSM Evolution</td>
</tr>
<tr>
<td>EGC</td>
<td>equal gain combining</td>
</tr>
<tr>
<td>EIRP</td>
<td>effective isotropic radiated power</td>
</tr>
<tr>
<td>FAF</td>
<td>floor attenuation factor</td>
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<tr>
<td>FDD</td>
<td>frequency division duplexing</td>
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<tr>
<td>FDMA</td>
<td>frequency division multiple access</td>
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<tr>
<td>FHMA</td>
<td>frequency hopped multiple access</td>
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<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>FLMTS</td>
<td>Future Land Mobile Telephone System</td>
</tr>
<tr>
<td>FSK</td>
<td>frequency-shift keying</td>
</tr>
<tr>
<td>GO</td>
<td>geometrical optics</td>
</tr>
<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile communication</td>
</tr>
<tr>
<td>GUI</td>
<td>graphical user interface</td>
</tr>
<tr>
<td>i.i.d.</td>
<td>independent and identically distributed</td>
</tr>
<tr>
<td>ICI</td>
<td>inter-carrier interference</td>
</tr>
<tr>
<td>IDFT</td>
<td>inverse discrete Fourier transform</td>
</tr>
<tr>
<td>IFFT</td>
<td>inverse fast Fourier transform</td>
</tr>
<tr>
<td>i.i.d.</td>
<td>identical independently distributed</td>
</tr>
<tr>
<td>IMT</td>
<td>International Mobile Telecommunication</td>
</tr>
<tr>
<td>IS</td>
<td>ideal selection</td>
</tr>
<tr>
<td>ISI</td>
<td>inter-symbol interference</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>ITU-R</td>
<td>International Telecommunication Union — Radiocommunication Sector</td>
</tr>
<tr>
<td>LMCS</td>
<td>local multipoint communication systems</td>
</tr>
<tr>
<td>LOS</td>
<td>line-of-sight</td>
</tr>
<tr>
<td>MAC</td>
<td>medium access control</td>
</tr>
<tr>
<td>MAI</td>
<td>multiple-access interference</td>
</tr>
<tr>
<td>MEA</td>
<td>multiple-element array</td>
</tr>
<tr>
<td>MIMO</td>
<td>multiple-input multiple-output</td>
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<tr>
<td>MISO</td>
<td>multiple-input single-output</td>
</tr>
<tr>
<td>MRC</td>
<td>maximal gain combining</td>
</tr>
<tr>
<td>MUI</td>
<td>multiple-user interference</td>
</tr>
<tr>
<td>NLOS</td>
<td>non line-of-sight</td>
</tr>
<tr>
<td>NMT</td>
<td>Nordic Mobile Telephone</td>
</tr>
<tr>
<td>OFDM</td>
<td>orthogonal frequency division multiplexing</td>
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<tr>
<td>OFDMA</td>
<td>orthogonal frequency division multiple access</td>
</tr>
<tr>
<td>PCB</td>
<td>printed circuit board</td>
</tr>
<tr>
<td>PDC</td>
<td>Personal Digital Cellular</td>
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<tr>
<td>PDF</td>
<td>probability density function</td>
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<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>PHY</td>
<td>physical</td>
</tr>
<tr>
<td>PIFA</td>
<td>planar inverted F-antenna</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>RTS</td>
<td>Request to Send</td>
</tr>
<tr>
<td>RV</td>
<td>random variable</td>
</tr>
<tr>
<td>SDMA</td>
<td>space division multiple access</td>
</tr>
<tr>
<td>SIMO</td>
<td>single-input multiple-output</td>
</tr>
<tr>
<td>SIR</td>
<td>signal-to-interference ratio</td>
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<tr>
<td>SMS</td>
<td>short message service</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
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<tr>
<td>STC</td>
<td>space-time coding</td>
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<tr>
<td>SVD</td>
<td>singular value decomposition</td>
</tr>
<tr>
<td>TACS</td>
<td>Total Access Mobile communication Systems</td>
</tr>
<tr>
<td>TDD</td>
<td>time division duplexing</td>
</tr>
<tr>
<td>TDMA</td>
<td>time division multiple access</td>
</tr>
<tr>
<td>ULA</td>
<td>uniform linear array</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
</tr>
<tr>
<td>UTD</td>
<td>uniform theory of diffraction</td>
</tr>
<tr>
<td>VCO</td>
<td>voltage controlled oscillator</td>
</tr>
<tr>
<td>VLSI</td>
<td>very large scale integration</td>
</tr>
<tr>
<td>VSWR</td>
<td>voltage standing wave ratio</td>
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<tr>
<td>WAF</td>
<td>wall attenuation factor</td>
</tr>
<tr>
<td>WECA</td>
<td>Wireless Ethernet Compatibility Alliance</td>
</tr>
<tr>
<td>WLAN</td>
<td>wireless local area network</td>
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Chapter 1

Introduction

The ability to communicate with people on the move has evolved remarkably since the first mobile radio installation on a steam bus by Marconi in 1897 [1, pp. 2–10]. Radio has since been recognised as the only practical method of establishing communication between mobile users [2, pp. 4–5]. The era of wireless communications, however, did not arrive until the availability of highly reliable, miniature, solid-state radio frequency (RF) hardware in the 1970s. The impact of wireless communications has been and will continue to be profound. This will soon allow the creation of a global wireless network that will deliver a wide variety of services [3, pp. 2–3].

A brief history of the evolution of wireless communications will provide insight into the future development of these technologies and their impact in the next several decades. In 1981, the first commercial analogue cellular system, the Nordic Mobile Telephone (NMT), was introduced in Sweden [2, pp. 563–567]. The deployment of Advanced Mobile Phone System (AMPS) in the United States followed shortly in 1983. These first generation cellular systems were primarily used for voice applications. A combination of subscriber base growth, the demand for new types of service and technological advances in communications led to the development of second generation (2G) digital systems.

At the end of 1991, the second generation digital Global System for Mobile communication (GSM) system was introduced in Europe [2, pp. 587–600]. The deployment of digital cellular systems in the United States (IS-54, IS-136 and IS-95) began in 1995 [4, pp. 5–10]. Due to advances in digital modulation techniques and lower bit-rate digital voice encoders, these 2G systems significantly increased spectral efficiency relative to first generation analogue systems. In addition to voice, these 2G systems support data traffic and short message service (SMS) [4, p. 8].

The fundamental limitation of these 2G systems, however, remains the low transmission rates of digital data [2, pp. 643–645]. It was generally accepted that the

\[\text{1A more thorough review of the development of cellular systems is presented in Appendix A.}\]
third generation (3G) cellular systems would need to provide high speed data services and maximised commonality between a group of core elements in the air interfaces of competing standards. The ultimate goal lies in ubiquity of services, which is achieved by total integration of several networks such as macro- and micro-cellular systems, indoors and short range wireless networks (such as wireless local area network (WLAN) and Bluetooth), and satellite systems [2, pp. 705–707]. It is hoped that total or global integration will eventually result in a universal standard which will make the use of multi-standard terminals unnecessary. This could be the fourth generation (4G) systems or the Future Land Mobile Telephone System (FLMTS).

This total integration paradigm is likely to generate unprecedented demand on high-performance indoor wireless communication systems. To create harmonious working between the wired and the wireless networks, data rates over the two networks should be made compatible as far as possible. Indoor wireless channels are, however, highly variable [5, p. 123] due to different building construction and materials, the presence of furniture, and people on the move. It is a major challenge to wireless communication system designers to overcome the impairments of the indoor wireless channels to sustain transmission rates of several Mbps. Many aspects of wireless communications are determined by standards organisations and are outside the control of system planners. In order to maximise the performance promised by these technologies, careful system planning and deployment is necessary.

Another driving force behind the increasing need for strategic deployment of indoor wireless systems lies in their easy deployment compared to wired systems. For example, WLAN technologies, in particular derivatives of the IEEE 802.11 standard [6, pp. 5–15], are currently experiencing major growth and have become popular as an inexpensive way for average computer users to achieve indoor connectivity without the need for wiring, which can be difficult to install in existing indoor environments. Business organisations also value the relative ease of integrating wireless access and the ability to roam with their existing network resources such as servers, printers and Internet connections [7, p. 1]. The marketing of Wi-Fi (wireless fidelity)\(^2\) has also been crucial in the success of these WLAN systems for ensuring interoperability of WLAN equipment from different vendors [8, pp. 1–2]. However, as these WLAN systems share the Industrial, Scientific and Medical (ISM) bands with incumbent systems\(^3\) [4, pp. 15–17], mutual interference can become the dominant performance-limiting factor. Strategic system planning and deployment can potentially optimise the performance of these systems by reducing the

\(^2\)The Wireless Ethernet Compatibility Alliance (WECA) markets Wi-Fi as the common name for IEEE 802.11b.

\(^3\)Potential interferers in the 2.4–2.483 GHz ISM band (for 802.11b/g) include 2.4 GHz cordless phones and devices based on the Bluetooth, WirelessUSB and ZigBee standards. Systems that could be affected by IEEE 802.11a WLANs in the 5 GHz band include radar [9] and HIPERLAN/2 [10].
1.1. The structure of this thesis

Accurate system performance estimation requires a basic understanding of indoor wireless communication systems and the indoor radio propagation environment. Consequently, it is important to build a foundation for these areas before considering system performance. Chapters 2 to 4 review the fundamentals of indoor wireless communications and the literature into the placement of base stations and the selection of base station antennas.

Chapter 2 provides an introduction to some of the key concepts of indoor wireless communications. This chapter also outlines some of the fundamental characteristics for indoor radio propagation that demonstrate the importance of appropriate planning and deployment of indoor wireless systems for satisfying the increasing demand of system performance and capacity. An introduction to key antenna principles and examples of antenna deployment in practical systems are also presented.
Chapter 3 reviews previous investigations into the influence of base station placement on the performance of indoor wireless systems. The existing strategies for the selection and deployment of base station antennas and their potential for improving system performance are also discussed. The areas of contributions of this thesis are identified and defined in this chapter.

Chapter 4 highlights different degrees of freedom available in the selection and deployment of base station antennas. A number of methodologies available for system performance estimation are discussed and details of the adopted methodology are presented.

The original contributions of this thesis are presented in Chapters 5 to 10, which are primarily concerned with quantifying the influence of the deployment of base station antennas on system performance. Published papers associated with this work include references [13–17].

In order to quantify the influence of these deployment strategies, a measurement-based approach has been adopted, in which propagation measurements in real-world environments are used to estimate the system performance in different deployment scenarios. Chapters 5 and 6 discuss the development of two automated measurement systems and the propagation study, respectively. The development of system models for the estimation of system performance is discussed in Chapter 7.

Chapter 5 highlights the development of two propagation measurement systems. These measurement systems are based on an existing measurement system from a previous researcher with modifications that allow automated measurements from directional antennas at different orientations and simultaneous multiple-channel measurements from MEAs. This automated technique demonstrates the feasibility of rapid collection of propagation data in indoor environments that can be used to improve system performance.

In Chapter 6, previously unpublished narrowband propagation measurements at 1.8 GHz undertaken in a number of indoor environments using the measurement systems outlined in Chapter 5 are presented. These measurements involve the use of directional antennas and MEAs, which are unprecedented in previous research for the environments considered. The primary objective of this propagation study was to provide a comprehensive propagation database for a range of environments and deployment scenarios that could be used directly in conjunction with mathematical techniques to estimate the performance of indoor wireless systems.

In Chapter 7, the development of a system model and the evaluation of various performance estimation techniques are presented. This is an extension to an existing system model for system performance analysis, which is used to evaluate the performance of various deployment strategies in Chapters 8 and 9. This extension enables the
performance estimation of systems employing MEAs. The fundamental assumptions of this system model are also discussed.

Chapters 8 and 9 discuss the system performance analyses of antenna deployment strategies employing single-element directional antennas and MEAs, respectively. The influence of other performance-limiting factors such as the physical environment, antenna orientation, external interference and interference to nearby systems are also considered. These performance estimates are based on the propagation database outlined in Chapter 6 and the system model discussed in Chapter 7. The relative performance of different antenna deployment options is quantified and the optimal deployment strategies are identified.

In Chapter 10, the major findings from Chapters 8 and 9 are presented from the perspective of system planning. This relates the deployment strategies discussed to the design and deployment of a practical system. The advantages and disadvantages of individual deployments strategies are outlined and recommendations are made for various system design scenarios. A number of possible future developments of this research are also presented.

Chapter 11 summarises the main findings of this thesis.

References


Chapter 2

Propagation for Indoor Wireless Communications

2.1 Introduction

In Chapter 1, the motivations for the development of high-performance indoor wireless communication systems have been outlined. One of the primary objectives of this thesis is to determine the influence of antenna deployment strategies on the performance of these systems. In order to achieve this objective, a general understanding of indoor wireless communication systems is required. This chapter provides an introduction to some of the key concepts of indoor wireless communications that are necessary for performance estimation of these systems. Some of the fundamental characteristics for indoor radio propagation are also outlined. The impairments of the radio channel demonstrate the importance of appropriate planning and deployment of indoor wireless systems for satisfying the increasing demand of system performance and capacity. An introduction to some fundamental antenna principles and examples of antenna deployment in practical systems are also presented.

Section 2.2 discusses the types of wireless systems considered in this thesis and reviews a number of existing techniques for improving their performance and capacities. In Section 2.3, a discussion on how radio signals propagate in indoor environments is presented. Section 2.4 outlines some of the basic antenna principles and reviews a number of antenna deployment examples. Finally, the chapter is summarised in Section 2.5.
2.2 Fundamentals of high performance wireless communication systems

In the broadest sense, *wireless communications* refers to any type of communications without a physical connection between the participating parties\(^1\). Various parts of the electromagnetic spectrum can be employed for communications, which includes the spectra of radiowaves, microwaves, visible light and infra-red. In this thesis, we shall confine the discussion to communications using radiowaves. Traditionally, the radio frequencies in the range 800 MHz to 2.5 GHz have attracted considerable interest in mobile communications due to their excellent propagation properties; though higher frequency bands at 5 GHz, 20 GHz, and even 60 GHz are being considered for indoor wireless local area networks (WLANs) or outdoor local multipoint communication systems (LMCS) [1, p. 54]. This thesis focuses on the discussion of indoor wireless communication systems in which all participating parties are located indoors with limited mobility (people walking with mobile devices). The overall communications process is monitored and coordinated through an extensive infrastructure of base stations. Mobile users connect to the network of base stations and request services such as voice, data and multimedia communications. High user capacity and high data rates are often required. Examples of such systems include third and fourth generation mobile communication systems and WLANs.

In wireless communication systems, the most basic form of communication channels is simplex channels that transmit messages in a single direction. The simplex channel from a base station to a mobile user is known as the forward channel or the downlink. The link from a mobile user to a base station is called the reverse channel or the uplink. A pair of downlink and uplink channels that enables two-way communications is called a duplex channel. In a duplex channel, the downlink and uplink channels can be either separated in frequency or time, as illustrated in Figure 2.1 [2, pp. 2–5]. In frequency division duplexing (FDD), the downlink and uplink channels occupy different parts of the frequency spectrum. In contrast, both channels occupy the same frequency spectrum in time division duplexing (TDD) but transmit at different instants of time.

One of the major disadvantages of wireless communications using radiowaves is that system capacity, which is quantified by the number of simultaneous users, is limited by the availability of frequency spectrum. This concept is demonstrated by the broadcasting architecture [2, pp. 1–2] illustrated in Figure 2.2(a), which is the most basic form of radio communication infrastructure. Communication between a central base station and multiple users within the service area is accomplished by assigning dedicated carrier

---

\(^1\)In strict sense, interactive face-to-face verbal communications may be regarded as a wireless communication system [1, p. 4].
Figures 2.1: The separation of uplink and downlink channels in (a) FDD and (b) TDD.

frequencies to individual users. The service coverage area of such systems can be increased by simply increasing the transmitting power of the central base station. This architecture, however, makes very inefficient use of the available spectrum in that the number simultaneous users supported within a given bandwidth per unit area is small. The development of contemporary and future wireless communication systems has, therefore, been concentrated on the improvement of spectral efficiency. Examples of these developments include frequency reuse and multiple access techniques, which are discussed in Sections 2.2.1 and 2.2.2.

2.2.1 Frequency Reuse

The cellular architecture [2, pp. 2–5] and the associated frequency reuse technique remove the limitation on the number of users for a given bandwidth by dividing the entire service area into smaller areas, known as cells, as illustrated in Figure 2.2(b). Each of these cells is covered by a low-power base station, which is interconnected with other base stations and the wider network infrastructure by radio and wired links. Each cell is assigned a subset of the total available frequency spectrum. While a cell can only support a limited number of users according to its assigned spectrum, the same subset of spectrum is reallocated/reused in other cells. For example, the shaded cells in Figure 2.2(b) employ the same subset of spectrum, and are referred to as co-channel cells. This reuse of the frequency spectrum increases the total capacity of the system; hence, it provides better spectral efficiency than the broadcast architecture.

One disadvantage of the cellular architecture is the introduction of co-channel interference, which is same band interference caused by unwanted signals transmitted
Figure 2.2: The topology of the (a) broadcast and (b) cellular architectures for wireless communication systems.

from nearby cells that employ the same subset of spectrum (these are referred to as co-channel cells). The shorter the distance between co-channel cells, the greater the influence of co-channel interference. This is a major concern in high capacity systems where small cell sizes are frequently required to support a high density of users. Severe co-channel interference can therefore occur and can greatly limit the performance of such systems. In addition, when a mobile user moves from one cell to another, a handoff process must be performed that retunes the mobile device to the frequency spectrum associated with the new cell [3, pp. 363–366]. This process increases the system complexity and can potentially interrupt the communications. In contrast, all users always connect to the central base station in the broadcast architecture regardless of their positions in the service area. Consequently, user mobility and interruptions due to handoffs are irrelevant in the broadcast architecture.

2.2.2 Multiple access techniques

Multiple access techniques enable the simultaneous sharing of the available frequency spectrum by multiple users [4, p. 395]. Frequency (or spatial) reuse is itself a form of multiple access technique that increases spectrum efficiency by assigning a subset of available spectrum in multiple cells. Alternatively, common multiple access techniques increase system capacity by simultaneously allocating the available bandwidth (in a cell) to multiple users. Common multiple access techniques include frequency division multiple
access (FDMA), time division multiple access (TDMA), frequency hopped multiple access (FHMA), code division multiple access (CDMA), orthogonal frequency division multiple access (OFDMA), space division multiple access (SDMA) and carrier-sense multiple access with collision avoidance (CSMA/CA). Since a CDMA system model has been considered in this thesis, an overview of CDMA is presented in this section. Other common multiple access schemes are outlined in Appendix B.

**CDMA**

Code division multiple access (CDMA), also known as direct sequence multiple access (DSMA) and direct sequence code division multiple access (DS-CDMA), is a spread spectrum technique in which the overall transmission bandwidth is several orders of magnitude greater than the minimum required radio frequency (RF) bandwidth\(^2\) [4, p. 404]. The total available bandwidth may be used by all users simultaneously as illustrated in Figure 2.3. Each user message is encoded with a unique user-specific code that is orthogonal to all other codes used in the system [4, pp. 405–407]. This user-specific code is called the spreading code, which is a pseudo-noise code sequence that has a chip rate several orders of magnitude greater than the data rate of the message. Thus, the signals from the active users combine with each other. The message is recovered at the receiver by correlating the received signals with the spreading code assigned to individual users. This process collects the energy spread over the transmission bandwidth into its original relatively narrow message bandwidth, which is illustrated in Figure 2.4. The processing gain \(G_p\) (also known as the spreading factor) is a key parameter in CDMA systems that is defined as,

\[
G_p(f) = \frac{\text{transmission bandwidth}}{\text{post-decorrelation bandwidth}}. \tag{2.1}
\]

CDMA systems intentionally use significantly higher transmission bandwidth than the modulating signal’s bandwidth, which provides considerable protection against multipath fading. The inherent frequency diversity of this wide bandwidth can mitigate the effects of small-scale fading. Rake receivers can be used to resolve delayed signal components and combine them to make effective use of the channel-induced multipath diversity [5, pp. 242–243].

Interference from other users are completely eliminated if mutual orthogonality exists between the spreading codes for the desired and interfering signals [1, p. 417]. If these spreading codes are not exactly orthogonal, the signals from other users appear

\(^2\)In contrast, the transmission bandwidth of FDMA and TDMA is of the same order of magnitude with the actual message bandwidth.
Chapter 2 - Propagation for Indoor Wireless Communications

Figure 2.3: User distinction in CDMA [4, p. 406].

Figure 2.4: Concepts of spreading and despreading in CDMA [1, pp. 416–420].
2.2. Fundamentals of high performance wireless communication systems

as multiple-user interference (MUI), also known as multiple-access interference (MAI). Radio channel impairments such as multipath and channel delay spread can also affect the orthogonality between the spreading codes resulting in MUI. In addition, this residual MUI can cause the near/far problem in CDMA systems, especially in the uplink due to its asynchronous nature [4, pp. 405–406]. Depending on the distances from the base station and other environmental factors, the received power from individual mobile users varies at the base station. The stronger received signal levels raise the noise floor for weaker signals, therefore decreasing the probability of the weaker signals being received. To optimise the spectrum usage, a power control scheme is usually implemented since any change in power by one user directly affects all other users sharing the bandwidth [1, pp. 411–412]. Power control assures that the power levels of all received signals at the base station’s receiver being identical, independent of their geographical locations. This solves the problem of a nearby mobile user capturing the base station’s receiver and suppressing the signals of far away users.

One of the most important advantages of CDMA in cellular environments is its near-unity frequency reuse factor [5, p. 242]. The use of uniquely-assigned, cell-specific spreading sequences in each cell site enables adjacent cells in a CDMA system to use the same frequency spectrum. In contrast, in FDMA and TDMA systems, the same frequency spectrum can be reused in different cells only with a sufficiently large cell separation distance where the influence of inter-cell interference is negligible. The universal frequency reuse of CDMA systems provides the potential of a substantial increase in user capacity per unit bandwidth. Another advantage is the ability to use soft handoff through macroscopic spatial diversity. Since all base stations can use the same frequency, a particular user can be simultaneously monitored by two or more base stations as the user roams across a cell boundary. Rake receivers can then be used at the mobile devices for combining signals from all the base stations involved in the handoff process [4, p. 407].

In both FDMA and TDMA systems, when the interference level exceeds a specified protection ratio, the receiver is captured by the interference and the channel is rendered unusable. In contrast, as the number of users increases in a CDMA system, the rise in cumulative interference is spread over the entire set of users sharing the frequency spectrum. This produces gradual degradation in the quality of all users. Consequently, there is no hard limit on the number of users in a CDMA system [1, p. 412]. Since self-interference and MUI are the primary performance-limiting factors for CDMA systems, any method that reduces the level of interference is capable of increasing the overall system performance [5, pp. 241–244]. For example, simple techniques include spatial isolation of users by cell sectorisation and discontinuous transmission relying on a voice activity detection. Others interference-reducing techniques involve sophisticated signal
processing such as interference cancellation [6], joint detection [7] and adaptive antenna arrays [8].

CDMA can be implemented either as a narrowband or wideband system. In narrowband systems, the transmission bandwidth of a single channel is less than the coherence bandwidth of the channel whereas for wideband systems, the transmission bandwidth is much larger than the coherence bandwidth [4, pp. 396–397]. Narrowband CDMA implementations include IS-95 whereas the 3G mobile communication standards W-CDMA and cdma2000 are examples of wideband CDMA systems [9, pp. 490–493]. In this thesis, a narrowband CDMA implementation has been considered due to its well-studied interference-limited performance characteristics.

2.3 The indoor radio propagation environment

In Section 2.2, an overview of the fundamentals for wireless communications has been presented. This discussion has concentrated on system-level development whereas in this section, the characteristics of radio channel propagation are discussed. In the development of mobile radio communication systems, extensive research has been performed for the understanding of propagation characteristics of radiowaves in outdoor environments. While the fundamentals of radiowave propagation remain the same in indoor environments, indoor radio channels differ from outdoor channels in two important aspects, namely (a) the propagation distances are typically much smaller, and (b) the physical variation of the environment is much greater for a much smaller range of transmitter-receiver separation distances [4, p. 123]. Indoor propagation is strongly influenced by local features, such as floor layout and building construction materials for walls, floors and ceilings [3, pp. 195–196]. This makes accurate prediction of the signal-to-interference ratio (SIR) using analytical techniques difficult.

2.3.1 Propagation mechanisms

The most basic mechanism for radio propagation is direct transmission, in which radio signals travel along the shortest path between the transmitter and receiver. This direct path can either be unobstructed (line-of-sight) or obstructed. Path (a) in Figure 2.5 is an example of obstructed direct transmission. The transmitted signals are likely to experience attenuation when passing through the obstacles. In addition to direct transmission, there are three main propagation mechanisms that influence indoor wireless systems, namely

\[^{3}\]Coherence bandwidth is defined as the range of frequencies over which the channel can be considered flat — approximately equal gain and linear phase for all spectral components within the range.
2.3. The indoor radio propagation environment

Figure 2.5: Possible propagation mechanisms in an indoor environment, including (a) transmission, (b) reflection, (c) diffraction and (d) scattering.

Reflection This occurs when a propagating electromagnetic wave strike an object. Depending on the electrical properties of the object, the wave can be partially reflected and partially transmitted or completely reflected in case of a perfect conductor [4, pp. 78–79]. Reflections typically occur at walls, floors and ceilings in indoor environments.

Diffraction This occurs when the direct path between the transmitter and receiver is obstructed by obstacles with abrupt changes such as a sharp edge or a corner. The change of fields behind the obstacle can be explained by Huygens’ principle, which states that all points on a wavefront can be considered as point sources for the production of secondary wavelet, and that these wavelets combine to produce a new wavefront in the direction of propagation [4, pp. 90–91]. Secondary waves that propagate into the shadowed region result in the apparent bending of waves around the obstacle. At high frequencies, diffraction depends on the geometry of the obstacles and the amplitude, phase and polarisation of the incident wave at the point of diffraction.
Scattering  This occurs when the propagating waves travel through a medium consisting of obstacles that are small compared to the wavelength and where the number of obstacles per unit volume is large. Scattering is produced by rough surfaces, small objects, or by other irregularities in the environment [4, pp. 100–101]. Scattering is expected to be commonplace in indoor environments where a large amount of clutter such as furniture and office equipment is present.

2.3.2 Multipath fading

As signals radiated from a base station travel through the indoor environment via different propagation mechanisms, the received signal envelope at the mobile users tends to vary as a function of distance and time. Three scales of signal fluctuation can be identified [2, pp. 67–69], namely small-scale fading, large-scale fading and distance-dependent path loss.

Small-scale fading

Small-scale fading is used to describe the rapid fluctuation of the amplitude of a radio signal over a short distance (in the order of half a wavelength) [2, pp. 67–69]. Fading is caused by interference between multiple versions of the transmitted signal that arrive at the receiver at slightly different times [4, pp. 139–141]. These multipath waves combine vectorially at the receiver resulting in a signal that can vary widely in amplitude and phase.

The Rayleigh distribution is commonly used to model the envelope (in volts) of multipath signals in wireless systems when there is no line-of-sight (LOS) between the transmitter and receiver [4, pp. 172–174]. Figure 2.6 shows the fading power of a Rayleigh distributed signal as a function of distance, which is simulated using Clarke’s scattering model [10, pp. 331–333]. The envelope probability density function (PDF) for a Rayleigh distributed received signal $v$ (in volts) is given by [3, pp. 125–127]

$$p(v) = \begin{cases} \frac{v}{\sigma^2} \exp \left( -\frac{v^2}{2\sigma^2} \right), & v \geq 0 \\ 0, & \text{otherwise} \end{cases}$$

(2.2)

where $\sigma^2$ is the mean power (in watts) of the multipath signal.

The Rician distribution was suggested by Rice [11] to model a sinusoidal wave in the presence of random noise. This distribution is, therefore, useful for the modelling of radiowave propagation in environments where there is a LOS or dominant signal component in addition to other multipath (Rayleigh) components. The envelope PDF
for a Rician distributed signal $v$ (in volts) is given by [12, pp. 328–334]

\[
p(v) = \begin{cases} 
\frac{v}{\sigma^2} \exp \left( -\frac{P^2 + v^2}{2\sigma^2} \right) I_0 \left( \frac{Pv}{\sigma^2} \right), & v \geq 0 \\
0, & \text{otherwise}
\end{cases}; \quad (2.3)
\]

where $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind, $P$ is the magnitude (field strength in volts) of the dominant signal and $2\sigma^2$ is the power (in watts) of the multipath components. The Rician distribution is often described in terms of the $K$-factor, which is defined as

\[
K = \frac{P^2}{2\sigma^2}, \quad (2.4)
\]

This $K$-factor can be interpreted as the power ratio of the dominant signal over the multipath components. Figure 2.7 shows the PDFs for several Rician distributions with different $K$-factors. The Rayleigh distribution can be regarded as a special case of Rician distribution when the magnitude of the dominant component tends to zero, namely $P \to 0, K \to 0$. In this case, (2.3) reduces to (2.2).

**Large-scale fading**

Large-scale fading is used to described the long-term fluctuation of the received signals when small-scale fading is averaged out over a localised area of the order of tens of wavelengths [2, pp. 67–69]. This type of signal fluctuation is due to the presence of
obstacles in the propagation path, hence it is also known as *shadowing*. The Lognormal distribution is commonly used to model this scale of fading [3, p. 155]. The envelope PDF for a lognormal distributed signal $v$ (in volts) is given by [3, pp. 232–233]

$$p(\bar{v}) = \begin{cases} \frac{20}{\bar{v}\sigma \ln 10\sqrt{2\pi}} \exp \left( -\frac{(20 \log \bar{v} - m)^2}{2\sigma^2} \right), & v \geq 0 \\ 0, & \text{otherwise} \end{cases} \quad (2.5)$$

where $m$ is the mean of the slow fading component (in dB), $\sigma$ is the standard deviation (in dB) and $\bar{v}$ is the mean of the fast fading voltage. Figure 2.8(a) demonstrates the Gaussian shape of the lognormal PDFs when plotted in logarithmic units whereas for Figure 2.8(b), it illustrates the asymmetrical shape of the PDFs in linear units.

**Distance-dependent path loss**

The third and largest scale of signal variation describes the attenuation of the received signal as the distance between the transmitter and receiver increases. This scale of signal variation is due to the spatial divergence of the wavefront in space over the given environment [2, pp. 67–69]. Figure 2.9 shows the linear relationship between the received signal (in dB) and the distance from the transmitter (in logarithmic units), in which small- and large-scale fading have been averaged out.
Figure 2.8: Lognormal probability density function in (a) logarithmic and (b) linear units ($m = 0$).
2.4 Antenna selection

While heavily dependent on the surrounding environment as outlined in Section 2.3, the propagation of radiowaves also depends on how they are generated. For example, the magnitude of the multipath components of a received signal can be reduced if the propagating radiowaves are focused in the LOS direction. It is therefore essential to obtain an understanding of the device that generates propagating radiowaves — the antenna.

2.4.1 Antenna fundamentals

An antenna is a physical structure that couples electromagnetic energy from a signal source to the propagation medium (such as free space) [9, pp. 85–86]. A transmit antenna bridges the signal source and the medium whereas a receive antenna intercepts electromagnetic energy incident on it and transfers the energy from the propagation medium to the receiver system. In the context of indoor wireless communication systems, key antenna parameters that can influence system performance include radiation pattern, beamwidth, gain and polarisation [9, pp. 91–96].

- The radiation pattern is a graphical representation of the received electric field (or as a function of magnetic field) at a constant radius from a transmitting antenna in any particular plane. Radiation patterns are usually presented as polar plots.

- The 3 dB beamwidth is the angle between the half-power (3 dB) points of the main
lobe on the radiation pattern of an antenna. This roughly defines the effective angle of coverage for an antenna.

- The *gain* of an antenna is defined as the ratio of the maximum radiation intensity of the antenna to the maximum radiation intensity of a reference antenna with the same power output. This effectively represents the redistribution of radiated energy relative to that for an ideal isotropic source.

- The *polarisation* of an antenna specifies the orientation of its electric field component. Maximum energy transfer is achieved if both transmitting and receiving antennas have identical polarisation.

These parameters are usually specified as free-space quantities and are subject to variations when the antenna is deployed in real environments. The variations are often due to the coupling between the antenna elements and nearby objects, such as steel-reinforced concrete walls and metal furniture. Field measurements are usually required to quantify the influence of the surrounding environment on these parameters.

### 2.4.2 Examples of antenna applications

A variety of antennas with different characteristics have been implemented in outdoor wireless communication systems. For example, sectored antennas are commonly used at the base stations of cellular systems to increase system capacity by reducing co-channel interference [4, pp. 57–60]. These antennas are essentially directional antennas that divide a cell into sectors and radiate energy into specified directions; hence, the number of effective interferers from nearby cells can be reduced. Another antenna application at the outdoor base stations of cellular systems is the use of smart antennas (or adaptive antenna arrays) for implementing spatial filtering [3, pp. 350–354]. This provides main-beam steering towards wanted signals and interference nulling for maximising the carrier-to-interference ratio (CIR). In contrast, azimuthally omni-directional antennas are generally used at mobile devices because the signals can arrive in a continuously changing random direction [1, pp. 293–295].

In indoor wireless systems, azimuthally omni-directional antennas (with a limited coverage in the vertical plane) are generally desired [9, pp. 412–413]. This can be realised with dipole-based antennas, such as telescopic $\lambda/4$-monopoles for cordless phones [9, p. 427]. Microstrip [13] and flat-panel antennas (such as the planar inverted F-antenna (PIFA) [14]) are also commonly used in indoor applications where antenna compactness and low-profile are important considerations [9, pp. 426–427].

In addition to the selection of antennas with appropriate characteristics, the deployment of antennas can also influence their performance in a practical system [15]. As the
desired antenna characteristics are subject to change when an antenna is deployed in a real environment, antenna deployment provides a degree of freedom for compensating the detrimental influence of the environment. This thesis focuses on determining the optimal deployment strategy for various deployment scenarios.

2.5 Summary

In this chapter, the fundamentals of high-performance wireless communication systems have been outlined. In particular, the frequency reuse and multiple access techniques that increase system capacities for the available frequency spectrum have been discussed. A narrowband [CDMA] system is assumed in this thesis for its well-studied interference-limited performance characteristics.

The basic mechanisms of radiowave propagation in indoor environments have been outlined. As transmitted signals travel to the receiver via different propagation mechanisms, fluctuations in received signal envelope are expected, which can be divided into three scales. Small-scale fading corresponds to the rapid signal fluctuations over a short distance relative to the wavelength. This kind of fading can be modelled by Rayleigh and Rician distributions for non-LOS and LOS environments, respectively. Large-scale fading, also known as shadowing, can be modelled by a lognormal distribution. The distance-dependent variability represents the decay of signal power as a function of distance from the transmitter when the small- and large-scale fading were averaged out.

As radiowave-generating devices, antennas play a vital part in determining how radiowaves propagate in the radio channel. The key antenna parameters that can influence system performance are outlined, which include radiation pattern, beamwidth, gain and polarisation. However, the values of these parameters are subject to change when the antennas are deployed in real environments. Strategic antenna deployment can take advantage of this variation and maximise the performance of the antennas.

References


Chapter 3

Indoor Wireless System Deployment

3.1 Introduction

In Chapter 2, the fundamentals of indoor wireless systems and the characteristics of indoor radio channels have been discussed. It was shown that propagation in indoor environments is, in general, complex and time-varying, which makes the operation of indoor wireless communication systems a challenging task. Signal processing techniques such as equalisation and channel coding are commonly used in indoor systems to mitigate the effects of the channel and therefore improve performance [1, pp. 299–358]. Alternatively, performance gains can be achieved by influencing how signals physically propagate in the indoor channel. This involves the coordinated strategic placement of indoor base stations to create an optimal propagation environment for the transmitted signals [2,3]. Moreover, the selection and deployment of base station antennas can further improve the performance of indoor systems [4].

In Section 3.2, a review of the literature considering the optimal placement of indoor base stations in typical multiple-floor office environments is presented. Section 3.3 outlines an extension of this study that quantifies the influence of external base stations. Section 3.4 discusses current strategies for the selection and deployment of base station antennas and their potential for improving system performance. An investigation into these antenna selection and deployment strategies is presented and the contributions of this research are outlined in Section 3.5. Finally, this chapter is summarised in Section 3.6.
3.2 Placement of indoor base stations

The primary focus in outdoor deployment is to provide adequate signal strength across the entire coverage area. In contrast, high-performance indoor wireless systems often require small cell sizes and a large number of base stations to provide large bandwidth and user capacity to highly localised areas. Consequently, severe co-channel interference from nearby cells can occur, which has the potential to significantly limit the performance of such indoor systems. These systems are also known as interference-limited systems. One of the main objectives for the strategic deployment of indoor systems is therefore to minimise co-channel interference among nearby indoor base stations.

An investigation into the deployment of an indoor wireless system in a typical, multi-storey office environment has been performed. Specifically, this study aims to reduce co-channel interference and therefore improve system performance by strategic placement of indoor base stations. A number of deployment scenarios were considered in an interference-limited direct sequence code division multiple access (DS-CDMA) system, in which the performance was determined by co-channel interference. The placement of a single co-channel base station on every floor of a multi-storey indoor environment was assumed in the deployment scenarios. The effects of base station antennas were neglected and conventional omni-directional base station antennas were assumed. A modified Seidel model and propagation measurement data, were used to quantify the downlink and uplink system performance in terms of outage probability.

This study identified a key propagation phenomenon — correlated shadowing — which was observed to have a significant influence on the optimal placement of indoor base stations. Correlated shadowing occurs when both the desired and interfering signals propagate via similar paths and therefore exhibit correlated mean path losses. It was suggested that in outdoor environments, the typically low level of correlation observed between desired and interfering signals is unlikely to significantly influence system performance. In contrast, strong positively or negatively correlated shadowing is common in indoor environments depending on the placement of the base stations. Hence, correlated shadowing is more likely to have a significant influence on the performance of indoor systems.

From the investigation in which was based on propagation measurements from a number of indoor environments, it was suggested that downlink system performance can be maximised by a vertically-aligned placement of base stations as illustrated in Figure 3.1(a). This deployment results in positively correlated shadowing that reduces the influence of co-channel interference on system performance. In contrast, the offset

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1In an outdoor cellular wireless system, the base stations are typically spaced far apart, each providing coverage to a large geographical area [1, pp. 25–26].
3.3 Placement of indoor base stations — with external illumination

Figure 3.1: Vertical ‘slice’ through buildings showing indoor base station deployment configurations for multiple floors.

deployment strategy (as illustrated in Figure 3.1(b)) results in negatively correlated shadowing which can degrade downlink system performance.

It was also noted that uplink system performance is dominated by the level of intra-floor (or intra-cell) interference, whereas for the downlink, inter-floor (inter-cell) interference dominates. Consequently, it was suggested that uplink system performance is relatively independent of the placement of base stations. The vertically-aligned deployment strategy, however, showed a slight improvement on uplink system performance over the offset deployment strategy.

3.3 Placement of indoor base stations — with external illumination

An extension to the study reviewed in Section 3.2 has been investigated in [3] by introducing outdoor (external) base stations. This study was intended to represent a deployment scenario in which outdoor macro- and micro-cellular coverage is complemented by indoor pico-cellular base stations, and vice versa. The same system model and performance estimation technique from [2] was adopted, and the correlation of the signals between outdoor and indoor base stations calculated from propagation measurements. As in [2], omni-directional antennas were used at all base stations. Two deployment scenarios that demonstrate the influence of outdoor-to-indoor signal correlation on indoor downlink system performance were considered and are illustrated in Figure 3.2(a) and (b). The indoor base station in Figure 3.2(a) is located near the outdoor base station. The propagation paths of the signals from the outdoor and indoor base stations have much in common resulting in a positive correlation. In contrast, a negative outdoor-to-indoor signal correlation was observed in Figure 3.2(b) where the signals from the indoor and outdoor base stations arrive at most of the measurement locations from opposite
directions. A better performance was obtained in the scenario with positive correlation than that with negative correlation. This reinforces the argument in [2] that positively correlated shadowing can improve system performance whereas for negative correlated shadowing, the influence is detrimental.

3.4 Selection and deployment of base station antennas

The optimal placement of base stations has been used to maximise performance of indoor systems in [2, 3]. However, the deployment of base stations is not limited to the placement of base stations but also includes the selection and deployment of base station antennas. Antennas in general can be divided into two categories, namely passive and active. Passive antennas refer to simple (non-powered) antenna structures without signal processing circuitry (e.g., dipole/patch antennas and antenna arrays with passive signal
3.4. Selection and deployment of base station antennas

3.4.1 Omni-directional antennas

Omni-directional antennas (such as the dipole and monopole) are characterised by their constant (or nearly constant in practical cases) antenna gain in the azimuthal plane. For example, Figure 3.4 shows the measured far-field radiation pattern of an omni-directional discone antenna in the azimuthal plane (see Appendix C). Due to their azimuthally uniform radiation patterns, omni-directional antennas are attractive candidates for wide-area coverage and mobile reception applications. They are also easily characterised by a single antenna gain parameters in system performance analysis. This type of antenna was considered in [2,3].
3.4.2 Directional antennas

In contrast to omni-directional antennas, directional antennas focus radiated energy in a particular direction(s). For example, Figure 3.5 illustrates the measured far-field radiation pattern of a directional microstrip patch antenna in the azimuthal plane (see Appendix C). The radiation pattern exhibits a distinct main beam that defines the boresight orientation of the antenna. The focussing ability of directional antennas can be useful in localising coverage and increasing the effective isotropic radiated power (EIRP). Practical directional antennas include single-element antennas (such as the microstrip patch) and multi-element antennas (such as Yagi-Uda arrays). Regardless of the number of antenna elements, passive directional antennas are single-port devices.

The effects of the deployment of directional antennas on system capacity has been investigated in [6]. In this study, a DS-CDMA system was considered and capacity was dominated by inter-cell interference. Electronically steerable directional antennas were deployed at the mobile devices. The total system capacity was evaluated as a function of the number of radio cells, referenced to the case employing omni-directional antennas on the mobile devices. The deployment of directional antennas showed a proportional increase in capacity with an increase in the number of radio cells whereas for omni-directional antennas, the capacity improvement was relatively small. It was suggested the deployment of directional antennas can be used to suppress inter-cell interference and, therefore, improve system capacity in a multi-cell system. In addition, it was shown that antenna beamwidth does not have a significant influence on system capacity. The
3.4. Selection and deployment of base station antennas

Influence of the physical orientation of fixed-beam base station directional antennas on system performance was, however, not determined. In this thesis, the influence of antenna orientation on system performance is quantified and the optimal deployment strategies for best system performance are identified.

3.4.3 MIMO antenna systems

A multiple-input multiple-output (MIMO) antenna system employs more than one transmitting and receiving signal branch as illustrated in Figure 3.6 [7]. The number of signal branches does not necessarily correspond to the number of antenna elements; instead, they represent the number of external input and output ports. MIMO systems require MEAs to transmit and receive on multiple signal branches. As these antenna elements are spatially separated, the propagation paths among the signal branches are different. Special signal processing and coding techniques can be used to exploit the spatial diversity of this channel and achieve a significant improvement in overall system performance [5, pp. 629–659].

The principles of MIMO systems were published by Foschini and Gans in 1996 [8, 9] and the first realtime prototype, V-BLAST, was demonstrated by Bell Laboratories in 1998 [10]. The capacity of a static channel, $n_T$-transmit, $n_R$-receive ($n_T$, $n_R$) MIMO system is given by

$$C = \log_2 \left| I_{n_R} + \left( \frac{\rho}{n_T} \right) \cdot HH^H \right| \text{ (bits/s/Hz)},$$

(3.1)

Figure 3.5: Measured $H$-plane radiation pattern of a directional microstrip patch antenna.
Figure 3.6: A general MIMO antenna system.

where $| \cdot |$ denotes the determinant, $n_T$ and $n_R$ are the number of transmit and receive antennas respectively, $I_{n_R}$ is the $n_R \times n_R$ identity matrix, $\rho$ is the average signal-to-noise ratio (SNR) at each receiver branch, $H$ is the normalised matrix channel impulse response, and $H^H$ denotes conjugate (or Hermitian) transpose.

The capacity of MIMO systems is proportional to the minimum number of antennas at the transmitter or receiver, $N = \min\{n_T, n_R\}$ [5, pp. 669–671]. This increase in capacity can be realised by $N$ parallel data channels in point-to-point link systems or $N$ orthogonal channels to $N$ users simultaneously in multiple-access systems. In general, MIMO techniques can be divided into those performing processing (a) only at the transmitter, (b) only at the receiver and (c) at both the transmitter and receiver [7]. The type of MIMO systems with transmitter processing only is most suitable for the downlink since no MIMO signal processing is required at the mobile devices. In contrast, MIMO systems with receiver processing only (such as V-BLAST) are most useful for the uplink since no MIMO signal processing is required at the mobile devices. The combination of these two techniques can realise high-capacity duplex channels with a simple transceiver structure at the mobile device. Although MIMO signal processing is not required at the mobile device, multiple radio frequency (RF) front-ends are still necessary. In the third type of MIMO systems, signal processing is performed at both the transmitter and the receiver. This type of MIMO system can, theoretically, provide the best performance at the expense of complex (and therefore costly) transceivers at the mobile devices. The increase in capacity can be obtained by implementing algorithms based on singular value decomposition (SVD) and space-time coding (STC).

While MIMO represents the general class of antenna systems involving multiple antennas, single-input multiple-output (SIMO) and multiple-input single-output (MISO)
3.4. Selection and deployment of base station antennas

are special cases of MIMO systems that employ a single antenna at the transmitter and receiver, respectively. Instead of conventional MIMO signal processing techniques, these systems employ alternative diversity techniques to either increase capacity or reduce interference.

SIMO systems

SIMO refers to systems employing a single antenna at the transmitter and multiple antennas at the receiver as illustrated in Figure 3.7. In contrast to receiver processing only MIMO systems, SIMO systems employ a single RF front-end at the transmitter. This significantly reduces the complexity of the transmitter but it also reduces the capacity gain relative to a full scale MIMO system. Diversity reception or beam-forming techniques are often employed in SIMO systems. Diversity reception techniques improve SNR using active signal combining scheme such as maximal gain combining (MRC) whereas beam-forming techniques (or smart antennas) modify the effective radiation patterns of the receive arrays to improve the signal-to-interference ratio (SIR). These systems are most suitable for the uplink where the signal processing hardware can be implemented at the base stations. This eliminates the need of complex signal processing hardware on mobile devices and reduces their costs.

MISO systems

MISO refers to systems with multiple antennas at the transmitter and a single antenna at the receiver as shown in Figure 3.8 [7]. MISO systems are most suitable for the downlink where the signal processing hardware can be implemented at the base stations resulting in simple mobile devices. A smart antenna at the base station, which tracks mobile users and
suppresses interference using beam-steering techniques, is an example of a MISO system.

3.5 The contributions of this thesis

The various antenna options discussed in Section 3.4 are theoretically applicable to mobile devices. The choice of antennas at mobile users is, however, often restricted due to the relatively large number of mobile users and their dynamic nature; hence, low-cost omni-directional antennas are frequently used. In this thesis, the investigation into antenna selection and deployment is therefore concentrated on base station antennas. This investigation is not limited to the choice of antenna types, but also includes the physical deployment (such as location and orientation) of the antennas in a practical system. The major aims of this research have been

- to quantify the influence of the deployment of directional antennas and MEAs at base stations on system performance, and
- to develop guidelines for optimal orientation of base station antennas.

The original contributions of this thesis are primarily concerned with presenting antenna selection and deployment strategies as alternative options for improving performance of indoor wireless systems and comparing the performance estimates of a range of deployment scenarios based on measured data. Published papers associated with this work include references [4,11–14]. These contributions are presented in Chapters 5 to 10 of this thesis.

In Chapter 5, the development of two propagation measurement systems is presented. These measurement systems are based on an existing measurement system [15, pp. 261–
In this chapter, a review of the literature into the placement of base stations and the selection of base station antennas has been presented. These deployment and selection strategies have been shown to have a significant influence on the performance of indoor wireless systems. Correlated shadowing was identified as a key parameter for the optimal placement of indoor base stations. It was suggested that strong correlations (both positive
and negative) between the desired and interfering signals are more likely to occur in indoor environments than outdoors; hence, correlated shadowing is more likely to have a substantial influence on the performance of indoor systems. The vertically-aligned deployment of indoor base stations was recommended for maximising downlink system performance due to strongly-positive correlated shadowing. A similar result was obtained in a study that evaluates the influence of outdoor-to-indoor signal correlation on indoor downlink system performance. It was suggested that positively correlated shadowing has a beneficial influence on system performance whereas for negative correlated shadowing, the influence is detrimental.

The deployment of directional antennas at the mobile devices has been shown to increase capacity as the number of cells increases. The influence of antenna orientation on optimal base station deployment, however, had not previously been determined. This is one of the objectives of this thesis that is to quantify the influence of the deployment of directional antennas on system performance.

MIMO antenna systems, which employ multiple transmit and receive antennas to exploit spatial diversity of the radio channel, can significantly increase system capacity. The full advantages of MIMO systems can be achieved when signal processing are employed at both the transmitter and receiver. Systems employing signal processing at transmitter or receiver only can still achieve a smaller capacity gain (relative to full-scale MIMO) with the advantage of reduced receiver or transmitter complexity.

Built on the foundation of this existing body of research, an investigation into the use of antenna-based deployment strategies for improving system performance has been suggested. The contributions of this thesis has been discussed.

References


Chapter 4

Investigation of Antenna Selection and Deployment

4.1 Introduction

A literature review has been presented in Chapter 3 of the research on the deployment of base stations in indoor wireless systems [1,2]. It is noted that previous research emphasises the importance of correct base station placement for optimal system performance. As an extension to this research, the influence of the selection and deployment of base station antennas on system performance is considered in this thesis. A brief overview of the use of different types of antennas in practical indoor wireless systems has been presented in Section 3.4.

In Section 4.2, the different degrees of freedom available in the selection and deployment of base station antennas are discussed. Section 4.3 outlines a number of methodologies available for evaluating the performance of these antenna options. The advantages and disadvantages of these methodologies are discussed and details of the adopted methodology are presented. A summary of the main findings of this chapter is presented in Section 4.4.

4.2 Degrees of freedom in antenna selection

In the deployment of indoor wireless systems, system planners are often given the freedom of choosing appropriate antennas at both the base stations and the mobile users. The choice of antennas at mobile users is, however, often restricted due to the relatively large number of mobile users and their dynamic nature; hence, low-cost omni-directional antennas are frequently used. In contrast, the selection of base station antennas can be easily incorporated into the design of the wireless infrastructure and coordinated by the
system planner. In this thesis, the investigation of antenna selection and deployment is therefore concentrated on base station antennas. This investigation is not limited to the choice of antenna types, but also includes the physical deployment (such as location and orientation) of the antennas in a practical system. Four aspects of antenna selection and deployment are considered in this thesis, namely (a) location, (b) orientation, (c) diversity, and (d) polarisation.

**Location**

Antenna location refers to the placement of the base station antennas relative to the operating environment. This is equivalent to the placement of base stations, which is outlined in Sections 3.2 and 3.3. The interactions between the antennas and the surrounding environment are often neglected in previous research [1,2]. These interactions can alter the radiation characteristics of the antennas and, therefore, influence the overall performance of the wireless system. An example of these interactions is demonstrated by the distorted coverage pattern of an omni-directional antenna as shown in Figure 6.18(a). Instead of radiating uniformly in the azimuthal plane, this omni-directional antenna appears to be highly directive in the corridors. The potential sources of interactions in environment include building structure and nearby metallic objects.

**Orientation**

When a conventional omni-directional antenna is deployed at a base station, its orientation (in the azimuthal plane) is irrelevant due to its uniform radiation pattern. In contrast, if a directional antenna (in the azimuthal plane) is used, the orientation of the antenna becomes an important parameter that determines the spatial distribution of transmitted signals in the environment. As explained in Section 3.4, a directional antenna focuses its radiation in a particular direction. By changing the orientation of a directional antenna, its effective coverage area in the environment can be altered. This can potentially improve system performance without any additional hardware and associated costs. Thus, the use of directional antennas may well offer a useful degree of flexibility in the planning and deployment of indoor wireless systems.

In indoor systems, aesthetics and cost are two particularly important factors. Since indoor base stations are often installed at the users’ premises, the antennas employed should be compact, inexpensive, and preferably hidden from the view of the users. Microstrip patch antennas (see Appendix C) satisfy all these requirements and, therefore, become an attractive candidate for indoor deployment. The use of microstrip patch antennas as directional antennas is assumed in the rest of this thesis, unless otherwise stated.
4.2. Degrees of freedom in antenna selection

Diversity

In previous sections, the discussion on antenna selection has been concentrated on single-element antennas. However, antenna arrays might also be a viable choice in the deployment of wireless systems. When an antenna array is employed at a base station, the individual antenna elements of the array provide different versions of the received signal as illustrated in Figure 4.1. Ideally, each version of received signals undergoes independent fading in a multipath environment. This introduces diversity into the system which can significantly improve the quality of reception if the multiple versions of the received signals are combined in an appropriate fashion [3, pp. 629–659].

The selection of antenna arrays involves the specifications of the individual antenna elements of the array that includes radiation characteristics, inter-element spacing, orientation and polarisation. Microstrip patch antenna elements have been considered as the basic building block for antenna arrays in this thesis. Array configurations consisting of identical antenna elements at various orientations and polarisations have been considered.

Polarisation

The polarisation of an antenna is defined by the orientation of the electric-field component of its transmitted electromagnetic wave [4, pp. 51–52]. The two most common types of antenna polarisations are linear and circular polarisation. For a linearly-polarised antenna, the electric-field component of the transmitted wave maintains a constant direction as the wave propagates in space. In the special case when the electric-field of the transmitted wave is normal to both the directional of propagation and the ground-plane (as illustrated in Figure 4.2(a)), the antenna is called vertically-polarised. Conversely, the antenna
is \textit{horizontally-polarised} if the electric-field is normal to the directional of propagation and parallel to the ground-plane, as shown in Figure 4.2(b). The electric-field of the transmitted wave from a \textit{circularly-polarised} antenna rotates at a constant angular velocity as it propagates in space. The electric-field, therefore, traces out a spiral path in the direction of propagation as illustrated in Figure 4.2(c).

The choice of antenna polarisation in a practical wireless system depends heavily on the environment that the system operates in. In environments where the direct line-of-sight path between the transmitting and receiving antennas is unobstructed, the transmitted signal tends to maintain its polarisation along the propagation path [5, pp. 332–335]. Consequently, a receiving antenna with matching polarisation to the transmitting antenna is usually preferred for minimising signal losses due to cross-polarisation. In contrast, the different propagation mechanisms in a multipath environment, such as reflection and diffraction, introduce different degrees of distortion to the polarisation of the transmitted signal. Although these distortions can cause severe signal losses due to cross-polarisation, it also introduces a degree of diversity that can be exploited to improve overall system performance.

4.3 Methodology for investigation

A number of antenna selection and deployment options have been identified in Section 4.2; however, their impact on system performance needs to be quantified. Antennas are clearly a vital component in indoor wireless systems, and their influence on system performance can be significant. Thus, a thorough study on the influence of these antenna options upon system performance is essential before implementing in a practical system. Due to the wide variety of antenna selection and deployment options, a systematic methodology must be formulated for this investigation. This enables direct comparisons of the system performance between different antenna options.

This research into antenna selection and deployment options is a logical extension to that in [6]; hence, a similar methodology has been employed. Figure 4.3 outlines the methodology adopted in this thesis. This methodology involves the performance estimation of a system employing one of the antenna selection and deployment options (see Section 3.4). Since antennas are the interface between the wired system and the wireless channel, they can influence how signals propagate in the environment. Consequently, this propagation must be modelled accurately for evaluating the true performance of different antenna options. An measurement-based performance estimation approach has been adopted. This approach is, however, time and labour intensive; therefore, an automated measurement system has been developed and is discussed in Chapter 5. This system is
4.3. Methodology for investigation

Figure 4.2: Polarisation of electromagnetic waves.
used in Chapter [6] in a programme of measurements in a variety of indoor environments and antenna configurations. System performance can then be estimated for individual scenarios using the system models developed in Chapter [7] for both downlink and uplink. The performance of different scenarios is compared in Chapters [8] and [9] to quantify the influence of the environment and antenna configurations on system performance.

### 4.3.1 Estimation of DS-CDMA system performance

Based on the system model developed in [6], a direct sequence code division multiple access (DS-CDMA) system has been considered in this thesis. The performance of a DS-CDMA system can be measured in terms of outage probability, which is calculated over all possible user locations across the entire environment. An outage at any given user location is defined to occur when the instantaneous bit-error-rate (BER) exceeds a specified threshold. When both the number of users in a system and the processing gain
are sufficiently large, the instantaneous composite interference of the received signal at a user is assumed to be Gaussian distributed. The BER of the received signal at the user can then be estimated by its instantaneous signal-to-interference ratio (SIR) using the Gaussian Approximation [7], namely

\[ \text{BER} \approx \Phi(\text{SIR}), \]  

(4.1)

where \( \Phi(\cdot) \) is the complementary Gaussian probability integral.

Assuming binary phase-shift keying (BPSK) modulation, the instantaneous SIR of a user in the downlink transmission of a multi-cell DS-CDMA system is given by [1]

\[ \text{SIR} = \frac{1}{\sqrt{\frac{\alpha}{3N}(K - 1 + \beta)}}, \]  

(4.2)

where \( \alpha \) is the voice activity factor, \( N \) is the processing gain, and \( K \) is the number of users in each cell. The variable \( \beta \) is location dependent, and is given by

\[ \beta = \frac{KP_{\text{int}}}{P_{\text{des}}}, \]  

(4.3)

where \( P_{\text{int}} \) and \( P_{\text{des}} \) are the instantaneous received power from the interfering and desired base station respectively. The ratio \( P_{\text{des}}/P_{\text{int}} \) is defined as the carrier-to-interference ratio (CIR) of the received signal at the user.

Similarly, the instantaneous SIR at the desired station in uplink transmission of a multi-cell DS-CDMA system is given by [1]

\[ \text{SIR} = \frac{1}{\sqrt{\frac{\alpha}{3N} \left( \frac{\psi + \xi}{\varphi} \right)}}, \]  

(4.4)

where \( \psi \) and \( \xi \) are the composite intra- and inter-cell interference power, respectively, and \( \varphi \) is the desired signal power. The ratio \( \varphi/(\psi + \xi) \) is defined as the CIR at the desired base station.

When \( N, K \) and \( \alpha \) are all fixed as system parameters, both the downlink and uplink system performance can be fully characterised by their respective CIRs. Hence, the challenge of estimating downlink and uplink system performance reduces to estimating the respective CIRs using either propagation modelling or field measurements. Sections 4.3.2 and 4.3.3 discuss the advantages and disadvantages of these estimation techniques.

Although this set of system performance equations is only a simplified model based upon a set of assumptions [6,8], it is adequate for quantifying the influence of different
antenna selection and deployment options on system performance. The absolute accuracy of the performance estimates is of secondary importance as the analysis presented focuses on comparing the relative performance for different deployment scenarios.

4.3.2 Disadvantages of propagation modelling

Propagation modelling refers to the prediction of signal strength (or path gain) at desired locations based on some predetermined parameters (such as path length and frequency) of the environment. The simplest propagation model is the free space model, or the Friis free space equation [5, pp. 70–74]. The free space received power $P_r$ for a receiver at a distance $d$ away from a transmitter is given by

$$P_t(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2},$$

(4.5)

where $P_t$ is the transmitted power, $G_t$ and $G_r$ are the antenna gain of the transmitting and receiving antennas respectively, and $\lambda$ is the wavelength. The free space equation (4.5) can be rearranged and expressed in terms of path gain as

$$PG(d) \text{[dB]} = P_R - P_T = 20 \log \left( \frac{\lambda}{4\pi d} \right) + G_T + G_R$$

(4.6)

where $PG$ is the path gain which is defined as the difference (in dB) between the receiver and transmitted power, $P_R$ and $P_T$ are the received and transmitted power in dBm respectively, $G_T$ and $G_R$ are the antenna gain of the transmitting and receiving antennas in dB respectively. In this model, path gain is a sole function of the separation distance between the transmitter and receiver. As this model effectively considers only the direct line-of-sight (LOS) path between the transmitter and receiver, its application is limited in practical environments that often contain other indirect signal paths. This model, however, forms the basis for more sophisticated propagation models that give a more accurate representation of real-world channels.

Empirical approach

The distance-dependent free space model provides a good estimate in outdoor environments with an unobstructed LOS path between the transmitter and receiver. In contrast, indoor environments are more complicated to model in the sense that they are time variant (for example, people move around, doors are closed) and the transmitted signal can be scattered by surrounding objects. This can lead to significant signal variability over a relatively short distance. Thus, statistical models based on the free space model are often adopted in indoor environments [3, pp. 165–167], and model the time-varying
4.3. Methodology for investigation

nature of indoor environments using a known statistical distribution (such as log-normal). More representative statistical models (such as the Seidel model adopted in [6]) require site-specific information that describes how signals propagate in the environments. This information [5, pp. 123–131] (such as path loss exponent, wall attenuation factor (WAF) and floor attenuation factor (FAF)) introduces additional degrees of freedom to better estimate the signal strength.

However, these statistical models are not applicable in the context of this thesis because they often assume the use of omni-directional antennas. They fail to provide information about the interactions between different types of antennas and the surrounding objects in indoor environments, which is the focus of this thesis. Although previous use of statistical models for directional antennas in outdoor mobile channels has been reported [9], the modelling for indoor environments requires more sophisticated deterministic models such as ray tracing and electromagnetic-based methods.

Deterministic approach

In contrast to the empirical (statistical) approach, ray tracing is a deterministic technique that estimates the propagation of electromagnetic waves using high-frequency asymptotic approximation [10, 11]. Ray tracing is based on geometrical optics (GO) that implies straight ray paths and power decay inversely proportional to distance squared. Transmission, reflection, refraction, or a combination of these can occur to the ray paths depending on the angle of incidence and the electromagnetic properties of the scatterers. Further accuracy can be achieved by incorporating diffraction using the uniform theory of diffraction (UTD) [12]. The received signal can then be estimated by summing up the dominant direct and scattered rays launching from the transmitter.

Ray tracing methods have been widely used for various propagation environments including both outdoor [13,14] and indoor [15–17] environments. In a ray tracing model for indoor environments, a building is represented by a set of polygonal walls. Each wall and other scatterers are classified with a material type of certain electromagnetic properties (such as permittivity and permeability), which can be obtained from architectural drawings or field measurements. The accuracy of the model is highly dependent on the accurate estimation of these geometrical and electromagnetic information, which can be time-consuming to collect. In addition, ray tracing methods are most accurate when the point of observation is many wavelengths from the nearest scatterers, and all scatters are large (compared to a wavelength) and smooth. These assumptions may not be true when the antennas of the transmitter and receiver are located in close proximity to the scatterers, which is not uncommon in indoor environments. In such situations, a computation-intensive electromagnetic method that solves Maxwell’s equations for the electric field
distribution is required. The boundary conditions of Maxwell’s equations represent
the physical properties of the walls and other obstacles that scatter the radiowaves.
However, such boundary conditions are highly complicated to formulate in a complex
indoor environment. An overview of recent developments in electromagnetic methods is
presented in [18].

Regardless of the technique employed, propagation modelling is only an approximation
and always produces discrepancies with real-world environments. It is therefore essential
to verify the results of such models with propagation measurements in the real environ-
ment.

4.3.3 Alternative approach — measurement-based performance
estimation

As an alternative approach to propagation modelling in the estimation of system perfor-
mance, the variables for desired signal and interference power in (4.2) and (4.4) can be
directly measured from the real indoor environment. This measurement-based approach
emulates the deployment of a practical system in its actual operating environment.

In this approach, base stations are deployed in desired locations, and measurements
are performed at representative locations of mobile users. Simplified transmitting and
receiving hardware is implemented. Specifically, a simple continuous-wave (CW) is
transmitted only without any modulation and high-level error coding schemes. This
simplified system enables the quick but representative evaluation of the radio channel
without the complexity and costs associated with a fully-operational system. The
measured data implicitly includes all the interactions between the antennas and the
surrounding environment. It also incorporates shadowing variations of the received signal,
whereas fast fading can be modelled by a known statistical model such as a Rayleigh or a
Rician distribution. Consequently, this approach is effective in identifying and quantifying
the performance of different antennas in the environment.

This measurement-based approach has also been adopted in previous research to
investigate the effects of antenna directivity [19], polarisation [20–22] and antenna
arrays [23] in indoor environments. The advantage of this measurement-based approach
is that the influence of propagation is included implicitly. This provides an unbiased
representation of the environment and, therefore, facilitates trustworthy performance
estimates.
4.3.4 Adopted performance estimation approach

Since this thesis focuses on antenna selection and deployment strategies, it is necessary to adopt a methodology that is able to quantify the effectiveness of such selection and deployment strategies in real-life systems. In the estimation of system performance, the measurement-based approach has been adopted because it inherently includes the interactions between the antennas and the environment. It also provides an unbiased representation of the radio channel without any assumptions on how signals propagate in the environment. Although this measurement approach is time and labour intensive, it can be significantly reduced by automating the measurement system and process. While simple statistical propagation models offer quick estimates of how signals propagate in an indoor environment, they do not consider the antenna factor. The ray tracing method provides a good compromise on the accuracy of signal prediction and computational complexity; however, it is just an approximation to the exact solution for electromagnetic fields, and sometimes fails for regions in close proximity to the scatterers. Electromagnetic methods that solve Maxwell’s equations for electromagnetic fields can sometimes provide an accurate representation of the indoor channel with antenna-specific details. However, they are computationally expensive and often require very detailed knowledge of the geometrical and electromagnetic characteristics of the environment. The data collection effort in these cases is comparable to that of performing a full-scale propagation measurement campaign in the indoor environment. As a consequence, the measurement-based approach is selected for estimating the received signal strength in this thesis. Instead of evaluating the accuracies of various propagation models as in [6], only the measurement-based performance estimation approach has been used in this thesis. The development of an accurate propagation modelling method is beyond the scope of this thesis.

4.4 Summary

In this chapter, a number of antenna selection and deployment options including antenna location, orientation, diversity and polarisation are discussed. The emphasis of this thesis is to evaluate and quantify the influence of these antenna options upon indoor system performance. A methodology has been chosen by adapting previous research [6] for this study. This methodology involves the formulation of a series of deployment scenarios and the estimation of their respective system performance. The advantages and disadvantages of various performance estimation approaches have been outlined; however, the measurement-based approached has been adopted for its accuracy and inherent information on the interactions between the antennas and the surrounding environment.
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References


Chapter 5

Propagation Measurement Systems for Performance Estimation

5.1 Introduction

In Chapter 4, a measurement-based performance estimation methodology was discussed for evaluating the influence of antenna selection and deployment strategies on system performance. Although an appropriate propagation database is a core component of this methodology, it did not exist for the environments considered in this study. The development of a propagation measurement system is therefore essential for constructing the required propagation database.

This chapter documents the development of two measurement systems that satisfy the requirements for evaluating various deployment strategies. In Section 5.2, the basic assumptions for the measurement system and the specific requirements for individual deployment strategies are discussed. Due to the diversity of requirements, two measurement systems have been developed and issues relating to their implementation are described in Sections 5.3 and 5.4 respectively. This chapter is summarised in Section 5.5.

5.2 Measurement system requirements

The basic objective of the proposed measurement system is to record propagation characteristics of the desired indoor environments and store these in a comprehensive propagation database. This propagation database can then be used in the analysis of system performance for different deployment strategies. Accordingly, the proposed measurement system must not only fulfil the basic requirements necessary for the construction of a propagation database, but also adapt to the specific features of individual deployment strategies.
Since an indoor wireless system with a cellular architecture has been considered, the proposed measurement system was divided into separate base and mobile stations. This modular design enables the reuse of the same mobile station for different configurations of the base station under different deployment scenarios. During the course of the measurements, the base stations remain stationary whereas the mobile stations would be moved around the environment recording propagation measurements at various locations. This discourages any cable connections between the base and mobile stations. Since a prolonged period of time is frequently needed to perform measurements at a large number of locations, the measurement environment must be kept stationary. This facilitates comparisons between different sets of measured data.

Indoor wireless systems such as wireless local area network (WLAN) systems and third/fourth generation mobile systems are considered in this thesis, which have a typical operating frequency in the range from 1.8 to 2.4 GHz. Consequently, the components of the measurement system, especially the antennas, must be designed to operate over this frequency range. In accordance to radiocommunications regulations, a short-term radio licence was obtained from the Radio Spectrum Management Group of the Ministry of Economic Development for the propagation measurements at the desired frequency band. The transmission of an unmodulated carrier without any bit-level information has been assumed. This greatly simplifies the design of the measurement system since only continuous-wave (CW) transmissions at a single frequency are required.

Another important design factor under consideration is the propagation characteristics of the measurement environment. In the desired frequency band of 1.8 to 2.4 GHz, the wavelength of the transmitted signal is of comparable size to the building structure and furniture in the indoor environment. As a result, severe distortion to the signal through various propagation mechanisms such as attenuation, reflection and diffraction can occur. Consequently, high-resolution measurements with short distances between measurement locations are necessary to record the complex propagation characteristics of the environment. As the signals tend to arrive at the receiver via different propagation mechanisms, the local received signal strength fluctuates due to multipath fading. It is therefore necessary to collect samples of the received signal around a local area at every measurement location and use these to calculate the local average and statistical distribution of the received signal.

Finally, due to the large number of measurements involved, it is advantageous to automate the overall measurement process. The automation of the measurement system saves data collection time and facilitates measurements with a wider range of deployment scenarios.

As a summary, the proposed measurement system satisfies a set of basic requirements,
namely

- separate base and mobile stations;
- no physical connection between base and mobile stations;
- configurable base station and a standard mobile station;
- a transmitter and receiver pair operating on unmodulated carrier signal at a single
  frequency over the range of 1.8 to 2.4 GHz;
- closely-spaced measurement locations;
- a receiver collecting a sample of measurements over a localised area at every
  measurement location; and,
- an automated measurement process.

In addition, specific requirements must be fulfilled for deployment strategies based on
(a) antenna location, (b) orientation, (c) polarisation and (d) diversity.

**Antenna location**

When assembling a propagation database for an indoor environment, received signal
strength measurements across the entire environment must be performed for every poten-
tial base station location. The potential base stations can be located indoors (providing
services to the environment) or outdoors (acting as external interferers). It would be
very time-consuming to perform measurements for individual base station locations in
sequence. The data collection time could be significantly reduced if measurements for
multiple base station locations could be performed simultaneously. Hence, the proposed
measurement system allows for simultaneous measurements of multiple base stations that
are distinguished by slightly different transmitting frequencies.

The intended analysis for this deployment strategy is based on the signal strength of
received signals; hence, the measurement system should record the received powers and
phase measurements are not necessary.

**Antenna orientation**

In order to explore the influence of antenna orientation on deployment, the proposed
measurement system must allow for both omni-directional and directional antennas on
the base stations. The orientation of the directional antennas should be freely adjustable
with a high level of accuracy. Given these requirements, it is advantageous to develop
an automated antenna orientation system, which should allow remote control of antenna orientation.

Similar to the antenna location deployment strategy, the analysis for the antenna orientation deployment strategy is based on power measurements of the received signals only. Recording of the signal phase is therefore not required.

**Antenna polarisation**

Linearly-polarised antennas are considered for the measurement system due to their simplicity. Vertical polarisation is the primary choice for antennas on both base and mobile stations in accordance with previous research [1]. However, the antenna at the base stations can be configured with variable polarisation. Furthermore, antenna polarisation can be extended into three-dimensions using an antenna structure with orthogonal planes of polarisation.

As in the previous case, power measurements of the received signals are adequate for the analysis of this deployment strategy, and phase measurements are not essential.

**Antenna diversity**

The deployment strategy of antenna diversity involves the use of a MEA at the receiver. A simple uniform linear array (ULA) design with two or more antenna elements is adequate in providing basic signal diversity for the intended analysis. Individual elements of the antenna array can be designed with different polarisations for minimising the mutual coupling between the elements. The mutual coupling can be further reduced by the use of a three-dimensional antenna array with orthogonal planes of polarisations.

The analysis of antenna diversity requires precise phase measurements between individual elements of the antenna array. Hence, the complex received signals must be recorded from individual elements of the antenna array simultaneously. For accurate complex voltage measurements, a phase reference between the base and mobile stations is essential.

**Summary of requirements**

In summary, the deployment strategies based on antenna location and orientation require a measurement system that supports simultaneous measurements from multiple base stations. The base stations should be configured with a choice of either omni-directional or directional antennas on an automated antenna orientation system. This measurement system is expected to record the power of the received signals. In contrast, a measurement system that records complex voltages of the received signals is required
for the deployment strategy based on antenna diversity. Antenna arrays with elements of different polarisations should be configured at the base stations. This measurement system would also satisfy the requirements for the deployment strategy based on antenna polarisation.

These diverse requirements suggest the development of two separate measurement systems: a power-based system for the deployment strategies based on antenna location and orientation; and, a complex-voltage-based system for the deployment strategies based on antenna polarisation and diversity.

5.3 The path-gain measurement system

A path-gain measurement system has been developed to collect signal power measurements. Using this measurement system, a high-resolution propagation database has been built for the analysis of system performance due to antenna location and orientation. Figure 5.1 shows an overview of the measurement system. At the transmitter side, a signal is generated and passed through feeder cables to an antenna that radiates the signal into the radio channel. The receiver side reverses the process and recovers the original transmitted signal. The measurement system gives an estimate of the path-gain of the radio channel, which is defined as the aggregate effect of the radiation properties of the antennas and the propagation characteristics of the radio channel.

Mathematically, the received signal power $P_r$ (in dBm) at the receiver is defined from the Friis free space equation [2, pp. 70–74], which reduces to

$$P_r = P_t - (L_{ft} + L_{fr}) + (G_t + G_r) + G_{\text{channel}},$$

(5.1)
where $P_t$ is the output power (in dBm) of the transmitter, $L_{ft}$ and $L_{fr}$ are the power losses (in dB) in the transmitter and receiver feeder cables respectively, $G_t$ and $G_r$ are the antenna gains (in dBi) for the transmitting and receiving antenna respectively, and $G_{\text{channel}}$ is the channel gain (in dB). Rearranging (5.1), the path-gain of the radio channel $PG$ (in dB) can be defined as

$$PG \triangleq G_{\text{channel}} + (G_t + G_r) = P_r - P_t + (L_{ft} + L_{fr}). \quad (5.2)$$

As shown in (5.2), measurements of the transmitted and received signal power must be performed for estimating the path-gain of the radio channel. However, the absolute level of the transmitted and received power is irrelevant given that the channel is linear and provided that the received power is above the noise floor. It is also essential to determine the power losses in the feeder cables for an accurate estimate of the path-gain value.

This measurement system is divided into two parts, namely base and mobile stations. Downlink transmission is assumed where signals propagate from the base station to the mobile station.

**The base station**

The base station is the transmitting end of the measurement system consisting of a signal generator, feeder cable and a transmitting antenna. Two types of signal generators were employed to provide the signal source. One type of signal generator was custom-built based on the Mini-Circuits POS-2000 voltage controlled oscillator (VCO) and the National Semiconductor LMX2320 frequency synthesiser [1, pp. 262–264], whereas the second type was a HP 8648C signal generator. Both types of signal generators generate a CW signal source at the operating frequency of around 1.885 GHz. The signal is radiated into the measurement environment via one of the transmitting antennas. The antennas were mounted on top of a mast at a height of 1.8 m. There were two types of transmitting antennas used, namely omni-directional and directional antennas. As shown in Figure 5.2(a), discone antennas [3] were selected as omni-directional antennas. On the other hand, microstrip rectangular patch antennas were designed and fabricated as directional antennas. The radiating elements of the patch antennas have a dimension of 48.3 mm × 37.6 mm with microstrip feed-line as shown in Figure 5.2(b). These patch antennas have a gain of 5.8 dB relative to the discone antennas and a 3 dB beamwidth of 65° at the resonant frequency of 1.885 GHz. The detailed specifications of the discone and patch antennas are presented in Appendix C.

The directional antennas can be configured in different orientations for the propagation measurements. For accurate and repeated orientation of the directional antennas, the antennas were mounted on a remote-controlled antenna rotator. The antenna rotator
5.3. The path-gain measurement system

receives commands from a host computer via a RS-232 interface and automates the orientation of the directional antenna in steps of one-degree resolution.

Propagation measurements can be performed simultaneously for multiple base stations at different locations in the environment. This significantly reduces the data collection time. The base stations differentiate themselves by transmitting on slightly different frequencies (typically 400 kHz apart) around the operating frequency of 1.885 GHz. A total of twelve base stations with omni-directional antennas and two base stations with directional antennas were employed in the measurements. The left hand side of Figure 5.3 shows the arrangement for multiple base stations measurements.

The mobile station

The mobile station is the receiving end of the measurement system and consists of an antenna, feeder cable and a test receiver. The mobile station antenna is a half-wavelength folded-dipole [4, pp. 458–462, 480–483] that was designed for an operating frequency of 1.885 GHz with a half-wavelength balun. The antenna was mounted on a rotating arm 0.5 m in radius, and was positioned at the same height as the base station antennas. The distance travelled by the antenna in one revolution of the rotating arm is approximately 20 wavelengths at the operating frequency. Measurements of the instantaneous received signal are performed while the antenna structure is rotated. Due to the repetitive nature of the measurement procedure, the rotation of the antenna structure has been automated using a rotator. The right hand side of Figure 5.3 shows the arrangement of the mobile station with an antenna rotator. A total of 360 evenly-spaced measurements are taken in one revolution of the antenna structure. The antenna rotator provides trigger pulses to the receiver at every degree of rotation. These pulses ensure accurate timing of the sampling instants.
Figure 5.3: Block diagram of the path-gain measurement system for a multiple-base-station arrangement.
5.3. The path-gain measurement system

The received signal from the antenna is recorded by a Rohde & Schwarz ESVN40 test receiver. A measurement is performed upon every trigger pulse from the antenna rotator. Due to its high sampling rate and the ability to scan across a list of frequencies, the test receiver is able to record the received signals from multiple base stations simultaneously. Hence, a total of 360 measurements can be performed for each individual base station in one revolution of the receive antenna.

The measurement process

The overall measurement progress is coordinated by control software on a host laptop computer at the mobile station. The control software was written in C/C++ under the Linux operating system. The software controls the rotation at the antenna rotator of the mobile station via an RS-232 interface, and sends instructions to and retrieves measured data from the ESVN40 test receiver via a GPIB interface. The host laptop connects wirelessly with the remote laptop using an IEEE 802.11b WLAN to eliminate any physical connections between the base and mobile stations. The WLAN operates at around 2.4 GHz; therefore, it does not interfere with the propagation measurements at 1.885 GHz.

During the first stage of the fully automated measurement cycle, the control software initialises the test receiver into the scanning mode for signal measurements. The software also resets the antenna rotators at both base and mobile stations and returns them to the reference orientation. The software then instructs the antenna rotator at the mobile station to move one revolution. The rotator indicates the measurement instants by sending trigger pulses to the test receiver as it rotates. The test receiver scans across the predefined frequency list and records the received signal power for up to 14 base stations at every trigger pulse. Next, the control software instructs the antenna rotators at the base stations to rotate the directional antennas into the next predefined orientation. Measurements at the mobile station are then repeated for all predefined antenna orientations. The entire measurement process is then repeated at all other mobile station locations successively.

5.3.1 Typical measurement results

A series of measurements have been performed in real indoor environments to verify the validity of the path-gain measurement system. Figure 5.4(a) shows the typical received signal for a base station with an omni-directional antenna in both line-of-sight (LOS) and non line-of-sight (NLOS) environments. The instantaneous path-gain measurements show a fading pattern as the receiving antenna travelled along a small circular locus on the rotating arm. More frequent fading is observed in the NLOS environment than in the LOS environment. In LOS environments, the fading of signal is most likely due to the
addition of a few dominant signal components, which produces occasional deep fades. In contrast, the large number of multipath signal components in NLOS environments tend to produce more frequent fades with smaller magnitude. The first row of Table 5.1 shows the mean path-gain measurements for the base station with an omni-directional antenna under both LOS and NLOS environments.

Similar measurements in the identical LOS and NLOS environments have been repeated for a base station with a directional antenna. The directional antenna has been oriented with its boresight direction (direction of maximum gain) pointing towards the mobile station. Figure 5.4(b) shows the fading patterns for this scenario, which is very similar to those in the scenario with an omni-directional antenna. The mean path-gain in the LOS environment for the directional antenna scenario is slightly higher than that of the case for omni-directional antenna. This increase in mean path-gain is expected due to the higher gain of the directional antenna. In contrast, the mean path-gain in the NLOS environment for the directional antenna scenario is slightly lower than that of the case for omni-directional antenna. This is thought to be due to the majority of the transmitted power being focused in the boresight direction, whereas less power is scattered into the NLOS environment.

Instead of pointing in the LOS direction towards the mobile station, the directional antenna on the base station can also be orientated at various angles relative to the LOS direction. The orientation of the directional antenna is labelled by the angle measured relative to (in a clockwise direction) the LOS direction as shown in Figure 5.5. The mean path-gain of different antenna orientations under both LOS and NLOS environments are presented in Table 5.1. It is clearly shown that the mean path-gain from a directional antenna varies with its orientation. Variations in mean path-gain measurements of up to 15 dB are observed. This observation suggests that the orientation of directional antennas can have a significant impact on performance of a wireless communication system.

### 5.4 The complex-voltage measurement system

As the path-gain measurement system records received powers to be used in the analysis of deployment strategies based on antenna location and orientation, a second measurement system has been developed to record complex voltages for the analysis of deployment strategies considering antenna polarisation and diversity. One of the distinctive features of the complex-voltage measurement system is that it records the received complex signals (both magnitude and phase) from a multi-element antenna array.

Figure 5.6 shows an overview of the complex-voltage measurement system. A transmitter generates a transmitted signal, which is passed through feeder cables to a
Figure 5.4: Typical measured data for a base station with (a) an omni-directional and (b) directional antennas under both LOS and NLOS conditions.
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Figure 5.5: The orientation of a directional antenna at the base station.

Table 5.1: Typical mean path-gain measurements for a base station with different antenna configurations (OA and DA denote omni-directional and directional antennas, respectively.)

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Orientation</th>
<th>Mean path-gain (dB)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LOS</td>
<td>NLOS</td>
<td></td>
</tr>
<tr>
<td>OA</td>
<td>N/A</td>
<td>-44</td>
<td>-73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0°</td>
<td>-40</td>
<td>-79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60°</td>
<td>-46</td>
<td>-71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120°</td>
<td>-53</td>
<td>-64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>180°</td>
<td>-47</td>
<td>-78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>240°</td>
<td>-53</td>
<td>-76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300°</td>
<td>-46</td>
<td>-77</td>
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<table>
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<th>DA</th>
<th></th>
<th></th>
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<td>0°</td>
<td>-40</td>
<td>-79</td>
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<td></td>
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<td>-46</td>
<td>-71</td>
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<td>240°</td>
<td>-53</td>
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<tr>
<td>300°</td>
<td>-46</td>
<td>-77</td>
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</tr>
</tbody>
</table>
5.4. The complex-voltage measurement system

Figure 5.6: Overview of the complex-voltage measurement system.

...single transmitting antenna. The transmitted signals travel through different propagation paths in the environment and arrive independently at different elements of the receiving antenna array. A receiver then records the complex voltages from the \( n \) antenna branches simultaneously. This type of radio channel with a single transmitting antenna and multiple receiving antenna branches is known as a single-input multiple-output (SIMO) channel [5, p. 275].

Mathematically, the received complex signal \( \mathbf{r} = [r_1, r_2, \ldots, r_n]^T \) at the receiver is given by [5, pp. 186–189]

\[
\mathbf{r} = \mathbf{h}s,
\]

(5.3)

where \( \mathbf{h} = [h_1, h_2, \ldots, h_n]^T \) is the complex channel responses for the \( n \) propagation paths including the effects of both the transmitting and receiving antennas, and \( s \) is the transmitted signal. The complex-voltage measurement system estimates the channel responses \( \mathbf{h} \) by determining the ratio between \( \mathbf{r} \) and \( s \).

Similar to the path-gain measurement system, the complex-voltage measurement system is divided into base and mobile stations. However, in contrast, the mobile station contains the transmitter, whereas the base station contains the receiver. Accordingly, signals propagate from the mobile station to the base station, often referred to as an uplink transmission.

The base station

The base station is the receiving end of the measurement system, and comprises an Agilent E8364A PNA series network analyser (PNA) with Option 014. The PNA is a conventional two-port, swept-frequency, vector network analyser. However, the additional component, Option 014, provides direct access to the four internal receivers of the PNA, which enables simultaneous measurements of multiple complex-voltage channels. In practice, one of the
internal receivers is used in the internal phase locking of the PNA. Consequently, three independent receiving channels are available for SIMO channel measurements. Since a two-port calibration is no longer valid for this configuration of the PNA, a normalisation procedure has been developed for correcting the cable losses and different sensitivity levels of the internal receivers. When normalising the receiver channels, the signal source is fed directly into the internal receivers in succession. These measurements establish the reference signal level for individual channels and are used to standardise all subsequent channel measurements.

A three-element antenna array provides the three signal channels into the PNA as shown in Figure 5.7. The antenna array is mounted on top of a mast at a height of 1.8 m. Figure 5.8 shows the three microstrip patch arrays used in the measurement system. The three array designs consist of identical linearly-polarised elements that are probe-fed square patches 37.8 mm in length, with a resonant frequency of 1.885 GHz. The first two arrays, namely SIMO1 and SIMO2, are ULA with $\lambda/2$ inter-element spacing. Figure 5.8(a) shows the layout of Array SIMO1. The dotted lines indicate the axes of polarisation for the antenna elements. It is clearly seen that all antenna elements are vertically polarised. This is the most common type of antenna array, which is regarded as a benchmark in the performance analysis of the antenna arrays. Array SIMO2 is a slight variation of Array SIMO1 with different element polarisations. Figure 5.8(b) shows the layout of Array
Table 5.2: Mutual coupling between antenna array elements at 1.885 GHz

| Antenna array | \(|S_{21}\)| (dB) between | Elements 1 and 2 | Elements 1 and 3 | Elements 2 and 3 |
|---------------|---------------------------|------------------|------------------|------------------|
| SIMO1         |                           | -24              | -36              | -24              |
| SIMO2         |                           | -41              | -35              | -34              |
| SIMO3         |                           | -49              | -40              | -45              |

SIMO2 and the axes of polarisation for its elements. The array’s first element from the left is vertically-polarised; the second element is horizontally-polarised; and, the third element has a 45° polarisation. This array has been designed for evaluating the impact of element polarisation on overall system performance. Figure 5.8(c) shows Array SIMO3, which is a cube-shaped array with all the elements facing outwards. These elements have orthogonal polarisations in the three-dimensional space. This array design was inspired from the isotropic electric field probes [6] used in electric-field sensing, which consist of three orthogonal electric dipoles and three detectors. In principle, this arrangement minimises the mutual coupling and signal correlation between the elements [7]. The detailed specifications of these antenna arrays are presented in Appendix C.

Table 5.2 shows the measured mutual coupling (\(|S_{21}\)| in dB) between different element pairs of the three antenna arrays considered. It is clearly shown that Array SIMO3 has the lowest mutual coupling between any of its element pairs. The table also demonstrates that cross-polarisation (such as Elements 1 and 2 of Array SIMO2) causes lower mutual coupling than large element spacing (such as Elements 1 and 3 of Array SIMO1). This observation is consistent with [8, 9], which suggests that low levels of cross-polarisation is a desirable choice for antenna array designs.

Similar to the directional antennas in the path-gain measurement system, the antenna arrays of this measurement system can be oriented in different directions for measurements. However, any physical movements in the antenna feeder cables would cause a distortion in the phase relationship between the antenna elements. Stable phase relationship is essential in the analysis of the performance of antenna diversity; hence, the orientation of the array is fixed throughout the measurements process. The array orientation is only changed after measurements across the entire environment have been completed. Since the feeder cables remain stationary during the entire measurement process, conventional radio frequency (RF) cables can be employed instead of phase-stable cables, which are usually used in complex-voltage measurements.
Figure 5.8: The layout of antenna arrays (a) SIMO1, (b) SIMO2 and (c) SIMO3. (The dotted lines indicate axes of polarisation for the antenna elements.)
5.4. The complex-voltage measurement system

The mobile station

The transmitting end of the measurement system, namely the mobile station, consists of a folded dipole on a rotating arm, an antenna rotator, a signal generator, and control software on a laptop computer. Instead of the internal signal source from the PNA, an external signal generator provides the signal source for the measurements. A HP 8648C signal generator provides the CW signal source at 1.885 GHz. The signal generator is synchronised with the PNA using the 10 MHz reference output from the PNA via a coaxial cable. This configuration enables a greater separation distance between the mobile and base station than using the internal signal source from the PNA. However, significant phase distortion can be introduced if the 10 MHz reference cable is disturbed during the measurement of local signal variations at a particular mobile location. The 10 MHz reference cable has been kept stationary during measurements at individual mobile locations to minimise this phase distortion. The phase changes introduced when the mobile station is moved to another location has been considered as a change in the measurement environment and, therefore, neglected.

The signal from the signal generator is fed into an omni-directional folded dipole antenna, which is mounted on an antenna rotator with a rotating arm 0.5 m in radius at the same height of the base station antenna. The antenna travels a distance of around 3.1 m in one revolution, which is approximately 20 wavelengths at the operating frequency. As the antenna structure is rotated, the antenna rotator sends out trigger pulses to the PNA for recording the instantaneous received signal at every degree of rotation. A total of 360 samples of the local signal variations are recorded for individual antenna elements in one revolution of the antenna structure. Phase distortion introduced in the feeder cable due to the rotation of the antenna structure is relatively small and, therefore, neglected in subsequent analysis.

The measurement process

Similar to the path-gain measurement system, the overall measurement progress of the complex-voltage measurement system is coordinated by the control software on a laptop computer at the mobile station. The control software has been written in Visual Basic for Application and is executed under Microsoft Excel for Microsoft Windows. The software controls the rotation of the antenna rotator at the mobile station via an RS-232 interface. It also communicates with the PNA using the DCOM protocol over a IEEE 802.11b WLAN link.

The control software initiates the measurement process by setting the PNA into external trigger measurement mode. The software then instructs the antenna rotator at the mobile station to rotate for one revolution. The rotator indicates the measurement
instants by sending trigger pulses to the PNA as it rotates. The PNA then records the complex voltages from the three antenna elements simultaneously upon every trigger pulse. The measurement process is then repeated at other mobile station locations.

5.4.1 Typical measurement results

A series of measurements have been performed using the complex-voltage measurement system. Figure 5.9 shows the typical received signal (in path-gain) for individual antenna elements of Array SIMO1 and SIMO2 when there is a clear LOS path between the broadside direction of the arrays and the mobile station. The fading patterns for individual elements of Array SIMO1 in Figure 5.9(a) are very similar due to the identical polarisation of the elements. This suggests that the signals from the transmitter travel similar propagation paths to the individual elements of the antenna array. In contrast, the fading pattern for Element 2 of Array SIMO2 in Figure 5.9(b) is distinctly different from that for Element 1 and 3 of the same array. This indicates that signals travel different propagation paths to the horizontally-polarised Element 2 compared to that of the vertically-polarised Element 1. The fading pattern of Element 3 shows a combined effect from Elements 1 and 2.

In general, the fading patterns in the LOS environment demonstrate low variability compared to that in the NLOS environment as shown in Figure 5.10. The average received signal power in the NLOS environment is also lower than that in the LOS environment. No clear similarity can be observed between the fading patterns for individual elements of both Array SIMO1 and SIMO2. This suggests that signals from the transmitter travel in different propagation paths to individual elements of the antenna array in the NLOS environment.

5.5 Summary

The designs of two propagation measurement systems have been outlined in this chapter. The measurement systems are designed to collect propagation measurements in various environments for constructing a propagation database. In accordance to the intended analysis on different antenna selection and deployment strategies, a number of design specifications have been imposed on the measurement systems. Due to the diversity of these specifications, two separate measurement systems have been developed, each fulfilling a subset of the design constraints.

The path-gain measurement system has been designed for the deployment strategies based on antenna location and orientation. It allows simultaneous measurements of multiple base stations and a selection of omni-directional and directional antennas at the
Figure 5.9: Typical measured data for a base station with Array (a) SIMO1 and (b) SIMO2 under the LOS environment.
Figure 5.10: Typical measured data for a base station with Array (a) SIMO1 and (b) SIMO2 under the NLOS environment.
base stations. An automated antenna orientation system has been developed to remotely control the orientations of the directional antennas for accuracy and repeatability. Instead of a single measurement, the measurement system records a sample of the received signal power over a localised area at every measurement location. This sample of measurements determines the local average and statistical distribution of the received signal.

On the other hand, the complex-voltage measurement system has been designed for deployment strategies utilising antenna polarisation and diversity. It consists of a single base and a single mobile station. A selection of antenna arrays with various configurations of element polarisations can be mounted on the base station. Instead of received power as in the case of the path-gain measurement system, the complex voltages from individual elements of the antenna array are recorded simultaneously.

These measurement systems have been employed in the propagation study presented in Chapter 6 to collect propagation data for various environments and deployment scenarios.

References


Chapter 6

The Indoor Environment — A Propagation Study

6.1 Introduction

In Chapter 5 the development of two propagation measurement systems were presented. These measurement systems enable the construction of a comprehensive propagation database that facilitates the investigation of various antenna deployment strategies, such as antenna orientation, polarisation and diversity.

This chapter documents a propagation study performed using the two custom-built measurement systems. A high resolution propagation database for various antenna deployment scenarios in different environments is produced. In Section 6.2, details of the indoor environments considered in the propagation study are presented. The propagation study is divided into two phases as listed in Table 6.1. Section 6.3 outlines Phase I of the study, which concentrates on measuring the power of the received signals. Using the path-gain measurement system described in Chapter 5, the local mean path-gain can be estimated for evaluating the system performance. Section 6.4 describes Phase II of the propagation study, which measures the complex voltage of the received signals using the complex-voltage measurement system. Both the magnitude and phase of the received signals are essential for the analysis of antenna diversity. These measurements also provide data for evaluating the performance of antenna polarisation deployment strategies. In both sections, the various deployment scenarios considered are presented and some representative measurement results are also included and discussed. This chapter is summarised in Section 6.5.


Table 6.1: The measurement campaign

<table>
<thead>
<tr>
<th>Measurement phase</th>
<th>Measurement system used</th>
<th>Measurement locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>Path-gain</td>
<td>Environment A, B and C</td>
</tr>
<tr>
<td>Phase II</td>
<td>Complex-voltage</td>
<td>Environment B</td>
</tr>
</tbody>
</table>

6.2 The environments considered

Three different indoor environments have been considered in the propagation study, which will hereafter be referred to as Environment A, B and C. All three locations are situated at the City Campus of The University of Auckland, New Zealand.

Environment A — Engineering Tower

Environment A is located on the eighth floor of the tower block of the School of Engineering Building, as shown in Figure 6.1. The building is a typical multi-storey, reinforced-concrete structure with a floor area of 18.5 m × 18.5 m. The exterior of the building essentially consists of glass windows with concrete slabs projecting out between floors. There are no buildings immediately adjacent to the eighth floor; however, there are buildings on the western and eastern sides of the building at a level equal to and below the sixth floor. Figure 6.2 shows the floor plan of Environment A. The floor area contains a central services core and many fixed-partitioned offices. The central core is constructed from steel-reinforced concrete and houses the lifts, stairwell and other building services. An internal corridor around the central core separates the core from the offices. The offices are partitioned with a mixture of timber and plasterboard that cause a minimal effect on radio wave propagation. Figure 6.3 shows the internal corridor with the central core to the left and offices to the right. The angle from which the photo was taken is indicated in Figure 6.2. The offices also contain metallic furniture that can influence radio wave propagation; for example, bookshelves, filing cabinets, and whiteboards.

Environment B — Science Building

Environment B is part of the floor area located on the second floor of the Science Building. As shown in Figure 6.4, the Science Building has a similar construction to the Engineering Tower in Environment A. Again, the exterior of the building essentially consists of glass windows with concrete slabs projecting out between floors. There are no buildings immediately adjacent to the Science Building. Figure 6.5 shows the floor plan of Environment B. The northern, eastern and southern sides of the floor area are all windowed, while the western side connects to the rest of the building. Instead of a
6.2. The environments considered

Figure 6.1: External view of Environment A — Engineering Tower.
central services core as in Environment A, there is an open-plan laboratory and a seminar room in the middle of the floor area. The laboratory is partitioned with aluminium-framed glass panels, whereas the seminar room is enclosed by a mixture of timber and plasterboard. Figure 6.6 shows a photo of the laboratory with the aluminium frames. The angle from which the photo was taken is indicated in Figure 6.5. In a manner similar to Environment A, there is a corridor that separates the laboratory and seminar room from the surrounding offices. The offices are also partitioned with a mixture of timber and plasterboard. The offices contain similar types of metallic furniture as in Environment A.

Environment C — Functions Room

Environment C is the Functions Room located at the first floor of the Student Union Cafeteria Building, as shown in Figure 6.7. The building has a similar concrete construction style with the buildings of Environments A and B. The floor plan shown in Figure 6.8 illustrates the internal layout of Environment C. Environment C is essentially an open-space hall area. The western, southern, and eastern sides of the floor are enclosed by concrete walls. The northern side is connected to the rest of the building. The northern side also accommodates a bar, kitchen and toilets. Glass windows are located on the southern side. The floor area is unobstructed except for a few concrete supporting
Figure 6.3: Internal view of Environment A.
Figure 6.4: External view of Environment B — Science Building.

Figure 6.5: Floor plan of Environment B. (The arrow indicates internal photo angle.)
6.2. The environments considered

Summary of the indoor environments

Figure 6.9 shows the relative sizes of the floor areas for Environment A, B and C. While Environment A is relatively isolated, Environment B and C are in close proximity, and their relative positions are shown in Figure 6.9(b).

Environments A and B are intended to represent typical environments where indoor wireless communication systems are likely to be deployed. The two locations have similar architecture, construction material and floor layout. The existence of a central services core is a distinctive feature of Environment A. The comparisons of the analysis results from the two locations can, therefore, demonstrate the impact of the central core upon system performance.

On the other hand, Environment C has a completely different type of construction and floor layout from Environments A and B. It represents a generic indoor environment close to Environment B. This enables the investigation of the interactions between two wireless systems that are in close proximity.
Figure 6.7: External view of Environment C — Functions Room.

Figure 6.8: Floor plan of Environment C.
6.3 Phase I — Path-gain measurements

In order to construct a high resolution propagation database for the three indoor environments considered, propagation measurements have been performed in the environments using the path-gain measurement system discussed in Section 5.3. Different base station configurations (specifically base station location, antenna types, antenna orientations, and antenna polarisations) and mobile station locations have been considered in each of the three indoor environments. In Phase I of the propagation study, antennas on all base and mobile stations were vertically polarised.

6.3.1 Deployment scenarios

The deployment of the wireless system in the propagation study involves positioning the base and mobile stations and selecting the base station antennas. Base station locations have been selected to provide coverage to the entire environment, whereas mobile station locations have been chosen to represent the distribution of users in a real system. The deployment scenarios for base stations in Environments A and B are very similar due the similarity in their floor layout. In contrast, an alternative deployment strategy for base stations has been adopted in Environment C due to its different floor layout.

Environment A

A total of eight base stations were installed in Environment A. Six of them were configured with omni-directional antennas and the remaining two with directional antennas. The locations of the base stations with omni-directional antenna are shown in Figure 6.10(a).

Figure 6.9: Relative sizes and positions of (a) Environment A, and (b) Environment B and C.
These locations are labelled from BS1 to BS6. The locations BS1 and BS2 were selected to cover the floor area evenly by dividing the floor area into two halves. They were used to provide services to users within Environment A. Locations BS3 to BS6 were sited on the roofs of the buildings adjacent to Environment A. Their relative positions to Environment A are illustrated in Figure 6.10(b). Locations BS3 to BS6, which have the same heights, are 8.5 m below locations BS1 and BS2. Since the outdoor base stations at locations BS3 to BS6 do not provide services to indoor users, they have been regarded as external interferers to the base stations inside Environment A. The six base station locations form six different base station configurations.

In addition to the omni-directional antennas, in Phase I we are also considering the performance of directional antennas. Accordingly, Figure 6.11(a) shows the floor plan of Environment A indicating the locations for the two base stations equipped with directional antennas. The locations BS7 and BS8 are essentially co-located with the locations BS1 and BS2 in Figure 6.10(a) respectively. At each of these locations, six base station configurations were considered corresponding to different orientations of the directional antenna in the azimuthal plane as illustrated in Figure 6.11(b). The orientations are labelled by their boresight angle measured relative to (in a clockwise direction) an eastward-pointing reference vector. A total of 12 permutations are therefore considered for the two base station locations. Table 6.2 lists the 18 base station configurations in Environment A employing either omni-directional or directional antennas.

Figure 6.12 shows the 42 mobile station locations considered in Environment A. The locations were chosen to provide an even distribution across the entire floor area; however, there was no location selected inside the central core due to access difficulties. This was not a particular concern since wireless connectivity is not expected to be available inside the central core. At every mobile station location, path-gain measurements from each of the 18 base station configurations were performed, in a manner similar to [1].

Environment B

There were a total of four base station locations considered in Environment B. Two of them were configured with omni-directional antennas and the other two, which are adjacent to the first two locations, were with directional antennas. The locations of the base stations with omni-directional antennas are labelled BS1 and BS2 in Figure 6.13(a). The relative locations of these base stations were identical to those in Environment A where coverage to the floor area is distributed evenly between the two base stations. There is also an external base station with an omni-directional antenna located in Environment C, as shown in Figure 6.13(b). For the purpose of this study, this latter base station was regarded as an interferer.
Figure 6.10: (a) Floor plan of Environment A indicating the locations of the base stations (denoted by ‘•’) that employ omni-directional antennas (Phase I); (b) three-dimensional diagram showing the relative positions of the floor area and base stations. The spheres denote the base station locations.
Figure 6.11: (a) Floor plan of Environment A indicating the locations of the base stations (denoted by ■) with directional antennas (Phase I); (b) the six orientations of the directional antennas at which measurements were performed.

Figure 6.12: Floor plan of Environment A indicating the mobile station locations (denoted by ‘×’) (Phase I).
Table 6.2: Base station configurations in Environment A (Phase I) (OA denotes omni-directional antenna; DA denotes directional antenna)

<table>
<thead>
<tr>
<th>Name of configuration</th>
<th>Base station location</th>
<th>Antenna</th>
<th>Antenna orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA1</td>
<td>BS1</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>OA2</td>
<td>BS2</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>OA3</td>
<td>BS3</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>OA4</td>
<td>BS4</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>OA5</td>
<td>BS5</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>OA6</td>
<td>BS6</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>DA1-000°</td>
<td>BS7</td>
<td>DA</td>
<td>0°</td>
</tr>
<tr>
<td>DA1-060°</td>
<td>BS7</td>
<td>DA</td>
<td>60°</td>
</tr>
<tr>
<td>DA1-120°</td>
<td>BS7</td>
<td>DA</td>
<td>120°</td>
</tr>
<tr>
<td>DA1-180°</td>
<td>BS7</td>
<td>DA</td>
<td>180°</td>
</tr>
<tr>
<td>DA1-240°</td>
<td>BS7</td>
<td>DA</td>
<td>240°</td>
</tr>
<tr>
<td>DA1-300°</td>
<td>BS7</td>
<td>DA</td>
<td>300°</td>
</tr>
<tr>
<td>DA2-000°</td>
<td>BS8</td>
<td>DA</td>
<td>0°</td>
</tr>
<tr>
<td>DA2-060°</td>
<td>BS8</td>
<td>DA</td>
<td>60°</td>
</tr>
<tr>
<td>DA2-120°</td>
<td>BS8</td>
<td>DA</td>
<td>120°</td>
</tr>
<tr>
<td>DA2-180°</td>
<td>BS8</td>
<td>DA</td>
<td>180°</td>
</tr>
<tr>
<td>DA2-240°</td>
<td>BS8</td>
<td>DA</td>
<td>240°</td>
</tr>
<tr>
<td>DA2-300°</td>
<td>BS8</td>
<td>DA</td>
<td>300°</td>
</tr>
</tbody>
</table>

Figure 6.13: Floor plans of (a) Environment B and (b) Environment C indicating the locations of the base stations that employ omni-directional antennas (denoted by ‘•’) (Phase I).
Figure 6.14: Floor plan of Environment B indicating the locations of the base stations that employ directional antennas (denoted by ‘■’) (Phase I).

Figure 6.15: Floor plan of Environment B indicating the mobile station locations (denoted by ‘×’) (Phase I).

Figure 6.14 shows the floor plan of Environment B, indicating the locations for the base stations equipped with directional antennas. The base station locations are labelled BS4 and BS5. Similar to Environment A, these locations are effectively co-located with the locations BS1 and BS2 from Figure 6.13(a) respectively. In addition, six base station configurations were considered for different orientations of the directional antenna at each of the locations as illustrated in Figure 6.11(b). Table 6.3 summaries the 15 base station configurations in Environments B and C.

A total of 76 mobile station locations were chosen in Environment B to evenly cover the entire floor area. These locations are denoted by ‘×’ in Figure 6.15. Path-gain measurements were performed at the same mobile station locations for each of the 15 base station configurations.
6.3. Phase I — Path-gain measurements

<table>
<thead>
<tr>
<th>Name of configuration</th>
<th>Base station location</th>
<th>Antenna configuration</th>
<th>Antenna orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA1</td>
<td>BS1</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>OA2</td>
<td>BS2</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>OA3</td>
<td>BS3</td>
<td>OA</td>
<td>N/A</td>
</tr>
<tr>
<td>DA1-000°</td>
<td>BS4</td>
<td>DA</td>
<td>0°</td>
</tr>
<tr>
<td>DA1-060°</td>
<td>BS4</td>
<td>DA</td>
<td>60°</td>
</tr>
<tr>
<td>DA1-120°</td>
<td>BS4</td>
<td>DA</td>
<td>120°</td>
</tr>
<tr>
<td>DA1-180°</td>
<td>BS4</td>
<td>DA</td>
<td>180°</td>
</tr>
<tr>
<td>DA1-240°</td>
<td>BS4</td>
<td>DA</td>
<td>240°</td>
</tr>
<tr>
<td>DA1-300°</td>
<td>BS4</td>
<td>DA</td>
<td>300°</td>
</tr>
<tr>
<td>DA2-000°</td>
<td>BS5</td>
<td>DA</td>
<td>0°</td>
</tr>
<tr>
<td>DA2-060°</td>
<td>BS5</td>
<td>DA</td>
<td>60°</td>
</tr>
<tr>
<td>DA2-120°</td>
<td>BS5</td>
<td>DA</td>
<td>120°</td>
</tr>
<tr>
<td>DA2-180°</td>
<td>BS5</td>
<td>DA</td>
<td>180°</td>
</tr>
<tr>
<td>DA2-240°</td>
<td>BS5</td>
<td>DA</td>
<td>240°</td>
</tr>
<tr>
<td>DA2-300°</td>
<td>BS5</td>
<td>DA</td>
<td>300°</td>
</tr>
</tbody>
</table>

Environment C

Measurements in Environment C share the same base station configurations with Environment B listed in Table 6.3. Path-gain measurements were performed at 21 mobile station locations that are indicated by ‘×’ in Figure 6.16.

6.3.2 Measurement results

The measurement results constitute the propagation database for the environments considered. These results also show the signal propagation mechanisms for different

Figure 6.16: Floor plan of Environment C indicating the mobile station locations (denoted by ‘×’) (Phase I).
Figure 6.17: Average path-gain measurements (dB) for base station configuration OA1 (Environment A, Phase I). ‘●’ denotes the base station location.

base station configurations. Measurement data from Phase I of the propagation study is presented in the form of path-gain values in dB. In each measurement environment, 360 path-gain samples were recorded for every combination of the base station configuration and mobile station location. These path-gain measurements were averaged (in linear units) to give an estimate of the local mean path-gain for the corresponding combination. For every base station configuration, local mean path-gain estimates were made at the full set of mobile station locations covering the entire environment. This approach allows direct comparisons between different base station configurations to be made. Full details of the comprehensive measurement results for all base station configurations considered are given in Appendix D.

Graphical presentation of measurement data

The measurement results can be presented visually to assist understanding of the mechanisms of signal propagation in the environment. In Figure 6.17 the local mean path-gain measurements for the base station configuration OA1 in Environment A are mapped on to the floor plan of the measurement environment. This enables a geographical visualisation of the distribution of path-gain measurements. This representation is, however, somewhat limited for observing the trend of the path-gain values across the environment.

Contour plots are an alternative graphical presentation that reveals the general coverage patterns of different base station configurations. An example of a contour plot is shown in Figure 6.18(a), which shows the path-gain measurements for the base station
configuration OA1 in Environment A. These contour plots are generated by triangle-based cubic interpolation [2, pp. 130–137] of the measured path-gain data at the mobile station locations. In other words, the contour plot provides an estimate to the path-gain values across the environment based on the interpolation of the measured values at the mobile station locations. The interpolation process can become inaccurate through walls and obstacles that cause sudden change in the path-gain values. For example, the steel-reinforced concrete walls of the central core in Environment A cause significant attenuation of the propagating signals. While there was no measurement performed inside the central core, the interpolation process failed to give a reasonable estimate of the path-gain values inside the central core. The central core in the contour plot is, therefore, deliberately masked to prevent confusion, and will not be considered later in this investigation.

The contour plots are filled in shades of gray. Light shades represent high path-gain values and dark shades represent low path-gain values. The contour lines are isolines representing the same path-gain values on different parts of the floor area. The contour lines in the contour plots presented in this chapter are 6 dB apart, unless otherwise stated.

Correlation statistics

Correlation coefficients can be used as an objective measure of the similarity between the path-gain contour plots of any two base station configurations. The correlation coefficient $\rho$ between signals from the $i^{th}$ and the $j^{th}$ base station configurations for the entire floor area is given by [1]

$$
\rho_{ij} = \frac{\sum_k (PG_{ik} - \overline{PG}_i) (PG_{jk} - \overline{PG}_j)}{\sqrt{\sum_k (PG_{ik} - \overline{PG}_i)^2} \sqrt{\sum_k (PG_{jk} - \overline{PG}_j)^2}}, \quad |\rho_{ij}| \leq 1, \quad (6.1)
$$

where $PG_{ik}$ (dB) is the mean path-gain between the $i^{th}$ base station and the $k^{th}$ mobile station location. Similarly $PG_{jk}$ (dB) is the mean path-gain between the $j^{th}$ base station and the $k^{th}$ mobile station location.

A correlation coefficient close to unity indicates a high degree of similarity between the path-gain contour plots of the two specified base station configurations. In contrast, a correlation coefficient close to zero suggests virtually no connection between the contour plots of the two configurations. The similarity between two contour plots decreases as the correlation coefficient tends to negative unity.
Measurement results for Environment A

Amongst the 18 base station configurations in Environment A, the two configurations with omni-directional antennas inside the floor area, namely configurations OA1 and OA2, have been selected as the reference cases for the two base station locations BS1 and BS2 respectively. These two particular configurations were chosen because similar base station configurations have been investigated in previous research [1,3]. This provides a basis for comparison of the measured results.

Figure 6.18(a) and (b) show the path-gain contour plots for the two reference configurations OA1 and OA2, respectively. In both scenarios, a deep shadow (dark-shaded) region can be seen diagonally opposite the base station. This suggests that the steel-reinforced concrete core causes a high attenuation to radio signals. This shadowing effect effectively blocks the line-of-sight (LOS) signal path from the base station to the other side of the core.

A channelling effect was observed in the two corridors leading to the base stations. This is indicated by the elongated contour lines at the corridors. The shape of the contour lines suggests that the signals from the base stations travel a much further distance through the corridors compared to a path penetrating through the adjacent offices. The lack of obstacles in the corridors is believed to be one of the propagation mechanisms that accounts for the strong channelling effect in the corridors. This introduces minimal attenuation to the propagating signals. In addition, reflections of the signals by the steel-reinforced concrete walls of the central core, the floor and the ceiling assist the propagation of the signal along the corridors.

Symmetry is also a common feature in the path-gain contour plots of the two reference scenarios. In Figure 6.18(a), the contour plot is symmetrical along the diagonal axis extending from the base station to the deep shadow region on the opposite side of the central core. This symmetrical shape of the contour plot suggests that the signal from the base station propagates in an identical manner on both sides of the axis of symmetry. Two factors have been identified as the causes for this symmetrical behaviour. Firstly, the use of omni-directional antenna at the base station ensures the uniform radiation of signals in all directions in the azimuthal plane. Secondly, the ‘loosely-symmetrical’ layout of the floor area provides similar propagation environments to the signals propagating along either side of the central core.

Figure 6.19 shows the path-gain contour plot for the base station configuration OA3 in Environment A. The base station in this configuration employs an omni-directional antenna and is located externally to Environment A in the eastern direction. The contour plot shows a gradual decrease in path-gain values from the right to the left side of the floor plan. A deep shadow is observed on the middle-left side of the floor plan next to
6.3. Phase I — Path-gain measurements

Figure 6.18: Path-gain contour plots for base station configurations (a) OA1 and (b) OA2 (Environment A, Phase I). (• denotes base station location; and, the contour lines are 6 dB apart.)

the central core. This shadowing effect is another example of the high signal attenuation property of the central core.

There is no noticeable channelling effect observed in this contour plot. The spacing of the contour lines indicates a gradual change in the magnitude of path-gain values inside the floor area. This is in contrast to the case of indoor base stations, which tend to create ‘hot spots’ and a more dramatic change in the magnitude of path-gain values within the floor area. Due to the close proximity to the measurement locations, indoor base stations have a tendency to cause more abrupt changes in path-gain measurements than outdoor base stations.

The path-gain contour plots for the base station configurations DA1-180° and DA1-300° are shown in Figure 6.20(a) and (b) respectively. Both configurations have the same base station location and employ the same directional antennas. Only the orientations of the directional antennas differ in the two configurations. The antenna of configuration DA1-180° points at an angle of 180° for example. Its path-gain contour plot is very similar to that for configuration OA1, which is a co-located base station with an omni-directional antenna. Dark shadow regions are observed at the north-west corner of both contour plots. Both scenarios also show a strong channelling effect in the corridors and have a line of symmetry in their contour plots. The correlation coefficient between the signals
from the two base station configurations is 0.98 (see Appendix D). This high correlation coefficient confirms the high level of similarity between the two contour plots. In contrast, the contour plot for configuration DA1-300° has a very different pattern compared to that for configurations OA1 and DA1-180°. Although a dark shadow region can still be observed at the north-west corner of the contour plot for configuration DA1-300°, it has extended towards the south-west corner of the contour plot. Channelling of the signal in the corridors is still observed but becomes asymmetric. A stronger channelling effect is observed in the corridor illuminated by the boresight direction of the directional antenna. The comparatively low correlation coefficient of 0.81 is consistent with these observations.

These examples illustrate that the ‘effective’ directive property of a directional antenna varies with its orientation relative to the environment. The orientation of an antenna in relation to the environment can either diminish or enhance its ‘effective’ coverage pattern and, therefore, influence system performance accordingly [4].

Measurement results for Environment B

There are 15 base station configurations in Environment B. Fourteen of them are located indoors with similar arrangements with those in Environment A. The two configurations with omni-directional antennas, configurations OA1 and OA2, have again been selected as the reference cases. The base station for configuration OA1 is located in the corridor,
Figure 6.20: Path-gain contour plots for the base station configurations (a) DA1-180° and (b) DA1-300° (Environment A, Phase I). ( ■ denotes base station location and the solid line indicates the orientation of the antenna. The contour lines are 6 dB apart.)
which is relatively the same location for configuration OA1 in Environment A. The only major difference between the two measurement environments is the absence of a central core in Environment B.

A contour plot for configuration OA1 is shown in Figure 6.21(a). A dark shadow region is observed at the corner diagonally opposite to the base station. The magnitude of the path-gain values in that region is, however, higher than those for Environment A. This suggests that the central laboratory introduces less signal attenuation than the central core in Environment A. A channelling effect is also observed in the corridors leading to the base station. Nevertheless, the effect is less pronounced than in Environment A. The contour lines inside the central laboratory indicate that the signal penetrates into the laboratory. This is in contrast to the case in Environment A where the signal is reflected back to the corridors due to the presence of a central core. Apart from these differences, the contour plot suggests that the signal from the base station propagates in a similar manner to the case in Environment A.

Figure 6.21(b) shows the contour plot and the base station location for configuration OA2 in Environment B. As opposed to configuration OA1, this configuration does not share the same base station location with configuration OA2 in Environment A, for which the contour plot is shown in Figure 6.18(b). The base station of the configuration in Environment B is located inside an office instead of in the corridor. In the contour plots of both scenarios, dark shadow regions are observed in the corner diagonally opposite the base stations. The shadow in Environment B exhibits higher path-gain values than that in Environment A despite a longer propagation distance for the signals. No channelling effect is observed in the corridors in Environment B. Instead, the shape of the contour lines suggests that the majority of the signal penetrates the hard-partition walls between offices. Overall, the contour plot suggests a similar propagation behaviour as configuration OA2 in Environment A.

Figure 6.22 shows the path-gain contour plot in Environment B for the base station configuration OA3, which is the only configuration with an external base station. The base station is located in Environment C and employs an omni-directional antenna. The contour plot shows a gradual and even decrease in path-gain values from the north to the south side of the floor area. Similar to Environment A, there is neither a noticeable channelling effect nor hot-spots observed in the contour plot for the external base station.

The path-gain contour plots for two typical base station configurations that employ directional antennas are presented in Figure 6.23(a) and (b). Figure 6.23(a) shows the contour plot for configuration DA1-120° that employs a directional antenna at the

\[1\] The hotspots on the contour plots (in the middle of the southern corridor) are the artifacts of the interpolation algorithm for generating the contour plots. The locations of these hotspots coincide with the measurement locations, as shown in Figure 6.15.
6.3. Phase I — Path-gain measurements

Figure 6.21: Path-gain contour plots for the base station configurations (a) OA1 and (b) OA2 (Environment B, Phase I). (‘•’ denotes base station location; and, the contour lines are 6 dB apart.)

Figure 6.22: Path-gain contour plot for the base station configuration OA3 (Environment B, Phase I). (The contour lines are 6 dB apart.)
orientation of $120^\circ$. The contour plot is very similar to the case of an omni-directional antenna in configuration OA1 (see Figure 6.21(a)), an observation supported by a very high correlation coefficient of 0.97 between the configurations.

Figure 6.23(b) shows the contour plot for configuration DA1-180° that employs a directional antenna directed into the corridor on the south side of the floor area. A strong channelling effect is suggested by the identical configuration from Environment A; however, the channelling effect observed is less pronounced than that from Environment A. It is thought that as the signal travelled along the corridor, it spreads out and penetrates the office walls and the central laboratory region. The relatively high path-gain values in the offices and laboratory on either side of the corridor effective reduces the channelling effect in the corridor.

Measurement results for Environment C

While sharing the same base station configurations as in Environment B, the majority of the base stations reside in Environment B for the measurements in Environment C. These are regarded as external interferers to the base stations in Environment C. Figure 6.24(a) shows the contour plot for configuration OA2, in which the base station is located in Environment B with an omni-directional antenna.

The wide spacings between the contour lines indicate a gradual change in the magnitude of path-gain values across the environment. The path-gain measurements
decrease with increasing distance from the base station, which is located in the south-east direction of the floor plan. In contrast to the external base station scenarios in Environment A, a smooth decay of path-gain is observed without any dark shadow regions. This is due to the lack of obstacles in Environment C.

The contour plot of the base station configuration OA3, which is the only configuration with a base station located in Environment C, is shown in Figure 6.24(b). The contour plot shows a hot-spot in close proximity to the base station. The path-gain values decay gradually and evenly in all directions as a function of distance from the base station. The use of an omni-directional antenna on the base station is the likely reason for the even decay of path-gain values.

6.4 Phase II — Complex-voltage measurements

Phase I of the propagation study facilitates the performance analysis of systems using single branch base station antennas, including both omni-directional and directional antennas. On the other hand, Phase II of the propagation study collected measurement data necessary for the analysis of antenna polarisation and diversity. Similar to Phase I, propagation measurements have been performed for different base station configurations at a number of mobile station locations across the indoor environment. The major differences are the use of the complex-voltage measurement system and the deployment of multi-element antenna arrays on the base stations. Instead of path-gain measurements, the
complex-voltage measurement system records the complex channel gain. In addition, the measurement system records the signals from the multiple antenna elements simultaneously. Those signals from multiple antenna elements can be combined for better reception quality as discussed in Section 7.4.1. However, this chapter presents the measurement results for individual antenna elements only.

6.4.1 Deployment scenarios

Similar deployment strategies as in Phase I of the propagation study have been adopted in Phase II. However, propagation measurements have been performed in Environment B only. The two selected base station locations are indicated in Figure 6.25 by ‘■’. The selected locations are intended to replicate the same base station locations as in Phase I. The base station location BS1 is identical to the one from Phase I. However, due to the occupancy of some of the offices, the location BS2 from Phase I became inaccessible. The location BS2 has been relocated to the corridor adjacent to its original position.

The base stations were configured with one of the three antenna arrays described in Section 5.4 at a particular orientation. Table 6.4 lists the seven base station configurations considered in the propagation study with their respective locations, antenna arrays, antenna orientations, and the set of mobile station locations. Due to the lack of an automated antenna rotator system, the number of base station configurations was minimised to a representative set of scenarios.

Since both antenna arrays SIMO1 and SIMO2 are uniform linear arrays (ULAs), their antenna orientations are described by their boresight angle measured relative to (in a clockwise direction) an eastward-pointing reference vector. The antenna orientation of the first base station configuration BS1-SIMO1-180° is shown in Figure 6.26(a). The orientation of 180° is intended to provide maximum coverage to the floor area by directing
Table 6.4: Base station configurations in Environment B in Phase II

<table>
<thead>
<tr>
<th>Name of configuration</th>
<th>Base station location</th>
<th>Antenna array</th>
<th>Array orientation</th>
<th>Mobile station locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS1-SIMO1-180°</td>
<td>BS1</td>
<td>SIMO1</td>
<td>180°</td>
<td>Full set</td>
</tr>
<tr>
<td>BS1-SIMO2-180°</td>
<td>BS1</td>
<td>SIMO2</td>
<td>180°</td>
<td>Full set</td>
</tr>
<tr>
<td>BS1-SIMO3-270°</td>
<td>BS1</td>
<td>SIMO3</td>
<td>270°</td>
<td>Full set</td>
</tr>
<tr>
<td>BS1-SIMO3-000°</td>
<td>BS1</td>
<td>SIMO3</td>
<td>000°</td>
<td>Partial set</td>
</tr>
<tr>
<td>BS1-SIMO2-060°</td>
<td>BS1</td>
<td>SIMO2</td>
<td>060°</td>
<td>Partial set</td>
</tr>
<tr>
<td>BS2-SIMO2-060°</td>
<td>BS2</td>
<td>SIMO2</td>
<td>060°</td>
<td>Partial set</td>
</tr>
<tr>
<td>BS2-SIMO2-240°</td>
<td>BS2</td>
<td>SIMO2</td>
<td>240°</td>
<td>Partial set</td>
</tr>
</tbody>
</table>

Figure 6.26: Antenna orientations of the base station configurations (a) BS1-SIMO1-180° and (b) BS1-SIMO3-270°. (The dotted line indicates the orientation for Element 2 of the antenna array.)

the antenna array boresight in the direction of the unobstructed corridor. Figure [6.26(b)] shows the array orientation for configuration BS1-SIMO3-270°. Since antenna array SIMO3 is a three-dimensional array, the solid line represents the orientation of the vertically-polarised element, namely Element 1. The dotted line indicates the orientation of its horizontally polarised element, namely Element 2. Element 3 of antenna SIMO3 always points upwards to the ceiling in the propagation study. This orientation of the array is aimed to provide maximum coverage to the floor area by pointing two elements directly at the two lengths of corridor.

In Table 6.4, the base station configurations BS1-SIMO3-000° and BS1-SIMO2-060° represent the scenarios with minimum coverage to the floor area by pointing the antenna away from the centre of the area. Both of the configurations BS2-SIMO2-060° and BS2-SIMO2-240° are located at the base station location BS2. Similarly, the two configurations correspond to the scenarios with maximum and minimum area coverage respectively.
Figure 6.27: Floor plan of Environment B indicating the (a) full and (b) partial set of mobile station locations (denoted by ‘×’) (Phase II).

There are two sets of mobile station locations in Phase II of the propagation study, namely the full set and the partial set. Figure 6.27(a) indicates the full set of mobile station locations by ‘×’. The full set of locations duplicates the same mobile station locations from Phase I except the ones inside some of the offices on the northern side of the floor area. Those offices were occupied during the measurements; therefore, the mobile station locations inside those offices were excluded from the measurement analysis.

The full set of mobile station locations is intended to provide a high resolution database of propagation data for each of the antenna arrays. This accounts for the first three base station configurations in Table 6.4. However, a reduced set of locations has been selected to reduce measurement time while still giving a representative view of the measurement environment. The rest of the configurations in Table 6.4 employ the partial set of locations. Figure 6.27(b) shows the partial set of mobile station locations by ‘×’.

6.4.2 Measurement results

Measurement data in Phase II of the propagation study is in the form of complex voltages that represent the complex channel gain. A set of three complex voltages were recorded simultaneously for the three elements in an antenna array. Similar to Phase I of the propagation study, a sample of 360 sets of complex-voltage measurements were recorded for every combination of base station configuration and mobile station location. For comparison with the measurement results in Phase I of the propagation study, these complex voltages were converted into path-gain values by squaring their magnitude. These path-gain values were then averaged to give an estimate the local mean path-gain for the corresponding combinations of base station configurations and mobile station locations. The set of path-gain values for the three elements in an antenna array were considered
individually as three closely-spaced base stations. For every base station configuration, path-gain values were estimated at mobile station locations across the entire environment. This allows the comparisons between different base station configurations.

Only representative results are presented in this section. The comprehensive measurement results for individual elements of all base station configurations are given in Appendix D. In contrast to Phase I of the propagation study, which presents the measurement results according to the different types and orientations of antennas, this section compares the measurement results according to various categories of antenna configuration.

Comparing full and partial mobile station locations

As explained in Section 6.4.1 two sets of mobile station locations were implemented in the propagation study, namely the full and the partial set. Table 6.4 lists the base station configurations with their corresponding sets of mobile station locations. Given the same base station configuration, different sets of mobile station locations can deliver different interpretations of the propagation environment. This can be demonstrated in Figure 6.28(a) and (b) that show the path-gain contour plots for Element 1 of the base station configuration BS1-SIMO1-180° with full and partial set of mobile station locations, respectively. Expectedly, Figure 6.28(a) is very similar to Figure 6.23(b), which shows the path-gain contour plot for configuration DA1-000° in Environment B for Phase I of the propagation study. The similarity between the contour plots is due to the sharing of the identical indoor environment, base station location, mobile station locations, directional antenna element, and antenna orientation by the two configurations.

In Figure 6.28(b), the contour plot of the partial set of mobile station locations shows the same general pattern with that of the full set of mobile station locations in Figure 6.28(a). However, due to the reduced number of data points, the contour lines exhibit a more gradual change in magnitude. This is illustrated by the wider spacings between the contour lines. Despite this distortion in the gradient of the contour lines, the measurement data obtained from the partial set of mobile station locations remains a good estimate to that of the full set of locations due to the high level of similarity between the contour plots.

The contour plots presented in the rest of this section employ the full set of mobile station locations, unless otherwise stated.

Comparing antenna elements

Since there are three antenna elements on each antenna array, a single measurement of the antenna array is equivalent to three separate measurements of closely-spaced antennas
Figure 6.28: Path-gain contour plots for Element 1 of the base station configuration BS1-SIMO1-180° (Environment B, Phase II) with (a) full and (b) partial mobile station locations. (■ denotes base station location; and, the contour lines are 6 dB apart.)

under the same base station configuration. Figure 6.29 shows the path-gain contour plots for the three antenna elements of the base station configuration BS1-SIMO1-180°. This configuration employs the antenna array SIMO1 at an orientation of 180°. All three elements of the array are vertically polarised. The contour plots of the three elements show a very similar general pattern, which are consistent with the near-unity correlation coefficients of 0.98–0.99 (see Appendix D). The contour plot of Element 1, as shown in Figure 6.29(a), demonstrates a strong channelling effect in the corridor north of the base station. This channelling effect, however, is not repeated in the contour plots of Element 2 and 3 of the same array. This is believed to be due to the relative positions of the antenna elements. Since Element 1 is the rightmost element on the array from the broadside direction, its radiation to the right is unobstructed. On the other hand, the radiation of Element 2 and 3 to their right is shielded by Element 1.

Comparing element polarisations

As outlined in Section 5.4, the elements of the antenna array SIMO2 have different polarisations. Element 1 and 2 are vertically and horizontally polarised respectively, whereas Element 3 has a 45° polarisation. The path-gain contour plots for individual elements of the base station configuration BS1-SIMO2-180° is shown in Figure 6.30. The contour plot for Element 1 (see Figure 6.30(a)) is virtually identical to that for Element 1 of array SIMO1 (see Figure 6.29(a)) at a correlation coefficient of 0.99 (see...
Figure 6.29: Path-gain contour plots of individual elements of the base station configuration BS1-SIMO1-180° (Environment B, Phase II). (The contour lines are 6 dB apart.)
Figure 6.30: Path-gain contour plots of individual elements of the base station configuration BS1-SIMO2-180° (Environment B, Phase II). (The contour lines are 6 dB apart.)

Appendix D). It is because both elements are vertically polarised with the same base station configuration. Figure 6.30(b), which shows the contour plot for Element 2, exhibits an overall reduction in the magnitude of path-gain values compared to that of Element 1. This is likely due to the fact that the mobile station employs a vertically polarised antenna, which results in significant cross-polarisation attenuation in the measured path-gain values for the horizontally polarised element. The 45° polarisation of Element 3 can be regarded as a combination of the vertical and horizontal polarisations from Element 1 and 2. Accordingly, the contour plot of Element 3 in Figure 6.30(c) demonstrates a mix of the features from the contour plots of both Element 1 and 2. The overall magnitude of the path-gain values lies in between those from the two former elements.

Another example of polarisation comparison is illustrated in Figure 6.31(a) and
6.5. Summary

The figures show the path-gain contour plots for Element 3 of the base station configurations BS1-SIMO3-270° and BS1-SIMO3-000° respectively. The contour plots are generated from measured data from the partial set of mobile station locations. In both scenarios, the elements point directly towards the ceiling. Both contour plots show very similar ranges of path-gain magnitudes; however, a noticeable difference is observed along the corridors leading to the antenna. The contour plot in Figure 6.31(a) clearly shows a stronger channelling effect along the length of corridor west of the base station than that in Figure 6.31(b). In contrast, Figure 6.31(b) shows a greater channelling effect in the length of corridor north of the base station than Figure 6.31(a). The discrepancies are considered as the result of different orientations of the polarisation axis of the antenna elements. In Figure 6.31(a), the polarisation axis of the antenna element is aligned with the length of corridor west of the base station. This is equivalent to a vertically polarised antenna element at an orientation of 270° being tilted at an elevation angle of 90° until it points towards the ceiling. The high path-gain values measured along the corridor is believed to be due to reflections from the ceiling. Signals from the vertically polarised mobile station antenna reflecting from the ceiling can reach the tilted element in the same polarisation with minimal cross-polarisation attenuation.

The same reflection mechanism is assumed to occur in the length of corridor north of the base station; however, the signal becomes cross-polarised with the base station antenna element resulting in high attenuation. Thus the strong channelling effect is only observed in the length of corridor west of the base station in Figure 6.31(a). Similarly, the base station antenna element in Figure 6.31(b) has an axis of polarisation that aligns with the length of corridor north of the base station. This results in a stronger channelling effect along that length of corridor than the one west of the base station.

6.5 Summary

In this chapter, a two-phase propagation study has been presented. Using the two custom-built measurement systems outlined in Chapter 5, propagation measurements have been performed in a number of indoor environments. These locations represent the typical operating environments of indoor wireless systems. Phase I of the propagation study measures the path-gain of the received signals, whereas Phase II records the complex voltage of the signals. A number of deployment scenarios have been considered. Base stations were installed with a selection of omni-directional antennas, directional antennas at different orientations, and antenna arrays with elements in different polarisations. Measurements were collected across the entire environment using a mobile station. A high resolution propagation database for individual environments has been created for the
evaluation of different antenna selection and deployment strategies, which are addressed in Chapter 8.

References


Chapter 7

System Model and Performance Estimation Techniques

7.1 Introduction

In Chapter 6, a propagation study has been described that underpins the system performance analysis of various deployment strategies in Chapters 8 and 9. This analysis also requires the specification of a system model together with corresponding measures for system performance. This chapter discusses the development of such a system model and the evaluation of various performance estimation techniques.

While separate system models have been developed for the downlink and uplink systems, it should be noted that they share a common radio interface. A list of assumptions used in the development of this common radio interface is outlined in Section 7.2. Sections 7.3 and 7.4 discuss the system models and performance estimation techniques for the downlink and uplink systems, respectively. The chapter is summarised in Section 7.5.

7.2 System model assumptions

A system model representing an indoor wireless communication system based on cellular technology has been adopted from [1, 2]. It is assumed that an infrastructure of base stations provides coverage to the entire indoor floor area, and mobile users connect to the base stations for desired services. Free movement of the mobile users is permitted within the floor area, and they are assumed to connect to a base station providing the strongest signal strength.

The communication system is considered to be a connection-oriented voice-based system [3, pp. 452–453]. This implies that users are assigned a dedicated communication
Table 7.1: System model specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple access technique</td>
<td>DS-CDMA</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>BPSK</td>
</tr>
<tr>
<td>Processing gain</td>
<td>511</td>
</tr>
<tr>
<td>Voice activity</td>
<td>0.5</td>
</tr>
<tr>
<td>Average number of concurrent users per base station</td>
<td>30</td>
</tr>
<tr>
<td>Channel coding</td>
<td>none</td>
</tr>
<tr>
<td>Minimum uncoded BER</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

channel during the full duration of their conversations. In this thesis, every base station in the system is assumed to have an average of 30 simultaneous connected mobile users, unless otherwise stated. A direct sequence code division multiple access (DS-CDMA) system [4, pp. 241–243] with a processing gain of 511 and a voice activity of 0.5 has been assumed. The combination of a large user base and a large processing gain results in an interference-limited system in which performance is dominated by the level of interference. Thermal noise in the system becomes relatively insignificant and has therefore been neglected in the system model.

The binary phase-shift keying (BPSK) modulation without channel coding [3, 238–242] has been assumed. An uncoded bit-error-rate (BER) of $10^{-3}$ has been selected as the minimum quality of service (for voice systems [5]). The radio communication channel is assumed symmetrical; hence, both downlink and uplink transmission share the same specifications. Table 7.1 summarises the specifications for the system model.

### 7.3 Estimation of downlink system performance

Based on the assumptions outlined in Section 7.2, a system model has been developed for the estimation of downlink system performance. This model describes an indoor wireless system operating in the identical measurement environments as discussed in Chapter 6. A number of techniques have been considered for the estimation of downlink system performance using measured data from Phase I of the propagation study, and include analytical and simulation techniques based on various signal fading models. Due to insufficient data however, downlink system performance could not be performed using measurements from Phase II of the propagation study.

#### 7.3.1 Downlink system model

In downlink transmission, radio signals propagate from base stations to mobile users. Using DS-CDMA however, a base station does not transmit exclusively to a single user.
7.3. Estimation of downlink system performance

Instead, the base station transmits to all connected users simultaneously on the same frequency channel and time slot. Users recover the desired signal using their assigned pseudo-random code. As a result, the signals for other users become interference to the desired user. This is known as *intra-cell interference* since the interference originates from the connected base station of the desired user [1]. The level of intra-cell interference is proportional to the number of concurrent users at the connected base station [2]. In addition to intra-cell interference, the desired user can also receive interference from nearby co-channel base stations, as shown in Figure 7.1. This is called *inter-cell interference*. The level of inter-cell interference is proportional to the number of users connected to the nearby base stations; also, it depends on the path gain from the nearby base stations to the desired user.

![Figure 7.1: Downlink transmission for a mobile user experiencing inter-cell interference.](image)

While the signals from both desired and interfering base station undergo independent fading as they propagate to the mobile, the instantaneous signal-to-interference ratio (SIR) at the mobile also varies. The instantaneous SIR at a mobile user for the downlink transmission of a [DS-CDMA] system is given by [1]

\[
SIR = \frac{1}{\sqrt{\frac{\alpha}{3N}(K - 1 + \beta)}},
\]

where \(\alpha\) is the voice activity factor (assumed to be 0.5), \(N\) is the processing gain (assumed to be 511), and \(K\) is the number of users in each cell (assumed to be 30). The variable \(\beta\)
is location dependent, and is given by
\[
\beta = \frac{KP_{\text{int}}}{P_{\text{des}}},
\]  
(7.2)
where \(P_{\text{int}}\) and \(P_{\text{des}}\) are the instantaneous received power from the interfering and desired base station, respectively. The ratio \(P_{\text{des}}/P_{\text{int}}\) represents the carrier-to-interference ratio (CIR) of the received signal at the desired user. Equation (7.1) takes into account both intra- and inter-cell interference, and thermal noise has been neglected (as for the reasons given in Section 7.2).

It is assumed that the processing gain and the number of concurrent users are sufficiently large for the instantaneous composite interference of the received signal at a user to be Gaussian distributed. The BER of the received signal at the desired user can then be estimated for its instantaneous SIR using the Gaussian Approximation [6]
\[
\text{BER} \approx \Phi (\text{SIR}),
\]  
(7.3)
where \(\Phi (\cdot)\) is the complementary Gauss probability integral.

System performance is quantified by the average outage probability over all possible user locations across the entire environment. Outage probability is defined as the probability that the BER exceeds a specific threshold (assumed to be \(10^{-3}\) as given in Table 7.1). Using (7.1)–(7.3), the average outage probability of a downlink system can then be estimated using either analytical or simulation techniques.

### 7.3.2 Analytical estimation technique

The analytical estimation technique used in this thesis assumes a fading model for the instantaneous received signals from the desired and interfering base stations. The outage probability of the system is then approximated by the theoretical outage probability of the assumed fading model. Two fading models have been considered, namely (a) Rayleigh and (b) Rician.

#### Rayleigh fading

In the Rayleigh fading model, the received signals at a user from all desired and interfering base stations are assumed to be independently Rayleigh distributed. This corresponds to a rich multipath environment without any dominant signal paths. The average outage probability \(P_{\text{out}}\) for a particular user location of a system under multiple Rayleigh
7.3. Estimation of downlink system performance

The outage probability of downlink systems with co-channel interferers is given by [7]

\[
P_{\text{out}} = 1 - \prod_{i=1}^{n} \frac{\Lambda_i}{r_p + \Lambda_i},
\]

where \( n \) is the number of co-channel interferers, \( \Lambda_i \) is the mean desired-signal to interfering-signal power ratio (equivalent to the CIR in a DS-CDMA system) for the \( i \)th interfering signal, and \( r_p \) is the protection ratio. The CIR \( \Lambda_i \), can be estimated using measured path-gain values from the propagation study discussed in Chapter 6. The protection ratio, \( r_p \), corresponds to a minimum threshold SIR value that can be obtained by solving (7.3) for the SIR that achieves the specified BER threshold.

**Rician fading**

In addition to the multipath signal components, the Rician fading model assumes the presence of a dominant signal component in the received signals at the user. This is believed to be a more representative model for indoor environments where there is a strong likelihood of a direct line-of-sight (LOS) signal path between the base stations and the mobile user. For the case of a Rician desired signal and a single Rician interferer, the outage probability is given by [8]

\[
P_{\text{out}} = Q \left( \sqrt{\frac{2K_1 R_1}{b_1 + R_1}}, \sqrt{\frac{2K_0 b_1}{b_1 + R_1}} \right) - \frac{b_1}{b_1 + R_1} \exp \left[ - \frac{K_1 R_1 + K_0 b_1}{b_1 + R_1} \right] I_0 \left( \frac{\sqrt{4K_1 K_0 R_1 b_1}}{b_1 + R_1} \right),
\]

where \( Q(\cdot) \) is the Marcum Q-function, \( I_0(\cdot) \) is the modified Bessel function of the first kind of zero order, \( K_0 \) and \( K_1 \) are the Rician \( K \)-factors of the desired and interfering signals respectively, \( R_1 \) is the protection ratio, and \( b_1 = \sigma_0^2 / \sigma_1^2 \), where \( \sigma_0^2 \) and \( \sigma_1^2 \) are the variances of the multipath components of the desired and interfering signals respectively. When both \( K_0 \) and \( K_1 \) tend to zero, so that neither received signal has a dominant multipath component, (7.5) reduces to (7.4) with \( n = 1 \) giving the outage probability for a single Rayleigh interferer.

The \( K \)-factors \( (K_0 \text{ and } K_1) \) and variances \( (\sigma_0^2 \text{ and } \sigma_1^2) \) of the desired and interfering signals are estimated from the measured data using the method-of-moments technique [9] and the mean of the Rician distribution [10, pp. 333–334]. The details of these estimation techniques are presented in Appendix E. The protection ratio, \( R_1 \), is identical to that in the Rayleigh fading scenario, which is determined by solving (7.3) for the SIR that achieves the specified BER threshold.

The expression in (7.5) with a single Rician interferer is a special case of (9) in [8] that accounts for multiple Rician interferers in a closed form expression. The derivation
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of the multiple-interferer expression, however, involves the assumption of equal mean and variance for the interferers. While independent mean and variance can be estimated from the measured data for individual interferers, the expression in [8] is insufficient for providing an accurate estimate to the outage probability in situations with multiple interferers. Consequently, this analytical estimation technique for Rician fading has (in this thesis) been restricted to estimating the outage probability for a single interferer.

7.3.3 Monte Carlo estimation technique

The Monte Carlo estimation technique explicitly models the short-term fading of the received signals. By generating random samples of the desired and interfering signals, it estimates the instantaneous CIR for the desired user. When $N$, $K$ and $\alpha$ are all fixed as system parameters, the BER of the received signal at the user can be fully characterised by its instantaneous CIR using (7.1), (7.2) and (7.3).
7.3. Estimation of downlink system performance

The overall simulation process is summarised in Figure 7.2. In each iteration of the simulation, a random user is selected from all the possible user locations in the measurement environment. The desired base station is identified by the stronger received signal strength at the user. Random samples of the received signals from the desired and interfering base station are then generated, which determines the instantaneous CIR at the user. Using the instantaneous CIR and specified system parameters, an estimate of the BER is calculated, which is compared with the specified BER threshold to determine if an outage has occurred. A total of $10^6$ iterations of the simulation are performed to estimate the average outage probabilities for the downlink under each deployment scenario.

The instantaneous samples of the received signals from the desired and interfering base station can be obtained using a number of algorithms. Three algorithms have been considered, which are based on (a) raw measured data, (b) Rayleigh, and (c) Rician random variables, respectively. All three algorithms are able to generate multiple independent and identically distributed (i.i.d.) interfering signals based on measured data.

### Raw measured data

This algorithm uses the raw measured samples of the instantaneous received signals from the propagation study directly in the simulation. Since 360 samples of the received signal from individual base stations have been recorded at every user location, a sample can be randomly selected as the instantaneous received signal power in the simulation. In every iteration of the simulation, a random sample is selected for each of the desired and interfering base stations. The instantaneous CIR is then calculated using the randomly selected samples.

The advantage of this technique is that the distribution of the received signal is implicitly included in the data. Consequently, this technique is regarded as the reference scenario for comparison with other generation techniques.

### Rayleigh random variables

This algorithm assumes a Rayleigh distribution for the received envelope at the user. In each iteration of the simulation, a sample is obtained from a Rayleigh random variable for each of received envelopes from the desired and interfering base stations. These Rayleigh random variables are generated based on the means of the corresponding measured data. The instantaneous CIR at the user can then be determined by the random samples. A detailed discussion of generating Rayleigh random variables is presented in Appendix E.

---

1The number of iterations has been determined experimentally to give repeatable estimates of the average outage probability for the system considered.
Rician random variables

Instead of a Rayleigh distribution, this algorithm assumes a Rician distribution for the received envelope at the user. A Rician random variable is generated with two parameters, namely the Rician $K$-factor and the variance. Both parameters are estimated from measured data. A detailed discussion of the estimation of Rician parameters and the generation of Rician random variables is presented in Appendix E.

7.3.4 Evaluation of downlink models

In Sections 7.3.2 and 7.3.3, five techniques have been described to estimate the performance of the downlink. This section evaluates and compares these estimation techniques in a scenario with two co-channel base stations. Consequently, a mobile user not only receives the signals from the desired base station but also from one interfering base station. Using the identical deployment of the base stations and propagation measurement data, the relative performance of the estimation techniques can be quantified.

Deployment scenarios

Two similar deployment scenarios at different environments have been considered for comparing the performance of the estimation techniques. Both scenarios employ two base stations with omni-directional antennas at similar locations. Figure 7.3(a) and (b) show the deployment scenarios with the locations of the base stations in Environment A and B, respectively. In both scenarios, a mobile user is assumed to connect to the base station with the stronger average received signal while simultaneously receiving interference from the other base station.
7.3. Estimation of downlink system performance

Analysis results

Figure 7.4(a) shows the average outage probabilities for the deployment scenario in Environment A using the different estimation techniques. The outage probabilities were determined as a function of the BER threshold assuming 30 users connected to each base station. In general, all five estimation techniques show a similar trend as a function of BER threshold. A higher BER threshold gives a lower outage probability since the instantaneous BER is less likely to exceed the threshold value. Virtually identical outage probabilities are observed for the analytical and simulation techniques based on the same fading model. This suggests that these two estimation techniques can substitute for each other in the system performance analysis. However, the use of the analytical estimation technique is preferred due to its lower computational requirements.

Considering the results of the Monte Carlo estimation technique based on raw measured data representing the true system performance, the estimates from the Rayleigh fading model appear to always overestimate the outage probability of the system. This can be explained by a higher signal variation in the Rayleigh fading model. Similarly, the estimates from a Rician fading model underestimate the outage probability for BER thresholds lower than $10^{-2}$. This is likely to be the consequence of the presence of a dominant signal component in the Rician fading model that reduces the signal variation. Despite small discrepancies, the estimates based on the Rayleigh or Rician fading models remain very good approximations to the true system performance. Since it is very computationally expensive to estimate the system performance using the Monte Carlo technique, the analytical estimation technique is preferred in the system performance analysis. Particularly, estimates based on the Rician fading model are more accurate (smaller discrepancies from the true system performance) than the Rayleigh fading model. Thus, the analytical estimation technique with a Rician fading model has been selected for the subsequent downlink system performance analysis.

Figure 7.4(b) shows the average outage probability for a deployment scenario in Environment B, which is similar to the one in Figure 7.4(a). It is clearly shown that the estimated outage probabilities follow the same overall trends to those in Environment A, despite an offset in the absolute outage probability. However, the estimates from the Rician fading model provide a better approximation to the actual outage probability in this environment. These observations suggest that while all the estimation techniques give good approximations to the real system outage probability independent of the environment, the estimates based on the Rician fading model tends to be more accurate in environments with the absence of obstacles, such as Environment B.

Using the analytical estimation technique with the Rician fading model, the outage probability as a function of the number of connected users per base station is illustrated in
Figure 7.4: Average downlink outage probability calculated using different estimation techniques for the deployment scenario in (a) Environment A and (b) Environment B.
7.4 Estimation of uplink system performance

In Section 7.3, the downlink system model has been presented. Many of the assumptions made in Section 7.3 are also true to the uplink. This section focuses on the development of the uplink system model and its associated performance estimation techniques. Separate system models have been developed for systems employing single-branch and multi-branch antennas, respectively. Phase I of the propagation study (see Section 6.3) provides measurement data for the performance analysis of systems with single-element antennas, and Phase II of the propagation study facilitates the performance evaluation of multi-branch antenna systems.

7.4.1 Uplink system model

In the uplink, radio signals propagate from the mobile users to a base station. A user is assumed to connect to the desired base station based on the strongest average received signal. For [DS-CDMA], multiple users transmit to the associated base station simultaneously on the same frequency channel. The base station then recovers the signal for the desired user using the user’s assigned pseudo-random code. The signals from other
users connected to the same base station are regarded as *intra-cell interference*. The level of intra-cell interference is, therefore, proportional to the number of concurrent users connected to the desired base station. In addition to intra-cell interference, interference can also originate from mobile users connected to adjacent base stations as shown in Figure 7.1. This kind of interference is called *inter-cell interference*. The level of inter-cell interference is proportional to the number of users in the adjacent cells; also, it is dependent on the path-gain between the interfering users and the desired base station.

**Power control**

Since mobile users can be spread throughout the entire environment, some users can be closer to the desired base station than others. When all users transmit equal output power, the *near-far* problem [3, pp. 405–407] can occur as discussed in Section 2.2. Thus, power control must be integrated into the uplink system model to eliminate this near-far problem. Power control is provided by each base station in a system and assures that each connected user provides the same signal level at the base station. The error resulting from the response time in the power control algorithm is modelled by a zero-mean log-normal random variable with a standard deviation $\sigma = 2$ dB [1].

One consequence of this power control scheme is a high level of mutual interference between mobile users connected to the same base station (i.e., intra-cell interference). This arises because the received signal power from the desired user is at the same level with the signals from other interfering users. This results in a low [CIR] for a large number
of interfering users. Alternatively stated, the number of users connected to a base station determines the level of intra-cell interference, which in turn influences the uplink system performance.

**Diversity combining**

In Phase II of the propagation study, multi-branch antennas (antenna arrays) were employed for recording multi-branch signals at the base stations. The received signals at individual antenna branches experience independent multipath fading introduced by the measurement environment and the inter-element spacing; hence, the signals fluctuate in magnitude. This fluctuation can cause momentary drops in the carrier-to-noise ratio (CNR) and, therefore, increase the outage probability of the system when the signal branches are considered separately. However, these signals branches can be weighted and linearly combined into a single output that fluctuates less rapidly. Some signal combining techniques can also improve the overall CNR and, therefore, decrease the outage probability. These diversity techniques were originally designed to improve the CNR of the antenna output in the presence of additive white Gaussian noise (AWGN); but, they have been adopted to enhance the CIR in this thesis. This approximation is based on the assumption that the DS-CDMA system considered has a sufficiently large processing gain and serves a sufficient number of users for the composite interference at the base stations to be Gaussian distributed.

Four diversity combining schemes have been considered, namely direct sum (DS), ideal selection (IS), equal gain combining (EGC) and maximal gain combining (MRC) [11, pp. 189–202]. All four schemes share the same basic structure for \( N \) antenna branches as illustrated in Fig. [7.7] [11, pp. 240–243]. Mathematically, the time-varying complex received signal matrix (in volts) at the antenna branches \( \mathbf{s}(t) = [s_1(t), s_2(t), ..., s_N(t)]^T \), is multiplied by the time-varying complex weight matrix, \( \mathbf{w}(t) = [w_1(t), w_2(t), ..., w_N(t)] \), where \( ^T \) denotes matrix transpose. The weighted signals from all antenna branches are then summed vectorially to give the combined output \( u(t) \), which is given by [11, p. 195]

\[
    u(t) = \mathbf{w}(t) \mathbf{s}(t). \tag{7.6}
\]

For notational convenience the time dependence \( t \) is omitted and (7.6) becomes

\[
    u = \mathbf{w}s. \tag{7.7}
\]

The weight vector \( \mathbf{w} \) is a function of the diversity scheme employed. A summary of the four diversity schemes under consideration is presented in this section whereas for comprehensive discussions of various diversity schemes and the derivation of corresponding
weight vectors, the reader is referred to [11, pp. 189–202], [12, pp. 308–314] and [13, pp. 554–573].

**Direct sum** The direct sum diversity scheme is simply a summation of the complex voltages from all the antenna branches. No modification to the signals is performed before the summation. The weight for the $n^{th}$ antenna branch can be given mathematically by

$$w_n^{DS} = 1$$ (7.8)

**Ideal selection** In the implementation of the IS diversity scheme, the antenna branch with the highest CIR is chosen as the antenna output. The signals from the other branches do not contribute to the final output. Mathematically, the weight for the $n^{th}$ antenna branch can be given by [11, p. 192]

$$w_n^{IS} = \begin{cases} 
1, & n = m, \text{ where } m | \gamma_m = \max[\gamma_n], \text{ for } n = 1, 2, \ldots, N \\
0, & \text{otherwise} 
\end{cases}$$ (7.9)

The variable $\gamma_n$ is the instantaneous CIR for the $n^{th}$ antenna branch and is given by

$$\gamma_n = \frac{|\alpha_n|^2}{|\beta_n|^2},$$ (7.10)

where $\alpha_n$ and $\beta_n$ are the complex received signals (in voltages) for the $n^{th}$ antenna branch from the desired user and the composite interference, respectively.

**Equal gain combining** In EGC, the signals from the antenna branches are co-phased and added coherently for a single antenna output. The weights for the adopted EGC
7.4. Estimation of uplink system performance

Diversity scheme is defined with the same expression as in [11, p. 200], which is given by

$$w_n^{\text{EGC}} = \exp(-j\alpha_n). \quad (7.11)$$

**Maximum ratio combining** [MRC] weights and combines the antenna branch signals to yield the highest instantaneous CIR possible with a linear combining technique. It emphasises branches with a high CIR more than branches with weak CIR. The weight of an antenna branch is directly proportional to the complex conjugate of the desired signal and inversely proportional to the composite interference power from other users. Mathematically, the weight for the $n^{\text{th}}$ antenna branch can be given by [11, p. 196]

$$w_n^{\text{MRC}} = \frac{\alpha_n^*}{P_n}, \quad (7.12)$$

where $*$ denotes complex conjugation and $P_n$ is the composite interference power given by

$$P_n = \frac{1}{2} |\beta_n|^2. \quad (7.13)$$

The IS, EGC and MRC diversity combining schemes are known as active combining schemes since they modify the signals, namely changing their magnitude and/or phase, before combining into a single output. In contrast, DS is defined as a passive combining scheme that does not alter the signals before summation. Active combining schemes require more complex signal processing hardware and, therefore, are more expensive to implement than passive combining schemes.

The single combined antenna output from these diversity combining schemes enables the estimation of system performance using the same estimation techniques based on a single-element antenna system. In addition to combining the signals from all the antenna branches into a single output, the signals from the individual antenna branches can also be regarded as separate antenna outputs. However, the measured data inherently records the mutual coupling and interactions between the antenna elements in the array, which implies that the signals from individual elements cannot be considered as independent. When considering the signal from a single antenna element, the other elements must be regarded as parasitic elements and terminated in a matched load [14, pp. 187–196].

**System performance**

As the signals from the desired and interfering users propagate to the desired base station through the time-varying environment, they undergo independent fading. Consequently, the CIR at the base station also becomes time-varying. After despreading, the instan-
aneous SIR at the desired station in uplink transmission of the DS-CDMA system considered can be given by [1]

\[
SIR = \frac{1}{\sqrt{\frac{\alpha}{3N} \left( \frac{\psi + \xi}{\varphi} \right)}}. \tag{7.14}
\]

where \( \alpha \) is the voice activity factor (assumed to be 0.5), \( N \) is the processing gain (assumed to be 511), \( \psi \) and \( \xi \) are the composite intra- and inter-cell interference power respectively, and \( \varphi \) is the desired signal power. The ratio \( \varphi/(\psi + \xi) \) is defined as the CIR at the desired base station before despreading.

Similar to the downlink case, it is assumed that the processing gain and the number of concurrent users are sufficiently large for the instantaneous composite interference at the desired base station to be Gaussian distributed. The BER at the desired base station can then be estimated by its instantaneous SIR using Gaussian Approximation [6]

\[
BER \approx \Phi(SIR). \tag{7.3}
\]

The performance of the uplink system is quantified by the average outage probability over all possible user locations across the entire environment. Outage probability is defined as the probability that the BER exceeds a specific threshold (assumed to be \( 10^{-3} \)). Using (7.14) and (7.3), the average outage probability of a uplink system can be estimated using both analytical and simulation techniques.

### 7.4.2 Analytical estimation technique

The analytical estimation technique for an uplink system is similar to that for a downlink system. It assumes a fading model for the instantaneous received signals from the desired and interfering mobile users. Unlike the downlink case, however, the analytical estimation technique for an uplink system is a combination of simulation and analytical calculations. The simulation component generates a large number of user distribution scenarios, while the analytical component calculates the theoretical outage probability for each scenario. The outage probabilities for all scenarios are averaged to give an estimate to the overall system performance. Figure 7.8 illustrates the steps in this estimation technique.

In each iteration of the simulation, a total of \( n \times K \) mobile users are randomly selected from all the possible user locations in the environment, where \( n \) is the number of co-channel base stations and \( K \) is the average number of mobile users in each cell. Every user connects to a desired base station based on the strongest average received signal. The base stations then perform power control that regulates the transmitted power of
7.4. Estimation of uplink system performance

7.4.3 Monte Carlo estimation technique

Instead of computing the outage probability using closed form equations, this estimation technique employs Monte Carlo simulation for evaluating the outage probability for the system's connected users. Next, a desired user is randomly chosen from the $n \times K$ users and its desired base station is determined. Assuming a Rayleigh fading model for all signals arriving at the desired base station, the theoretical outage probability is calculated using (7.4).

A total of $10^6$ iterations of the simulation are performed for every deployment scenario to estimate the average outage probabilities of the uplink system. The number of iterations has been determined experimentally to give repeatable results.
uplink. Random samples of the desired and interfering signals arriving at a base station are generated in the simulation, which determine the instantaneous CIR. Using (7.14) and (7.3), with specified $N$ and $\alpha$ as system parameters, the BER of the system can be calculated by the instantaneous CIR. Figure 7.9 summarises the overall simulation process.

In each iteration of the simulation, a total of $n \times K$ mobile users are randomly selected from all the possible user locations in the environment, where $n$ is the number of co-channel base stations and $K$ is the average number of mobile users in each cell. Every user connects to a desired base station based on the strongest average received signal. The base stations then perform power control that regulates the transmitted power of their connected users. Next, a desired user is randomly chosen from the $n \times K$ users and its desired base station is determined. Random samples of the received signals from the desired and interfering users are then generated, which determines the instantaneous CIR at the desired base station. Using the instantaneous CIR and specified system parameters, an estimate of the BER for the iteration is calculated, which is compared with the specified BER threshold to determine if an outage has occurred. A total of $10^6$ iterations of the simulation are performed for every deployment scenario to estimate the average outage probabilities of the uplink system.

Similar to the downlink case, the instantaneous samples of received signals from the desired and interfering station can be generated using a number of algorithms based on raw measured data, Rayleigh and Rician random variables as outlined in Section 7.3.3. In addition to magnitude, phase information are also generated for the instantaneous samples when a multi-branch antenna is employed. However, these instantaneous samples become complex quantities. A fourth type of generation algorithm has been adopted in the analysis of the measurement data from Phase II of the propagation study, in which antenna arrays were employed. This algorithm generates instantaneous samples of the received signal using correlated Rayleigh random variables.

**Correlated Rayleigh random variables**

Based on [15,16], a modified algorithm of generating correlated Rayleigh random variables has been developed and is presented in Appendix E. This algorithm generates a set of complex Rayleigh random variables for individual antenna branches with a matching correlation coefficient matrix to the measured data in terms of magnitude. However, the phases of the random variables remain independent between antenna branches.

---

2 The number of iterations has been determined experimentally to give repeatable results.
7.4. Estimation of uplink system performance

Determine the connected base station for every selected user

Randomly select desired user

Estimate instantaneous received signals at the connected base station

Calculate instantaneous CIR

Calculate instantaneous BER

Has an outage occurred?

Power control according to connected base station

Randomly select desired user

Determine the connected base station for the desired user

Have $10^6$ trials been completed?

Increment outage count

Start

Randomly select $n \times K$ mobile users

No

Yes

End

Figure 7.9: Flow chart of the Monte Carlo estimation technique for the uplink.
7.4.4 Evaluation of uplink models

Using the performance estimation techniques discussed in Sections 7.4.2 and 7.4.3, a performance analysis of an uplink system has been performed. The system considered consists of two co-channel base stations. Consequently, an individual base station would not only receive signals from its own connected users but also interfering signals from users connected to another base station. The relative performance of the estimation techniques are evaluated and compared using measured data of various deployment scenarios.

The analysis is divided into two parts. In Part I, the performance of the estimation techniques for systems employing single-element antennas on the base stations is evaluated. Phase I of the propagation study provides the required measurement data for this part of the analysis. In Part II, the analysis concentrates on systems employing multi-branch antennas, which is based on measured data from Phase II of the propagation study.

Part I — Deployment scenarios

In Part I of the uplink performance analysis, the same deployment scenarios from the downlink system analysis have been considered as shown in Figure 7.3(a) and (b). Both scenarios in Environments A and B employ two base stations with omni-directional antennas. The base stations are located at similar locations in both environments. A total of 60 concurrent users have been considered in the system, while each individual user connects to a base station based on the stronger average received signal. On average, 30 users are therefore connected to each individual base station.

Part I — Analysis results

Figure 7.10(a) shows the average uplink outage probabilities for the deployment scenario in Environment A using different estimation techniques. Overall, the outage probabilities for different estimation techniques follow a similar trend as a function of BER threshold. A higher BER threshold leads to a lower outage probability since the instantaneous BER is less likely to exceed the threshold value. Good agreement is observed between the outage probabilities of the analytical and simulation techniques with a Rayleigh fading model. This suggests that the two estimation techniques are interchangeable in the performance analysis. The analytical technique offers an advantage over the simulation technique as it is slightly less computationally expensive. Since there is no closed form expression for multiple Rician interferers, the computational complexity of the analytical estimation technique with a Rician fading model exceeds that of the simulation estimation technique. As good agreement exists between the results from these two techniques, the analytical
technique with Rician fading model was not evaluated for the uplink.

Considering the results of the raw measured data technique representing the true system performance, the results from a Rayleigh fading model tend to overestimate the real outage probability. This is believed to be due to the high signal variation in the fading model. In contrast, the results from a Rician fading model underestimate the real outage probability. This is likely due to the reduced signal variation by the dominant signal component in the fading model. Figure 7.10(b) shows the outage probabilities of different estimation techniques under a similar deployment scenario in Environment B. The estimates from the Rayleigh fading model maintain a consistent level of accuracy in both environments, whereas the estimates from the Rician fading model are slightly more accurate in Environment B. However, the lack of analytical estimation technique with a Rician fading model limits its application in the performance analysis. Consequently, the analytical estimation technique with a Rayleigh fading model has been selected in subsequent uplink system performance analysis.

Using the analytical estimation technique with a Rayleigh fading model, the outage probability for various average numbers of connected users per base station is illustrated in Figure 7.11. It is clearly shown that as the number of connected users increases, the outage probability also increases due to a higher level of intra- and inter-cell interference.

Part II — Deployment scenario

Instead of single-element antennas, Part II of the uplink performance analysis evaluates systems employing antenna arrays on the base stations. Figure 7.12 shows the deployment scenario considered. Array SIMO2 was employed on both base stations at the orientations 180° and 60°, respectively. Similar to the analysis of single-element antenna systems, a total of 60 concurrent users are assumed in the system; alternatively, 30 users are connected to each base station on average. Individual users connect to the desired base station based on the stronger received signal averaged across the antenna branches.

Part II — Analysis results

Figure 7.13 shows the average outage probabilities for different diversity combining schemes outlined in Section 7.4.1. The outage probability for the case of a single antenna branch is also shown as a reference. The outage probabilities were determined using the raw measured data estimation technique. It is clearly shown that the MRC scheme offers the lowest outage probability, which is over one order of magnitude lower than that of the single antenna branch. The EGC gives a higher outage probability than the MRC scheme, whereas the DS scheme gives the highest outage probability out of the four diversity combining schemes. The DS scheme appears to give an average outage
Figure 7.10: Average uplink outage probability using different estimation techniques for the deployment scenarios in (a) Environment A and (b) Environment B.
7.4. Estimation of uplink system performance

Figure 7.11: Average uplink outage probability as a function of average number of connected users per base station for the deployment scenario in Environment A.

Figure 7.12: Deployment scenario in Environment B employing base stations with antenna arrays.
probability across the three antenna branches. The relative performance observed between the diversity combining schemes is consistent with the literature [11–13]. The MRC scheme was employed in subsequent analysis of diversity combining in this section, unless otherwise stated.

Similar to Part I of the analysis, the performance of different estimation techniques for antenna arrays is presented in Figure 7.14. Regarding the results from the raw measured data estimation technique as the true system performance, the estimates from both uncorrelated Rayleigh and Rician fading model underestimate the real outage probability. In particular, the uncorrelated Rician fading model gives a much lower outage probability than the uncorrelated Rayleigh fading model. It is believed that the uncorrelated dominant signal components in the antenna branches enhance the CIR when constructively combined. In contrast, the estimates from the correlated Rayleigh fading model tend to overestimate the real outage probability while also being more accurate. With similar computational complexity between different modelling techniques, the correlated Rayleigh fading model has been selected for subsequent uplink system performance analysis with antenna arrays in this thesis. As a summary, Table 7.2 shows the system performance estimation techniques employed under different scenarios.

Using the simulation estimation technique with the correlated Rayleigh fading model, the outage probability for various average numbers of connected users per base station is illustrated in Figure 7.15. Similar to the case of single-element antenna systems, the outage probability increases with an increase in the number of concurrent users due to a
Figure 7.14: Average uplink outage probability using different estimation techniques for the deployment scenario with antenna arrays in Environment B.

Table 7.2: Adopted estimation techniques

<table>
<thead>
<tr>
<th>Base station antenna type</th>
<th>Number of base stations</th>
<th>Downlink</th>
<th>Uplink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-element</td>
<td>≤ 2</td>
<td>Analytic (Rician)</td>
<td>Analytic (Rayleigh)</td>
</tr>
<tr>
<td></td>
<td>&gt; 2</td>
<td>Simulation (Rician)</td>
<td></td>
</tr>
<tr>
<td>Multi-element</td>
<td>&gt; 1</td>
<td>N/A</td>
<td>Simulation (correlated Rayleigh)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>with [MRC] diversity scheme</td>
</tr>
</tbody>
</table>
higher level of intra- and inter-cell interference.

7.5 Summary

A voice-based DS-CDMA indoor wireless communication system has been considered for the analysis of system performance. The major assumptions for the system models include a sufficiently large number of mobile users and a large processing gain, which enables performance estimation based on Gaussian approximation. An interference-limited system has been presumed in which performance is determined by the level of interference only. Thermal noise has been neglected in the system models.

A number of system models have been considered including analytical and simulation estimation techniques, and the use of various fast-fading models. Separate system models have been selected for the estimation of downlink and uplink system performance, respectively. However, identical specifications for the radio interface have been assumed for both downlink and uplink.

The downlink system model employs an analytical estimation technique combined with a Rician fading model. This model gives an more accurate estimation and faster computational speed than other estimation techniques. Since the analytical technique can only estimate the performance of a system with a maximum of two base stations, the simulation estimation technique combined with the Rician fading model has been
adopted in the scenarios with more than two base stations (such as scenarios involving external interference). The simulation technique gives virtually identical estimates to the analytical technique but requires significantly more computation time.

Two separate uplink system models have been selected for single- and multi-branch antenna systems, respectively. The system model for single-element antennas is based on the analytical estimation technique and Rayleigh fading model due to its accuracy and fast computational speed. On the other hand, the simulation estimation technique with correlated Rayleigh fading model has been employed for the scenarios with multi-branch antennas. This approach produces more accurate system performance estimates than the other techniques considered. The use of the MRC diversity combining scheme has also been selected as the default combining scheme for the rest of this thesis, unless otherwise stated.

References


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tions*, ser. Kluwer international series in engineering and computer science ; SECS 599.


communications*, ser. IEE electromagnetic waves; no. 50. London: Institution of


fading envelopes for spread spectrum applications,” *IEEE Commun. Lett.*, vol. 4,

[16] S. Sorooshyari and D. Daut, “Generation of correlated rayleigh fading envelopes for
Chapter 8

System Performance for Directional Antenna Deployment

8.1 Introduction

In Chapter 7, a set of system models were proposed to evaluate the performance of an indoor wireless system employing various antenna selection and deployment options. Using these system models, a performance analysis of the measured data from the propagation study discussed in Chapter 6 was performed. This chapter outlines the analysis results for Phase I of the propagation study (outlined in Section 6.3), in which the antenna deployment strategies employing directional antennas are considered. The analysis results for Phase II of the propagation study (outlined in Section 6.4), which evaluate antenna array-based deployment strategies, is discussed in Chapter 9.

This chapter is divided into two parts. Firstly, the influence of different deployment strategies on downlink system performance is discussed in Section 8.2. Secondly, the investigation for uplink system performance is presented in Section 8.3. Finally, a summary of the major findings of this chapter is presented in Section 8.4.

8.2 Downlink system performance

In this thesis, a base station configuration specifies the location, antenna type and orientation for a single base station. In contrast, a deployment scenario is a collection of base stations, each having its own configuration, that constitute the overall wireless system. A comparative approach has been used to quantify the influence of various performance-limiting factors on the downlink by considering a number of deployment scenarios. These performance-limiting factors include the physical environment, antenna orientation, external interference and interference to nearby systems. Using this approach,
the system performance of different deployment scenarios is determined and referenced to that of a benchmark deployment scenario. These deployment scenarios are summarised in Table 8.1 and are represented by icons that provide visual distinction among different deployment scenarios. Table 8.2 shows the icons of the different types of antennas employed in the deployment scenarios. These icons are reproduced throughout this chapter as a visual aid for distinguishing individual deployment scenarios in the discussion.

### 8.2.1 The benchmark deployment scenario

A deployment scenario with two co-channel base stations in Environment A has been considered as the benchmark scenario. The two base stations were located near the diagonally opposite corners of the central core as illustrated in Figure 8.1. Both base stations were configured with omni-directional antennas and are labelled OA1 and OA2.

Using measured data and the analytical estimation technique with a Rician fading model [1] discussed in Sections 6.3 and 7.3 respectively, the average outage probability for
8.2. Downlink system performance

Table 8.2: Antenna Icons

<table>
<thead>
<tr>
<th>Antenna name</th>
<th>Icon</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omni-directional antenna (OA)</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>Directional antenna (DA)</td>
<td></td>
<td>the arrow indicates the orientation of the antenna (bore-sight direction)</td>
</tr>
</tbody>
</table>

Figure 8.1: Floor plan of Environment A indicating the locations of the base stations (denoted by ‘•’) in the benchmark scenario (Phase I).
this deployment scenario was estimated to be 0.008. This implies that the bit-error-rate (BER) drops below the threshold \(10^{-3}\) 0.8% of the time on average. This is consistent with [2, 3] under similar deployment scenarios.

The contour plot in Figure 8.2 shows the distributions of the average carrier-to-interference ratio (CIR) for this deployment scenario across the floor area. The light-shaded regions represent high average CIRs whereas the dark-shaded regions correspond to low average CIRs. In regions of low CIRs, the instantaneous CIR is more likely to drop below the threshold for adequate quality of service due to multipath fading of the desired and interfering signals. Hence, most outages occur at low CIR regions. The proportion of the low CIR regions in the environment can, therefore, be used as an indicator to the average outage probability. A high percentage of low CIR regions in the environment suggests a high average outage probability. Consequently, the most effective approach to reduce outage probability (or improve system performance) is to minimise the low CIR regions by careful deployment of the base stations.

8.2.2 The physical environment

The influence of physical environments on system performance can be quantified by evaluating the performance of two similar deployment scenarios in different environments. For example, Figure 8.3 shows a deployment scenario in Environment B, which is similar to the benchmark scenario in Environment A (as shown in Figure 8.1). The base stations
were configured with omni-directional antennas and were located at the same positions relative to the floor area as in the benchmark scenario. The average outage probability for this scenario was estimated to be 0.013, which is 63% higher than the benchmark scenario. Since the radio-opaque central core in Environment A is the main distinctive feature between the two environments, these results suggest that this obstacle accounts for the difference in outage probabilities. Alternatively, the presence of the obstacle reduces the outage probability in Environment A.

This reduction can be explained by the change of CIR distribution across the environments. For example, Figure 8.4 shows the contour plot for CIR in the deployment scenario in Environment B. This demonstrates a higher proportion of low CIR regions relative to that in Environment A. In both environments, the low CIR region lies at the midpoint of the two base stations where the received power from both base stations are approximately equal. The central core in Environment A, however, coincides with the low CIR region and effectively behaves as a physical cell boundary separating the signals from the two base stations. This reduces the regions of low CIR and therefore decreases the overall outage probability. The level of influence is likely determined by the location of obstacles. For example, a smaller reduction in outage probability would be expected if the central core in Environment A is located in a high CIR region.

8.2.3 The choice of antenna orientation

Although the presence of obstacles that are opaque to radiowaves can improve system performance, the use of obstacles in system deployment is limited by the physical layout of indoor environments. Alternatively, a new degree of freedom can be introduced in the deployment of indoor wireless systems when fixed-radiation pattern directional antennas
are employed at the base stations instead of azimuthally omni-directional antennas. An exponential increase in the number of deployment scenarios is obtained for different combinations of antenna orientations at individual base stations.

**Environment A**

A case study of this deployment strategy has been evaluated in the deployment scenario shown in Figure 8.5. Identical base station locations from the benchmark scenario were considered. Instead of omni-directional antennas, one of these base stations was configured with a directional antenna in one of the six equi-spaced orientations (0°, 60°, 120°, 180°, 240° and 300°) as indicated in the figure.

Average outage probabilities were estimated for all antenna orientations, which were normalised to that of the benchmark scenario and are summarised in Table 8.3. A normalised value less than unity implies that the average outage probability is lower than that of the benchmark scenario whereas for a normalised value greater than unity, the corresponding deployment scenario has a relatively high average outage probability (indicating inferior system performance). A range of normalised outage probabilities from 0.68 to 1.36 are observed in Table 8.3, which indicates that a 68% reduction to a 36% increase in system performance were achieved solely by changing the orientation of a single directional antenna.

A second deployment scenario employing an omni-directional and a directional antenna was considered and is illustrated in Figure 8.6. The corresponding normalised outage probabilities for this scenario were calculated and are summarised in Table 8.4. A similar

**Figure 8.4:** The CIR contour plot for the deployment scenario employing base station configurations OA1 and OA2 (Environment B, Phase I). (● denotes base station location.)
8.2. Downlink system performance

Figure 8.5: The deployment scenario employing base station configurations DA1 and OA2 (Environment A, Phase I). (The radial lines represent antenna orientations.)

Table 8.3: Normalised downlink outage probabilities for base station configurations DA1 and OA2 (Environment A, Phase I)

<table>
<thead>
<tr>
<th>Orientation of DA1</th>
<th>Normalised outage probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1.10</td>
</tr>
<tr>
<td>60°</td>
<td>0.90</td>
</tr>
<tr>
<td>120°</td>
<td>1.28</td>
</tr>
<tr>
<td>180°</td>
<td>1.30</td>
</tr>
<tr>
<td>240°</td>
<td>0.92</td>
</tr>
<tr>
<td>300°</td>
<td>0.68</td>
</tr>
</tbody>
</table>
range of outage probabilities (0.87–1.45) are observed.

The deployment strategy employing antenna orientation has been further studied by considering the deployment scenario employing directional antennas on both of the base stations, as illustrated in Figure 8.7. Average outage probabilities were estimated for every combination of antenna orientation and are summarised in Table 8.5. A wider range of outage probability (0.44–1.66) was obtained compared to the scenarios with a single directional antenna. The influence of BER threshold on this outage probability range is demonstrated in Figure 8.8, which shows the minimum and maximum normalised outage probabilities for various BER threshold values. Note that the normalised values are virtually invariant with the BER threshold. This suggests that the impact of antenna orientation on system performance is independent of the BER threshold — at least over the range of BERs considered in this study. The influences of other system parameters on the outage probability range are also shown in Figure 8.9. Similar to the BER threshold,
8.2. Downlink system performance

Figure 8.7: The deployment scenario employing base station configurations DA1 and DA2 (Environment A, Phase I). (The radial lines represent antenna orientations.)

Table 8.5: Normalised downlink outage probabilities for different combinations of base station configurations DA1 and DA2 (Environment A, Phase I)

<table>
<thead>
<tr>
<th>Config, DA1</th>
<th>0°</th>
<th>60°</th>
<th>120°</th>
<th>180°</th>
<th>240°</th>
<th>300°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1.36</td>
<td>0.88</td>
<td>0.44</td>
<td>0.87</td>
<td>0.83</td>
<td>1.03</td>
</tr>
<tr>
<td>60°</td>
<td>1.01</td>
<td>0.70</td>
<td>0.44</td>
<td>0.93</td>
<td>1.21</td>
<td>1.09</td>
</tr>
<tr>
<td>120°</td>
<td>1.06</td>
<td>1.05</td>
<td>0.77</td>
<td>0.95</td>
<td>1.31</td>
<td>1.18</td>
</tr>
<tr>
<td>180°</td>
<td>1.00</td>
<td>1.66</td>
<td>0.95</td>
<td>0.88</td>
<td>1.15</td>
<td>1.30</td>
</tr>
<tr>
<td>240°</td>
<td>0.92</td>
<td>1.05</td>
<td>0.93</td>
<td>0.86</td>
<td>1.13</td>
<td>0.99</td>
</tr>
<tr>
<td>300°</td>
<td>0.63</td>
<td>0.48</td>
<td>0.48</td>
<td>0.58</td>
<td>0.69</td>
<td>0.53</td>
</tr>
</tbody>
</table>

the actual values of these system parameters are arbitrary and do not affect the minimum and maximum normalised outage probabilities — at least for the ranges considered.

Figures 8.10(a) and (b) show the CIR contour plots for deployment scenarios with the minimum and maximum outage probabilities, respectively. It is clearly shown that different orientations of the directional antennas significantly change the distribution of CIR across the floor area. In Figure 8.10(a), the proportion of low CIR (dark-shaded) regions is substantially less than that of the benchmark scenario (Figure 8.1), which corresponds to a 56% reduction in average outage probability. The antennas point at different parts of the floor area, which minimises self-interference in the wireless system. This deployment scenario, however, has the potential to increase the external interference to nearby systems as energy is directed outwards from the floor area. In contrast, the antennas face each other in the deployment scenario of highest average outage probability
Figure 8.8: Minimum and maximum normalised outage probabilities as a function of BER threshold for deployment scenarios with directional antennas (Environment A, Phase I). The dotted line indicates the BER threshold assumed in this thesis.

as illustrated in Figure 8.10(b). The high proportion of dark-shaded regions indicates a high level of self-interference. The advantage of this deployment scenario is the potential to reduce interference to external systems since most of the radiated energy is contained within the floor area.

The two deployment examples shown in Figure 8.10 suggest that system planners can control the relative levels of self- and external interference in an indoor environment by careful selection of the orientation of directional antennas. This tradeoff between self- and external interference is further discussed in Section 8.2.5.

In Table 8.7, the highest outage probability occurs at the combination of base station configurations DA1 at 180° and DA2 at 60°. When considering the deployment scenarios employing directional antenna DA1 and omni-directional antenna OA2, as shown in Table 8.3, the highest outage probability is observed at the same orientation of 180° for DA1. Similarly, directional antenna DA2 at 60° gives the highest outage probability from the configurations between antennas OA1 and DA2 as shown in Table 8.4. This suggests that the highest outage probability configuration for two directional antennas can be determined with fewer measurements, namely two sets of measurements between a directional and an omni-directional antenna.

This method of prediction, however, was not as accurate for the determination of the antenna configuration for the lowest outage probability. From the configurations between directional antenna DA1 and omni-directional antenna OA2, the lowest outage probability
8.2. Downlink system performance

(a) Number of users per cell

(b) Processing gain

Minimum outage probability
Maximum outage probability

Normalised outage probability

Minimum outage probability
Maximum outage probability

Normalised outage probability
Figure 8.9: Minimum and maximum normalised outage probabilities as a function of (a) number of users per cell, (b) processing gain, and (c) voice activity factor for deployment scenarios with directional antennas (Environment A, Phase I). The dotted lines indicate the default system parameter values.

Figure 8.10: The CIR contour plots for the deployment scenarios with the (a) minimum (0.44) and (b) maximum (1.66) outage probability (Environment A, Phase I).
8.2. Downlink system performance

Figure 8.11: The deployment scenario employing base station configurations (a) DA1 and OA2, and (b) OA1 and DA2 (Environment B, Phase I). (The radial lines represent antenna orientations.)

is observed at the orientation of 300° for DA1. Similarly, the lowest outage probability is observed at an orientation of 180° for DA2 for configurations between antennas OA1 and DA2. At these orientations of their respectively directional antennas, a normalised outage probability of 0.58 was obtained, which is close to, but higher than, the minimum outage value of 0.44. The difference between the prediction and actual measurement highlights the complexity of the interaction between the two antennas and the environment.

Environment B

The influence of the physical environment on the deployment of directional antenna was quantified by considering similar deployment scenarios in different environments. Figure 8.11 shows two deployment scenarios employing a single omni-directional and a single directional antenna, which are similar to those in Environment A. The corresponding normalised average outage probabilities were estimated and are listed in Tables 8.6 and 8.7. In both scenarios, high outage probabilities are observed when the directional antenna at one base station points towards the other base station. This antenna configuration raises the level of self- (or inter-cell) interference and, therefore, increases the overall outage probability. In contrast, low outage probabilities occur when the directional antenna points away from the other base station, hence, minimising the level of interference.

Similar to Environment A, the deployment scenario employing two directional antennas was considered and is illustrated in Figure 8.12. The corresponding normalised average outage probabilities were calculated and are summarised in Table 8.8. A narrower range of normalised outage probabilities (0.56–1.08) is observed compared with that in Environment A (0.44–1.66). This suggests that the presence of radio-opaque obstacles
Table 8.6: Normalised downlink outage probabilities for base station configurations DA1 and OA2 (Environment B, Phase I)

<table>
<thead>
<tr>
<th>Orientation of DA1</th>
<th>Normalised outage probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.76</td>
</tr>
<tr>
<td>60°</td>
<td>0.51</td>
</tr>
<tr>
<td>120°</td>
<td>0.97</td>
</tr>
<tr>
<td>180°</td>
<td>1.18</td>
</tr>
<tr>
<td>240°</td>
<td>1.06</td>
</tr>
<tr>
<td>300°</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Table 8.7: Normalised downlink outage probabilities for base station configurations OA1 and DA2 (Environment B, Phase I)

<table>
<thead>
<tr>
<th>Orientation of DA2</th>
<th>Normalised outage probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.97</td>
</tr>
<tr>
<td>60°</td>
<td>1.05</td>
</tr>
<tr>
<td>120°</td>
<td>0.95</td>
</tr>
<tr>
<td>180°</td>
<td>1.03</td>
</tr>
<tr>
<td>240°</td>
<td>0.93</td>
</tr>
<tr>
<td>300°</td>
<td>0.98</td>
</tr>
</tbody>
</table>

does not only reduce the outage probability, but also amplifies the influence of antenna orientation on outage probability.

Figures 8.13(a) and 8.13(b) shows the CIR contour plots for the deployment scenarios with the minimum and maximum outage probabilities in Environment B, respectively. The antenna orientations corresponding to the minimum and maximum outage probability are almost identical to those in Environment A. This suggests that, in general, minimum outage probability can be obtained by pointing the directional antennas into different parts of the environment whereas for maximum outage probability, it can be achieved if

Table 8.8: Normalised outage probabilities for different combinations of base station configurations (Environment B, Phase I)

<table>
<thead>
<tr>
<th>Config. DA1</th>
<th>Config. DA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0° 0.82</td>
</tr>
<tr>
<td>60°</td>
<td>0.65 0.76</td>
</tr>
<tr>
<td>120°</td>
<td>0.95 0.95</td>
</tr>
<tr>
<td>180°</td>
<td>1.02 1.08</td>
</tr>
<tr>
<td>240°</td>
<td>1.05 0.98</td>
</tr>
<tr>
<td>300°</td>
<td>0.98 0.67</td>
</tr>
<tr>
<td>0°</td>
<td>60° 0.76</td>
</tr>
<tr>
<td>120°</td>
<td>0.65 0.56</td>
</tr>
<tr>
<td>180°</td>
<td>0.56 0.72</td>
</tr>
<tr>
<td>240°</td>
<td>0.72 0.76</td>
</tr>
<tr>
<td>300°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>0°</td>
<td>120° 0.67</td>
</tr>
<tr>
<td>60°</td>
<td>0.56 0.56</td>
</tr>
<tr>
<td>180°</td>
<td>0.72 0.72</td>
</tr>
<tr>
<td>240°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>300°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>0°</td>
<td>180° 0.89</td>
</tr>
<tr>
<td>60°</td>
<td>0.72 0.72</td>
</tr>
<tr>
<td>120°</td>
<td>0.72 0.72</td>
</tr>
<tr>
<td>240°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>300°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>0°</td>
<td>240° 0.89</td>
</tr>
<tr>
<td>60°</td>
<td>0.72 0.72</td>
</tr>
<tr>
<td>120°</td>
<td>0.72 0.72</td>
</tr>
<tr>
<td>180°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>240°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>300°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>0°</td>
<td>300° 0.89</td>
</tr>
<tr>
<td>60°</td>
<td>0.72 0.72</td>
</tr>
<tr>
<td>120°</td>
<td>0.72 0.72</td>
</tr>
<tr>
<td>180°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>240°</td>
<td>0.76 0.76</td>
</tr>
<tr>
<td>300°</td>
<td>0.76 0.76</td>
</tr>
</tbody>
</table>

Table 8.8: Normalised outage probabilities for different combinations of base station configurations (Environment B, Phase I)
Figure 8.12: The deployment scenario with base station configurations DA1 and DA2 (Environment B, Phase II). (The radial lines represent antenna orientations.)

Figure 8.13: The CIR contour plots for the deployment scenarios with the (a) minimum (0.56) and (b) maximum (1.08) outage probability (Environment B, Phase I).

the antennas are pointing towards each other.

A quantitative measure for the difference in the CIR distributions of two deployment scenarios is obtained by comparing their cumulative distribution functions (CDFs). For example, Figure 8.14 shows the CDFs for the CIR of the deployment scenarios with minimum and maximum outage probability in Environments A and B. The relatively smooth gradient of the CDFs for the deployment scenarios in Environment B indicates an even distribution of low and high CIR values. The CDF for the case of minimum outage probability in Environment B demonstrates a small increase (3.5 dB at the 50th percentile) in the whole range of CIR values over the case of maximum outage probability. In contrast, the CDF for the deployment scenarios with the maximum outage probability
in Environment A shows a high percentage of low CIR values. It can be seen that 33.5% of the CIR values are less than 10 dB in this deployment scenario whereas for the case of minimum outage probability, the proportion is only 10%.

8.2.4 The presence of external interference

In addition to internal obstacles and antenna orientations as discussed in Sections 8.2.2 and 8.2.3, the presence of external interference can also influence the performance of indoor systems. This influence is likely to be detrimental for the interference-limited system considered. The analysis for the deployment scenarios from Sections 8.2.2 and 8.2.3 was repeated under the influence of external interference. Instead of an analytical technique, the Monte Carlo estimation technique using a Rician fading model (as discussed in Section 7.3) was employed for estimating the average outage probabilities in these deployment scenarios.

Environment A

The influence of external interference on system performance was evaluated in a deployment scenario similar to the benchmark scenario (discussed in Section 8.2.1) with the addition of an external interfering base station. Four possible locations (BS3–BS6) for the external base station were considered as illustrated in Figure 8.15. This external base station was configured with an omni-directional antenna. Mobile users were assumed to
receive interference from one of the internal base stations and the external base station. The interference power from the external base station was modelled as a fraction of the average received power from the internal base station, and the power ratio between them is defined as the carrier-to-external-interference ratio (CEIR). The outage probabilities for the deployment scenarios of four possible locations of external base stations were estimated as a function of CEIR and are illustrated in Figure 8.16. These outage probabilities were normalised relative to that of the benchmark scenario without external interference. A significant increase in outage probability is observed when the CEIR is less than 20 dB. For example, the outage probability is approximately two times greater than that of the benchmark scenario at an average CEIR of 20 dB, at which the external interference power is only one-hundredth of that from the internal base station. The level of influence, however, decays rapidly as the CEIR increases. This influence becomes negligible (less than 1% increase in outage probability) when the CEIR rises above 30 dB.

In Figure 8.16, similar outage probabilities are observed for deployment scenarios with different locations of external base stations. This suggests that the location of the external interferer does not have a significant influence on overall outage probability. The influence of external interferer’s location on the distribution of CIR is illustrated in Figure 8.17, which shows the CDFs for CIR at a CEIR of 20 dB. The CDF for the benchmark scenario without external interference is also shown as a reference. The CDFs for the scenarios with external interference show a clear shift to the left from that of the benchmark scenario, which is not unexpected since the presence of external interference reduces the overall CIR. Otherwise, the CDFs for the scenarios with external interference appear to be similar, which indicate a high degree of similarity among the distributions of CIR.

The analysis of external interference has been concentrated on deployment scenarios employing omni-directional antennas; however, scenarios employing directional antennas at the internal base stations were also considered. For example, the minimum normalised
Figure 8.16: Normalised average outage probability for the benchmark scenario in Environment A under a single external interferer (Phase I).

Figure 8.17: The CDF for CIR of the benchmark scenario with single external interferer at a CEIR of 20 dB (Environment A, Phase I).
outage probabilities for the scenarios employing two directional antennas at the internal base stations are illustrated in Figure 8.18 as a function of CEIR. It is clearly seen that these outage probabilities are lower than those of the benchmark scenarios (Figure 8.16) regardless of the location of the external interferer. The actual outage values for the scenarios employing two omni-directional or two directional antennas are summarised in Table 8.9. In the case of minimum outage probability, the deployment scenarios employing directional antennas show a consistent reduction in outage probability over the scenarios employing omni-directional antennas, especially at high CEIRs. At a CEIR greater than 20 dB, the average outage probability is lower than that of the benchmark scenario without external interference. This suggests that appropriate deployment of directional antennas at the base stations can reduce the degradation on system performance due to external interference. However, certain configurations of the directional antennas can also cause a significant increase in outage probability, as shown by the case of maximum outage probability in Table 8.9.

The relative power level of external interference can also affect the optimum antenna orientations to yield the minimum (and maximum) outage probability. Although optimal antenna orientations vary for different locations of the external interfering base station, the same deployment trends can be observed, as shown in Table 8.9. At high external interference power (a low CEIR), the directional antennas are observed pointing towards the external interferer, which increases the internal signal level. Although this
Table 8.9: Normalised outage probabilities for various deployment scenarios with external interfering base station OA6 (Environment A, Phase I) († denotes benchmark scenario)

<table>
<thead>
<tr>
<th>CEIR (dB)</th>
<th>Normalised outage prob. with omni-directional antennas</th>
<th>Deployment scenarios with directional antennas</th>
<th>Normalised outage prob.</th>
<th>Normalised outage prob.</th>
<th>Antenna orientation at</th>
<th>Antenna orientation at</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum case</td>
<td>Maximum case</td>
<td>DA1</td>
<td>DA2</td>
<td>DA1</td>
<td>DA2</td>
</tr>
<tr>
<td>0</td>
<td>19.28</td>
<td>17.60</td>
<td>180°</td>
<td>180°</td>
<td>27.12</td>
<td>0°</td>
</tr>
<tr>
<td>10</td>
<td>7.06</td>
<td>5.70</td>
<td>180°</td>
<td>180°</td>
<td>12.83</td>
<td>300°</td>
</tr>
<tr>
<td>20</td>
<td>2.11</td>
<td>1.62</td>
<td>0°</td>
<td>120°</td>
<td>3.92</td>
<td>0°</td>
</tr>
<tr>
<td>30</td>
<td>1.12</td>
<td>0.57</td>
<td>0°</td>
<td>120°</td>
<td>1.88</td>
<td>180°</td>
</tr>
<tr>
<td>40</td>
<td>1.01</td>
<td>0.44</td>
<td>0°</td>
<td>120°</td>
<td>1.68</td>
<td>60°</td>
</tr>
<tr>
<td>No external interference</td>
<td>1.00†</td>
<td>0.44</td>
<td>0°</td>
<td>120°</td>
<td>1.66</td>
<td>180°</td>
</tr>
</tbody>
</table>

arrangement of antennas increases the internal interference between the internal base stations, the improvement in CEIR justifies this deployment strategy and reduces the overall outage probability across the floor area. In contrast, when the external interference power level is low (a high CEIR), the internal interference between the internal base stations becomes the dominant performance-limiting factor. Consequently, minimum outage probability is observed when the antennas are pointed to different parts of the floor area and away from each other, which minimises the internal interference. In the case of maximum outage probability, the antennas at both internal base stations point away from the floor area when the external interference power is high. This antenna arrangement reduces the signal level within the floor area and, hence, minimises the CIR. The presence of the strong external interference overwhelms the benefit of the reduced internal interference and increases the overall outage probability. As internal interference becomes the dominant source of interference when the external interference power is low, the antennas point towards each other to increase internal interference resulting in a high outage probability.

The implication of the dependence of optimal antenna orientation on the strength of external interference is demonstrated in Figure 8.19. In this example, the base station configurations DA1 at 0° and DA2 at 120° were employed, which are the optimal antenna orientations for the lowest outage probability in the absence of any external interference. Figure 8.19 shows the outage probability for these fixed antenna orientations as a function of CEIR under the influence of the external interfering base station OA6. The outage probabilities for the scenarios employing omni-directional antennas and directional
8.2. Downlink system performance

Figure 8.19: Normalised average outage probability for the scenario employing directional antennas at fixed orientations under the influence of the external interfering base station OA6 (Environment B, Phase I).

antennas at the optimal orientations are also shown for comparison. It can be seen that the deployment of directional antennas, even at fixed orientations optimised for no external interference, always provides a lower outage probability than the case of omni-directional antennas. This observation provides confidence to system planners for deploying directional antennas in a system regardless of the strength of external interference since the deployment would not degrade future system performance as levels of external interference increase. While there is no penalty on system performance for fixing the antenna orientations, a further performance gain can be obtained by optimising the antenna orientations to account for the power level of external interference.

Environment B

In addition to Environment A, the presence of external interference in Environment B was also considered. Figure 8.20 shows a base station in Environment C that interferes with the base stations in Environment B. This is a typical example which shows that a wireless system in one building may interfere with a system in another building. In the benchmark scenario, all internal (Environment B) and external (Environment C) base stations were configured with omni-directional antennas. The outage probability for this scenario is illustrated in Figure 8.21 as a function of CEIR, which was normalised relative to that of the benchmark scenario without external interference. Similar to Environment A, the outage probability decreases as the CEIR increases. Figure 8.21 also shows the outage
minimum and maximum outage probabilities when the base stations in Environment B were configured with directional antennas. At a high level of external interference (a low CEIR), the outage probability for the scenario employing omni-directional antennas (OA) approaches the minimum outage probability achieved by the scenario employing directional antennas (Minimum DA). In contrast, the outage probability for scenario OA is close to the maximum outage probability from the directional antennas (Maximum DA) at low level of external interference (a high CEIR). This suggests that the deployment of directional antennas is most efficient for reducing outage probability at low level of external interference.

8.2.5 Interference to an adjacent system

In Section 8.2.4, the base station in Environment C was considered as an interferer to the wireless system in Environment B. The base stations in Environment B, however, can equally act as interferers to the wireless system in Environment C. Figure 8.22 shows the floor plan of Environment C indicating the location of an internal base station and the relative positions of the interfering base stations from Environment B. A single-base station deployment scenario employing an omni-directional antenna was considered in Environment C, which implies no internal co-channel interference. As a consequence, the outage probability is zero by definition based on the interference-limited system model. The only source of interference originates externally from the two base stations in Environment B.

The outage probability for the scenario in Figure 8.22 is illustrated in Figure 8.23 as a function of CEIR. No normalisation was performed because the outage probability of a
Figure 8.21: Normalised average outage probability for deployment scenarios with the single external interferer OA3 (Environment B, Phase I).

Figure 8.22: The deployment scenario with base station configuration OA3 (Environment C, Phase I).
single-cell system is theoretically zero for the case without external interference. A linear decrease in outage probability is observed as the CEIR increases. This linear relationship is likely the result of the external interference being the single performance-limiting factor in the entire system. In contrast, a non-linear influence on outage probability due to external interference was observed for deployment scenarios in Environments A and B, where co-channel interference between the internal base stations accounts for another performance-limiting factor.

Figure 8.23 also shows the minimum and maximum outage probabilities when the base stations in Environment B were configured with directional antennas at various orientations. It is clearly shown that the outage probability for the scenario employing omni-directional antennas is closer to the maximum outage probability. This suggests that the use of directional antennas in Environment B is more likely to provide a reduction in outage probability in Environment C compared to the use of omni-directional antennas.

The optimal antenna orientations for the minimum (and maximum) outage probability scenario under different CEIRs are summarised in Table 8.10. In general, the minimum outage probability was achieved when both of the directional antennas point away from Environment C (at an orientation of 60°). Conversely, maximum outage probability resulted when both directional antennas point towards Environment C (at an orientation of 240°). The actual outage values from Table 8.10 also suggest that different antenna orientations of one system can create more than one order of magnitude change in outage probability in an nearby single-cell system.
8.2. Downlink system performance

### Table 8.10: Average outage probabilities for various deployment scenarios with external interferers in Environment B (Environment C, Phase I)

<table>
<thead>
<tr>
<th>CEIR (dB)</th>
<th>Average outage prob. with omni-directional antennas</th>
<th>Deployment scenarios with directional antennas</th>
<th>Minimum case</th>
<th>Maximum case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average outage prob.</td>
<td>Antenna orientation at</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DA1</td>
<td>DA2</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.218</td>
<td>0.028</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>10</td>
<td>0.032</td>
<td>0.003</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>20</td>
<td>0.003</td>
<td>0.000</td>
<td>0°</td>
<td>60°</td>
</tr>
<tr>
<td>30</td>
<td>0.000</td>
<td>0.000</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>40</td>
<td>0.000</td>
<td>0.000</td>
<td>180°</td>
<td>60°</td>
</tr>
<tr>
<td>No external interference</td>
<td>0.000</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

8.2.6 Summary of downlink deployment strategies

In the planning of the downlink deployment for an indoor wireless system, one of the most important factors to consider is the layout of the environment. It is crucial to identify any features of the environment that may interact with the propagation of radio signals. Obstacles that are opaque to radio signals, such as steel-reinforced walls and metallic furniture, are attractive candidates for physical cell boundaries. These obstacles can minimise the level of inter-cell interference and, therefore, reduce the overall outage probability of the system. A 63% improvement in outage probability has been obtained in an environment with a steel-reinforced structural core acting as a physical cell boundary compared to a similar environment without a comparable radio-opaque obstacle. This improvement in system performance is achieved with no additional hardware cost.

The deployment of directional antennas at base stations in place of conventional omni-directional antennas has been shown as another attractive strategy for improving system performance. Different antenna orientations introduce variability in system performance, which can be either beneficial or detrimental. In the best case, a 54% reduction in outage probability referenced to the scenario employing omni-directional antennas has been obtained whereas in the worst case, a 66% increase has been measured. The deployment of directional antennas influence outage probability by altering the focus of transmitted signals and, hence, the CIR across the environment. In general, the best system performance can be achieved by pointing the directional antennas towards different parts of the environment, to minimise inter-cell interference. Inferior system performance is likely to occur when the directional antennas are orientated towards each other resulting in severe inter-cell interference. Obstacles that act as physical cell boundaries have been
shown to amplify the effectiveness of directional antennas resulting in a greater variability of the outage probability. Careful planning and deployment is therefore necessary to realise the performance improvements offered by directional antennas.

Due to the high bandwidth requirements, the cell sizes of indoor wireless systems tend to be small, which causes a high probability of inter-system (or external) interference. It has been shown from measured data that external interference can cause a significant increase (up to 2400%) in the outage probability of an indoor wireless system. In general, directional antennas can be deployed to minimise the influence of external interference to a certain extent (20% to 60%) by focusing the desired signals towards the regions exposed to external interference. Fortunately, the impact of external interference depends heavily on its power level relative to the average desired signal power. It has been shown that external interference becomes negligible (causing less than 1% increase on outage probability) when the \( \text{CEIR} \) is greater than 30 dB. This guideline is based on a system in which performance is limited by internal interference, namely more than one co-channel base station in the system. Otherwise, it is advantageous to minimise the influence of external interference on system performance using appropriate deployment of directional antennas.

### 8.3 Uplink system performance

In Section 8.2, the system performance analysis for the downlink is presented. This analysis was repeated for the uplink and is presented in this section. Similar to the downlink case, a number of deployment scenarios were considered and are summarised in Table 8.1. The performance-limiting factors evaluated include the physical environment, the choice of antenna orientation, and the presence of external interference. The interference of an indoor system to nearby systems is also discussed.

#### 8.3.1 The benchmark deployment scenario

The same benchmark deployment scenario from the downlink analysis in Environment A was considered as illustrated in Figure 8.1. The two co-channel base stations were configured with omni-directional antennas, which are labelled OA1 and OA2. Using measured data and the analytical estimation technique with a Rayleigh fading model [4, pp. 172–174] discussed in Sections 6.3 and 7.3 respectively, the average outage probability for this deployment scenario was estimated to be 0.117. This is consistent with \([2, 3]\) for similar deployment scenarios. It should be noted that this outage probability is much higher than that of the downlink as presented in Section \([8.2.1]\) (0.008). This is due to relatively high level of interference in the uplink, which is the aggregate total from all
mobile users whereas for the downlink, the only source of interference comes from the co-channel base station.

8.3.2 The physical environment

The influence of physical environments on the uplink outage probability can be quantified by evaluating the performance of two similar deployment scenarios in different environments. For example, Figure 8.3 shows a deployment scenario in Environment B, which is virtually identical to the benchmark scenario in Environment A (as shown in Figure 8.1). The base stations were configured with omni-directional antennas and were located at the same positions relative to the floor area as in the benchmark scenario. The average outage probability for this scenario was estimated to be 0.075, which is 8% higher than the benchmark scenario. The change in the physical environment, specifically the exclusion of the central core, is believed to account for this increase in outage probability. However, this increase in outage probability is significantly lower than the 63% increase observed in the downlink. It is likely due to the difference in the composition of the interference. In the downlink, the only source of interference comes from a base station on the diagonally opposite side of the floor area. Most of the interfering signal would be obstructed by the central core in Environment A, hence the lower outage probability. In contrast, a large number of mobile interferers are scattered across the floor area in the uplink case. The central core in Environment A is, therefore, less effective in shielding interfering signals to the connected base station.

8.3.3 The choice of antenna orientation

In Section 8.3.2, it is shown that the presence of obstacles that are opaque to radiowaves can improve uplink system performance. Alternatively, a new degree of freedom can be introduced in the deployment of indoor wireless systems when fixed-radiation pattern directional antennas are employed at the base stations instead of azimuthally omni-directional antennas. The influence of this deployment strategy on uplink system performance was evaluated and is presented in this section.

Environment A

The analysis of uplink system performance employing directional antennas was performed using the same deployment scenarios used in the downlink as illustrated in Figures 8.5–8.7. Identical base station locations were considered as in the benchmark scenario; however, directional antennas were employed at the base stations. The directional antennas were configured in one of the six equi-spaced orientations (0°, 60°, 120°, 180°, 240° and 300°).
as indicated in Figures 8.5–8.7. Average uplink outage probabilities were estimated for all combinations of antenna orientations. These outage probabilities were normalised to that of the benchmark scenario and are summarised in Table 8.11. A range of normalised outage probabilities from 0.94 to 1.07 are observed. This range is relatively small with respect to the downlink, in which a range of 0.44–1.66 was observed. This suggests that the deployment of directional antennas causes minimal influence on uplink system performance.

In contrast to the downlink, which alters the distribution of CIR across the environment, the use of directional antennas in the uplink essentially modifies the system outage probability by changing the distribution of users connected to individual base stations. As discussed in Section 7.4.1, intra-cell interference, which is determined by the distribution of users to individual base stations, is the dominant performance-limiting factor in the power-controlled uplink. Consequently, the distribution of connected users has a direct influence on system performance. When omni-directional antennas are exclusively deployed at the base stations, the distribution of connected users depends on the layout of the environment and the relative locations of the base stations. An unbalanced load of users is most likely a consequence of the asymmetrical nature of the environment and base station locations. The use of directional antennas effectively introduce a new degree of freedom for redistributing the users to individual base stations. This can be demonstrated in Figure 8.24 that shows the uplink outage probability in Environment A as a function of the proportion of total number of users connected to base station BS1. The benchmark deployment scenario yielded a normalised outage probability of 1.00 at a proportion value of 0.61, representing 61% of the total number of mobile users in the system connected to base station BS1. In comparison, the deployment scenarios employing directional antennas achieved a range of different proportions of connected users with various outage

### Table 8.11: Normalised uplink outage probabilities for different combinations of base station configurations (Environment A, Phase I)

<table>
<thead>
<tr>
<th>Config.</th>
<th>OA1 1.00</th>
<th>OA1 1.00</th>
<th>OA1 1.06</th>
<th>OA1 1.01</th>
<th>OA1 1.00</th>
<th>OA1 1.03</th>
<th>OA1 1.03</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA2 0°</td>
<td>1.03</td>
<td>1.07</td>
<td>1.01</td>
<td>0.94</td>
<td>0.98</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>OA2 60°</td>
<td>1.01</td>
<td>1.04</td>
<td>1.01</td>
<td>0.95</td>
<td>1.00</td>
<td>1.01</td>
<td>1.03</td>
</tr>
<tr>
<td>OA2 120°</td>
<td>1.01</td>
<td>1.01</td>
<td>1.03</td>
<td>0.97</td>
<td>1.00</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>OA2 180°</td>
<td>1.03</td>
<td>1.00</td>
<td>1.06</td>
<td>1.00</td>
<td>1.01</td>
<td>1.05</td>
<td>1.04</td>
</tr>
<tr>
<td>OA2 240°</td>
<td>1.02</td>
<td>1.00</td>
<td>0.99</td>
<td>0.98</td>
<td>0.99</td>
<td>1.03</td>
<td>1.00</td>
</tr>
<tr>
<td>OA2 300°</td>
<td>0.98</td>
<td>0.98</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.97</td>
</tr>
</tbody>
</table>

### Section 8.11: System Performance for Directional Antenna Deployment

...
probabilities. The minimum outage probability occurs at a proportion value of 0.45, which is close to the proportion value of 0.5 that corresponds to an even load between the two base stations. This deviation is likely to be the consequence of the asymmetrical layout of the environment, base station locations and the presence of the central core.

Figure 8.25(a) illustrates the distribution of connected users for the benchmark scenario employing two omni-directional antennas. In contrast, the user distribution of the deployment scenario employing directional antennas with the minimum outage probability is shown in Figure 8.25(b). A qualitative comparison between Figure 8.25(a) and (b) clearly demonstrates how the use of directional antennas can alter the distribution of connected users between base stations.
Figure 8.25: Floor plans of Environment A showing the distribution of connected mobile users in the scenarios employing (a) omni-directional antennas and (b) directional antennas with minimum outage probability (Phase I). (‘×’ denotes users connected to base station BS1; ‘○’ represents connection to base station BS2.)
Table 8.12: Normalised uplink outage probabilities for different combinations of base station configurations (Environment B, Phase I)

<table>
<thead>
<tr>
<th>Config.</th>
<th>OA2</th>
<th>0°</th>
<th>60°</th>
<th>120°</th>
<th>180°</th>
<th>240°</th>
<th>300°</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA1</td>
<td>1.00</td>
<td>1.04</td>
<td>0.97</td>
<td>1.00</td>
<td>1.05</td>
<td>1.03</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>0°</td>
<td>0.95</td>
<td>0.95</td>
<td>0.93</td>
<td>0.95</td>
<td>0.97</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>60°</td>
<td>0.92</td>
<td>0.93</td>
<td>0.93</td>
<td>0.92</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>DA1</td>
<td>1.00</td>
<td>1.07</td>
<td>1.01</td>
<td>1.03</td>
<td>1.05</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>120°</td>
<td>0.96</td>
<td>0.99</td>
<td>0.96</td>
<td>0.98</td>
<td>0.99</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>180°</td>
<td>1.01</td>
<td>1.07</td>
<td>1.01</td>
<td>1.03</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>240°</td>
<td>1.00</td>
<td>1.03</td>
<td>0.98</td>
<td>1.01</td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>300°</td>
<td>0.94</td>
<td>0.96</td>
<td>0.92</td>
<td>0.95</td>
<td>0.94</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Environment B

The influence of directional antennas on uplink system performance was also evaluated in Environment B. The deployment scenarios considered are virtually identical to those in Environment A and are illustrated in Figures 8.5–8.7. The normalised average outage probabilities for the scenarios employing directional antennas were estimated and are presented in Table 8.12. A narrow range of normalised outage probability (0.92–1.07) was observed, which is similar to that in Environment A. Considering the central core in Environment A as being the distinctive feature between the two environments, the small outage probability ranges obtained suggest that the presence of an obstacle does not amplify the influence of antenna orientation on uplink outage probability. This is in contrast with the findings in Section 8.2.3 that suggests the presence of an obstacle increases the range of downlink outage probability for scenarios employing directional antennas. The discrepancy between the uplink and downlink results is likely to be due to the distributed mobile interferers in the uplink that de-emphasise the influence of the obstacle.

Similar to Environment A, the distribution of connected users in Environment B is illustrated in Figure 8.26. The benchmark deployment scenario employing exclusively omni-directional antennas yielded a normalised outage probability of 1.00 at a proportion value of 0.61, representing 61% of the total number of mobile users in the system connected to base station BS1. The actual distribution of connected users is illustrated in Figure 8.27(a). In contrast, the use of directional antennas changes this user distribution and achieved the minimum outage probability at a proportion value of 0.45, which is shown graphically in Figure 8.27(b). This deployment scenario creates a more balanced load between the two base stations than the benchmark scenario.
Figure 8.26: Normalised uplink outage probability as a function of the proportion of total number of users connected to base station BS1 (Environment B, Phase I). (‘OA’ denotes the scenario employing omni-directional antennas and ‘DA’ denotes directional antennas.)

Figure 8.27: Floor plans of Environment B showing the distribution of connected mobile users in the scenarios employing (a) omni-directional antennas and (b) directional antennas with minimum outage probability (Phase I). (‘×’ denotes users connected to base station BS1; ‘○’ represents connection to base station BS2.)
8.3. Uplink system performance

Environment C
(Adjacent system)

Mobile user

External interference

Environment B
(System of interest)

Figure 8.28: The deployment scenario for uplink performance analysis (Environment B, Phase I).

8.3.4 The presence of external interference

Similar to the downlink, the presence of external interference can also influence the uplink performance of an indoor wireless system. The influence of external interference on uplink outage probability was evaluated in a deployment scenario in Environment B, which is similar to that discussed in Section 8.3.2. In addition to internal interference within the environment, external interference was considered from mobile users in Environment C as illustrated in Figure 8.28. These mobile users connect to the base station in Environment C but their transmitted signals interfere with the system in Environment B. The average interference power from these mobile users was modelled as a fraction of the average received signal power from the users in Environment B and the power ratio between them is defined by the CEIR (see Section 8.2.4). System performance in terms of average outage probability was then estimated using the analytical estimation technique with the Rayleigh fading model as discussed in Section 7.3.

Figure 8.29 shows the outage probability as a function of average CEIR for the deployment scenario employing omni-directional antennas at the base stations in Environment B. This outage probability was normalised relative to the case without external interference, namely the benchmark scenario. In Figure 8.29, the outage probability decreases as the CEIR increases. This is similar to that observed in the downlink, but the magnitude
Figure 8.29: Normalised average uplink outage probability for deployment scenarios with external interference from Environment C (Environment B, Phase I). (‘OA’ denotes the scenario employing omni-directional antennas at the indoor base stations. Similarly, ‘DA’ denotes directional antennas.)

The normalised outage probability is comparatively smaller than the downlink case at low CEIRs. At a CEIR of 20 dB, the outage probability is only 0.8% higher than the benchmark scenario, which suggests that the influence of external interference is negligible for CEIRs greater than this value. This threshold CEIR is lower than that in the downlink (30 dB), which is likely due to the presence of a relatively high level of internal interference in the uplink. This internal interference is contributed by all individual mobile users in the system. The addition of external interference would only cause a marginal increase in the total interference level and, therefore, a slight degradation on uplink system performance. In contrast, co-channel interference from the internal base stations is the only source of internal interference in the downlink. Consequently, the addition of external interference can significantly increase the total interference level.

Figure 8.29 also shows the outage probabilities for the deployment scenarios employing directional antennas at the base stations in Environment B with the minimum and maximum outage probabilities. The actual outage values and antenna orientations of these deployment scenarios are summarised in Table 8.13. Similar to the downlink, the appropriate deployment of directional antennas can reduce the degradation of uplink system performance due to external interference. However, certain configurations of the directional antennas can also cause a significant increase in uplink outage probability. The use of directional antennas is effective at reducing the outage probability at all levels of external interference, especially at low CEIRs. At a CEIR of 0 dB, a 38% reduction
### Table 8.13: Normalised uplink outage probabilities for various deployment scenarios with external interference from Environment C (Environment B, Phase I) († denotes benchmark scenario)

<table>
<thead>
<tr>
<th>CEIR (dB)</th>
<th>Normalised outage prob. with omni-directional antennas</th>
<th>Deployment scenarios with directional antennas Minimum case</th>
<th>Maximum case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normalised outage prob.</td>
<td>Antenna orientation at</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DA1</td>
<td>DA2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.67</td>
<td>1.03</td>
<td>300°</td>
</tr>
<tr>
<td>10</td>
<td>1.08</td>
<td>0.93</td>
<td>300°</td>
</tr>
<tr>
<td>20</td>
<td>1.01</td>
<td>0.92</td>
<td>60°</td>
</tr>
<tr>
<td>30</td>
<td>1.00</td>
<td>0.92</td>
<td>60°</td>
</tr>
<tr>
<td>40</td>
<td>1.00</td>
<td>0.92</td>
<td>60°</td>
</tr>
<tr>
<td>No external interference</td>
<td>1.00†</td>
<td>0.92</td>
<td>60°</td>
</tr>
</tbody>
</table>

In outage probability was observed for the scenario employing directional antennas over that employing omni-directional antennas. The antenna orientations for this scenario are illustrated in Figure 8.30(a). Antenna DA2 was directed towards the floor area that was exposed to the external interference. This improves the CEIR in this region and, therefore, reduces the overall outage probability. In contrast, the two antennas were pointed away from the floor area in the scenario with the maximum outage probability as illustrated in Figure 8.30(b). This minimises the received signal power from the mobile users and increases the received power from the external interference.

### 8.3.5 Interference to an adjacent system

While the influence of external interference on uplink system performance was quantified in Section 8.3.4, the reverse scenario was evaluated and is presented in this section. The case study shown in Figure 8.31 corresponds to a scenario in which the signals from the mobile users in Environment B interfere with a nearby system in Environment C. These interfering signals were regarded as external interference to the system in Environment C. In contrast to the deployment scenario in Environment B that consists of two internal base stations (as discussed in Section 8.3.4), a single base station was employed in Environment C.

Similar to Section 8.3.4, the uplink outage probability of the system in Environment C was estimated as a function of average CEIR for the deployment scenario with omni-directional antennas configured on the base stations in Environment B, as illustrated in Figure 8.32. This outage probability was normalised relative to the scenario without external interference, namely the benchmark scenario. A significant increase in outage
Figure 8.30: Floor plans of Environment B showing the distribution of connected mobile users in the scenarios employing directional antennas with (a) minimum and (b) maximum outage probability (Phase I). (‘×’ denotes users connected to base station BS1; ‘O’ represents connection to base station BS2.)

Figure 8.31: The deployment scenario in Environment C for uplink performance analysis.
8.3. Uplink system performance

Figure 8.32: Normalised average uplink outage probability for deployment scenarios with external interference from Environment B (Environment C, Phase I). (‘OA’ denotes the scenario of omni-directional antennas at the indoor base stations. Similarly, ‘DA’ denotes directional antennas.)

probability was observed at low CEIRs, although the outage probability decays rapidly as the CEIR increases until it reaches a steady state for CEIRs greater than 30 dB. At a CEIR of 20 dB, the outage probability is 18% higher than that in the benchmark scenario, compared to the 0.8% increase for the scenario in Environment B (as discussed in Section 8.3.4). This discrepancy is believed to be the consequence of the single-base station deployment in Environment C. External interference is the only performance-limiting factor in this scenario whereas for Environment B, both internal and external interference exist.

Figure 8.32 also shows the minimum and maximum outage probabilities when directional antennas were employed in Environment B. At a CEIR of 20 dB, a range of normalised outage probability (1.14–1.54) was observed. It is clearly shown that the outage probability for the deployment of omni-directional antennas in Environment B is closer to the bottom end of the range. This suggests that the use of directional antennas on external interfering base stations would most likely increase the outage probability of a nearby system compared to the case employing omni-directional antennas.

8.3.6 Summary of uplink deployment strategies

A number of factors affecting uplink system performance have been discussed in Section 8.3. The optimal uplink system performance can be achieved if these factors are
considered in the planning of an indoor wireless system. System planners must appreciate that the operating conditions for the uplink are very different to the downlink even under the same deployment scenario. An uplink outage probability of more than one order of magnitude higher than that of the downlink case was observed. This is due to a large number of interfering mobile users in the uplink whereas for the downlink, interference originates from a few base stations only. These distributed sources of interference reduce the effectiveness of the deployment strategy based on the physical environment, which uses radio-opaque obstacles as physical cell boundaries. A 8% reduction in uplink outage probability was measured in an environment with a steel-reinforced structural core acting as a physical cell boundary compared to a similar environment without the obstacle. This is much smaller than the 63% reduction observed in the downlink case.

The antenna orientation deployment strategy has also demonstrated minimal impact on the uplink outage probability. A percentage change from -8% to +7% for the nominal outage probability (in a scenario employing omni-directional antennas) was measured as a result of different orientations for directional antennas at the base stations. This range is significantly smaller than that in the downlink case (-54% to a +66%). Similarly, this is likely the result of the distributed nature of the interference in the uplink.

The antenna orientation deployment strategy, however, provides the advantage of balancing the load between base stations in the uplink. In a conventional system employing omni-directional antennas at the base stations, an uneven distribution of connected users across the individual base stations can often result due to the asymmetrical nature of the environment and the layout of the base stations. Since uplink system performance depends heavily on the number of users connected to individual base stations, this uneven distribution of users can impede the overall system performance. The deployment of directional antennas introduces flexibility for changing the distribution of connected users. Optimal loading between the base stations can then be realised for better overall uplink system performance.

The third performance-limiting factor considered is the co-channel interference from nearby wireless systems, namely external interference. In the worst case, a two-fold increase in outage probability (compared to the case without external interference) was observed for a deployment scenario employing omni-directional antennas. This is significantly less than the downlink case, in which up to a 2400% increase in outage probability was observed. Since intra-cell interference is the dominant performance-limiting factor in the uplink, the addition of external interference merely introduces a fractional increase in outage probability. Similar to the downlink, the influence of external interference becomes negligible (causing less than 1% increase on outage probability) when the CEIR is greater than 30 dB.
When external interference is present, the deployment of directional antennas at the internal base stations has been shown to have an equal chance of improving or degrading system performance depending on the antenna orientations. In contrast, this deployment of directional antennas is more likely to degrade the performance of nearby systems compared to the deployment scenario employing omni-directional antennas.

8.4 Summary

In this chapter, an investigation on the influence of physical environment, antenna orientation, external interference and interference to nearby systems on both downlink and uplink system performance has been presented. Deployment scenarios employing single-element antennas (namely omni-directional and directional antennas) at the base stations were considered. A comparative approach has been adopted to evaluate and quantify the influence of the performance-limiting factors by comparing the estimated outage probabilities of different deployment scenarios. The influence of these factors has been shown to be more effective in the downlink than the uplink.

The use of radio-opaque obstacles as physical cell boundaries is an attractive deployment strategy because it can produce considerable improvement in downlink system performance (up to 60% was observed) at no additional hardware cost. The deployment of directional antennas at the base stations introduces a new degree of freedom into the system which can either improve system performance or mitigate the negative influence of other performance-limiting factors. In the best case, a 54% reduction in downlink outage probability was observed using this antenna orientation deployment strategy.

External interference has demonstrated a significant degradation on downlink system performance; however, a relatively small influence was observed in the uplink. The level of influence is heavily dependent on the power level of the external interference relative to the desired signal power. Analysis results suggest that external interference becomes negligible (causing less than 1% increase on outage probability) in both downlink and uplink when the CEIR is greater than 30 dB.

References


Chapter 9

System Performance for Antenna Array Deployment

9.1 Introduction

In Chapter 8, the various deployment strategies based on directional antennas was discussed. The influences of a number of performance-limiting factors have been evaluated and quantified for the deployment of single-element antennas on the base stations. As an extension, this chapter outlines the analysis results for Phase II of the propagation study (discussed in Section 6.3), which concentrates on the deployment strategies employing MEAs. The performance-limiting factors considered in Chapter 8 are revisited for the perspective of antenna arrays. In addition, the influence of different diversity combining techniques on system performance is also examined. The influences of various performance-limiting factors (e.g., different antenna arrays and array orientation) on uplink performance are evaluated in Section 9.2. Section 9.3 outlines the comparisons between two methods that determine the optimum base station connections for mobile users. Finally, the chapter is summarised in Section 9.4.

9.2 Uplink system performance

In a manner similar to directional antennas, the deployment of MEAs in indoor wireless systems introduces a new degree of freedom due to the choice of array orientations. In addition, the availability of multiple signal channels allows further deployment flexibility through the selection of diversity combining techniques. Similar to the case of directional antennas, the influence of the deployment of antenna arrays on system performance is evaluated in a two-cell system using a comparative approach. Three types of antenna arrays have been considered as listed in Table 9.1. The performance analysis reported
is limited to the uplink due to the availability of measured data. The uplink system performance of a number of deployment scenarios was evaluated and referenced to that of a benchmark deployment scenario, which is defined as the scenario employing two omni-directional antennas as illustrated in Figure 8.3. These deployment scenarios are summarised in Table 9.2 together with an iconic depiction. These icons are used throughout this chapter as a visual aid for distinguishing individual deployment scenarios in the discussion.

Uplink system performance was determined in terms of average outage probability using the Monte Carlo estimation technique with a correlated Rayleigh fading model [1, 2] as outlined in Section 7.4. The analysis results are discussed in Sections 9.2.1 to 9.2.5. The use of the average-power connection technique [3, pp. 131–134] was assumed, unless otherwise stated. A discussion of an alternative uplink user-connection technique
Table 9.2: Deployment scenarios considered (OA and DA denote omni-directional and directional antennas, respectively)

<table>
<thead>
<tr>
<th>Type of antenna</th>
<th>Deployment scenario icons</th>
<th>Sections in which deployment scenarios are discussed</th>
</tr>
</thead>
<tbody>
<tr>
<td>at base station</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BS1</td>
<td>x</td>
<td>§9.2.1, §9.2.3</td>
</tr>
<tr>
<td>BS2</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Array OA</td>
<td></td>
<td>§9.2.1, §9.2.3</td>
</tr>
<tr>
<td>Array DA</td>
<td></td>
<td>§9.2.2, §9.2.3</td>
</tr>
<tr>
<td>Array Array</td>
<td></td>
<td>§9.2.4</td>
</tr>
</tbody>
</table>

is presented in Section 9.3.

9.2.1 Combination of antenna array and omni-directional antenna

The first case study considered was the scenario employing a single antenna array in a 2-cell system as illustrated in Figure 9.1. Antenna array SIMO1 was employed at base station BS1 in Environment B at an orientation of 180°. Array SIMO1 is a linear array with three vertically-polarised elements, which have an inter-element spacing of λ/2, as shown in Figure 9.2. The remaining base station BS2 was deployed with an omni-directional antenna.

Using measured data from Phase II of the propagation study as discussed in Section 6.4, the average outage probabilities were estimated for individual antenna elements using various diversity combining schemes including maximal gain combining (MRC), equal gain combining (EGC), ideal selection (IS) and direct sum (DS) [4, pp. 189–202]. These estimated outage probabilities were normalised to that of the benchmark scenario and are summarised in Table 9.3. The average outage probability of the benchmark deployment, which employs omni-directional antennas on both base stations BS1 and BS2, was estimated to be 0.136. The outage probability for the deployment scenario employing a directional antenna at base station BS1 at an orientation of 180° is also shown as a reference. Identical antenna elements and orientation was employed in this...
Figure 9.1: Floor plan of Environment B indicating the base station configurations in the scenario employing Array SIMO1 at 180° and a omni-directional antenna (Phase II).

Figure 9.2: Antenna array SIMO1.
Table 9.3: Normalised uplink outage probabilities for the deployment scenario employing Array SIMO1 at 180° and an omni-directional antenna (Phase II) († denotes benchmark scenario)

<table>
<thead>
<tr>
<th>Antenna config. at BS1</th>
<th>Diversity scheme</th>
<th>Normalised outage probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA</td>
<td>N/A</td>
<td>1.00†</td>
</tr>
<tr>
<td>DA at 180°</td>
<td>N/A</td>
<td>1.02</td>
</tr>
<tr>
<td>SIMO1 at 180°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MRC</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>EGC</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>IS</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>DS</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Element 1</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Element 2</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>Element 3</td>
<td>1.04</td>
</tr>
</tbody>
</table>

scenario; hence, an outage probability similar to those for individual antenna elements (with two parasitic elements) of the antenna array is expected, as shown in Table 9.3.

Table 9.3 also shows the relative performance among different diversity combining schemes. Using the DS scheme, the outage probability achieved is effectively an average over those of the individual antenna elements. In contrast, the IS and EGC schemes reduced the outage probability to around 39% and 36% of that in the benchmark scenario, respectively. The MRC scheme achieved the biggest reduction in outage probability at 29% of that in the benchmark scenario, which is expected since MRC is the optimum of all linear combiners [4, p. 275].

9.2.2 Combination of antenna array and directional antenna

In contrast to the deployment scenario in Section 9.2.1 that combines an antenna array with a omni-directional antenna, the combinations of an antenna array and a directional antenna at various orientations is considered in this section. A directional antenna was deployed at base station BS2 and six equi-spaced orientations (0°, 60°, 120°, 180°, 240° and 300°) were considered as illustrated in Figure 9.3. Average uplink outage probabilities were estimated for every orientation of the directional antenna and are summarised in Table 9.4. The outage probabilities for the scenarios employing an omni-directional and a directional antenna at base station BS1 are also shown as a reference.

In Table 9.4, the outage probabilities for the individual antenna elements and the DS diversity scheme vary in the same manner as those of the reference scenarios employing two directional antennas. The lowest outage probabilities are observed at an antenna orientation of 60° for the directional antenna at base station BS2. In contrast, the
Figure 9.3: Floor plan of Environment B indicating the base station configurations in the scenario employing Array SIMO1 at 180° and a directional antenna.

Table 9.4: Normalised uplink outage probabilities for the deployment scenarios employing Array SIMO1 at 180° and a directional antenna

<table>
<thead>
<tr>
<th>Antenna config. at BS1</th>
<th>Antenna config. at BS2</th>
<th>DA</th>
<th>0°</th>
<th>60°</th>
<th>120°</th>
<th>180°</th>
<th>240°</th>
<th>300°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>OA</td>
<td>1.10</td>
<td>0.93</td>
<td>0.98</td>
<td>1.09</td>
<td>1.07</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DA at 180°</td>
<td>1.15</td>
<td>1.00</td>
<td>1.05</td>
<td>1.10</td>
<td>1.11</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>MRC</td>
<td></td>
<td>0.21</td>
<td>0.30</td>
<td>0.28</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>EGC</td>
<td></td>
<td>0.30</td>
<td>0.35</td>
<td>0.34</td>
<td>0.29</td>
<td>0.28</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>IS</td>
<td></td>
<td>0.34</td>
<td>0.38</td>
<td>0.38</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>DS</td>
<td></td>
<td>1.12</td>
<td>0.97</td>
<td>1.01</td>
<td>1.09</td>
<td>1.09</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>Element 1</td>
<td></td>
<td>1.13</td>
<td>0.98</td>
<td>1.01</td>
<td>1.10</td>
<td>1.08</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>Element 2</td>
<td></td>
<td>1.13</td>
<td>0.98</td>
<td>1.01</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>Element 3</td>
<td></td>
<td>1.17</td>
<td>0.98</td>
<td>1.02</td>
<td>1.14</td>
<td>1.13</td>
<td>1.14</td>
</tr>
</tbody>
</table>
variations in outage probabilities for the three active diversity schemes, namely MRC, EGC and IS, are opposite to those of the reference scenario. At the same antenna orientation of 60° at base station BS2, the highest outage probabilities are observed for the active diversity schemes. This is believed to be a consequence of the failure of the user-connection algorithm in utilising the additional system capacity introduced by the active diversity schemes. The current user-connection technique connects individual mobile users to the base station with the strongest signal strength. This assumes a homogeneous type of antenna and identical system capacities on individual base stations. This technique, however, fails to fully utilise the additional capacity introduced by the deployment of Array SIMO1 and an active diversity scheme at base station BS1 by assigning more users to it.

9.2.3 Alternative antenna arrays

In addition to Array SIMO1, the system performance for the deployment of two alternative array designs were also evaluated. These alternative arrays are based on identical antenna elements as in Array SIMO1 but at different polarisations [5, pp. 51–52]. The choice of alternative arrays based on element polarisation is due to their ease of fabrication, compact geometry and potential for additional degrees of diversity.

Linear array — SIMO2

Antenna array SIMO2 is a linear array similar to Array SIMO1 but consisting of antenna elements at different polarisations as shown in Figure 9.4. The first two antenna elements of Array SIMO2 are vertically- and horizontally-polarised, respectively whereas the third element has a 45° polarisation. This antenna array is used to evaluate the influence of polarisation diversity on system performance. Similar to the deployment scenarios employing Array SIMO1, Array SIMO2 was deployed at base station BS1 in Environment B at an orientation of 180° as illustrated in Figure 9.5. Base station BS2 was deployed with either an omni-directional antenna or a directional antenna at a certain orientation. Table 9.5 summarises the normalised uplink outage probabilities of the deployment scenarios employing Array SIMO2. Overall, the outage probabilities are similar to those of Array SIMO1 as presented in Tables 9.3 and 9.4, which is expected since Array SIMO2 has similar geometry with Array SIMO1.

In the third column of Table 9.5, the outage probabilities for individual antenna elements and various diversity combining schemes are shown for the deployment scenario employing an omni-directional antenna at base station BS2. While Element 1 of Array SIMO2 has the similar outage probability as in the case of Array SIMO1 in Table 9.3, the outage probabilities for Elements 2 and 3 are significantly higher than those of Array
Figure 9.4: Antenna array SIMO2.

Figure 9.5: Floor plan of Environment B indicating the base station configurations in the scenario employing Array SIMO2 at 180° and an omni-directional antenna.

Table 9.5: Normalised uplink outage probabilities for the deployment scenarios employing Array SIMO2 at 180° and a directional antenna

<table>
<thead>
<tr>
<th>Antenna config. at BS1</th>
<th>Antenna config. at BS2</th>
<th>MRC</th>
<th>EGC</th>
<th>IS</th>
<th>DS</th>
<th>Element 1</th>
<th>Element 2</th>
<th>Element 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMO2 at 180°</td>
<td>OA</td>
<td>OA</td>
<td>OA</td>
<td>OA</td>
<td>OA</td>
<td>OA</td>
<td>OA</td>
<td>OA</td>
</tr>
<tr>
<td>0°</td>
<td>0.33</td>
<td>0.37</td>
<td>0.42</td>
<td>0.93</td>
<td>0.97</td>
<td>1.12</td>
<td>0.99</td>
<td>1.12</td>
</tr>
<tr>
<td>60°</td>
<td>0.26</td>
<td>0.32</td>
<td>0.38</td>
<td>1.03</td>
<td>1.06</td>
<td>1.27</td>
<td>1.09</td>
<td>1.09</td>
</tr>
<tr>
<td>120°</td>
<td>0.32</td>
<td>0.36</td>
<td>0.41</td>
<td>0.93</td>
<td>0.97</td>
<td>1.13</td>
<td>1.09</td>
<td>1.11</td>
</tr>
<tr>
<td>180°</td>
<td>0.31</td>
<td>0.35</td>
<td>0.40</td>
<td>0.95</td>
<td>0.98</td>
<td>1.13</td>
<td>1.09</td>
<td>1.11</td>
</tr>
<tr>
<td>240°</td>
<td>0.23</td>
<td>0.29</td>
<td>0.36</td>
<td>1.02</td>
<td>1.06</td>
<td>1.26</td>
<td>1.09</td>
<td>1.11</td>
</tr>
<tr>
<td>300°</td>
<td>0.19</td>
<td>0.26</td>
<td>0.33</td>
<td>1.05</td>
<td>1.09</td>
<td>1.31</td>
<td>1.11</td>
<td>1.09</td>
</tr>
<tr>
<td>DA</td>
<td>0.33</td>
<td>0.37</td>
<td>0.42</td>
<td>0.93</td>
<td>0.97</td>
<td>1.12</td>
<td>0.99</td>
<td>1.12</td>
</tr>
<tr>
<td>0°</td>
<td>0.26</td>
<td>0.32</td>
<td>0.38</td>
<td>1.03</td>
<td>1.06</td>
<td>1.27</td>
<td>1.09</td>
<td>1.09</td>
</tr>
<tr>
<td>60°</td>
<td>0.31</td>
<td>0.35</td>
<td>0.40</td>
<td>0.95</td>
<td>0.98</td>
<td>1.13</td>
<td>1.09</td>
<td>1.11</td>
</tr>
<tr>
<td>120°</td>
<td>0.23</td>
<td>0.29</td>
<td>0.36</td>
<td>1.02</td>
<td>1.06</td>
<td>1.26</td>
<td>1.09</td>
<td>1.11</td>
</tr>
<tr>
<td>180°</td>
<td>0.19</td>
<td>0.26</td>
<td>0.33</td>
<td>1.05</td>
<td>1.09</td>
<td>1.31</td>
<td>1.11</td>
<td>1.09</td>
</tr>
<tr>
<td>240°</td>
<td>0.23</td>
<td>0.26</td>
<td>0.33</td>
<td>1.05</td>
<td>1.09</td>
<td>1.31</td>
<td>1.11</td>
<td>1.09</td>
</tr>
<tr>
<td>300°</td>
<td>0.19</td>
<td>0.26</td>
<td>0.33</td>
<td>1.05</td>
<td>1.09</td>
<td>1.31</td>
<td>1.11</td>
<td>1.09</td>
</tr>
</tbody>
</table>
SIMO1. This is likely due to the polarisation mismatch between the array elements and the vertically-polarised antenna elements at the mobile users. This polarisation mismatch, which causes a greater reduction of signal strength for the desired line-of-sight (LOS) signals than the scattered interfering signals, reduces the carrier-to-interference ratio (CIR) and therefore increases the average outage probability. Similarly, the slightly higher outage probabilities of Array SIMO2 compared to those of Array SIMO1 for the MRC, EGC and IS diversity schemes suggest that the effect of polarisation mismatch outstrip the performance gain obtained by polarisation diversity. In contrast, an improvement on outage probability over that of Array SIMO1 was observed for the DS diversity scheme. This suggests that the polarisation diversity introduced by Array SIMO2 only benefits passive diversity combining schemes such as DS while causing a minimum effect on active schemes such as MRC, EGC and IS.

Table 9.5 also shows the outage probabilities for the deployment scenarios employing Array SIMO2 and a directional antenna. Similar to the case of Array SIMO1, the outage probabilities for the individual antenna elements and the passive DS diversity scheme vary in the same manner as those for the scenarios employing two directional antennas. The variations in outage probabilities for the remaining three active diversity schemes are, in contrast, opposite to the scenarios employing two directional antennas. This suggests that different deployment strategies must be considered in scenarios where base stations are deployed with a combination of single-element antennas and antenna arrays with an active diversity scheme.

**Cubic array — SIMO3**

In contrast to Arrays SIMO1 and SIMO2 (which are both linear arrays) Array SIMO3 is a three-dimensional cubic array. This antenna consists of three linearly-polarised rectangular patches that are arranged in orthogonal polarisation planes in the three-dimensional space, as shown in Figure 9.6. Due to the absence of an unambiguous boresight direction as in Arrays SIMO1 and SIMO2, the orientation of this array is specified by the direction of its Element 1, namely the vertically-polarised element. Figure 9.7 shows the location and orientation of Array SIMO3 in the deployment scenarios considered. Similar to the deployment scenarios of Arrays SIMO1 and SIMO2, the base station BS2 is deployed with either an omni-directional antenna or a directional antenna at a certain orientation.

The normalised average uplink outage probabilities for various deployment scenarios employing Array SIMO3 were estimated and are summarised in Table 9.6. In general, the outage probabilities for the same deployment scenarios employing active diversity combining schemes are higher than those of Arrays SIMO1 or SIMO2. For example,
Figure 9.6: Antenna array SIMO3.

Figure 9.7: Floor plan of Environment B indicating the base station configurations in the scenario employing Array SIMO3 at 270° and an omni-directional antenna.
normalised outage probability for the deployment scenario employing an omni-directional antenna on base station BS1 is 0.37 for the MRC scheme compared to 0.29 in the case of Array SIMO1. This is a 7% net loss on system performance for deploying Array SIMO3 over Array SIMO1. The outage probabilities for the scenarios employing directional antennas (0.27–0.37) are also higher than those employing Array SIMO1 (0.20–0.30). Similar to the case of Array SIMO2, this is believed to be a consequence of the polarisation mismatch between array elements and the antennas at the mobile users. While the polarisation of Element 1 in Array SIMO3 aligns with the antenna polarisation of mobile users, the orthogonal polarisations of Elements 2 and 3 can significantly reduce the received power of the desired signal at those elements. This reduces the CIR and, therefore, increases the overall outage probability. Overall, Array SIMO3 does not offer any performance advantages over Arrays SIMO1 and SIMO2 when active diversity combining schemes are employed. In contrast, the outage probabilities for deployment scenarios employing the DS scheme are consistently lower than those of Arrays SIMO1 and SIMO2. This suggests that Array SIMO3 is not suitable for deployment in systems employing active diversity combining but is a good candidate for systems employing passive schemes that combine multiple signal branches from an array into a single output. The implementation of Array SIMO3 in a practical indoor systems is, however, limited due its non-planner shape, which is difficult to hide from the view of users.

### 9.2.4 The choice of array orientation

In addition to the arrangement of antenna elements, the orientation of an antenna array can also influence the overall system performance. An alternative orientation for each of the Arrays SIMO2 and SIMO3 were considered as illustrated in Figure 9.8. These antenna orientations were assumed to minimise the signal coverage in the environment. Although
Figure 9.8: Floor plans of Environment B indicating the base station configurations in the scenario employing array (a) SIMO2 at 60° or (b) SIMO3 at 0°, and an omni-directional antenna.

Figure 9.8 only shows the deployment scenarios employing an omni-directional antenna at base station BS2, the scenarios employing directional antennas are also considered. The normalised average uplink outage probabilities for these deployment scenarios were estimated using the MRC diversity scheme and are summarised in Table 9.7.

The outage probabilities for the scenarios employing a directional antenna at base station BS1 at the same orientation of Array SIMO2 (an orientation of 60°) are also shown in the first row of the table as a reference. At this orientation of the directional antenna at base station BS1, the outage probabilities are consistently lower than those at the orientation of 180° as shown in Table 9.4. The orientation of 60° at base station BS1 produces a more even distribution of connected users between the two base stations. However, the opposite effect was observed when the directional antenna is replaced by Array SIMO2 at the same orientation. The outage probabilities increase as the array orientation changes from 180° to 60°. This is consistent with the argument that an uneven distribution of connected users is favoured in the deployment scenarios employing an antenna array. Using the average-power connection technique, the array orientation of 60° reduces the number of users connected to base station BS1 and, hence, increases the overall outage probability.

The third row of Table 9.7 shows the outage probabilities for deployment scenarios employing Array SIMO3 at an orientation of 0° at base station BS1. These outage probabilities are higher than those at the orientation of 270° as shown in Table 9.6. This increase in outage probability is likely due to a lower received power of the desired signals as the vertically-polarised element (Element 1 of the array) points away from the floor area.
Table 9.7: Normalised uplink outage probabilities for the deployment scenarios employing Array SIMO2 or SIMO3 at alternative orientations

<table>
<thead>
<tr>
<th>Antenna config. at BS1</th>
<th>Antenna config. at BS2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OA 0° 60° 120° 180° 240° 300°</td>
</tr>
<tr>
<td>DA</td>
<td>0.86 0.88 0.88 0.86 0.90 0.91 0.90</td>
</tr>
<tr>
<td>SIMO2</td>
<td>0.44 0.44 0.43 0.41 0.38 0.35 0.36</td>
</tr>
<tr>
<td>SIMO3</td>
<td>0.44 0.41 0.43 0.41 0.33 0.33 0.33</td>
</tr>
</tbody>
</table>

Figure 9.9: Floor plan of Environment B indicating the locations of base stations in the scenario employing Array SIMO1 at 180° on base station BS1 and Array SIMO2 at 60° on base station BS2.

9.2.5 Combination of antenna arrays

In contrast to Sections 9.2.1 to 9.2.4 that consider deployment scenarios employing a single antenna array and either an omni-directional or a directional antenna, the deployment scenarios considered in this section employ two antenna arrays of different types and orientations. For example, Figure 9.9 shows one of these scenarios that employs Array SIMO1 (at an orientation of 180°) at base station BS1 and Array SIMO2 (at an orientation of 60°) at base station BS2. The normalised average outage probabilities for these scenarios were estimated using the MRC diversity scheme and are summarised in Table 9.8. The outage probabilities for the scenarios employing directional antennas at the same orientations of the arrays are also shown in Table 9.9 as a reference. A significant reduction in outage probability (90-98% of the benchmark deployment scenario) was observed for the deployment of two antenna arrays. This reduction is unmatched by any combinations of single-element antenna and antenna array.

Regardless of the type and the orientation of the array employed at base station BS1, higher outage probabilities were observed when the array at base station BS2 was
Table 9.8: Normalised uplink outage probabilities for the deployment scenarios employing two antenna arrays

<table>
<thead>
<tr>
<th>Base station config. at BS1</th>
<th>Base station config. at BS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMO2</td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td>240°</td>
</tr>
<tr>
<td>SIMO1</td>
<td>180°</td>
</tr>
<tr>
<td>0.061</td>
<td>0.096</td>
</tr>
<tr>
<td>SIMO2</td>
<td>180°</td>
</tr>
<tr>
<td>0.032</td>
<td>0.041</td>
</tr>
<tr>
<td>SIMO3</td>
<td>270°</td>
</tr>
<tr>
<td>0.028</td>
<td>0.024</td>
</tr>
</tbody>
</table>

Table 9.9: Normalised uplink outage probabilities for the deployment scenarios employing two directional antennas

<table>
<thead>
<tr>
<th>Base station config. at BS1</th>
<th>Base station config. at BS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA</td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td>240°</td>
</tr>
<tr>
<td>DA</td>
<td>180°</td>
</tr>
<tr>
<td>1.00</td>
<td>1.11</td>
</tr>
<tr>
<td>DA</td>
<td>60°</td>
</tr>
<tr>
<td>0.88</td>
<td>0.91</td>
</tr>
</tbody>
</table>

deployed at an orientation of 240° compared to those at 60°. This observation is consistent with the scenarios employing two single-element directional antennas. A reduction in outage probability was also observed when the orientation of Array SIMO2 at base station BS1 changes from 180° to 60°, regardless of the orientation of the array at base station BS2. This change in outage probability is also identical to the scenarios employing two directional antennas. The similarities between the scenarios employing antenna arrays and directional antennas suggest that the same deployment strategies for improving system performance employing single-element directional antennas can be equally applicable to scenarios employing antenna arrays exclusively. In these situations, the capacities of individual base stations are identical due to the use of antennas of a homogeneous type. The maximum system performance can, then, be achieved with an even distribution of connected users between individual base stations. In contrast, base stations with different capacities can result if different types of antennas are deployed. For example, a base station employing an antenna array with an active diversity combining scheme has a much higher capacity than a base station employing a single-element antenna. Consequently, the maximum performance can only be obtained if a higher proportion of users was connected to the base stations with higher capacities.

In addition, the outage probabilities for the scenarios employing Array SIMO2 or
SIMO3 at base station BS1 are significantly lower than (less than half of) those employing Array SIMO1 regardless of array orientation. This is believed to be due to the introduction of polarisation diversity in Arrays SIMO2 and SIMO3. This finding is significant in the perspective of system planning because additional performance due to polarisation diversity can be obtained with virtually no additional hardware complexity and cost. While the fabrication process of linear Arrays SIMO1 and SIMO2 are virtually identical, the manufacturing complexity and cost of Array SIMO3 can be higher than the linear arrays due to its three-dimensional geometry. Since there is no clear improvement on system performance over the use of Array SIMO2, the deployment of Array SIMO3 in real-world systems can be limited due to its cost and size.

9.2.6 Summary of uplink system performance

In Sections 9.2.1 to 9.2.5, the uplink system performance of various deployment scenarios have been presented. The results of these scenarios were divided into three categories, namely the scenarios employing (a) two directional antennas, (b) an antenna array and a directional, and (c) two antenna arrays. The overall system performance for each category was obtained by averaging the outage probabilities for the deployment scenarios of the respective category over different antenna orientations and types. The average outage probability for the category of two directional antennas was estimated to be 0.97. This average outage probability of less than unity implies that the deployment of directional antennas has an advantage, namely a 3% reduction in outage probability on average, over the benchmark deployment scenario employing two omni-directional antennas.

The average outage probabilities for the remaining two categories are summarised in Table 9.10 according to different diversity combining schemes. System performance improvement of more than one order of magnitude was observed for the deployment scenarios employing two antenna arrays and one of the active diversity combining schemes relative to the scenarios employing two directional antennas. A performance gain of around 60% was also obtained by the deployment scenarios employing an antenna array and a directional antenna. This provides a useful guideline to system planners in the choice of antennas for the deployment of indoor wireless systems. For example, the use of active diversity schemes requires additional hardware and cost for the multiple signal branches. The deployment of antenna arrays is, therefore, justified only if a significant increase in system performance is required. In contrast, partial deployment of antenna arrays is an attractive low-cost alternative in situations where a performance gain of less than around 60% is required.

The deployment of antenna arrays and the DS diversity scheme could be regarded as an interim solution that provides a marginal increase in system performance requiring
only minimal changes to the existing system. An upgrade to system performance can be achieved at a later stage by implementing active diversity combining schemes as demand emerges.

9.3 Uplink user-connection techniques

In Section 9.2, the outage probabilities for various deployment scenarios were estimated based on the average-power connection technique. In addition to the deployment of antennas, the choice of user-connection technique [3, pp. 131–134] also has the potential to influence the overall system performance. In this section, two user-connection techniques are discussed, namely (a) the average-power connection technique and (b) the carrier-to-interference ratio (CIR) connection technique.

9.3.1 Average-power connection technique

The average-power connection technique has been adopted in [6] for estimating the outage probability of a system employing omni-directional antennas. This technique assumes the broadcast of pilot signals from every base station in the system to all mobile users. Individual mobile users then connect to the base station with the strongest average power of the pilot signal. Minimal intelligence at the mobile devices is required to determine the average received power. The normalised outage probabilities (estimated using this connection technique and the MRC diversity combining scheme) for the deployment scenarios considered in Section 9.2 are shown as a function of the proportion of total users connected to base station BS1 in Figure 9.10.

In the deployment scenarios employing two single-element directional antennas, which are denoted by ‘×’ in Figure 9.10, a slightly positive correlation between the outage probability and the proportion of users connected to base station BS1 was observed starting from a proportion of 0.5. This suggests that as the distribution of users changes from a balanced loading (a proportion of 0.5) to an uneven loading (a proportion greater than 0.5), the overall system performance degrades. In contrast, a negative correlation

Table 9.10: Average outage probabilities for the categorised deployment scenarios estimated using the average-power connection technique

<table>
<thead>
<tr>
<th></th>
<th>Array and DA</th>
<th>Arrays only</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRC</td>
<td>0.31</td>
<td>0.04</td>
</tr>
<tr>
<td>EGC</td>
<td>0.36</td>
<td>0.10</td>
</tr>
<tr>
<td>IS</td>
<td>0.41</td>
<td>0.16</td>
</tr>
<tr>
<td>DS</td>
<td>0.96</td>
<td>0.96</td>
</tr>
</tbody>
</table>
between the outage probability and the proportion of users connected to base station BS1 is observed for the deployment scenarios employing an antenna array and a single-element directional antenna, which are denoted by ‘○’ in Figure 9.10. This observation indicates that the overall system performance improves as more users are connected to base station BS1 (employing the antenna array). The deployment of an antenna array introduces diversity and significantly increases the capacity of base station BS1 relative to base station BS2. The additional capacity is utilised and overall system performance is consequently enhanced when more users are connected to the base station employing the antenna array.

A positive correlation was observed starting from a proportion of 0.5 in the scenarios employing two antenna arrays, which are denoted by ‘□’ in Figure 9.10. Similar to the scenarios employing two directional antenna, this indicates that overall system performance degrades as the distribution of users changes from a balanced loading to an uneven loading.

### 9.3.2 Carrier-to-interference-ratio connection technique

Similar to the average-power connection technique, broadcast of pilot signals is assumed from the base stations to the mobile users in the CIR connection technique. Individual mobile users connect, however, to the base station with the highest CIR instead of average received power of the pilot signal. This requires higher signal processing complexity at
Table 9.11: Average outage probabilities for the categorised deployment scenarios estimated using the CIR connection technique

<table>
<thead>
<tr>
<th></th>
<th>Array and DA</th>
<th>Arrays only</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRC</td>
<td>0.60</td>
<td>0.06</td>
</tr>
<tr>
<td>EGC</td>
<td>0.74</td>
<td>0.13</td>
</tr>
<tr>
<td>IS</td>
<td>0.79</td>
<td>0.20</td>
</tr>
<tr>
<td>DS</td>
<td>1.28</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The mobile devices for determining the CIRs of the pilot signals. The outage probabilities for the deployment scenarios considered in Section 9.2 were recalculated using the CIR connection technique and are summarised in Table 9.11. The DS combining scheme was assumed in the determination of the CIR due to its simplicity. The average outage probability for the category of two directional antennas was estimated to be 1.18, which is higher than that estimated using the average-power connection technique (0.97). The average outage probabilities for the remaining two categories are also higher than those estimated using the average-power connection technique as shown in Table 9.10. This indicates that the CIR connection technique, although with more complicated signal processing at the mobile devices, provides a lower overall system performance than the simpler average-power connection technique. The average outage probability of 0.93 for the category of two antenna arrays with the DS diversity scheme is the only exception that is lower than that estimated using the average-power connection technique (0.96). This suggests that the CIR connection technique can potentially improve system performance when the same diversity combining algorithm is used to calculate the CIR for user-connection.

The normalised outage probabilities (estimated using this connection technique and the MRC diversity combining scheme) for the deployment scenarios considered in Section 9.2 are shown as a function of the proportion of total users connected to base station BS1 in Figure 9.11. The proportion varies from 0.33 to 0.55, suggesting that this connection method favours less than half of the total number of users to base station BS1. In all categories, the lowest probabilities were observed at a proportion of around 0.5. This suggests that the best system performance can be obtained with an even distribution of mobile users between the base stations.

9.4 Summary

In this chapter, the uplink system performance for various deployment scenarios employing antenna arrays has been evaluated. These deployment scenarios include combinations of different array types, array orientations, diversity combining schemes and user-connection
Overall, the deployment scenarios employing exclusively antenna arrays and the MRC diversity combining scheme achieved the best system performance, which is at least an order of magnitude better than that of the benchmark deployment scenario. This performance gain was achieved by exploiting signal diversity using one of the active diversity combining schemes. Beside the performance gain, array orientations provided the same variation in system performance as in the scenarios employing exclusively directional antennas. This suggests that the deployment strategies for optimising system performance using directional antennas, which are discussed in Chapter 8, are equally applicable to systems employing antenna arrays exclusively. Among the three antenna arrays considered in this chapter, the linear array SIMO2 that employs elements of different polarisations achieved the best combination of performance and cost. This array provides additional performance gain by introducing polarisation diversity, which is achieved without a corresponding increase in manufacturing complexity and cost relative to Array SIMO1.

The deployment scenarios employing a single antenna array and a single-element antenna demonstrated a 60% improvement in system performance. Since additional hardware and cost are required for the implementation of antenna arrays and active diversity schemes, the partial deployment of antenna arrays becomes an attractive option for improving system performance with a limited budget. The deployment of antenna

![Figure 9.11: Normalised uplink outage probability as a function of the proportion of total users connected to base station BS1 estimated using the average-power connection technique.](image-url)
arrays at the remaining base stations can be performed in stages as demand grows. This partial deployment of antenna arrays, however, requires a different set of deployment strategies for optimising system performance. In this group of deployment scenarios, Arrays SIMO2 and SIMO3 demonstrated inferior performance than Array SIMO1 due to polarisation mismatch between the array elements and the antennas at the mobile devices. Conversely, when combined with the passive DS diversity combining scheme, Arrays SIMO2 and SIMO3 achieved a slight performance gain relative to the benchmark deployment scenario.

Two uplink user-connection techniques were evaluated. Although with a higher complexity and implementation cost, the CIR connection technique failed to offer better system performance over the average-power connection technique.

References


Chapter 10

Implications for System Planning

10.1 Introduction

In Chapters 8 and 9, the discussion concentrated on the estimation of system performance for various antenna selection and deployment scenarios. However, a key question has yet to be answered, which is ‘what sort of guidelines can we draw from the analysis results that enable system planners to design and deploy better indoor wireless communication systems?’ Accordingly, in this chapter conclusions are drawn from the analysis results outlined in Chapters 8 and 9 from the system planning perspective.

In Section 10.2, an evolutionary path for antennas in indoor wireless systems is suggested. Section 10.3 discusses the practical issues involved in the deployment of directional antennas in an indoor system. This includes the issues relating to the physical environment, antenna orientation and external interference. Section 10.4 focuses on the deployment of antenna arrays and elaborates on performance-limiting factors such as array configuration, diversity combining schemes and antenna orientation. A discussion of alternative user-connection approaches is presented in Section 10.5. Section 10.6 outlines the future recommendations for the investigation of antenna selection and deployment strategies of this thesis. Finally, this chapter is summarised in Section 10.7.

10.2 An evolutionary path for antenna systems

Figure 10.1 shows an evolutionary path for a system from the deployment of single-element antennas (such as conventional omni-directional antennas and directional antennas) to multiple-element antennas and active signal processing techniques (such as antenna arrays, smart antennas and multiple-input multiple-output (MIMO) systems). At the bottom end (low-cost and low-performance region of Figure 10.1) of the upgrade path, the deployment of omni-directional antennas represents a ‘traditional’ indoor wireless
system with relatively low level of system performance and a low implementation cost. In contrast, recent research concentrates on the high end of the evolutionary path that uses active signal processing techniques such as smart antennas and MIMO. These advanced techniques provide a significant increase in both performance and costs compared to conventional systems [1]. This sudden increase in system performance and implementation cost creates a gap between the two ends of the evolutionary path. The proposed deployment of directional antennas and antenna arrays with a diversity combining scheme effectively bridges this gap by offering moderate performance gain at low implementation costs. This provides a smooth transition from conventional to high-performance antenna systems as demand dictates.

10.3 Deployment of directional antennas

When engineering a new indoor wireless communication system, system planners are often given a high degree of flexibility in choosing various components with matching performance and cost requirements of the system that satisfy current and future demands. System planners can also take advantages of the surrounding environment to improve system performance. In contrast, it might be a relatively difficult task to upgrade the performance of an existing system. In this case, system planners must evaluate and
quantify the advantages and disadvantages of all the available upgrade options within the
constraints of the existing system. While existing base stations are expensive to relocate,
the replacement of omni-directional antennas by directional antennas at these base
stations would be a cost-effective alternative option. The flexibility of antenna orientation
(subject to physical and aesthetic constraints) enables the modification of signal coverage
from the same base station locations and, therefore, can improve the overall system
performance without the costs associated with relocation. When designing a new system
or upgrading an existing indoor wireless system, system planners also need to identify
any external co-channel interference and quantify its influence on system performance.
Appropriate counter-measures can then be implemented to maintain the desired level of
performance. The issues of the surrounding environment, antenna orientation and external
interference is further discussed in Sections 10.3.1 to 10.3.3.

10.3.1 Physical environment

When planning for a new system or making modifications to an existing system, one of the
most cost-effective tools available to system planners for improving system performance
is incorporating the surrounding environment into the design of the system. This requires
the identification of electromagnetically-opaque features in the environment, such as
steel-reinforced walls, whiteboards (in metal backing), metal filing cabinets and shelves.
Substantial performance gain can be achieved by aligning cell boundaries with these
radiowave-opaque obstacles. These obstacles then act as physical cell boundaries that
can significantly reduce inter-cell interference between adjacent cells. This incorporation
of the physical environment into the system design is particularly important to systems
employing omni-directional antennas exclusively due to the lack of flexibility in controlling
signal coverage from the antennas. Using this deployment strategy, the analysis results in
Sections 8.2 and 8.3 demonstrated a 63% and 8% improvement for downlink and uplink
systems, respectively. This deployment strategy is also beneficial for system employing
directional antennas as a further 12% improvement in downlink system performance was
observed.

10.3.2 Antenna orientation

When the freedom to relocate existing base stations is not available, the next most
cost-effective option for upgrading an existing system is probably the deployment of
directional antennas. This deployment strategy involves replacing the existing omni-
directional antennas at the base stations with directional antennas and orientating them to
optimise overall system performance. This approach does not require any additional signal
processing hardware at the base stations and, therefore, does not increase the complexity of the system. Low-profile/low-cost microstrip patch antennas are attractive candidates for this deployment strategy. As an average of around 60% (downlink) and 7% (uplink) improvement in system performance was demonstrated from analysis in Sections 8.2 and 8.3 respectively, this deployment strategy is an low-cost alternative to expensive signal processing techniques when a moderate performance gain is required.

Although field measurements are often needed to validate the optimal antenna orientations, analysis results from Section 8.2 suggests that measured data from a single directional antenna can provide an approximation to the optimal antenna orientations for the scenarios employing two directional antennas. This can significantly reduce the time and labour involved in the deployment of directional antennas. Analysis results also indicate that improvements in downlink system performance is often obtained when the directional antennas point towards different regions of the environment. This ensures adequate signal level across the entire environment while minimising inter-cell interference between nearby cells. In contrast, degradation of downlink system performance relative to the reference scenario employing exclusively omni-directional antennas is often a consequence of antennas pointing towards each other. This produces a high level of inter-cell interference as the signal coverage of the base stations overlaps. This antenna configuration, however, can reduce signal leakage that may interfere with adjacent systems. The ability to control this signal leakage is a valuable tool to system planners for meeting statutory regulations on electromagnetic interference and preventing unauthorised access to the wireless system outside the service area. Hence, the deployment of directional antennas can not only improve downlink system performance, but also provides the flexibility to system planners for reducing signal leakage.

As shown in Section 8.3 the deployment of directional antennas has a relatively small influence on uplink system performance compared to the downlink. In general, the optimal uplink performance can be obtained by allocating mobile users evenly to available base stations. The deployment of directional antennas provides the flexibility of adapting the signal coverage of individual base stations to enable balanced distribution of mobile users across the environment.

10.3.3 External interference

Regardless of the selection and deployment of base station antennas, indoor wireless systems are vulnerable to co-channel interference from nearby systems. Hence, system planners are advised to consider the influence of external interference on system performance in the design of such systems. Analysis results from Section 8.2.4 shows that external interference can cause a significant degradation on downlink system performance;
however, a relatively small impact was observed in uplink system performance as shown in Section [8.3.4]. External interference can come from different directions and power levels; however, its power level relative to the average desired signal power of the indoor base stations is the dominant factor determining its influence on system performance. In both downlink and uplink cases, the analysis results suggest that the influence of external interference is negligible (causing less than 1% increase on outage probability) when the carrier-to-external-interference ratio (CEIR) is higher than 30 dB. It is, therefore, necessary for system planners to make modifications to incorporate measures in the system design to mitigate the effect of external interference if its power level is above this threshold.

The deployment of directional antennas at the indoor base stations is one of the solutions for mitigating the influence of external interference on system performance. Compared to the deployment of conventional omni-directional antennas, this deployment strategy introduces flexibility into the system that optimises signal coverage for combating external interference. In general, it is best to orientate the antennas towards the regions of the environment that are directly exposed to external interference. This can increase the power level of desired signal in those regions and, therefore, reduce the influence of external interference on system performance. The analysis results suggest that the optimal antenna orientations depend on the strength of external interference. However, it has been shown that the deployment of directional antennas, even at fixed orientations optimised for the absence of external interference, always provide a better system performance than the case of omni-directional antennas. This provides confidence to system planners for deploying directional antennas to a system regardless of the strength of external interference since the deployment would not degrade future system performance as the level of external interference increases. Although there is no penalty on system performance for fixing the antenna orientations, a further performance gain can be obtained by optimising the antenna orientations to the power level of external interference.

### 10.4 Deployment of antenna arrays

While the deployment of directional antennas is a low-cost alternative for a moderate system performance gain, the deployment of antenna arrays at the base stations is a feasible option for system planners for satisfying the increasing demand on system performance that exceeds that provided by directional antennas. In addition to the physical installation, the deployment of antenna arrays also involves the investment in multi-channel signal processing hardware. This represents a major financial expense and must be justified by sufficient demand. From the analysis results presented in Section [9.2],
this deployment strategy can achieve more than one order of magnitude improvement in uplink system performance relative to a system employing conventional omni-directional antennas.

Similar to the case with directional antennas, the deployment of antenna arrays introduces a new degree of freedom into the system design through array orientation. In addition, the choice of array configuration and diversity combining scheme are also factors that can influence the overall system performance. These deployment options are further discussed in Sections 10.4.1 and 10.4.2.

10.4.1 Array configuration and diversity combining schemes

In contrast to single-element antennas (such as omni-directional and directional antennas) antenna arrays can provide multiple signal outputs for diversity reception. Consequently, there are additional degrees of freedom on the choice of array configuration and diversity combining schemes in the deployment of antenna arrays. In this thesis, array configuration refers to the arrangement of antenna elements in an array. In Section 9.2, the uplink system performance for various combinations of array configuration and diversity combining scheme have been evaluated and the analysis results suggest that there is no single combination excelling in every deployment scenario. However, the optimal combinations have been identified for three groups of deployment scenarios.

In the first group of deployment scenarios, all base stations in the system are deployed with antenna arrays with an active diversity combining scheme. This group of scenarios demonstrated the greatest improvement in system performance, which is over one order of magnitude greater than the reference scenario that employs exclusively omni-directional antennas. The highest implementation costs are, however, associated with this group of scenarios due to the requirement of complex signal processing hardware. The combination of antenna array SIMO2 and the maximal gain combining (MRC) diversity scheme provides the best system performance for this group of deployment scenarios, which is likely a result of the introduction of polarisation diversity.

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The exclusive deployment of antenna arrays on every base station in an indoor system can be prohibitively expensive due to the large number of base stations involved and the increased performance far exceeds the actual demand. In such circumstances, a partial deployment of antenna arrays might be an attractive alternative to system planners. If antenna arrays are deployed on some of the base stations only and the remaining base stations are deployed with single-element antennas, the overall implementation cost can decrease proportionally. A performance gain of appropriately 70% was still observed for this group of scenarios in the analysis from Section 9.2. In contrast to the exclusive deployment of antenna arrays, optimal system performance was achieved by the
10.4. Deployment of antenna arrays

The vertical-polarised elements of Array SIMO1 provide maximum signal reception and outperform the introduction of polarisation diversity in Array SIMO2.

The third group of deployment scenarios refers to the deployment of antenna arrays with the direct sum (DS) passive diversity combining scheme. This type of deployment effectively converts an antenna array into a directional antenna and did not demonstrate any performance gain over the use of directional antennas in the analysis from Section 9.2. This suggests that the replacement of directional antennas with antenna arrays is not likely to cause any penalty on system performance. Consequently, system planners can deploy antenna arrays as single-element directional antennas without upgrading the signal processing hardware at the base stations. The required hardware for active diversity combining scheme can be installed only when demand for system performance increases. This can be regarded as an interim solution or an initial stage for a complete upgrade of the entire antenna system.

10.4.2 Array orientation

Similar to the case of directional antennas, the deployment of antenna arrays introduces a new degree of freedom into the system design through array orientation. The optimal array orientations can reduce inter-cell interference and, therefore, improve overall system performance. Analysis results from Section 9.2 indicate that as antenna arrays are deployed exclusively throughout a system, the optimal array orientations are identical to those of a system employing exclusively directional antennas. This is a particular advantage for upgrading a system employing directional antennas with antenna arrays since the optimal antenna orientations can be directly reused.

In contrast, the optimal arrays orientations must be determined separately for the partial deployment of antenna arrays, in which a combination of antenna arrays and single-element antennas are used. Fortunately, the reduction in system performance due to non-optimal array orientations (around 10%) is much less than the performance gain achieved by the introduction of signal diversity (appropriately around 60-70%). Despite a reduced improvement on system performance, it can be advantageous for system planners to deploy antenna arrays according to the optimal array orientations for the exclusive deployment of arrays. This ensures a smooth upgrade path for the exclusive deployment of antenna arrays when demand increases.
10.5 Alternative user-connection approaches

In addition to the selection and deployment of base station antennas, an alternative technique for potentially improving system performance is by changing how mobile users connect to their desired base stations — the user-connection approach. User-connection approaches often require additional signal processing hardware to determine the optimal connection strategy; hence, they can be expensive to implement. This high implementation cost limits their application in practical systems and is likely justified only when combined with other active signal processing techniques, such as the deployment of antenna arrays with active diversity combining scheme. Two user-connection approaches, namely the average-power based and carrier-to-interference ratio (CIR) based connection approaches, were discussed in Section 9.3. Analysis results show that the CIR based connection approach, despite its additional complexity and hardware requirement, fails to provide performance gain over the conventional average-power based connection approach. As a consequence, the average-power based connection approach remains the preferred user-connection approach for the deployment of indoor systems regardless of the antenna selection and deployment options.

10.6 Recommendations for future development

This thesis provides a significant contribution to answering the question of how to go about selecting and deploying base station antennas for future (and upgrading existing) indoor wireless communication systems. This section outlines a number of possible extensions to this research that could help further understanding of the problem.

CSMA/CA and OFDM system performance evaluation

In this thesis, particular emphasis has been placed on the performance estimation of direct sequence code division multiple access (DS-CDMA) indoor wireless communication systems due to their popularity in third generation mobile communications systems (3G) [2, pp. 649–652]. The proposed optimal antenna deployment strategies are specific to DS-CDMA systems. It would be useful to consider other potential multiple access protocols, which could possess different sets of performance-limiting factors and therefore influence the optimal deployment of base station antennas. In particular, carrier-sense multiple access with collision avoidance (CSMA/CA) (adopted in IEEE 802.11b) and orthogonal frequency division multiplexing (OFDM) (implemented in IEEE 802.11a and g) have attracted much attention recently due to the increasing popularity of wireless
local area network (WLAN) systems. OFDM is also likely to be implemented in fourth generation systems (4G). System performance analyses of CSMA/CA and OFDM systems that are similar to those considered in this thesis would be a useful contribution.

Wideband issues

Narrowband transmission is assumed throughout this thesis due to its well-studied interference-limited system performance analysis. Proposed future indoor systems are, however, likely to be predominantly wideband systems due to the increasing demand of greater system performance and capacity. With bandwidths appreciably greater than the coherence bandwidth of the indoor channel, the estimates of system performance are likely to be different to those in narrowband systems. It is therefore appropriate to investigate some of the possible implications on the estimates of system performance due to the incorporation of wideband channel characteristics in the system model. This wide bandwidth also affects the selection of antennas in which the use of wideband antennas with consistent radiation characteristics over a wide frequency range can be advantageous.

Analysis of circularly-polarised antennas and MIMO

As an extension to previous research [3, 4], directional antennas and MEAs have been considered in this thesis. These antennas are based on linearly-polarised elements. It would be useful to extend this study to include antennas with circularly-polarised elements that are common in practical indoor wireless systems. In addition, this study is aimed to provide a migration path that bridges the gap between systems employing conventional omni-directional antennas and MIMO antenna systems using directional antennas and MEAs. The performance evaluation of MIMO systems using the system model considered in this thesis is a logical extension to this study.

Development of antenna-oriented propagation models

In this thesis, propagation measurements are directly employed for the estimation of system performance without the use of propagation modelling. This measurement-based approach is, however, inevitably site-specific, which is partially mitigated in this study by considering a number of environments. The development of accurate and computationally efficient propagation models that incorporate the effects of different types of antennas is the next essential stage for the investigation antenna-based deployment strategies.

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1 A brief discussion of CSMA/CA and OFDM is given in Appendix B
10.7 Summary

In this chapter, the results of the analysis results from Chapters 8 and 9 are discussed from the perspective of system planning. The various antenna selection and deployment options are summarised in an evolutionary upgrade path for indoor wireless systems. The system performance and implementation costs increases, in ascending order, from the deployment of conventional omni-directional antennas to directional antennas, and eventually antenna arrays. Based on the analysis results, the deployment of directional antennas is an attractive low-cost option for system planners to improve the downlink system performance up to 60%, and up to 7% for the uplink, relative to the deployment of conventional omni-directional antennas. In contrast, the deployment of antenna arrays and an active diversity combining scheme, which has a high implementation cost, can accomplish an uplink performance improvement of more than one order of magnitude compared to the case employing omni-directional antennas. Hence, the choice of antenna selection and deployment option depends on the actual demand for system performance and the financial resources available to system planners.

Other deployment issues that system planners should incorporate into the system design include the physical environment, external interference and the choice of user-connection approach. When deploying a wireless system in a new indoor environment, system planners are advised to take advantage of radiowave-opaque obstacles in the surrounding environment to physically separate adjacent cells. This results in a performance gain that can be easily achieved with no addition hardware and associated cost. It also eliminates many interference problems in the future development of the system. Secondly the use of directional antennas has been seen to be effective in mitigating the detrimental influence of external interference on system performance. Appropriate deployment of directional antennas is beneficial to system performance and would not degrade future system performance as the level of external interference increases. While the average-power based user-connection approach remains the preferred option, an alternative technique can be an attractive option if its hardware complexity is justified by the performance gain.

A number of possible future development of this research are presented. These recommendations include system performance evaluation for CSMA/CA and OFDM systems, wideband implementations, and systems employing circularly-polarised antennas and MIMO antenna systems. An investigation into propagation models that incorporate the effect of antennas is also suggested.
References


Chapter 11

Conclusions

This thesis has focused on the planning and deployment of future indoor wireless communication systems such as wireless local area networks (WLANs) and 3/4G mobile communication systems. As an extension to previous research on the optimal placement of indoor and outdoor base stations, particular emphasis has been placed on the selection and deployment of base station antennas. Instead of expensive active signal processing techniques (such as smart antennas and multiple-input multiple-output (MIMO) systems) the deployment of directional antennas and MEAs have been considered as a low-cost option for improving the performance of indoor wireless systems. In this thesis, the influences of various deployment strategies on system performance have been quantified and a set of deployment recommendations have been proposed from the perspective of system planning. These deployment strategies are primarily aimed to reduce co-channel interference, which is often the dominant performance-limiting factor of high-performance indoor wireless communication systems.

In order to evaluate these deployment strategies in real-world deployment scenarios, a measurement-based approach has been adopted for its accuracy and inherent information on the interactions between the antennas and the surrounding environment. In this approach, measured propagation data was directly used in performance estimations without any propagation modelling. A two-phase propagation study has been performed in a number of typical indoor office environments using two custom-built automated measurement systems. Measurements of the path-gain and complex amplitude of the received signals were used in the performance estimation of various deployment strategies.

A voice-based, narrowband direct sequence code division multiple access (DS-CDMA) system model was assumed. The choice of a DS-CDMA system model is due to its popularity in third generation mobile communication systems (3G) and its well-studied interference-limited performance characteristics. Both analytical and Monte Carlo performance estimation techniques were used and fast fading of the received signals was
modelled by the Rayleigh and Rician fading models. System performance estimations were based on the Gaussian approximation, which includes a number of assumptions, namely

- a sufficiently large number of mobile user;
- a large processing gain;
- interference-limited; and,
- neglecting thermal noise.

It has been shown from system performance analysis that the performance of indoor wireless systems can be improved if the effects of the surrounding environments were incorporated into the engineering of these systems. It has been demonstrated that electromagnetically-opaque obstacles in the surrounding environment can be used as physical cell boundaries to separate adjacent cells. This can reduce inter-cell interference and improve downlink system performance up to 60% at no additional hardware cost. This can also eliminate many interference problems in the future development of the system.

An alternative deployment option that can improve system performance is the deployment of single-element directional antennas at the base stations. This is especially useful when the relocation of base stations is impractical in upgrading existing systems. A new degree of freedom in system planning is introduced when omni-directional antennas in a ‘traditional’ system are replaced with directional antennas, where orientation can be adjusted for optimal system performance. It has been seen that the use of directional antennas is more influential in the downlink system performance than that in the uplink. In the best scenarios, improvement on system performance of 60% (downlink) and 7% (uplink) relative to the case of omni-directional antennas was observed. In these scenarios, the directional antennas tends to point towards different regions of the environment, which minimises the inter-cell interference. With no additional signal processing hardware, the deployment of directional antennas is a low-cost option for a moderate performance gain.

External interference can cause a significant degradation to downlink system performance; however, a relatively small influence has been observed in the uplink. This influence is heavily dependent on the power level of the external interference relative to the desired signals of the indoor system. It has been seen that external interference becomes negligible (causing less than 1% increase on outage probability) in both downlink and uplink when the average desired signal power is more than 30 dB stronger than the average external interference power. The use of directional antennas has been seen to be effective in mitigating the detrimental influence of external interference on system performance. Appropriate deployment of directional antennas is beneficial to system
performance and would not degrade future system performance as the level of external interference increases.

Similar to single-element directional antennas, the deployment of MEAs has been shown to have the potential to improve system performance. In addition to array orientation, further flexibility has been achieved through the selection of element polarization and diversity combining scheme. The uplink system performances for various array configurations have been quantified and the combination with the maximal gain combining (MRC) diversity combining scheme demonstrated the highest performance gain (more than one order of magnitude greater than the case employing omni-directional antennas). The variations in system performance as a function of array orientation were observed to be the same with the scenarios employing directional antennas, which suggests that the optimal antenna orientations for the case of directional antennas are equally applicable to systems employing antenna arrays exclusively. As additional signal processing hardware is required for the implementation of the active diversity schemes, the partial deployment of MEAs on a selection of the base stations in a system becomes an attractive option for improving system performance with a limited budget. A performance gain of up to 60% has been obtained for this partial deployment of MEAs. The optimal array orientations are, however, different to the case of directional antennas and must be determined separately.

From the perspective of system planning, the choice of antenna selection and deployment options depends on the current and future demand for system performance and the financial resources available. The system performance and implementation costs increases, in ascending order, from the deployment of conventional omni-directional antennas to directional antennas, and eventually MEAs. This forms an evolutionary path and provides a smooth transition from conventional to high-performance antenna systems as demand dictates. When a moderate performance gain (up to 60% in the downlink and 7% in the uplink) is required from a system employing conventional omni-directional antennas, the deployment of directional antennas provides an attractive low-cost upgrade option. As the demand for system performance increases (for more than one order of magnitude), the progressive deployment of MEAs with an active diversity combining scheme satisfies the performance requirements at proportionally increased implementation costs. An additional advantage of this evolutionary path is that the optimal antenna orientations determined in the deployment of directional antennas can be directly reused for the exclusive deployment of MEAs.

A number of recommendations relevant to the ongoing development of antenna selection and deployment strategies have been suggested. System performance evaluation for carrier-sense multiple access with collision avoidance (CSMA/CA) and orthogonal fre-
quency division multiplexing (OFDM) systems, wideband implementations, investigation into systems employing circularly-polarised antennas and MIMO antenna systems, and the development of propagation models that incorporate the effect of antennas have been identified as areas of future research.

The selection and deployment of base station antennas have the potential to increase the performance of indoor wireless communication systems. These low-cost deployment strategies complement other more expensive active signal processing techniques in providing high system performance at affordable costs. As the demand for the mass deployment of indoor wireless systems grows, the development of inexpensive performance-improving techniques will become increasingly important. These requirements highlight the need to continue with the investigation of antenna selection and deployment strategies such as those presented in this thesis.
Appendix A

The Evolution of Mobile Communication Systems

A brief history of the evolution of wireless communications will provide insight into the future development of these technologies and their impact in the next several decades. During 1981 to 1986, several cellular systems were designed and implemented in Europe and North America. In 1981, the first commercial analogue cellular system, the Nordic Mobile Telephone (NMT), was introduced in Sweden [1, pp. 563–567]. The deployment of Advanced Mobile Phone System (AMPS) in the United States followed shortly in 1983. Other major commercial implementations include Total Access Mobile communication Systems (TACS) in the UK, NEC in Japan and C450 in Germany [1, pp. 566–567]. Since their inception the growth of first generation cellular systems has exceeded predictions. The cellular systems in large cities remained in danger of facing saturation despite injection of additional spectrum and capacity [1, pp. 567–569]. A combination of subscriber base growth, the demand for new types of service and technological advances in communications led to the development of second generation (2G) digital systems.

At the end of 1991, the second generation digital Global System for Mobile communication (GSM) system was introduced in Europe [1, pp. 587–600]. Prior to the introduction of GSM, the European countries originally had incompatible national cellular standards and GSM was designed as a unified standard across the nations of Europe [2, pp. 5–10]. GSM has become a de facto standard of the world and is available in more than 150 countries. Versions of GSM (namely DCS1800 in Europe and DCS1900 in the United States) are also available, providing low power microcellular service [1, pp. 587–600]. GSM systems employ time division multiple access (TDMA), in which mobile units are allocated time slots in channels occupying a 200 kHz bandwidth. The choice of TDMA was due to its better system performance provided by the rapid switching between time slots and the absence of intermodulation products, making it more attractive in multichannel
applications. The possibility of using smaller cells was seen another advantage of TDMA over frequency division multiple access (FDMA) that was used in first generation systems.

The deployment of digital cellular systems in the United States began in 1995 [2, pp. 5–10] and two competing standards were prescribed, namely TDMA and code division multiple access (CDMA). TDMA (IS-54 and IS-136) was chosen because it allowed a smoother transition from the first to second generation cellular systems and provided greater flexibility in data rates and services [1, pp. 567–587]. In contrast, CDMA attracted much interest but the technology of the day was not sufficiently mature to justify its use. It took a few years of technological advances for Qualcomm to announce a cellular mobile communication system based on direct sequence code division multiple access (DS-CDMA), which was later standardised as IS-95. The 2G technology used in Japan for digital cellular telephony is known as Personal Digital Cellular (PDC), which uses a variation of TDMA. These 2G digital systems enjoyed many advantages over first generation analogue systems, for example [2, p. 7]:

- significantly increased spectral efficiency due to advances in digital modulation techniques and lower bit-rate digital voice encoders;
- to mitigate harsh radio propagation environments by the development of digital source and channel encoding techniques; and,
- reduction in size and cost of mobile devices due to the advancements in the area of very large scale integration (VLSI) design.

The fundamental limitation of these 2G systems, however, remains the low transmission rates of digital data (maximum at 9.6 kbits/s for GSM and IS-95) [1, pp. 643–645]. This severely limits the ability to support numerous newly emerged applications such as fast Internet access, fast file transfer and messaging services. It was generally accepted that the third generation (3G) cellular systems would need to provide users accessibility to a host of telecommunication services including voice, data, facsimile, and multimedia. In addition, freedom of the users to configure the network to suit their equipment and application regardless of their location and mobility were expected. The migration from first to second generation cellular systems was difficult due to the transition from analogue to digital nature. However, the migration from 2G to 3G systems was somewhat easier due to the common digital platform and this transition was indeed desirable in light of the popularity and enormous investment in 2G systems. The migration of GSM and IS-136 to 3G systems (W-CDMA) has been achieved via General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE). The IS-95 system can migrate to cdma2000 via IS-95B, a system with upgraded specifications [1, pp. 646–649].
In 2001, the first commercial 3G system entered into service in Japan. The standards for 3G systems (IMT-2000)\(^1\) are governed by the International Telecommunication Union — Radiocommunication Sector (ITU-R). The main features of IMT-2000 include high speed data services and maximised commonality between a group of core elements in the air interfaces of competing standards. The data rates are 144 kbps and 384 kbps for wide area application and 2.048 Mbps for local area applications [1, pp. 650–652]. Wide and local area applications are distinguished by the speed of the mobile devices — wide area suggests vehicle users and local area corresponds to pedestrian and in-building users. The ultimate goal of ITU-R lies in ubiquity of services, which is achieved by total integration of several networks such as macro- and micro-cellular systems, indoors and short range wireless networks (such as wireless local area network (WLAN) and Bluetooth), and satellite systems [1, pp. 705–707]. It is hoped that total or global integration will eventually result in a universal standard which will make the use of multi-standard terminals unnecessary. This could be the fourth generation (4G) systems or the Future Land Mobile Telephone System (FLMTS).

References


\(^1\)The terms Universal Mobile Telecommunication System (UMTS) and International Mobile Telecommunication (IMT) (or 3G) are synonymous [1, p. 650].
Appendix B

Multiple Access Techniques

In Chapter 2, the discussion of multiple access techniques has been concentrated on code division multiple access (CDMA), which has been considered for system analysis in this thesis. This appendix outlines other common multiple access techniques in wireless communications including frequency division multiple access (FDMA), time division multiple access (TDMA), frequency hopped multiple access (FHMA), orthogonal frequency division multiple access (OFDMA), space division multiple access (SDMA) and carrier-sense multiple access with collision avoidance (CSMA/CA).

B.1 FDMA

Frequency division multiple access (FDMA) allocates individual users in a cell unique frequency bands or channels of the spectrum available to that cell [1, pp. 397–400] as illustrated in Figure B.1. These channels are assigned on demand to users who request service in a time-continuous manner until the termination of the service. During the service period, these radio resources are not available to other users — even if they are not being used. Due to the limited transmission rate available to individual channels, FDMA systems are generally narrowband, such as the analogue standard Advanced Mobile Phone System (AMPS) [1, pp. 483–484]. The main advantages of FDMA are low inter-symbol interference (ISI)\(^1\), low overheads, and simple hardware [2, pp. 412–414]. It is worth noting that the transmit power of individual channels is allowed to vary and does not affect the other channels [2, p. 409]. Consequently, power control is not required and this reduces system complexity. The major drawbacks of FDMA include higher base station cost than TDMA, requirement of a duplexer in the mobile device and perceptible degradation of link quality during handoffs.

\(^1\)The reader is referred to [1, pp. 169–170] for detailed explanation on frequency selective fading and ISI.
B.2 TDMA

Time division multiple access (TDMA) divides the available frequency spectrum into time slots, and in each time slot only one user is allowed to either transmit or receive using the entire allocated spectrum [1, pp. 400–404] as illustrated in Figure B.2. The transmission in [TDMA] is discontinuous, that is users transmit in bursts which are confined to the cyclically repeating time slots allocated to them. This implies that, unlike in [FDMA] systems that accommodate analogue modulation, digital modulation must be used with [TDMA]. In a [TDMA] system, time slots are grouped into frames. The number of slots per frame depends on several factors including radio frequency (RF) bandwidth, modulation format and transmission rate [2, pp. 408–412]. [TDMA] can be implemented either as a narrowband or wideband system. IS-54 (digital advanced mobile phone system (DAMPS)) and IS-136 are examples of narrowband systems whereas Global System for Mobile communication (GSM) uses moderately wide bandwidth and DECT is a wideband implementation [2, p. 410]. The advantages of [TDMA] include lower base station costs than [FDMA] and the elimination of the duplexer that is essential in [FDMA]. The major disadvantages include the complexity associated with synchronisation and the dynamic slot alignment operation subsystem, equalisation to mitigate ISI resulting from channel delay spread and inter-channel interference.
In both [FDMA] and [TDMA], the transmission bandwidth is of the same order of magnitude with the actual message bandwidth. In contrast, frequency hopped multiple access (FHMA) is a spread spectrum technique, in which the overall transmission bandwidth is several orders of magnitude greater than the minimum required [RF] bandwidth [1, p. 404]. In a [FHMA] system, the carrier frequency of the narrowband modulated signal for an individual user hops or varies in a pseudo-random fashion over a set of [RF] carriers [1, pp. 404–405] as illustrated in Figure B.3. There are generally two types of hopping, namely slow and fast. In slow hopping, several message symbols are transmitted during each hop whereas for fast hopping, a message symbol is divided into a number of chips and frequency is hopped every chip. Similar to [FDMA], [FHMA] is generally narrowband since a frequency hopped signal occupies a single, relatively narrow channel at any given point in time. [FDMA] provides inherently diversity against frequency selective fading. It also eliminates the requirement of synchronisation since signals can be detected non-coherently. The major obstacles lie in the technological constraints in producing fast frequency synthesisers [2, pp. 420–422].

**B.4 OFDMA**

Orthogonal frequency division multiple access (OFDMA), also known as orthogonal frequency division multiplexing (OFDM), is based on $M$-ary frequency-shift keying (FSK)
and constitutes a specific form of multi-carrier modulation technique [3, pp. 244–247]. This technique solves the problem of [ISI] encountered in transmission of high speed data over channels with significant delay spread by reducing the signaling rate. The original serial data stream at $R$ bits/s is multiplexed into $N$ parallel data streams of rate $R/N$ [2, pp. 423–424]. The influence of channel delay spread on individual data streams is reduced since the data rate per carrier is decreased accordingly. The major challenge is to find a method to generate a large number of orthogonal carriers in such a way that only the desired signal is available at carriers and all other signals pass through zeros. The choice of a rectangular transmission pulse enables the generation of orthogonal carriers in the frequency domain using the inverse discrete Fourier transform (IDFT), which can be implemented efficiently as an inverse fast Fourier transform (IFFT). Although the actual frequency spectra of individual carriers partially overlap, the receiver can recover the message symbols mapped onto a given carrier by exploiting the orthogonality between the carriers. A functional block diagram of a OFDM system is shown in Figure B.4.

The major disadvantage of OFDM is that the orthogonality between carriers is only preserved if the receiver is perfectly synchronised to the transmitter both in terms of time and frequency. However, channel impairments including channel delay spread, random phase and frequency fluctuations can affect this orthogonality [2, pp. 710–712]. The influence of inter-carrier interference (ICI) due to channel delay spread can be reduced by increasing the signalling interval duration, which is achieved by appending a cyclic prefix to an OFDM symbol. This prefix is usually derived from the last portion of the OFDM symbol. At the receiver, this prefix is removed to recover the original message symbol.
as illustrated in Figure B.4(b). To remove the effects of random phase and frequency (Doppler) fluctuations, however, channel estimation is necessary. Current examples of OFDM technologies include wireless local area network (WLAN) systems based on the IEEE 802.11a and 802.11g standards.

**B.5 SDMA**

Space division multiple access (SDMA) controls the radiated energy for each user in space and differentiates them by spatially filtering transmitted power from individual users [1, pp. 409–410]. For example, spot beam antennas are used to serve individual users in Figure B.5. SDMA can be easily combined with other multiple access techniques such as FDMA, TDMA and CDMA. This can be regarded as the microscopic case of frequency reuse in which the same spectrum is reused within a cell. Typical applications of SDMA include sectored antennas [4] and smart antennas [5] at the base stations. In the limiting case of infinitesimal beamwidth and infinitely fast tracking ability, smart antennas implement optimal SDMA with channels that are free from the interference of all other users in the cell. All users within the system would then be possible to communicate using the same spectrum simultaneously.
Appendix B · Multiple Access Techniques

Figure B.5: A SDMA system serving different users with spot beams.

B.6 CSMA/CA

In contrast to other physical (PHY) layer multiple access techniques discussed in this appendix, CSMA/CA\(^2\) is the medium access control (MAC) layer protocol for the IEEE 802.11 family of standards [6, pp. 4–5]. In this protocol, a device senses for a free medium before transmitting. If the medium is busy, the transmission is deferred and a backoff algorithm within a contention window is executed. The backoff procedure follows a binary exponential variation; the time interval between each transmission is generated randomly, following a uniform distribution in the range \((0,\ell]\) where \(\ell\) is the length of the contention window [7, pp. 105–110]. This window length depends on the number of times that a packet has been transmitted; for the first transmission, it takes a value defined as \(\ell_{\text{min}}\) (minimum contention window), which is successively increased in whole powers of two, up to a maximum value of \(\ell_{\text{min}}\).

To ensure collision avoidance, access to the medium is secured using a four-way handshake as illustrated in Figure B.6. To send a direct transmission to another node, the source node transmits a short Request to Send (RTS) packet that is addressed to the intended destination. If that destination hears the transmission and is able to received, it replies with a short Clear to Send (CTS) packet. The source node then sends the data, and the recipient acknowledges all transmitted packets by returning a short Acknowledgement (ACK) packet for every transmitted packet received [6, pp. 4–5].

---

\(^2\)Ethernet uses carrier-sense multiple access with collision detection (CSMA/CD).
Figure B.6: Four-way handshake in CSMA/CA [6, p. 5].

References


Appendix C

The Propagation Measurement Systems

This appendix provides additional details to the components of the two measurement systems used in this thesis, especially on the design and characterisation of the antennas used. This material complements the discussion of the measurement systems in Chapter 5. Additional information for the path-gain measurement system is presented in Section C.1 whereas Section C.2 shows the details for the complex-voltage measurement system.

C.1 Components of the path-gain measurement system

The path-gain measurement system was designed to collect signal power measurements. It simultaneously records power measurements from multiple base stations that employ a selection of omni-directional and directional antennas. An overview of the measurement system is illustrated in Figure C.1. An automated antenna orientation system was developed to remote control the orientation of the directional antennas for its accuracy and repeatability. Instead of a single measurement, this measurement system records a sample of the received signal power over a localised area at every measurement location. The local average and statistical distribution of the received signals can then be determined from this sample.

C.1.1 Signal generators

Two types of signal generators are used in this measurement system, both generating a continuous-wave (CW) signal source at the operating frequency of around 1.885 GHz. The first type of signal generators is custom-built by a previous researcher [1, pp. 262–264]
Figure C.1: Block diagram of the path-gain measurement system for a multiple-base-station arrangement.
C.1. Components of the path-gain measurement system

Figure C.2: The custom-built signal generator.

Figure C.3: A HP 8648C signal generator.

based on the Mini-Circuits POS-2000 voltage controlled oscillator (VCO) and the National Semiconductor LMX2320 frequency synthesiser as shown in Figure C.2. The frequency of the signal output is programmed using a computer via the parallel port interface and the power output is approximation 18 dBm. The second type of generator is a HP 8648C signal generators as shown in Figure C.3. The front panel keypad is used to programme the frequency and power of the signal output.

C.1.2 Receiver

A Rohde & Schwarz ESVN40 test receiver, as shown in Figure C.4, is used to measure and record the received signal strength from multiple transmitters each with slightly different frequencies. The list of transmitter frequencies is programmed into the ESVN40 using a computer via the GPIB interface. The measured data is also transferred to the computer
C.1.3 Antenna rotators

Antenna rotators are used to remote-control the orientations of the directional antennas at the base stations and rotate the antenna structure at the mobile station for collecting samples around a localised area. An antenna rotator consists of a stepper motor and a controller box, which are shown in Figures C.5(a) and (b), respectively. The stepper motor controls the orientation of the antenna within one degree of accuracy. The controller box contains a microprocessor that receives commands from a computer via a RS-232 interface and provides trigger pulses to the test receiver at every degree of rotation. These pulses ensure accurate timing of the sampling instants.

C.1.4 Mobile station antenna — folded dipole

A folded dipole antenna, which is illustrated in Figure C.6, is deployed at the mobile station as the receiving antenna. This type of antennas has good impedance matching characteristics and can be characterised directly using a network analyser. This antenna is designed for an operating frequency of 1.885 GHz and its dimensions were determined using the design procedure from [2, pp. 458–462]. The coaxial balun does not only balance the inherently unbalanced coaxial transmission line but also acts as a step-up impedance transformer for matching the 50 ohms coaxial line to the 300 ohms folded dipole antenna [2, pp. 480–483]. The physical length of the λ/2 coaxial balun is affected by the velocity in the coax and is approximately 70% of the electrical length [3, pp. 402–403].

The dimensions of the final antenna design are summarised in Table C.1. The antenna is attached to a piece of printed circuit board (PCB) for mechanical support as demonstrated in Figure C.6(c). This PCB support does not have a significant influence.
Figure C.5: The (a) stepper motor and (b) controller box of an antenna rotator.
Table C.1: Parameters for folded dipole antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>1.885 GHz</td>
</tr>
<tr>
<td>Length</td>
<td>79.8 mm</td>
</tr>
<tr>
<td>Height</td>
<td>7.98 mm</td>
</tr>
<tr>
<td>Balun length</td>
<td>55.9 mm</td>
</tr>
</tbody>
</table>

on the radiation characteristics of the antenna; however, a slight increase in voltage standing wave ratio (VSWR) was observed relative to the case without the PCB support. Figure C.7 shows the measured input impedance and VSWR for the folded dipole antenna with the PCB support. At the mobile station, this antenna is mounted on an antenna rotator with a rotating arm 0.5 m in radius, which is shown in Figure C.8.

C.1.5 Base station antennas — discone

Discone antennas, which are illustrated in Figure C.9, are deployed at the base stations as omni-directional antennas. These antennas were designed and fabricated by a previous researcher [1] and are optimised for frequencies in the region of 1.8 GHz. Details regarding the design of discone antennas can be found in [4]. Figure C.10 shows the measured input impedance and VSWR for one of the discone antennas used in the measurement system. The radiation pattern of the same antenna was measured in a propagation range as demonstrated in Figure C.11. This antenna was mounted on an antenna rotator and its $H$-plane radiation pattern was measured by a reference antenna, which is the folded dipole antenna. Figure C.12 shows the $H$-plane radiation pattern for this antenna, which is normalised to its maximum gain.
C.1. Components of the path-gain measurement system

\[ \frac{\lambda}{2} = 79.8 \text{ mm} \]

\[ 0.05\lambda = 7.98 \text{ mm} \]

\[ z_1 = \frac{z_0}{4} \text{ (unbalanced)} \]

\[ z_2 \text{ (balanced)} \]

\[ \text{Balun } \left( \frac{\lambda}{2} \right) \]

**Figure C.6:** Schematics of (a) a folded dipole antenna and (b) a \( \lambda/4 \) balun; (c) photo of the folded dipole antenna and balun used.
Figure C.7: Measured (a) input impedance and (b) VSWR for the folded dipole antenna over the frequency range 1.6–2.0 GHz.

Figure C.8: The folded dipole antenna mounted on the rotating arm of an antenna rotator.
Figure C.9: (a) Schematic and (b) photo of a discone antenna used.
Appendix C · The Propagation Measurement Systems

Figure C.10: Measured (a) input impedance and (b) VSWR of a discone antenna over the frequency range 1.6–2.0 GHz.

Figure C.11: Antenna radiation pattern measurement in the propagation range.
Figure C.12: Measured radiation pattern of a discone antenna.
Appendix C

The Propagation Measurement Systems

C.1.6 Base station antennas — microstrip patch

Rectangular microstrip patch antennas are deployed at the base stations as directional antennas. The construction of a basic microstrip patch is illustrated in Figure C.13 [5]. The microstrip antennas used in the measurement system were fabricated on standard double-sided FR4 PCB using the photo-etching method. The PCB material is made of woven fiberglass reinforced epoxy resin with a thickness of 1.44 mm. The copper layers have a measured thickness of 0.04 mm.

These antennas were designed for an operating frequency of 1.885 GHz and their dimensions were determined using the design procedure from [6, pp. 31–84]. The width of the rectangular patch $W$ (in metres) is given by [6, p. 57]

$$W = \frac{c}{2f_r} \left( \frac{\varepsilon_r + 1}{2} \right)^{-\frac{1}{2}}, \quad (C.1)$$

where $c$ is the speed of light ($3 \times 10^8$ ms$^{-1}$), $f_r$ is the resonant frequency (in Hz), and $\varepsilon_r$ is the relative dielectric constant of the substrate. The relative dielectric constant of the FR4 substrate was determined experimentally using shunt stub and series resonant microstrip elements [7].

The length of the microstrip patch $L$ (in metres) is given by [6, pp. 46, 57]

$$L = \frac{c}{2f_r \sqrt{\varepsilon_{\text{eff}}}} - 2\Delta l, \quad (C.2)$$

where

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{12h}{W} \right)^{-\frac{1}{2}}, \quad (C.3)$$

**Figure C.13:** Construction of a microstrip patch antenna showing fringing fields that account for radiation.
and
\[ \Delta l = 0.412h \left( \frac{\varepsilon_{\text{eff}} + 0.3}{\varepsilon_{\text{eff}} - 0.258} \right) \left( \frac{W}{h} + 0.8 \right). \]  
(C.4)

The variables \( \varepsilon_{\text{eff}} \) and \( h \) are the effective dielectric constant and height of the substrate respectively, and \( \Delta l \) is the fringe factor due to the fringing field on the edges of the patch.

A microstrip feed line is used to excite the patch at the centre of its edge. For an impedance of 50 ohms, the width of the feed line \( w \) (in metres) was determined using the design procedure from [8, pp. 11–12].

For wide strips \((w/h > 2)\),
\[ \frac{w}{2h} \pi = \frac{377\pi}{2\sqrt{\varepsilon_r Z_{0m}}} - 1 - \ln \left( \frac{377\pi}{2\sqrt{\varepsilon_r Z_{0m}}} - 1 \right) + \frac{\varepsilon_r - 1}{2\varepsilon_r} \left[ \ln \left( \frac{377\pi}{2\sqrt{\varepsilon_r Z_{0m}}} - 1 \right) + 0.293 - \frac{0.517}{\varepsilon_r} \right], \]  
(C.5)

where \( Z_{0m} \) is the impedance of the microstrip line.

For narrow strips \((w/h < 2)\),
\[ \frac{2h}{w} = \frac{1}{4} e^{h'} - \frac{1}{2} e^{-h'}, \]  
(C.6)

where
\[ h' = \left( \frac{\varepsilon_r + 1}{2} \right)^{\frac{1}{2}} \frac{Z_{0m}}{60} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \left( 0.226 + \frac{0.120}{\varepsilon_r} \right). \]  
(C.7)

The values of these parameters and the dimensions of the final antenna design are summarised in Table C.2. Figure C.14 shows the schematic and a photo of the final antenna design. The dimensions of the ground plate was arbitrarily chosen to allow approximately \( \lambda/2 \) clearance around the radiating element. From experiments not shown, the size of the ground plate was observed to have minimal influence on the input impedance and VSWR of the antenna. The \( H \)-plane radiation patterns, however, show that nulls in the back lobes of the antenna become more predominant as the size of the ground plate increases. It is worth noting that no attempt was made to match the impedance between the feed line and the radiating element, which leads to a low radiation efficiency (a high VSWR). This antenna design is still adequate as a directional antenna for the use in the measurement system.

Figure C.15 shows the measured input impedance and VSWR for one of the microstrip patch antenna used. Figure C.12 shows the measured \( H \)- and \( E \)-plane radiation patterns for the same antenna, which are normalised to its maximum gain. This antenna has a gain of 5.84 dB relative to the discone antenna in the \( H \)-plane (i.e., azimuthal plane).
Appendix C

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Width, \( W = 48.30 \text{ mm} \)

Length, \( L = 37.60 \text{ mm} \)

Line width, \( w = 2.74 \text{ mm} \)

Figure C.14: (a) Schematic and (b) photo of a microstrip patch antenna used.
### Table C.2: Parameters for microstrip patch antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>$f_r$</td>
<td>1.885 GHz</td>
</tr>
<tr>
<td>Relative dielectric constant</td>
<td>$\varepsilon_r$</td>
<td>4.4289</td>
</tr>
<tr>
<td>Thickness of substrate</td>
<td>$h$</td>
<td>1.44 mm</td>
</tr>
<tr>
<td>Patch width</td>
<td>$W$</td>
<td>48.3 mm</td>
</tr>
<tr>
<td>Patch length</td>
<td>$L$</td>
<td>37.6 mm</td>
</tr>
<tr>
<td>Feed line width</td>
<td>$w$</td>
<td>2.74 mm</td>
</tr>
<tr>
<td>Ground plate width</td>
<td></td>
<td>150 mm</td>
</tr>
<tr>
<td>Ground plate length</td>
<td></td>
<td>150 mm</td>
</tr>
</tbody>
</table>

![Figure C.15](image1.png)

**Figure C.15:** Measured (a) input impedance and (b) VSWR for a microstrip patch antennas over the frequency range 1.6–2.0 GHz.

![Figure C.16](image2.png)

**Figure C.16:** Measured radiation patterns of a microstrip patch antenna used.
C.2 Components of the complex-voltage measurement system

The complex-voltage measurement system was designed to simultaneously record complex voltages from individual elements of a MEA. An overview of the measurement system is illustrated in Figure C.17. The folded dipole antenna discussed in Section C.1.4 is used as the transmitting antenna at the mobile station. A sample of the channel responses (complex-voltage measurements) is collected over a localised area at every measurement location when the antenna structure rotates for one revolution. The local average and statistical distribution of the received signals can then be determined from this sample.

C.2.1 Receiver

An Agilent E8364A PNA series network analyser with Option 014, as shown in Figure C.18, is used to measure and record the complex received signals from individual elements of an antenna array. The PNA is programmed into the CW time sweep measurement mode with external trigger. Control software on a remote computer is used to monitor the operations of the PNA using the distributed component object model (DCOM) over a IEEE 802.11b wireless local area network (WLAN) connection.
C.2. Components of the complex-voltage measurement system

Fig. C.18 shows the graphical user interface (GUI) of the control software.

**C.2.2 Base station antennas — multiple-element array**

Antenna arrays with microstrip patch antenna elements are used at the base station. These arrays consist of identical elements that are separated at $\lambda/2$. In contrast to the microstrip patch antennas used in the path-gain measurement system, the elements of these antenna arrays were fabricated using 3M™ 1181 EMI Copper Foil Shielding Tape, which is a smooth copper foil with a conductive acrylic pressure-sensitive adhesive. The copper foil has a thickness of 0.04 mm, which is the same as the copper layer of the PCB used in the antennas of the path-gain measurement system. The copper foil was cut into the desired dimensions and adhered onto a piece of single-sided FR4 PCB. The use of the copper foil significantly reduces the antenna fabrication time with respect to the photo-etching technique.

As opposed to rectangular radiating elements in the path-gain measurement system, square patches were used in the complex-voltage measurement system. The use of square patches avoids ambiguity in measuring the inter-element spacing for the array. A slightly different design technique for the antenna elements was adopted as discussed in [5], which uses an iterative process to determine the length $L$ of the square patch. In this algorithm,
the initial value of $L$ is obtained by

$$L = \frac{c}{2f_r \sqrt{\varepsilon_r}}, \quad (C.8)$$

where $c$ is the speed of light ($3 \times 10^8 \text{ms}^{-1}$), $f_r$ is the resonant frequency (in Hz), and $\varepsilon_r$ is the relative dielectric constant of the substrate. The effective relative permittivity $\varepsilon_{\text{eff}}$ for the square patch is given by

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{12h}{L} \right)^{-\frac{1}{2}}, \quad (C.9)$$

where $h$ is the height of the substrate. With this value of $\varepsilon_{\text{eff}}$, the fringe factor $\Delta l$ can be determined by

$$\Delta l = 0.412h \frac{(\varepsilon_{\text{eff}} + 0.300) \left( \frac{L}{h} + 0.262 \right)}{(\varepsilon_{\text{eff}} - 0.258) \left( \frac{L}{h} + 0.813 \right)}. \quad (C.10)$$

An improved value of $L$ can be obtained using (C.2)

$$L = \frac{c}{2f_r \sqrt{\varepsilon_{\text{eff}}}} - 2\Delta l. \quad (C.2)$$
C.2. Components of the complex-voltage measurement system

### Table C.3: Parameters for array elements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>( f_r )</td>
<td>1.885 GHz</td>
</tr>
<tr>
<td>Relative dielectric constant</td>
<td>( \varepsilon_r )</td>
<td>4.4289</td>
</tr>
<tr>
<td>Thickness of substrate</td>
<td>( h )</td>
<td>1.44 mm</td>
</tr>
<tr>
<td>Patch length</td>
<td>( L )</td>
<td>37.8 mm</td>
</tr>
<tr>
<td>Inset length</td>
<td>( x )</td>
<td>2.74 mm</td>
</tr>
<tr>
<td>Ground plate width</td>
<td></td>
<td>80 mm</td>
</tr>
<tr>
<td>Ground plate length</td>
<td></td>
<td>80 mm</td>
</tr>
</tbody>
</table>

This estimate of \( L \) can be refined by performing a few iterations using (C.9), (C.10) and (C.2).

A coaxial feed is used to excite the radiating element for better impedance matching. The coaxial connector is attached to the back side of the printed circuit board and the coaxial centre conductor is attached to the antenna conductor, as illustrated in Figure C.20 [6, pp. 23–25]. The initial inset length for the feed-point \( x \) was determined analytically for an impedance match of 50 ohms. The variation of input impedance as a function of feed-point position \( R(x) \) is approximated by [5]

\[
R(x) = R_0 \cos^2 \left( \frac{\pi x}{L} \right),
\]

where \( R_0 \) is the resistance at the edge of the patch and \( x \) is the distance from the edge. This initial inset length is then refined with actual measurements to obtain a better impedance match.

The parameters and dimensions of the final element design are summarised in Table C.3. Figure C.21 shows the schematic of an individual antenna element. The size of the ground plate was chosen to allow approximately \( \lambda/4 \) clearance around the radiating element. This ensures a \( \lambda/2 \) inter-element spacing when two or more elements are aligned side-by-side on the same plane. A single element has a measured VSWR of 1.38 at the operating frequency of 1.885 GHz.

Three antenna arrays were constructed using the basic antenna elements and their photos are shown in Figure C.22. Figure C.23 shows the measured VSWR for these antenna arrays. The mutual coupling \( (S_{21}) \) between the elements were also measured and is summarised in Table C.4.
Figure C.20: (a) Radiating element excited using a coaxial probe; (b) a photo showing the coaxial probe.

Figure C.21: An antenna array element.
C.2. Components of the complex-voltage measurement system

Figure C.22: The SIMO antenna arrays used.
Figure C.23: Measured VSWR for the SIMO antenna arrays used.

Table C.4: Mutual coupling between antenna array elements at 1.885 GHz

| Antenna array | $|S_{21}|$ (dB) between Elements 1 and 2 | Elements 1 and 3 | Elements 2 and 3 |
|---------------|----------------------------------------|------------------|------------------|
| SIMO1         | -24                                    | -36              | -24              |
| SIMO2         | -41                                    | -35              | -34              |
| SIMO3         | -49                                    | -40              | -45              |
C.2. References

References


Appendix D

Measurement Results of the Propagation Study

The measurement results of the propagation study discussed in Chapter 6 is presented in this appendix. The propagation study is divided into two phases, which measure the power and complex voltage of the received signals, respectively. The measurement results for Phase I of the study are illustrated as path-gain contour plots in Section D.1. The correlation coefficients between co-located base stations are also presented. The path-gain contour plots for individual array elements in Phase II of the propagation study are shown in Section D.2. The correlation coefficients between individual elements of co-located arrays at similar orientations are also presented.

D.1 Phase I — Path gain measurements

Three measurement environments were considered in this phase of the propagation study, namely Environments A, B and C. The locations of the base and mobile stations of individual environments are illustrated in Figures D.1–D.6 and are summarised in Table D.1 Figures D.7–D.18 show the path-gain contour plots for various base station configurations in the three environments and are summarised in Table D.2. The correlation coefficients between co-located base station configurations for the entire floor areas in Environments A and B were also calculated and are summarised in Tables D.3 and D.4.
### Table D.1: Summary of base and mobile station locations (Phase I)

<table>
<thead>
<tr>
<th>Environment</th>
<th>Figures in which base station locations are shown</th>
<th>Figures in which mobile station locations are shown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment A</td>
<td>Figures D.1 and D.2</td>
<td>Figure D.3</td>
</tr>
<tr>
<td>Environment B</td>
<td>Figures D.4(a) and D.5</td>
<td>Figure D.6(a)</td>
</tr>
<tr>
<td>Environment C</td>
<td>Figure D.4(b)</td>
<td>Figure D.6(b)</td>
</tr>
</tbody>
</table>

### Table D.2: Summary of path-gain contour plots for various base station configurations (Phase I) (OA and DA denote omni-directional and directional antennas, respectively.)

<table>
<thead>
<tr>
<th>Environment</th>
<th>Base station</th>
<th>Type of antenna</th>
<th>Figure number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment A</td>
<td>BS1</td>
<td>OA</td>
<td>D.7(a)</td>
</tr>
<tr>
<td></td>
<td>BS2</td>
<td>OA</td>
<td>D.7(b)</td>
</tr>
<tr>
<td></td>
<td>BS3</td>
<td>OA</td>
<td>D.8(a)</td>
</tr>
<tr>
<td></td>
<td>BS4</td>
<td>OA</td>
<td>D.8(b)</td>
</tr>
<tr>
<td></td>
<td>BS5</td>
<td>OA</td>
<td>D.8(c)</td>
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<td></td>
<td>BS6</td>
<td>OA</td>
<td>D.8(d)</td>
</tr>
<tr>
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<td>DA</td>
<td>D.9</td>
</tr>
<tr>
<td></td>
<td>BS8</td>
<td>DA</td>
<td>D.10</td>
</tr>
<tr>
<td>Environment B</td>
<td>BS1</td>
<td>OA</td>
<td>D.11(a)</td>
</tr>
<tr>
<td></td>
<td>BS2</td>
<td>OA</td>
<td>D.11(b)</td>
</tr>
<tr>
<td>Environment C</td>
<td>BS3</td>
<td>OA</td>
<td>D.12</td>
</tr>
<tr>
<td></td>
<td>BS4</td>
<td>DA</td>
<td>D.13</td>
</tr>
<tr>
<td></td>
<td>BS5</td>
<td>DA</td>
<td>D.14</td>
</tr>
<tr>
<td></td>
<td>BS1</td>
<td>OA</td>
<td>D.15(a)</td>
</tr>
<tr>
<td></td>
<td>BS2</td>
<td>OA</td>
<td>D.15(b)</td>
</tr>
<tr>
<td></td>
<td>BS3</td>
<td>OA</td>
<td>D.16</td>
</tr>
<tr>
<td></td>
<td>BS4</td>
<td>DA</td>
<td>D.17</td>
</tr>
<tr>
<td></td>
<td>BS5</td>
<td>DA</td>
<td>D.18</td>
</tr>
</tbody>
</table>
Figure D.1: Floor plan of Environment A indicating the locations of the base stations (denoted by ‘●’) employing omni-directional antennas (Phase I).

Figure D.2: (a) Floor plan of Environment A indicating the locations of the base stations (denoted by ‘■’) employing directional antennas (Phase I); (b) the six orientations of the directional antennas at which measurements were performed.
**Figure D.3:** Floor plan of Environment A indicating the mobile station locations (denoted by ‘×’) (Phase I).

**Figure D.4:** Floor plans of (a) Environment B and (b) Environment C indicating the locations of the base stations that employ omni-directional antennas (denoted by ‘●’) (Phase I).
Figure D.5: Floor plan of Environment B indicating the locations of the base stations that employ directional antennas (denoted by ‘■’) (Phase I).

Figure D.6: Floor plans of (a) Environment B and (b) Environment C indicating the mobile station locations (denoted by ‘×’) (Phase I).
Figure D.7: Path-gain contour plots for the omni-directional antennas at base stations (a) BS1 and (b) BS2 (Environment A, Phase I). ('•' denotes base station location; and, the contour lines are 6 dB apart.)
Figure D.8: Path-gain contour plots for the omni-directional antennas at base stations BS3 to BS6 (Environment A, Phase I). (Base stations BS3 to BS6 are external base stations, as illustrated in Figure D.1 and, the contour lines are 6 dB apart.)
Figure D.9: Path-gain contour plots for different orientations of the directional antenna at base station BS7 (Environment A, Phase I). (■ denotes base station location and the solid line indicates the orientation of the antenna. The contour lines are 6 dB apart.)
Figure D.10: Path-gain contour plots for different orientations of the directional antenna at base station BS8 (Environment A, Phase I). (■ denotes base station location and the solid line indicates the orientation of the antenna. The contour lines are 6 dB apart.)
Figure D.11: Path-gain contour plots for the omni-directional antennas at base stations (a) BS1 and (b) BS2 (Environment B, Phase I). (‘•’ denotes base station location; and, the contour lines are 6 dB apart.)

Figure D.12: Path-gain contour plots for the omni-directional antenna at base station BS3 (Environment B, Phase I). (The contour lines are 6 dB apart.)
Figure D.13: Path-gain contour plots for different orientations of the directional antenna at base station BS4 (Environment B, Phase I). (‘■’ denotes base station location and the solid line indicates the orientation of the antenna. The contour lines are 6 dB apart.)
Figure D.14: Path-gain contour plots for different orientations of the direction antenna at base station BS5 (Environment B, Phase I). ('■' denotes base station location and the solid line indicates the orientation of the antenna. The contour lines are 6 dB apart.)
Figure D.15: Path-gain contour plots for the omni-directional antennas at base stations (a) BS1 and (b) BS2 (Environment C, Phase I). (The contour lines are 6 dB apart.)

Figure D.16: Path-gain contour plots for the omni-directional antenna at base station BS3 (Environment C, Phase I). (‘●’ denotes base station location; and, the contour lines are 6 dB apart.)
Figure D.17: Path-gain contour plots for different orientations of the directional antenna at base station BS4 (Environment C, Phase I). (The contour lines are 6 dB apart.)
Figure D.18: Path-gain contour plots for different orientations of the directional antenna at base station BS5 (Environment C, Phase I). (The contour lines are 6 dB apart.)
Table D.3: Correlation coefficients for the mean path-gain between two co-located base stations in Environment A (Phase I)

(a) Base station BS1

<table>
<thead>
<tr>
<th>Base station config.</th>
<th>OA</th>
<th>0°</th>
<th>60°</th>
<th>120°</th>
<th>180°</th>
<th>240°</th>
<th>300°</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA</td>
<td>1.00</td>
<td>0.90</td>
<td>0.95</td>
<td>0.98</td>
<td>0.97</td>
<td>0.88</td>
<td>0.81</td>
</tr>
<tr>
<td>0°</td>
<td>0.90</td>
<td>1.00</td>
<td>0.96</td>
<td>0.91</td>
<td>0.88</td>
<td>0.91</td>
<td>0.92</td>
</tr>
<tr>
<td>60°</td>
<td>0.95</td>
<td>0.96</td>
<td>1.00</td>
<td>0.97</td>
<td>0.90</td>
<td>0.87</td>
<td>0.88</td>
</tr>
<tr>
<td>DA1</td>
<td>0.98</td>
<td>0.91</td>
<td>0.97</td>
<td>1.00</td>
<td>0.95</td>
<td>0.89</td>
<td>0.83</td>
</tr>
<tr>
<td>120°</td>
<td>0.97</td>
<td>0.88</td>
<td>0.90</td>
<td>0.95</td>
<td>1.00</td>
<td>0.89</td>
<td>0.79</td>
</tr>
<tr>
<td>180°</td>
<td>0.88</td>
<td>0.91</td>
<td>0.87</td>
<td>0.89</td>
<td>0.89</td>
<td>1.00</td>
<td>0.94</td>
</tr>
<tr>
<td>240°</td>
<td>0.81</td>
<td>0.92</td>
<td>0.88</td>
<td>0.83</td>
<td>0.79</td>
<td>0.94</td>
<td>1.00</td>
</tr>
<tr>
<td>300°</td>
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<td>0.90</td>
<td>0.92</td>
<td>0.95</td>
<td>1.00</td>
<td>0.89</td>
<td>0.91</td>
</tr>
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(b) Base station BS2

<table>
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<tr>
<th>Base station config.</th>
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<th>60°</th>
<th>120°</th>
<th>180°</th>
<th>240°</th>
<th>300°</th>
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</thead>
<tbody>
<tr>
<td>OA</td>
<td>1.00</td>
<td>0.96</td>
<td>0.92</td>
<td>0.85</td>
<td>0.96</td>
<td>0.97</td>
<td>0.97</td>
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<td>0°</td>
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<td>0.90</td>
<td>0.96</td>
</tr>
<tr>
<td>60°</td>
<td>0.92</td>
<td>0.90</td>
<td>1.00</td>
<td>0.92</td>
<td>0.93</td>
<td>0.89</td>
<td>0.91</td>
</tr>
<tr>
<td>120°</td>
<td>0.85</td>
<td>0.74</td>
<td>0.92</td>
<td>1.00</td>
<td>0.91</td>
<td>0.89</td>
<td>0.83</td>
</tr>
<tr>
<td>180°</td>
<td>0.96</td>
<td>0.90</td>
<td>0.93</td>
<td>0.91</td>
<td>1.00</td>
<td>0.97</td>
<td>0.95</td>
</tr>
<tr>
<td>240°</td>
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<td>0.90</td>
<td>0.89</td>
<td>0.89</td>
<td>0.97</td>
<td>1.00</td>
<td>0.96</td>
</tr>
<tr>
<td>300°</td>
<td>0.97</td>
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<td>0.91</td>
<td>0.83</td>
<td>0.95</td>
<td>0.96</td>
<td>1.00</td>
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</table>
Table D.4: Correlation coefficients for the mean path-gain between two co-located base stations in Environment B (Phase I)

(a) Base station BS1

<table>
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<th>Base station config.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OA</td>
</tr>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>OA</td>
<td>1.00</td>
</tr>
<tr>
<td>0°</td>
<td>0.94</td>
</tr>
<tr>
<td>60°</td>
<td>0.93</td>
</tr>
<tr>
<td>120°</td>
<td>0.97</td>
</tr>
<tr>
<td>180°</td>
<td>0.92</td>
</tr>
<tr>
<td>240°</td>
<td>0.94</td>
</tr>
<tr>
<td>300°</td>
<td>0.94</td>
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</table>

(b) Base station BS2

<table>
<thead>
<tr>
<th>Base station config.</th>
<th>Base station config.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OA</td>
</tr>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>OA</td>
<td>1.00</td>
</tr>
<tr>
<td>0°</td>
<td>0.97</td>
</tr>
<tr>
<td>60°</td>
<td>0.96</td>
</tr>
<tr>
<td>120°</td>
<td>0.97</td>
</tr>
<tr>
<td>180°</td>
<td>0.99</td>
</tr>
<tr>
<td>240°</td>
<td>0.97</td>
</tr>
<tr>
<td>300°</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Table D.5: Summary of mobile station locations and path-gain contour plots (Phase II)

<table>
<thead>
<tr>
<th>Base station</th>
<th>Antenna array</th>
<th>Orientation</th>
<th>Mobile station locations</th>
<th>Figure number</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS1</td>
<td>SIMO1</td>
<td>180°</td>
<td>Full set</td>
<td>D.21</td>
</tr>
<tr>
<td></td>
<td>SIMO2</td>
<td>180°</td>
<td>Full set</td>
<td>D.22</td>
</tr>
<tr>
<td></td>
<td>SIMO3</td>
<td>270°</td>
<td>Full set</td>
<td>D.23</td>
</tr>
<tr>
<td></td>
<td>SIMO3</td>
<td>0°</td>
<td>Partial set</td>
<td>D.24</td>
</tr>
<tr>
<td></td>
<td>SIMO2</td>
<td>60°</td>
<td>Partial set</td>
<td>D.25</td>
</tr>
<tr>
<td>BS2</td>
<td>SIMO2</td>
<td>60°</td>
<td>Partial set</td>
<td>D.26</td>
</tr>
<tr>
<td></td>
<td>SIMO2</td>
<td>240°</td>
<td>Partial set</td>
<td>D.27</td>
</tr>
</tbody>
</table>

Figure D.19: Floor plan of Environment B indicating the base station locations (denoted by ‘■’) (Phase II).

D.2 Phase II — Complex voltage measurements

In Phase II of the propagation study, measurements were performed in Environment B only. The locations of the base and mobile stations are illustrated in Figures D.19 and D.20, respectively. Two sets of mobile station locations were employed, which are summarised in Table D.5. Figures D.21–D.27 show the path-gain contour plots for individual array elements in various base station configurations and are summarised in Table D.5. The correlation coefficients between individual elements of co-located arrays at similar orientations were also calculated and are summarised in Table D.6.
Figure D.20: Floor plan of Environment B indicating the (a) full and (b) partial set of mobile station locations (denoted by ‘×’) (Phase II).

Table D.6: Correlation coefficients for the mean path gain between individual elements of antenna arrays at base station BS1 in Environment B (Phase II) (#1, #2 and #3 denotes Element 1, 2 and 3, respectively.)

<table>
<thead>
<tr>
<th>Base station config.</th>
<th>SIMO1 at 180°</th>
<th>Base station config.</th>
<th>SIMO2 at 180°</th>
<th>SIMO3 at 270°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#1</td>
<td>#2</td>
<td>#3</td>
<td>#1</td>
</tr>
<tr>
<td>SIMO1 at 180°</td>
<td>1.00</td>
<td>0.99</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>#2</td>
<td>0.99</td>
<td>1.00</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>#3</td>
<td>0.98</td>
<td>0.98</td>
<td>1.00</td>
<td>0.98</td>
</tr>
<tr>
<td>SIMO2 at 180°</td>
<td>0.99</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>#2</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>#3</td>
<td>0.98</td>
<td>0.98</td>
<td>0.99</td>
<td>0.97</td>
</tr>
<tr>
<td>SIMO3 at 270°</td>
<td>0.87</td>
<td>0.85</td>
<td>0.86</td>
<td>0.89</td>
</tr>
<tr>
<td>#2</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.94</td>
</tr>
<tr>
<td>#3</td>
<td>0.94</td>
<td>0.95</td>
<td>0.94</td>
<td>0.94</td>
</tr>
</tbody>
</table>
Figure D.21: Path-gain contour plots for individual elements of array SIMO1 at 180° on base station BS1 (Environment B, Phase II). (The solid line indicates the orientation of the element. The contour lines are 6 dB apart.)

Figure D.22: Path-gain contour plots for individual elements of array SIMO2 at 180° on base station BS1 (Environment B, Phase II). (The contour lines are 6 dB apart.)
Figure D.23: Path-gain contour plots for individual elements of array SIMO3 at 270° on base station BS1 (Environment B, Phase II). (The dotted line indicates the axis of polarisation and; the contour lines are 6 dB apart.)

Figure D.24: Path-gain contour plots for individual elements of array SIMO3 at 0° on base station BS1 (Environment B, Phase II). (The dotted line indicates the axis of polarisation and; the contour lines are 6 dB apart.)
Figure D.25: Path-gain contour plots for individual elements of array SIMO2 at 60° on base station BS1 (Environment B, Phase II). (The contour lines are 6dB apart.)
D.2. Phase II — Complex voltage measurements

(a) Element 1
(b) Element 2
(c) Element 3

Path gain (dB)

Figure D.26: Path-gain contour plots for individual elements of array SIMO2 at 60° on base station BS2 (Environment B, Phase II). (The contour lines are 6 dB apart.)

Figure D.27: Path-gain contour plots for individual elements of array SIMO2 at 240° on base station BS2 (Environment B, Phase II). (The contour lines are 6 dB apart.)
Appendix E

Statistical Distributions in Wireless Communications

This appendix reviews the basic statistical distributions that are commonly used in wireless communications and is associated mainly with Chapters 2 and 7. The generation of random variables based on these distributions is also discussed, which is useful in the simulation of wireless channels.

E.1 The Rayleigh distribution

The Rayleigh distribution is commonly used to model the envelope of an individual multipath component of received signals in wireless systems [1, pp. 172–174]. The envelope probability density function (PDF) of a Rayleigh distribution is given by [2, pp. 125–127]

\[
p(v) = \begin{cases} 
\frac{v}{\sigma^2} \exp \left( -\frac{v^2}{2\sigma^2} \right), & v \geq 0 \\
0, & \text{otherwise} 
\end{cases} 
\]  

(E.1)

where \( \sigma^2 \) is the mean power (in watts) of the multipath component.

E.1.1 Generation of independent Rayleigh random variables

A complex Rayleigh random variable (RV) \( n \) can be generated by combining two quadrature identical independently distributed (i.i.d.) Gaussian RVs, namely

\[
n = N_I + j N_Q, 
\]

(E.2)

where \( N_I \) and \( N_Q \) are independent Gaussian RVs, with a mean of zero and a standard deviation of \( \sigma \).
E.1.2 Generation of correlated Rayleigh random variables

The generation of correlated Rayleigh random variables is useful in the modelling of the received signals from individual elements of MEAs. The algorithm adopted in this thesis is based on [3] with a modification based on [4] that corrects for the positive definiteness of a covariance matrix.

This algorithm generates $N$ ($N \geq 2$) correlated complex Rayleigh random variables with a desired envelope covariance (or cross-correlation coefficient) matrix. The starting point is the desired covariance matrix of the Rayleigh envelopes ($r_1, r_2, \ldots, r_N$), given by

$$
\hat{K}_r = \begin{pmatrix}
\sigma^2_{r_1} & \hat{\rho}_{r_1,2} & \hat{\rho}_{r_1,3} & \cdots & \hat{\rho}_{r_1,N} \\
\hat{\rho}_{r_2,1} & \sigma^2_{r_2} & \hat{\rho}_{r_2,3} & \cdots & \hat{\rho}_{r_2,N} \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
\hat{\rho}_{r_N,1} & \hat{\rho}_{r_N,2} & \hat{\rho}_{r_N,3} & \cdots & \sigma^2_{r_N}
\end{pmatrix}.
$$

(E.3)

This covariance matrix can be calculated directly from measured data.

**Step 1** Normalise this matrix to create the normalised covariance matrix

$$
K_r = \begin{pmatrix}
1 & \rho_{r_1,2} & \rho_{r_1,3} & \cdots & \rho_{r_1,N} \\
\rho_{r_2,1} & 1 & \rho_{r_2,3} & \cdots & \rho_{r_2,N} \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
\rho_{r_N,1} & \rho_{r_N,2} & \rho_{r_N,3} & \cdots & 1
\end{pmatrix},
$$

(E.4)

where $\rho_{r_{i,j}} = \hat{\rho}_{r_{i,j}} / \sqrt{\sigma^2_{r_i} \sigma^2_{r_j}}$.

**Step 2** For each cross-correlation coefficient $\rho_{r_{i,j}}$, compute the corresponding $\rho_{g_{i,j}}$ by numerically solving

$$
\rho_{r_{i,j}} = \frac{(1 + |\rho_{g_{i,j}}|) E_i \left( \frac{2 \sqrt{|\rho_{g_{i,j}}|}}{1 + |\rho_{g_{i,j}}|} \right) - \pi}{2 - \frac{\pi}{2}},
$$

(E.5)

where $E_i(\eta)$ denotes the complete elliptic integral of the second kind with modules $\eta$.

**Step 3** Generate $N$ uncorrelated complex Gaussian random variables $V = v_1, v_2, \ldots, v_N$ each with variance $\sigma^2_g$. 

Step 4  The desired normalised covariance matrix $K_g$ for the uncorrelated complex Gaussian random variable $V$ is given by

$$K_g = \begin{pmatrix}
1 & \rho_{g1,2} & \rho_{g1,3} & \cdots & \rho_{g1,N} \\
\rho_{g2,1} & 1 & \rho_{g2,3} & \cdots & \rho_{g2,N} \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
\rho_{gN,1} & \rho_{gN,2} & \rho_{gN,3} & \cdots & 1
\end{pmatrix}. \quad (E.6)$$

Step 5  Determine the colouring matrix $L$ corresponding to $K_g$. The colouring matrix is the lower triangular matrix such that $LL^T = K_g$ where $L^T$ represents the transpose of $L$.

Step 6  Generate correlated complex Gaussian random variables using $W = LV$.

Step 7  The $N$ envelopes of the Gaussian random variables in $W$ correspond to Rayleigh random variables $(r'_1, r'_2, \ldots, r'_N)$ with normalised covariance matrix $K_r$ and equal variance

$$\sigma_r^2 = \left(2 - \frac{\pi}{2}\right) \frac{1}{2} \sigma_g^2. \quad (E.7)$$

Step 8  Create the desired Rayleigh envelops $(r_1, r_2, \ldots, r_N)$ from the random variables $(r'_1, r'_2, \ldots, r'_N)$ by evaluating $r_i = A_i r'_i$ where $A_i = \sigma_{r'i}/\sigma_r$.

In Step 5, the Cholesky decomposition [5, pp. 168–169] is used to determine the colouring matrix $L$. Cholesky decomposition, however, requires the matrix being factorised to be positive definite, which may not be valid in realistic channel measurements. This limitation can be averted by finding a positive matrix $\hat{K}_g$ that closely approximate a non-positive definite matrix $K_g$ in the Frobenius sense [4].

1. Perform the factorisation $K_g = UAU^T$, where $U$ is a complete set of orthonormal eigenvectors and $A$ is a matrix with the eigenvalues in the diagonal $A = \text{diag}(\lambda_1, \lambda_2, \ldots, \lambda_N)$.

2. Obtain the matrix $\hat{A} = \text{diag}(\hat{\lambda}_1, \hat{\lambda}_2, \ldots, \hat{\lambda}_N)$, where $\hat{\lambda}_i = \lambda_i$ if $\lambda_i > 0$, else $\hat{\lambda}_i = \varepsilon$ for a small positive value $\varepsilon$.

3. Calculate $\hat{K}_g = U\hat{A}U^T$, where $\hat{K}_g$ will be a positive definite, close approximation of $K_g$ in the Frobenius sense.
E.2 The Rician distribution

The Rician distribution was suggested by Rice [6] to model a sinusoidal wave with random noise. This distribution is, therefore, useful for the modelling of radiowave propagation in environments where a line-of-sight (LOS) or dominant signal component is present in addition to other multipath (Rayleigh) components. The envelope PDF of a Rician distribution is given by [5, pp. 328–334]

\[
p(v) = \begin{cases} 
\frac{v}{\sigma^2} \exp\left(-\frac{P^2 + v^2}{2\sigma^2}\right) I_0 \left(\frac{Pv}{\sigma^2}\right), & v \geq 0 \\
0, & \text{otherwise}
\end{cases} \tag{E.8}
\]

where \( I_0(\cdot) \) is the zeroth-order modified Bessel function of the first kind, \( P \) is the magnitude (field strength in volts) of the dominant signal and \( 2\sigma^2 \) is the power (in watts) of the multipath components. The Rician distribution is often described in terms of a parameter \( K \) defined as

\[
K = \frac{P^2}{2\sigma^2}, \tag{E.9}
\]

which can be interpreted as the power ratio of the dominant signal over the multipath components.

E.2.1 Generation of independent Rician random variables

From the definition of the Rician distribution [6], the envelope \( R \) of a complex Rician RV can be represented by

\[
|R| = |P + n|, \tag{E.10}
\]

where \(|\cdot|\) denotes the modulus, \( P \) is the sinusoidal wave, and \( n \) is complex Gaussian noise. In the context of radiowave propagation, \( P \) and \( n \) represent the complex voltages of the dominant signal component and the Rayleigh (multipath) components, respectively. An envelope Rician RV can be formed by substituting \( P \) with a constant (namely the field strength of the dominant signal) and \( n \) with a complex Rayleigh RV.

Envelope Rician RVs are useful in Monte Carlo simulations that exploit the statistical properties of the RVs. These RVs, however, lack the correlation properties between samples in the time domain. It is possible to obtain proper time-correlation between samples by spectrally shaping \( n \) and replacing \( P \) with a rotating phasor at a specified Doppler frequency.
E.2.2 Estimation of the Rician $K$-factor

Moment-based techniques have been adopted for estimating the $K$-factor of a Rician distributed sample in previous research [7–9]. This approach calculates the moments of the measured sample and uses them as estimators to the moments of the theoretical Rician distribution. It is then possible to calculate the $K$-factor of the measured sample by solving the moments equations simultaneously. Since Rician distributions have two degrees of freedom, two moment equations are required for solving the two parameters ($P$ and $\sigma$). A simple estimator $\hat{K}_{2,4}$ [8] can be expressed in closed form in terms of the second- and fourth-order sample moment of the measured field strength, namely

$$\hat{K}_{2,4} = \frac{\mu_4 - 2\mu_2^2 - \mu_2\sqrt{2\mu_2^2 - \mu_4}}{\mu_2^2 - \mu_4},$$  \hspace{1cm} (E.11)

where $\mu_2$ and $\mu_4$ are the second- and fourth-order sample moments, respectively. The derivation of (E.11) is given in Section E.2.3. A thorough performance analysis of this estimator is given in [8], which shows a good compromise between statistical performance and computational simplicity. An alternative form of this estimator was independently proposed in terms of the moments of signal power instead of field strength [9].

E.2.3 Derivation for the estimator $\hat{K}_{2,4}$

The estimator $\hat{K}_{2,4}$ can be derived from the $n^{th}$ moment equation of a Rician RV [5, pp. 333–334], which is given by

$$E[V^n] = 2^{n/2}\sigma^n \Gamma\left(\frac{n}{2} + 1\right) {}_1F_1\left(-\frac{n}{2};1;\frac{-P^2}{2\sigma^2}\right),$$  \hspace{1cm} (E.12)

where \(\Gamma(\cdot)\) is the gamma function, and \( {}_1F_1(\cdot;\cdot;\cdot) \) is the confluent hypergeometric function.

It can be shown that the second- and fourth-order moments can be reduced to

$$E[V^2] = 2\sigma^2 \left(1 + \frac{P^2}{2\sigma^2}\right),$$  \hspace{1cm} (E.13)

and

$$E[V^4] = 8\sigma^4 + 8P^2\sigma^2 + P^4,$$  \hspace{1cm} (E.14)

respectively.

An estimator to the $K$-factor can then be obtained by combining (E.9), (E.13) and (E.14).
Step 1  Solving for $P$

Rearrange (E.13)

$$E[V^2] = \mu_2 = 2\sigma^2 + P^2$$

$$2\sigma^2 = \mu_2 - P^2. \tag{E.15}$$

Substitute (E.15) into (E.14)

$$E[V^4] = \mu_4 = 2(2\sigma^2)^2 + 4P^2(2\sigma^2) + P^4$$

$$\mu_4 = 2(\mu_2 - P^2)^2 + 4P^2(\mu_2 - P^2) + P^4$$

$$= 2(\mu_2 - P^2)(\mu_2 - P^2 + 2P^2) + P^4$$

$$= 2(\mu_2 - P^2)(\mu_2 + P^2) + P^4$$

$$= 2\mu_2^2 - 2P^4 + P^4$$

$$= 2\mu_2^2 - P^4$$

$$(P^2)^2 = 2\mu_2^2 - \mu_4$$

$$P^2 = \sqrt{2\mu_2^2 - \mu_4}$$

$$P = \pm \left(2\mu_2^2 - \mu_4\right)^{\frac{1}{2}}. \tag{E.16}$$

Since $P^2$ (power of dominant signal) must be positive, therefore the root $\sqrt{2\mu_2^2 - \mu_4}$ is always positive.

Step 2  Solving for $\sigma$

Substitute (E.16) into (E.15)

$$2\sigma^2 = \mu_2 - \sqrt{2\mu_2^2 - \mu_4}$$

$$\sigma = \pm \left(\frac{\mu_2 - \sqrt{2\mu_2^2 - \mu_4}}{2}\right)^{\frac{1}{2}}. \tag{E.17}$$

Step 3  Solving for $K$

Divide (E.16) by (E.17)

$$K = \frac{P^2}{2\sigma^2}$$

$$\tilde{K}_{2,4} = \frac{\sqrt{2\mu_2^2 - \mu_4}}{\mu_2 - \sqrt{2\mu_2^2 - \mu_4}}.$$
Let \( a = \sqrt{2\mu_2^2 - \mu_4} \)

\[
\hat{K}_{2,4} = \frac{a}{\mu_2 - a} = \frac{a(\mu_2 + a)}{(\mu_2 - a)(\mu_2 + a)} = \frac{a\mu_2 + a^2}{\mu_2^2 - a^2}.
\]

Substitute \( a = \mu_2 \sqrt{2\mu_2^2 - \mu_4} \)

\[
\hat{K}_{2,4} = \frac{\mu_2 \sqrt{2\mu_2^2 - \mu_4} + 2\mu_2^2 - \mu_4}{\mu_2^2 - 2\mu_2^2 + \mu_4} = \frac{\mu_4 - 2\mu_2^2 - \mu_2 \sqrt{2\mu_2^2 - \mu_4}}{\mu_2^2 - \mu_4}.
\] (E.18)

References


[8] C. Tepedelenlioglu, A. Abdi, G. Giannakis, and M. Kaveh, “Performance analysis of moment-based estimators for the \( K \) parameter of the Rice fading distribution,” in