Mechanistic Modelling of Single-Floor Office Environments

Eva Chi-Ken Lai

Abstract

Engineering high performance indoor wireless communication systems requires sound system deployment strategies. In order to deploy systems effectively, propagation models that can reliably and yet efficiently characterise radio propagation behaviour are needed. This thesis describes the philosophy, the logical development, and the performance of a mechanistic modelling approach which is intended for use in system planning. In the investigation, the deployment of a single base station in a single-floor office environment is considered. The environment is systematically divided into several generic canonical geometries including an open plan office and corridor, a single corner, a double corner, and a discrete obstacle which are then separately analysed. The dominant mechanisms which govern the energy propagation in each canonical geometry have been identified using both the ray and the FDTD methods. Mechanistic models with different levels of complexity (i.e. by including different mechanisms) for a real office environment have been formulated. In particular, the detailed internal layout and the effect of environmental clutter have been considered. A mechanistic model which has shown to balance the model accuracy and complexity is identified. The performance of the mechanistic model is then evaluated by comparing with existing indoor propagation models and the experimental measurements.

Mechanistic models are shown to be most efficient when a line-of-sight path exists or when the material of internal partitions is nearly electromagnetically transparent. In these cases, direct and a singly-reflected components are found to be the dominant mechanisms which need to be considered. In the presence of a single corner which causes shadowing to a subset of receiving locations, the complexity of the mechanistic models is shown to increase as none of the propagation components is universally dominant. In particular, five components including direct, up to doubly-reflected, a diffracted, and combined reflected-diffracted components appear to be significant in different parts of the shadowed region. Reflected components tend to be more significant as the operating frequency increases. Regardless of the attenuation caused by the environmental obstruction, when a double corner or a centrally-located discrete obstacle is present the majority of the energy is evidenced to propagate around rather than transmit directly through.
Acknowledgements

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<td>1G</td>
<td>First Generation Mobile Service</td>
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<td>2D</td>
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<td>Digital Enhanced Cordless Telecommunications</td>
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<td>Incident Shadow Boundary</td>
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<td>ISM</td>
<td>Industrial, Scientific, and Medical</td>
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<td>RSB</td>
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<td>Radio Spectrum Management</td>
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<td>SIR</td>
<td>Signal-to-Interference Ratio</td>
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<tr>
<td>TE</td>
<td>Transverse Electric</td>
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<td>Transverse Magnetic</td>
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<td>ULF</td>
<td>Ultra Low Frequency</td>
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<td>Wall Attenuation Factor</td>
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<td>Wi-Fi</td>
<td>Wireless-Fidelity</td>
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<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
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<td>WLAN</td>
<td>Wireless Local Area Network</td>
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Chapter 1

Introduction

1.1 The New Era of Wireless Communications

With the tremendous success for the development of wireless communication technologies in the past ten to twenty years, wireless communications have become an important part of modern society. Although first generation (1G) of wireless mobile communication systems (based on analog technology) were introduced in the 1980s, it was not until the 1990s that second generation (2G) digital mobile systems with improved spectral efficiency and voice quality were introduced. Since then there has been an explosive growth in the popularity of wireless communication services. Third generation (3G) mobile service networks were developed in the early 2000s to satisfy the demands of high transmission speed and quality for multimedia services. More recently, possible candidates of fourth generation (4G) mobile service networks such as the Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) have been deployed in many countries to further improve the transmission speed and provide mobile broadband connectivity across whole cities [1,2].

Along with the widespread use of mobile telecommunications, indoor wireless communication systems have become popular. This is largely attributed to wireless local area networks (WLANs) which have the ability to deliver inexpensive untethered broadband connectivity using unlicensed spectrum inside buildings [3]. As the demand of wireless services grows, innovative solutions for deploying high performance yet cost effective broadband wireless systems in high user-density areas (e.g. office environments) are required. Exploring the feasibility of femtocells is an example of this which attempts to increase the service coverage, capacity, and transmission data rate in indoor local areas [4]. A femtocell is a small indoor cellular base station that operates in licensed spectrum and allows the mobile users to connect to the mobile operator’s network via broadband internet connections [5, p. 4]. Although new wireless technologies will continue to emerge to
fulfill the demand for high data rate services, a good system deployment strategy remains an important element to achieve optimal system performance and therefore the success of future indoor wireless technology.

1.2 Factors which Limit System Performance

Indoor environments are complicated as they are often highly variable in both layout and construction materials. Typical indoor environments range from single-level residential houses through to multi-storey office buildings, with a range of construction materials such as timber, drywall, glass, and reinforced concrete. It is found that the environmental layouts and the materials from which internal partitions are made can influence the radio propagation behaviour significantly, and therefore may affect the system performance. For example, the presence of a concrete services core can cast significant radio shadows on receivers and result in the degradation of system performance in terms of signal-to-noise ratio (SNR) and outage probability [6]. Therefore, a good understanding of the radio propagation behaviour is required to deploy wireless systems strategically, and thus achieve the desired system performance.

The use of frequency spectrum for different applications is managed by the local government\textsuperscript{1}. Other than the frequency bands in which only licensed users may transmit (e.g. for cellphone transmission) or no one may transmit (i.e. reserved for radio astronomy), unlicensed frequency bands can be used for other transmissions provided that users follow the required regulations. The commonly used indoor wireless applications such as WLANs, cordless phones, and Radio-frequency identification (RFID) technologies have been established to operate in unlicensed spectrum (e.g. Industrial, Scientific, and Medical (ISM) bands). With the increased number of indoor wireless systems competing for limited spectrum allocations, increased levels of co-channel interference which can degrade system performance have arisen. Therefore, propagation models which can reliably predict signal strengths from both desired and interfering devices in an efficient manner are required for system planning.

1.3 Existing Propagation Modelling Techniques

Numerous propagation studies have been undertaken to characterise the indoor radio channel statistically using experimental measurements (e.g. [7, 8]). Not only are such measurements time consuming and expensive, they cannot be transported to other en-

\textsuperscript{1}In New Zealand, the usage of frequency spectrum is allocated by The Radio Spectrum Management group (RSM).
environments without additional validation. In recent years, propagation models which take building features into account have been developed to estimate system coverage and reliability for successful system deployments (e.g. [9–11]). In particular, ray methods are most often used as they are generally simple and can be computationally efficient. However, they must be used cautiously for indoor environments, as some of the propagation effects (e.g. dielectric wedge diffraction) are non-ray optical in nature [12, 13]. In addition, significant computational effort may be required in some situations to account for large numbers of rays propagating in the environments [14]. Recent advances in computational capabilities are allowing alternative numerical techniques such as the Finite-Difference Time-Domain (FDTD) method [15] to solve electrically-large propagation problems. For example, the FDTD has been used directly to study propagation in single-floor geometries [16–18], and multi-floor problems [19–21]. Results have shown that the FDTD predictions are generally accurate, but excessive computational effort and detailed environmental information are required.

A useful propagation model which can provide valuable assistance in deploying a high performance wireless system should have the desired characteristics as follows:

- Be able to provide meaningful estimates of the required output parameters (e.g. local mean [22, p. 155]);
- Does not require detailed information of the physical environment;
- Be computationally efficient; and
- Be transportable for use in other environments.

It is clear that there is always a trade-off between the model accuracy and complexity. Unfortunately, existing indoor propagation models are not able to achieve the balance between these two constraints. Moreover, they do not contain all the desired characteristics of a useful model aforementioned. For this reason, innovative indoor propagation modelling approaches which are suitable for use in system planning are required.

1.4 Objectives and Structure of this Thesis

This thesis proposes a mechanistic modelling approach which aims to improve computational efficiency against existing propagation models while retaining the physical underpinning of the propagation process. Given several components arriving at a receiving location, the basis of this approach is to consider only the main contributors to the received power. A significant advantage with this approach is that the model would be able to estimate useful output parameters (e.g. local mean) in an efficient manner, and ignore
insignificant contributions. Among various building types, office buildings have exhibited the most demand for high capacity and high data rate wireless services. Therefore, this thesis focuses on the radio propagation in single-floor office environments.

The objectives of this research are:

- To identify dominant propagation mechanisms in typical single-floor office environments;
- To formulate mechanistic models based on the dominant mechanisms identified; and
- To assess the performance of a mechanistic modelling approach.

In order to achieve these objectives, The School of Engineering Tower at The University of Auckland has been chosen as a test site for the indoor propagation study. This building is constructed from steel-reinforced concrete with a centrally-located concrete services core, and is typical of many conventional office buildings. In this thesis, ray-based models and the FDTD method have been adopted to investigate the electromagnetic nature of radiowave propagation, and hence to identify the dominant propagation mechanisms in this environment. Because the environment is electrically-large in nature, it has been divided into several canonical geometries including an open plan office and corridor, a single corner, a double corner, and a discrete obstacle. The dominant propagation mechanisms in a specific layout can then be isolated. Mechanistic models are formulated based on the dominant mechanisms identified for the test site. By comparing the mechanistic path loss predictions with the measurements, the performance of the mechanistic modelling approach can be evaluated.

The Structure of this Thesis

This thesis is comprised of ten chapters, and the related publications to this research are in [23, 24]. The unique contributions of this thesis are detailed in Chapters 5–8 and have been divided into two parts (A and B). Part A of the investigation (Chapters 5–7) describes a comprehensive sequential propagation study of the canonical geometries, from which the dominant propagation mechanisms are identified. Part B of the investigation (Chapter 8) proposes the mechanistic models with varying complexity for a real office environment, and evaluates the performance of the mechanistic models. A detailed overview of the chapters in this thesis is given as follows.

Chapter 2 discusses the common propagation phenomena and received signal variations observed in practice. A survey of existing propagation modelling approaches that can be used to predict signal strength in indoor environments are reviewed. Additionally, the characterisation of complex building walls (e.g. composite and reinforced concrete
walls) for accurate modelling of indoor radio propagation is presented. It was found that existing propagation models either lack of transportability or are computationally intensive, and thus they are not suitable for use in system planning. This induces the need of an innovative propagation modelling approach which is the major thrust of this thesis.

**Chapter 3** introduces the philosophy and the modelling process of the mechanistic modelling approach advocated in this thesis. The mechanistic modelling approach is based on ray methods which are known to be inaccurate in some situations. As a result, an electromagnetic modelling technique — Finite-Difference Time-Domain (FDTD) — is implemented to validate the ray models formulated. Two test cases involving a dielectric slab and a single room environment are investigated to demonstrate the performance of the ray models. Altogether, the FDTD and the ray models are used for the radio propagation studies presented in this thesis.

**Chapter 4** gives an overview of the investigations presented in this thesis. A real office building was chosen as a test site to study the indoor propagation. Initially, this environment has been investigated using the FDTD method. Due to the complicated composite field pattern, it is very challenging to identify the dominant energy paths. Therefore, the environment has been systematically divided into generic canonical geometries including an open plan office and corridor, a single corner, and a double corner and a discrete obstacle, which are investigated in detail in Chapters 5–7, respectively.

**Chapter 5** investigates radiowave propagation in an open plan office and corridor geometry. A ray model which considers the candidate dominant energy components is formulated and validated with the FDTD simulations. This ray model is subsequently used to identify the dominant mechanisms which have the significant contribution to the received signal strength. Several parameters including the prediction accuracy requirement, the material properties, the transmitter location, and the frequency selection which can potentially affect the radio propagation behaviour are examined.

**Chapter 6** investigates radiowave propagation in the presence of a single corner. The purpose of this chapter is to identify the dominant mechanisms which govern the energy propagation when a subset of receiving locations are shadowed. Similarly, a ray model which has been validated with the FDTD simulations is used for such a role. Specifically, the effects of the corner material properties, the exterior glass windows, the frequency selection, and the geometrical relationship between transmitter and corner are investigated.

**Chapter 7** investigates radiowave propagation in the presence of a double corner and a discrete obstacle. Initially, the investigation considers an infinite extent discrete obstacle where the energy can only transmit through or propagate around one side of the discrete obstacle. Subsequently, the geometry is extend to a centrally-located discrete obstacle where the energy can transmit through or propagate around both sides of the discrete
obstacle to the deeply shadowed region. Several parameters which can potentially affect the dominant mechanisms including the internal structure of the discrete obstacle, the exterior glass windows, and the system operating frequency are examined.

Chapter 8 formulates mechanistic models with varying degrees of complexity for a real office environment. The level of environmental detail required to achieve an acceptable prediction accuracy is investigated. In addition, a heuristic approach for characterising the effect of environmental clutter (e.g. bookshelves, desks, and filing cabinets) is proposed. The outcome of this chapter is to provide a guideline on how to select the appropriate mechanisms to achieve a balance between the model accuracy and complexity. The performance of the mechanistic model is also evaluated by comparing with the experimental measurements and existing propagation models.

Chapter 9 discusses the practical implications of using mechanistic models for engineering design. Recommendations for future work are also presented.

Chapter 10 presents the key conclusions drawn from this thesis. Detailed descriptions of the computation of effective reflection coefficient for a ray model and the data-processing techniques for the FDTD results are presented in Appendices A and B. Additional results to validate the ray models adopted for the investigations are presented in Appendix C.
Chapter 2

Indoor Radio Propagation and Modelling Techniques

2.1 Introduction

Indoor wireless systems such as wireless local area networks (WLAN) and femtocells which are used to improve mobile services (e.g. third generation (3G) and later mobile networks) inside buildings, have emerged to provide reliable and seamless connectivity. As they are usually deployed in close proximity, it has led to increased levels of co-channel interference which can degrade the system performance. The system performance is heavily dependent on the nature of the propagation environment and the system deployment strategy. Therefore, propagation models which can reliably predict signal strengths from both desired and interfering devices in an efficient manner are required for system planning. However, indoor environments are highly variable in both layout and construction materials which makes modelling propagation very challenging in general.

This chapter provides an overview of indoor radio propagation behaviour and existing modelling techniques in the literature. Section 2.2 describes the phenomena influencing the propagation of radio signals. The characteristics of the received signals due to fast fading, shadowing, and range dependence are explained. Section 2.3 presents a literature review on indoor propagation modelling and it has been divided into two parts. The first part surveys existing propagation modelling approaches including the empirical/statistical models and the site-specific models for environments that contain more than one building walls, hence hereafter referred to as *macroscopic structures*. The advantages and disadvantages of different modelling approaches are also discussed. As accurate field predictions become increasingly important, accurate characterisation of common building walls has received attention. The second part of the literature review presents studies that have investigated environments that contain only one building wall, hence hereafter referred
to as *microscopic structures*. Significant findings and their implications for propagation modelling are discussed. Finally, Section 2.4 summarises the chapter.

### 2.2 An Overview of Indoor Radio Propagation

Indoor radio propagation is heavily influenced by the nature of the propagation environment (e.g. the building layout and the construction materials). Generally, the observed propagation phenomena can be attributed to *direct transmission*, *reflection*, *diffraction*, and *scattering* [25, p. 69]. As the received signal is usually a combination of multiple components propagated along different paths, the amplitudes and phases of these components will be different. Hence, the received signal levels can vary significantly even over relatively short distances. Section 2.2.1 describes basic radio propagation phenomena with an illustration of these propagation paths in a hypothetical office environment. Characteristics of received signal strength resulting from multipath propagation are presented in Section 2.2.2.

#### 2.2.1 Indoor Radio Propagation Phenomena

In any given location, the received signal is usually comprised of several components which propagate along different paths and therefore have encountered different obstacles [9]. Typically, these components propagate from the following paths:

- **Direct path** — The shortest path between a transmitter and a receiver. This includes a line-of-sight (LOS) path with no intervening obstacles, and a non line-of-sight (NLOS) path with obstacles (e.g. walls) in between.

- **Reflected path** — The path where a wave impinges upon an object which is large compared to the wavelength of the propagating wave and then reflects towards the opposite direction of the incident wave. Reflection from flat surfaces such as the ceiling, floor, or walls could potentially support a significant amount of energy to receivers.

- **Diffracted path** — The path when a receiver is shadowed by a surface with sharp irregularities (edges), the propagating wave bends around the obstacle to reach the receiver.

- **Scattered path** — The path when a wave hits objects which are small compared to the wavelength of the propagating wave (e.g. door knobs) and then scattered in several different/nonspecular directions.
Ray methods are based on high frequency asymptotic techniques and have been commonly used to describe the characteristics of radio propagation [26]. Specifically, orthogonal trajectories to the wave fronts along which the electromagnetic energy flows have been modelled as rays [27, p. 69]. It should be noted that ray methods are only applicable when the size of objects which interact with the propagating wave is large compared to the wavelength. Since common frequency bands used for indoor wireless applications are usually between 1.8–5.8 GHz (the wavelengths of which correspond to 17 cm and 5 cm, respectively), using ray methods to represent most of the radio propagation phenomena observed in indoor environments is thought to be appropriate. However, it should be noted that some indoor propagation phenomena are non-ray optical in nature (e.g. dielectric wedge diffraction). As a consequence, applying ray methods to represent such an effect may have a reduced prediction accuracy. This issue is further discussed in Section 6.2.2.

Fig. 2.1 illustrates the radio propagation phenomena which have been represented as rays in a hypothetical office environment. Due to the presence of the internal partitions between offices (e.g. path T1–T2), environmental clutter (e.g. path T2–T3), or the corner in the corridor (e.g. path T1–T3), the direct path (coloured red) is likely to encounter one or more obstacles. Therefore, appropriate methods for estimating the transmission loss through obstacles are required for accurate propagation modelling in indoor environments.

Reflection from a surface is generally regarded as an important propagation process which has been found to contribute significantly to the received signal strength [11,24,28]. If an incident wave impinges on a perfectly conducting surface, then all the incident energy is reflected back with the reflected angle equal to the incident angle. If an incident wave impinges on a dielectric object, then part of the energy is transmitted through, part of the energy is reflected back, and part of the energy is absorbed. The material properties, wave polarisation, angle of incidence, and frequency are the parameters which can influence the extent of energy reflection/transmission. In Fig. 2.1, reflected paths (coloured blue) from glass windows (e.g. path T1–T2) and concrete walls (e.g. path T2–T3) are potential dominant energy paths and may need to be considered.

Diffraction is another common indoor propagation phenomenon which causes the propagating wave to “bend” and propagate around obstructions. This phenomenon is particularly important in the situation when a receiving location is heavily shadowed by a significant obstacle. For example, Fig. 2.1 shows that a propagating wave originating from Terminal T1 has diffracted around the concrete corner to reach Terminal T3. If the concrete corner is highly lossy and thus causes significant attenuation to the direct path,
the energy that propagates via the diffracted path (coloured green) may be the major contributor to the received signal strength.

Scattering occurs when the radio wave impinges on objects which have rough surfaces or small dimensions compared to the wavelength of the propagating wave [25, p. 78]. For example, scattered paths can result when a radio wave impinges on a door knob and then propagates to the receiving terminal. However, scattering is non-ray optical phenomenon and is therefore not illustrated in Fig. 2.1.

2.2.2 Received Signal Strength

Propagation environments are generally time-varying, and they consist of objects and scatterers which cause components to propagate via different paths to reach a receiving location. Due to the components arriving at a receiver having different amplitudes and phases, they add constructively or destructively resulting in fading. Generally, there are short-, medium-, and long-term variations in received signals.

A hypothetical indoor environment shown in Fig. 2.2 is used to demonstrate the characteristics of typical received signals simulated with a 2D Finite-Difference Time-Domain (FDTD) method. In this example, a 1.0 GHz transmitter (TA) was deployed at a fixed location in corridor A and the signals were sampled along a receiving trajectory (---) in corridor B. The corridor walls are assumed to be made from 0.3 m thick lossy concrete slabs ($\varepsilon_r = 6$ and $\sigma = 50 \text{ mS/m}$). It can be seen that a line-of-sight (LOS) path only ex-
ists at certain locations along the receiving trajectory (i.e. 2–4 m from point X). Fig. 2.3 shows the received signal (in blue) along the receiving trajectory indicated in Fig. 2.2. The mean of the received signal (in red) was obtained by taking the spatial average over a $2\lambda \times 2\lambda$ ($0.6 \text{ m} \times 0.6 \text{ m}$) sector.

**Figure 2.2:** Plan of a hypothetical environment to obtain a received signal strength profile. The 1.0 GHz transmitter is indicated by TA, whereas the signal receiving trajectory is indicated by - - -.

**Figure 2.3:** Received signal strength along the receiving trajectory shown in Fig. 2.2.
Short-Term Variations

Short-term variation is the rapid fluctuation in the instantaneous received signal (e.g. the blue trace shown in Fig. 2.3), also known as fast fading. Fast fading occurs due to multipath components arriving at a receiver which combine constructively and destructively. The signal variation has been observed as much as three or four orders of magnitude (30 dB or 40 dB) over a distance as low as a fraction of a wavelength [25, p. 70]. The mean received signal which has been averaged over a local area such that the effect of fast fading is eliminated is referred to as local mean (e.g. the red trace shown in Fig. 2.3) [22, p. 155]. In practice, the local mean has a great significance as it is the parameter required for meaningful system performances (e.g. the outage probability) to be estimated. Therefore, the term “received signal strength” used in this thesis is always referred to the local mean.

Depending on the characteristics of the propagation environment, the variation of the received signal envelope (i.e. electric field strength) can be modelled statistically using a Rayleigh or Rician distribution [25, pp. 172–176]. For the situation when none of the components arriving at a receiver is dominant, the signal variation can be modelled using the Rayleigh distribution. This usually applies for non line-of-sight (NLOS) scenarios. On the other hand when a dominant component is present at a receiving location, the signal variation can be modelled using the Rician distribution. This generally applies for the situation when a LOS path is present. However, it should be noted that the significance of the components arriving at the receiving location is also heavily dependent on the operating frequency. For example at high frequencies, components propagating via other paths (e.g. reflected paths) may have amplitudes which are comparable to that from a LOS path. Instead of using the Rician distribution, the Rayleigh distribution would be more appropriate to describe the short-term signal variation [29].

Medium-Term Variations

Medium-term variation is the slow variation of the received signal, also known as slow fading. Slow fading occurs due to environmental obstacles which shadow the receiving location. It is usually observed to occur over a longer distance than that observed for the fast fading, and can be described with the log-normal distribution [22, p. 115]. The mean received signal which has been averaged over a wide area such that the effects of both fast fading and shadowing are eliminated is referred to as area mean [22, p. 156].

Long-Term Variations

Long-term variation determines the area mean, and is used to describe the received signal strength when the distance between the transmitter and receiver varies. This signal
variation can be described by an inverse power law of the transmitter and receiver separation distance, $d$ (i.e. $1/d^n$, where $n$ is the path loss exponent). Depending on the propagation environment, the path loss exponent $n$ can range between 2–5 in outdoor environments [25, p. 104]. For indoor environments, the path loss exponent $n$ is dependent on the internal layout of the environment. For example, $n$ is found to be less than 2 (which is less than in free space) in corridors from the impulse measurements [30], whereas $n$ is found to be in between 2–4 in offices [25, pp. 126–129].

2.3 Indoor Radio Propagation Modelling

A literature review on modelling of indoor radio propagation is presented in two parts with the structure shown in Fig. 2.4. The first part reviews existing indoor propagation models that are used to model macroscopic structures (i.e. environments containing more than one building walls), and are broadly divided into two types — Empirical/Statistical and Site-Specific. Empirical/statistical models are usually a set of equations that are derived from experimental measurements [14]. These equations are simple and can be used to predict the local mean efficiently. On the other hand, site-specific models are based on electromagnetic methods such as the ray-tracing and Finite-Difference Time-Domain (FDTD) methods. The predictions can be very accurate (even for predicting fading envelopes) provided that the environmental details are known and have been included in the physical model for the simulation [11, 18]. Recently, hybrid models which combine more than one electromagnetic models have emerged as another promising indoor propagation modelling approach and are reviewed.

In recent years, a detailed description of building walls has been used to accurately model indoor radio propagation for improving the system performance. The second part of the literature review presents different approaches which have been adopted to characterise microscopic structures (i.e. environments containing only one building wall) including the cinder block, the reinforced concrete and the composite walls. Significant findings and implications for propagation modelling are also discussed.

2.3.1 Empirical/Statistical Models

In the early indoor radio propagation studies, researchers have undertaken extensive experimental measurements in different types of buildings to obtain radio propagation characteristics [7, 8, 31–36]. It was first found by Alexander [31, 32] that the mean path loss, $PL$ (dB) between transmitter and receiver of separation distance, $d$ could be represented
by a power law and given by

\[ PL(d) = m \log(d) \]  \hspace{1cm} (2.1)

where \( m \) is the gradient parameter used to indicate the signal decay rate in the building. A great advantage of this simple model is that it can be easily applied to an indoor environment with a single input parameter (i.e. the transmitter and receiver separation distance, \( d \)). However, the prediction accuracy is greatly dependent on the gradient parameter \( m \) derived from each building construction type through measurements. As a result, a series of measurements in different commercial buildings and houses is required. Furthermore, this simple model does not consider any internal details which are known to have an effect on radio propagation. As a consequence, predictions in highly complicated regions (e.g. regions which are heavily shadowed by significant obstacles) may not be accurate.

To improve the model prediction accuracy, physical details of the propagation environment (e.g. architectural configurations and building materials) need to be considered. Lafortune et al. [7] have developed algebraic expressions similar to the Alexander model for predicting the path loss in an office building, except for that more input parameters which describe the environment are specified. These input parameters include obstacles between antennas (e.g. walls, doors, and windows), and transmitting antenna locations (e.g. in a corridor or a room). Similarly, the International Telecommunication Union [37]
has also developed the ITU-R model\(^1\) which considers the effects of frequency, building type, and floor attenuation.

The presence of shadowing obstacles will have a significant impact on radio propagation. To investigate the effect of shadowing obstacles, Akerberg [38] has proposed the Ericsson model\(^2\) which indicates the upper and lower limits of the path loss to account for shadowing. Also Seidel \textit{et al}. [8] have developed the log-distance model which considers both the increase of the path loss due to propagation distance, \(d\) and the path loss variations that occur due to shadowing. The formulation of the log-distance model is given by

\[
PL(d) = PL(d_0) + 10n \log \left( \frac{d}{d_0} \right) + X_\sigma
\]

where \(PL(d_0)\) is the path loss at a reference distance (usually at 1 m), \(n\) is the path loss exponent, and \(X_\sigma\) (dB) is a zero mean log-normally distributed random variable which accounts for the variability in a distance dependent path loss due to shadowing. The parameters \(n\) and \(X_\sigma\) are both derived from experimental measurements, and they have been grouped based on the general surroundings (e.g. the building type and the number of floors between transceivers). In the literature, it is shown that the log-distance model leads to a pessimistic prediction of system performance compared with the experimental measurements [39]. This may be due to the impact of specific environmental features (e.g. walls between transmitting and receiving antennas) that have not been considered explicitly.

As there are often obstructions between transmitting and receiving antennas, Seidel \textit{et al}. [8] have subsequently proposed the wall attenuation factor (WAF) model which considers the effects of soft partitions and concrete walls. It is assumed that the path loss always increases with distance as in free space \((n = 2)\), and additional attenuation which caused by the obstructions is included explicitly. The mean path loss predicted by the WAF model is given by

\[
PL(d) = 20 \log \left( \frac{4\pi d}{\lambda} \right) + p \times \text{WAF}_{\text{soft}} + q \times \text{WAF}_{\text{concrete}}
\]

where \(p\) and \(q\) are the number of soft partitions and concrete walls between the transmitter and receiver, respectively, \(\text{WAF}_{\text{soft}}\) and \(\text{WAF}_{\text{concrete}}\) are respectively soft partitions and concrete walls attenuation factors that derived from experimental measurements. Similarly, the European Cooperation of Scientific and Technology Research [40] has also

\(^1\)A detailed formulation of the ITU-R model is described in Chapter 8.
\(^2\)A detailed formulation of the Ericsson model is described in Chapter 8.
developed the COST 231 multi-wall model\textsuperscript{5}, but a greater variety of walls are considered. Furthermore, the floor attenuation factor (FAF) which is used to account for the loss due to propagation between floors is included. By considering more internal details, it is shown that a more accurate predictions can be achieved compared to the log-distance model \cite{8}. However, additional input parameters regarding the location and type of the walls are required.

To further improve the accuracy of empirical propagation models, Cheung \textit{et al.} \cite{41} have proposed a high-level empirical model to consider the important propagation effects observed. The Cheung model includes (i) a distance dependent path loss exponent, $n(d)$, (ii) an angle dependent wall attenuation factors $WAF(\theta)$, and (iii) diffraction. Although the prediction accuracy of the Cheung model is shown to outperform other existing empirical models (e.g. described in Eqs. (2.1)–(2.3)), the trade-off is that additional tuning parameters need to be included which complicate the model.

Empirical/statistical propagation models are generally simple to apply, and accurate for environments where experimental measurements were conducted. Performing experimental measurements is time-consuming and expensive. Additionally, the input parameters for the empirical/statistical propagation models are usually qualitative (e.g. the building types and the number of floors between transceivers) and subjective to the assessment criteria. A significant shortcoming of empirical/statistical models is that they cannot be transported to other environments without additional modification. As a consequence, differences between the predicted and measured results could be large in highly complicated regions. It is therefore recommended to use empirical/statistical models when the prediction accuracy is not a critical requirement.

\subsection{2.3.2 Site-Specific Models}

In recent years, site-specific models have emerged as highly promising modelling techniques for providing useful system performance estimates \cite{14,42}. Contrary to empirical/statistical models, site-specific models take detailed building features into consideration to accurately predict path loss. In this section, some popular site-specific models such as ray-tracing \cite{10,11,28,43–45}, Finite-Difference Time-Domain (FDTD) \cite{16–18,20,24,46}, and hybrid \cite{9,47,48} models are reviewed.

\textsuperscript{5}A detailed formulation of the COST 231 multi-wall model is described in Chapter 8.
Ray-Tracing Models

Highly complicated wall structures with varying material properties and the presence of environmental clutter make predicting the multipath components very challenging. To approximate and include these effects into a ray-tracing model in the design of wireless communication systems, the concept of effective building material properties was introduced by Seidel [43]. The effective material properties are empirically adjusted based on the difference between the measured and predicted power delay profiles. By altering the material properties of the walls, not only the effect of large-scale geometry is included, the scattering effect caused by environmental clutter are also considered. The outcome of this concept has revealed that the amplitudes and arrival times of individual multipath components can generally be predicted. This suggests that accurate multipath predictions may be achieved by modelling walls with appropriate effective relative dielectric constants. Again, the main drawback of this approach is lack of a physical basis. Moreover, measurements are required to determine the applicability of an effective dielectric constant and the appropriate values to use in a site-specific propagation prediction model.

There are a range of walls (e.g. cinder block and reinforced concrete walls) which have been commonly used in building construction. In order to create a physical model that can accurately represent the propagation environment, Tarng et al. [44] introduced the idea of patch-wall models. Patch-wall models are physical models which are formed from patches of different dielectric constants and physical sizes. Uniform-wall models that assume the walls with the same dielectric constant have also been implemented for comparison. The results show that the prediction accuracy has not been significantly improved (e.g. improvement in the mean error and standard deviation are approximately 1 dB) by using the patched-wall model. This suggests that good representation of walls using an uniform-wall model may be adequate to achieve an acceptable prediction accuracy.

In contrast with focusing on the development of physical models which are intended to represent propagation environments accurately, Honcharenko et al. [28] used a ray-tracing model to investigate radio propagation mechanisms in a single-floor office environment. Propagation mechanisms have particular significance as they explain the propagation phenomena (e.g. transmissions and reflections) observed in practice. As a result, propagation models which are formulated based on the mechanisms have a physical basis and therefore reliable. It is found that as long as the first Fresnel zone of the transmitting and receiving antennas lies within the vertical clear space between the ceiling and the furniture or the floor, the path loss can be considered as in free space. By contrast, the signal will experience additional attenuation if the first Fresnel zone becomes larger than
the clear space. The additional attenuation has also shown to be influenced by environmental clutter (e.g. furniture). Both the specular reflection from and the transmission through the interior walls are found to be significant and need to be considered. In some cases when the transmission loss through interior walls is significant, diffraction around the corner or propagation along exterior walls could become dominant. This is the first work which attempts to explain the significant effects observed using the mechanisms. As this approach has a physical basis while remaining computationally efficient, it may have a significant role towards the development of generalised propagation models.

It is well known that ray methods can sometimes be inaccurate due to non-ray optical propagation phenomena, such as dielectric wedge diffraction. Kouyoumjian et al. [49] developed the Uniform Theory of Diffraction (UTD) to model diffraction around perfectly conducting wedges, and the results have shown to be accurate. Unfortunately, applying the UTD to indoor environments may not be appropriate as the majority of objects are usually made of dielectric materials. A number of researchers [10–13,50] have attempted to improve the accuracy of ray methods by heuristically modifying the UTD to account for the diffracted fields caused by dielectric objects. The results have been shown that with the appropriate estimates of the diffracted fields, the prediction accuracy in both the illuminated and shadowed regions can be improved. However, the heuristic UTD developed are inherently site-specific in nature and may only be accurate for a particular environment. As a result, the general applicability of heuristic UTD remains uncertain.

**FDTD Models**

Recent advances in computational resources have allowed the application of FDTD methods to model electrically-large indoor propagation problems. Due to high computational requirements, application of the FDTD method to date has mainly focused on the investigation of 2-dimensional geometries [16–21,24,46,51]. In most of the investigations, only the large-scale geometry (e.g. walls that are extended from floor to ceiling) has been used to represent the environment, and are usually modelled by homogeneous dielectric slabs. The presence of environmental clutter (e.g. furniture and personnel) is assumed to stir the field variations only, and therefore has been neglected. Although the FDTD method has shown to estimate signal coverage and fading characteristics accurately in the representative environment, the complexity and requirement for detailed knowledge of the physical geometry and layout prohibit the FDTD method for use on a day-to-day basis.

Modern office/commercial buildings are usually constructed from complex walls (e.g. composite and reinforced walls). The FDTD method is highly flexible and therefore is
well suited to modelling propagation in the presence of inhomogeneous lossy dielectric objects. In the literature, there are only a few studies which have considered detailed wall structures in the FDTD simulations for determining channel parameters [16,51]. For example, Yun et al. [16] modelled concrete blocks by a hollow periodic structure in detail and solved the entire problem with a 2D FDTD method. It is shown that the difference of local mean power in 40%–50% of the total area can be observed between the complex and simple wall cases. In addition, the mean Rician $K$ factors of simple wall cases are found to be larger than that of the slab walls by 3–5 dB. These results suggest that detailed modelling of wall structures is important in the accurate characterisation of fading statistics in indoor wireless channels.

In recent years, few attempts [19,20,23,24] have focused on identifying dominant mechanisms in indoor environments using the FDTD method. Dominant mechanisms have a significant importance as they are the major contributors to the received signal strength. As a result, formulating a propagation model based on dominant mechanisms can provide meaningful estimates of the local mean. As there are only a few dominant mechanisms present at a receiving location, the computations can therefore be made efficiently [28]. In addition, dominant mechanisms explain the physical phenomena observed in practice and therefore likely to be transported to other environments. This approach is a very important step towards the development of useful propagation models suitable for system planning. Before a mechanistic model can be fully developed, identifying dominant mechanisms in generic indoor environmental layouts are needed.

**Hybrid Models**

Hybrid models are usually formed by combining two or more electromagnetic models. For example, a common combination in the literature is a ray-tracing method and an FDTD method [9,47,48]. The ray-tracing method can be computationally efficient, and is therefore used to analyse wide areas. The FDTD method on the other hand is computationally intensive, but is able to accurately model the effect of complex lossy walls (e.g. reinforced concrete walls). For this reason, the FDTD method is used to estimate scattered fields in areas that are close to complex walls and where ray-based solutions are not sufficiently accurate. The results have shown that a more accurate modelling of radio propagation can be achieved compared to a standard ray-tracing model, while remaining computationally tractable.

Tarng et al. [52] developed a hybrid model with a slightly different approach, that is based on combining a two-dimensional (2D) ray-tracing model and a statistical model to characterise multipath fading in indoor environments. Unlike hybrid models which com-
bine ray-tracing and FDTD methods that consider the detailed environmental features, the simple 2D ray-tracing method is used to describe the effects of the large-scale geometry. The scattering effects due to rough surfaces and/or environmental clutter (e.g. furniture and personnel) are characterised by a small-scale fading model. Specifically, a scattering factor $r$ is introduced to describe the clutter strength of the propagation environment. It is found that heavy-cluttering situations are likely to occur when (i) many environmental clutter are present, and (ii) a single environmental clutter is very close to the transmitting and/or receiving antennas.

**Practical Implications**

In general, site-specific models can be highly accurate provided that the physical models used for the simulation represent the propagation environments adequately. However, there is always a trade-off between the model accuracy and complexity. A more accurate model requires more environmental information to be considered. As a result, higher computational requirement is necessary. Although hybrid models are developed in an attempt to model propagation accurately while remaining computationally tractable, they are neither simple nor computationally efficient enough for system planning purposes.

As model prediction accuracy is heavily dependent on the environmental detail provided, it raises the question of what should be the level of detail required so that useful estimates of output parameters (e.g. local mean) can be obtained. In addition, measurement results have suggested that environmental clutter (e.g. furniture) can affect indoor propagation characteristics significantly [37, p. 15]. However, a majority of work to date has assumed that the presence of environmental clutter only contributes to the small-scale fading, and does not alter the dominant energy paths. These two issues for site-specific models are of the concern and have been further addressed in Chapter 8.

**2.3.3 Characterisation of Building Walls**

As accurate modelling of radio propagation is needed for the deployment of high performance indoor wireless systems, the characterisation of building walls have received attention. While some of the investigations have focused on determining the electromagnetic properties of building walls (e.g. the dielectric constant and conductivity) [34, 53–56], some have concentrated on the effects of complex walls (e.g. reinforced and composite walls) [9, 16, 57–60]. In this section, methods to obtain accurate material properties of common building walls are reviewed. The effects of complex walls which are investigated using electromagnetic methods are reported.
Wall Materials

The electromagnetic properties of building materials can be determined by either performing measurements in a laboratory [53, 55, 61], or by conducting in-situ measurements [34, 62]. A free space technique is usually employed to measure the transmission and reflection coefficients of typical building materials. Additionally, a multiple successive internal reflection model is used to test the sensitivity of measured permittivity and conductivity of the sample [53, 62]. To improve the accuracy of material property estimates, advanced data-processing techniques such as time-gating and deconvolution techniques are used to remove the effects of a non-ideal measurement environment and the measurement equipment [54]. More recently, Grosvenor et al. [55] attempted to further improve the accuracy by processing the measured data in three stages. Firstly, the measured data is inverse transformed from the frequency domain to the time domain. Secondly, the measured pulse is isolated by a time-gating technique. Lastly, the isolated pulse is transformed back to frequency domain to obtain the reflection and transmission coefficients. From the results, the material properties of the sample measured can be determined.

Although considerable effort is devoted to measure the electromagnetic properties of building materials, the results obtained are heavily dependent on the sample variability as well as the frequency. For example, it was found that the concrete loss due to ionic conductivity is dominant at frequencies below 1.0 GHz, whereas water dipolar relaxation becomes the significant loss mechanism at higher frequencies [62, p. 9]. It was also noted that the dielectric properties can be affected by the moisture content rather than the material itself if the water content is high. This might explain the significant discrepancy for some of the measured electromagnetic properties (at 5.0–5.8 GHz) which have been reported by different researchers listed in Table 2.1.

<table>
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**Table 2.1:** The measured electromagnetic properties of typical building materials from various studies.
Complex Walls

Complex walls such as cinder blocks wall and reinforced concrete wall illustrated in Fig. 2.5 have been commonly used in building construction. A cinder block wall is formed by many hollow concrete blocks with a periodic web variation. A reinforced concrete wall consists of a concrete slab with a reinforcing structure (usually is made of conducting bars e.g. steel) embedded inside. Reinforcing structures have various geometrical designs ranging from simple lattice type to more complex arrangements for higher strength purposes. Due to the periodicity and complex structures inside the walls, scattering process caused by complex walls may become more complicated compared to a single dielectric slab alone.

Characterisation of complex walls based on analytical and numerical methods is popular because the wall details can be accurately modelled. Furthermore, the effects of various wall parameters (e.g. wall thickness, spacing and diameter of reinforcing bars) can be investigated in a straightforward manner. For example, Honcharenko et al. [57] examined the transmission and reflection characteristics of cinder blocks wall using Floquet analysis. It was found that higher space harmonics resulting from the periodic structure can diffract strongly at the walls, and so a significant power enhancement in locations where a specular signal does not exist is observed. Chu et al. [63, 64] formulated a periodic surface integral to study reinforced concrete walls. The results show that a change of the spacing between reinforcing bars can result in rapid variations in the reflected and transmitted characteristics.

Dalke et al. [58] and Richalot et al. [59] examined reinforced concrete walls using the FDTD method and the Finite-Element Method (FEM), respectively. The results have shown that the reflection and transmission behaviours are significantly different from the case of a single concrete slab when the side length of the reinforcing structure is small compared to the wavelength. In addition, the transmitted field fluctuates significantly and the variation is greatly dependent on the geometry of reinforcing structure and the wall thickness. A Method of Moments/Green’s Function (MoM/GF) model has been used to investigate a reinforced concrete slab [65]. Although the complicated scattering process of the reinforcing structure has shown to cause field variations, the average received signal is similar to that observed with a concrete slab alone, except for the case when separation distances between transmitter and receiver are small. Similar observation has been reported by Holloway et al. [66] who analysed composite walls and their effects on short path propagation using the homogenisation technique. It was found that a difference of 5–10 dB in received signal strength can occur for short propagation paths compared to that for a single dielectric slab.
Figure 2.5: An illustration of cinder blocks wall and reinforced concrete wall, which are both commonly used in building construction.
It is clear that the characteristics of complex walls are greatly dependent on the internal structure. Despite the fact that it is very challenging (if possible) to determine the internal structure of the complex walls, a propagation model which considers a detailed wall structure may become overly complicated and therefore not suitable for use in system planning. Fortunately, it may be possible to model a complex wall as a single homogeneous dielectric slab. Although it is shown that the received signals for short propagation paths vary significantly for the case of a complex wall, the average signal strength is however similar to that observed for a single dielectric slab alone. This finding is useful as it implies that complex walls can be considered without significantly increasing the model complexity and computational burden.

2.4 Contribution of This Thesis

Engineering high performance indoor wireless systems requires good system deployment strategies. In order to deploy a system effectively, a good propagation model which can efficiently yet reliably predict the radio propagation is required. A number of existing propagation models which have been reviewed in Section 2.3 are summarised in Table 2.2. It is clear that models which are simple and computationally efficient cannot be transported to other environments without modification. On the contrary, models which consider detailed environmental features and therefore accurate are often computationally intensive. As a result, none of the existing propagation models are suitable for use in planning high performance wireless systems.

A useful engineering model should have the physical underpinning of the computational electromagnetic models, but also be computationally efficient. For this reason, a mechanistic modelling approach is proposed in this thesis. The philosophy of the mechanistic modelling approach is to estimate useful output parameters based on only the dominant mechanisms, thus it is expected to be computationally efficient. Herein, dominant mechanisms are referred to as the main contributors to the received signal strength at a receiving location. To investigate the feasibility of mechanistic modelling approach, this thesis has undertaken detailed propagation studies in a sequential canonical geometries including an open plan office and corridor, a single corner, a double corner, and a discrete obstacle. The objective of the studies is to identify the dominant mechanisms in a specific environmental layout. The outcome of the investigations can be very useful towards the development of mechanistic models, which are likely to play an important role in the engineering of future high performance indoor wireless systems.
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Table 2.2: A comparison of various propagation models for predicting propagation behaviour in indoor environments.
2.5 Summary

This chapter has presented the commonly observed propagation phenomena and the characteristics of received signal variations due to fast fading, slow fading, and range dependence. Various modelling techniques that are used to predict propagation behaviour in indoor environments have been reviewed. Moreover, the characterisation of complex walls (e.g. cinder blocks wall and reinforced concrete wall) for accurate modelling of indoor radio propagation are presented. It was shown that the electromagnetic properties of building walls are dependent on the sample condition and the frequency. Moreover, internal structure of complex walls (e.g. the periodic hollow web and reinforcing bars) can complicate the reflected and transmitted fields behaviour. Fortunately, it was found that complex walls may generally be modelled by homogeneous dielectric slabs as the mean received signal strength for both cases are similar, except for short propagation paths.

The propagation models that are used to investigate radio propagation in indoor environments can be broadly categorised as either empirical/statistical or site-specific. A comparison for a number of different propagation models reviewed is presented in Table 2.2. It has shown that although the empirical/statistical models are simple and computationally efficient, but they do not explain the physical phenomena observed in the experimental measurements, and therefore cannot be transported to other environments without modification. While site-specific models are based on computational electromagnetics and can therefore be accurate, a major disadvantage is that the requirement of large computational overhead which may be inappropriate for system planning.

A useful engineering model should have the physical underpinning of the propagation process while remaining computationally efficient. For this reason, a mechanistic modelling approach which considers only the main contributors to the received signal strength is proposed in this thesis. The philosophy of mechanistic modelling approach is presented in Chapter 3.
Chapter 3

Mechanistic Modelling of Indoor Environments

3.1 Introduction

In Chapter 2, a description of the radio propagation phenomena observed in practice and methods for characterising radio signal variations due to fast fading, slow fading, and distance-dependency are presented. Many existing indoor propagation modelling approaches were found to either lack transportability or be computationally intensive, therefore not suitable for use in engineering design. A useful engineering model should be able to capture the underpinning physics of the propagation process on a deterministic basis, while predicting useful output parameters (e.g. the local mean) in an efficient manner. This thesis proposes a mechanistic modelling approach and investigates its feasibility for such a role.

This chapter provides an overview of the propagation modelling techniques adopted and developed in this thesis. Section 3.2 describes the philosophy and modelling process of a mechanistic modelling approach. Section 3.3 presents the foundations and boundary condition for the Finite-Difference Time-Domain method (FDTD). One of the roles of the FDTD in this thesis is to assist in the understanding of the observed propagation phenomena in the environment investigated. In addition, the FDTD is used extensively for validating the applicability and evaluating the performance of the ray models. Two test cases considering a dielectric slab (A) and a single room environment (B) are investigated in Section 3.4. In particular, Test Case A is used to demonstrate the electromagnetic field interactions with finite thickness dielectric slabs. Test Case B is used to demonstrate the transportability of the propagation mechanisms from 2D to 3D. Finally, a summary of this chapter is presented in Section 3.5.
3.2 Mechanistic Modelling

Currently, ray-methods are frequently used for characterising electromagnetic propagation in indoor environments. A significant advantage of using ray-methods is that their canonical application is straightforward [26]. However, when considering complicated indoor environments, the propagation processes are not always strictly ray optical in nature. The question then arises as to how the simplicity of ray-methods might be preserved, whilst acceptable predictions can be made without incurring an unreasonable computational burden.

The mechanistic modelling investigated in this thesis was devised to address these needs. In typical indoor environments, the received signal at any given location is usually comprised of a number of components propagating over different paths [9]. Of these components, some will contribute significantly to the received power, and these will hereafter be referred to as mechanisms. As an aside, it is important to note that this received power is not the instantaneous received power at a point in space. Instantaneous power and its associated fading envelope are greatly dependent on the fine scale of the physical environment. To accurately determine the specific nature of this fading envelope would require a very detailed characterisation of all scattering obstacles present in the environment. Fortunately, this level of prediction is unnecessary as fading can approximately be described by a stochastic characterisation (e.g. Rayleigh or Ricean distributed fading), which in turn requires only a good estimation of the statistical moments (such as the local mean). The local mean usually refers to the average signal level over a few wavelengths of the local sector, so the rapid fluctuations due to multipath fading are removed. Practically this means that a propagation model only needs to provide a reliable estimate of the local mean for a meaningful estimate of system performance to be made (e.g. the outage probability). As estimating the local mean does not require the consideration of components which do not contribute significantly to the received power, these components would not be regarded as mechanisms and can therefore be safely omitted from further consideration. This now leads to the question as to how these mechanisms can be identified for particular scenarios.

An FDTD analysis of a problem can sometimes give useful insight into what the candidate mechanisms are. Sometimes however, a plurality of multipath components in some regions makes such an identification challenging. In these cases, exciting the FDTD lattice using a Gaussian modulated pulse can give a useful estimate of the channel impulse response, from which the candidate mechanisms can sometimes be inferred [20]. In any event, an FDTD analysis in conjunction with measurements and experience can be used to identify likely candidate mechanisms in a majority of cases. The approach adopted
herein is to initially hypothesise candidate mechanisms as geometrical optic (GO) rays. Estimates of the local mean are then obtained by their superposition and validated using the FDTD\textsuperscript{1}. Power contributions of the various candidate mechanisms are ranked and those with lesser\textsuperscript{2} contribution discarded. What remains are the mechanisms which dominate the received power, and their superposition will estimate the local mean to the required accuracy.

One of the key advantages of mechanistic modelling is that the mechanisms are likely to be the same for similar environments in different locations. As a result, one might expect mechanistic models to be transported to other environments with greater confidence than measurement-based (empirical) models (e.g. Seidel model [8]). In addition, observations to date have shown that the received power is generally dominated by small numbers of mechanisms in any given location, which can therefore be evaluated efficiently [28].

### 3.3 Finite-Difference Time-Domain Method (FDTD)

The finite-difference time-domain (FDTD) algorithm is a grid-based numerical modelling method used to solve engineering problems dealing with electromagnetic wave interactions with material structures. Current FDTD modelling application ranges from near DC (Earth-ionosphere waveguides at ultra low frequencies (ULF) [67,68]) through microwaves (radar technology [69,70], antennas [71,72], and biomedical treatments [73,74]) to visible light (photonic crystals [75,76] and nanoplasmonics [77,78]). The role of the FDTD in this research is to assist in the understanding of the physical process of electromagnetic propagation in indoor environments. In this section, the foundations of the FDTD and the selection criteria for its associated parameters are discussed. The adopted method for treating boundary condition and its effectiveness are also presented.

#### 3.3.1 The Yee Algorithm

In 1966, Yee proposed a algorithm for staggering the vector components of the electric ($E$) and magnetic ($H$) fields on a rectangular unit cell of Cartesian computational grids, which is known as the Yee space lattice. As shown in Fig. 3.1, these vector components are positioned in a cubic unit cell of the Yee space lattice so that every $E$ component in three-dimensional space is surrounded by four circulating $H$ components, and every $H$ component in three-dimensional space is surrounded by four circulating $E$ components.

\textsuperscript{1}It is possible that the candidate mechanisms which are present in the environment are non-ray optical in nature (e.g. energy propagating around/through dielectric wedges [12,13]). Fortunately, results in Chapters 6 and 7 have shown that the presence of such mechanisms are often physically localised and their impact is therefore minimal.

\textsuperscript{2}The term “lesser” is somewhat dependent on the model prediction accuracy and reliability. These parameters will be discussed further in Chapters 5–8.
Figure 3.1: Position of the electric and magnetic field vector components about a cubic unit cell of the Yee space lattice [15, p. 76].
component is surrounded by four circulating $E$ components. This spatial arrangement is very powerful as it represents the unification of the $E$ and $H$ components for characterising electromagnetic wave phenomena described by Maxwell’s equations.

Furthermore, the Yee algorithm also centres the $E$ and $H$ components in time in a leapfrog arrangement. As illustrated in Fig. 3.2, the $E$ and $H$ components are updated in a staggered fashion so that $E$ component updates are conducted midway during each time step between successive $H$ component updates, and vice versa. For computer simulation, this means the computation for all the $E$ components in space would have to be completed and stored in memory for a particular time instant using previously stored $H$ components. Then in the next time instant, all the $H$ components in space are computed and stored in memory using the $E$ components just computed. These processes alternate until the designated number of time steps have been completed.

Based on the Yee algorithm, the finite-difference expressions can be derived for the two-dimensional transverse magnetic propagation mode with respect to $z$ direction (TM$_z$) which consists of $H_x$, $H_y$, and $E_z$ components as indicated by [15, pp. 80–93]

$$E_z|^{n+1/2}_{i-1/2,j+1/2} = C_a E_z|^{n-1/2}_{i-1/2,j+1/2} \cdot E_z|^{n-1/2}_{i-1/2,j+1/2} + C_b E_z|^{n-1/2}_{i-1/2,j+1/2}$$

$$\cdot \left( H_y|^{n}_{i,j+1/2} - H_y|^{n}_{i-1,j+1/2} + H_x|^{n}_{i-1/2,j+1/2} - H_x|^{n}_{i-1/2,j+1} \right) \quad (3.1)$$

$$H_x|^{n+1}_{i-1/2,j+1} = D_a H_x|^{n}_{i-1/2,j+1} \cdot H_x|^{n}_{i-1/2,j+1} + D_b H_x|^{n}_{i-1/2,j+1}$$

$$\cdot \left( E_z|^{n+1/2}_{i-1/2,j+1/2} - E_z|^{n+1/2}_{i-1/2,j+3/2} \right) \quad (3.2)$$

$$H_y|^{n+1}_{i,j+1/2} = D_a H_y|^{n}_{i,j+1/2} \cdot H_y|^{n}_{i,j+1/2} + D_b H_y|^{n}_{i,j+1/2}$$

$$\cdot \left( E_z|^{n+1/2}_{i+1/2,j+1/2} - E_z|^{n+1/2}_{i+1/2,j+1/2} \right) \quad (3.3)$$

where $C_a$, $C_b$, $D_a$, and $D_b$ are the coefficient arrays which represent distinct material media in the FDTD space lattice. These coefficient arrays are given by [15, p. 85]

$$C_a|_{i,j} = \left( 1 - \frac{\sigma_{i,j} \Delta t}{2 \varepsilon_{i,j}} \right) / \left( 1 + \frac{\sigma_{i,j} \Delta t}{2 \varepsilon_{i,j}} \right) \quad (3.4)$$

$$C_b|_{i,j} = \left( \frac{\Delta t}{\varepsilon_{i,j} \Delta} \right) / \left( 1 + \frac{\sigma_{i,j} \Delta t}{2 \varepsilon_{i,j}} \right) \quad (3.5)$$
Figure 3.2: Space-time chart showing the use of central differences for the space derivatives and leapfrog for the time derivatives for modelling wave propagation in one-dimension. Initially, both electric ($E$) and magnetic ($H$) fields are zero everywhere in the grid [15, p. 78].
\[ D_a|i,j| = \left(1 - \frac{\sigma^*_{i,j} \Delta t}{2 \mu_{i,j}} \right) / \left(1 + \frac{\sigma^*_{i,j} \Delta t}{2 \mu_{i,j}} \right) \] (3.6)

\[ D_b|i,j| = \frac{\Delta t}{\mu_{i,j} \Delta} \left(1 + \frac{\sigma^*_{i,j} \Delta t}{2 \mu_{i,j}} \right) \] (3.7)

where \( \Delta t \) denotes the time step size, \( \Delta \) denotes the grid size, and \( \sigma, \varepsilon, \mu, \) and \( \sigma^* \) denote conductivity, permittivity, permeability, and magnetic loss of the material, respectively.

Similarly, the finite-difference expressions can be derived for the two-dimensional transverse electric propagation mode with respect to \( z \) direction, which consists of \( E_x, E_y, \) and \( H_z \) components as indicated by [15, pp. 80–93]

\[ E_x|i,j+1/2|^{n+1/2} = C_a, E_x|i,j+1/2| \cdot E_x|i,j+1/2|^n_{n-1/2} + C_b, E_x|i,j+1/2| \cdot (H_z|i,j+1|^{n} - H_z|i,j|^{n}) \] (3.8)

\[ E_y|i-1/2,j+1|^{n+1/2} = C_a, E_y|i-1/2,j+1| \cdot E_x|i-1/2,j+1|^{n-1/2} + C_b, E_y|i-1/2,j+1| \cdot (H_z|i-1,j+1|^{n} - H_z|i,j+1|^{n}) \] (3.9)

\[ H_z|i,j+1|^n+1 = D_a, H_z|i,j+1| \cdot H_z|i,j+1|^n + D_b, H_z|i,j+1| \cdot \left( E_x|i,j+1/2|^n+1/2 - E_x|i,j+3/2|^n+1/2 + E_y|i-1/2,j+1|^n+1/2 - E_y|i-1/2,j+1|^n+1/2 \right) \] (3.10)

where \( C_a, C_b, D_a, \) and \( D_b \) are the coefficient arrays which represent distinct material media in the FDTD space lattice, and are given by Eqs. (3.4)–(3.7).

### 3.3.2 Numerical Dispersion and Stability

Due to the fundamental limitation of grid-based algorithms, the phase velocity of propagating waves can differ from the speed of light (i.e. \( c = 3 \times 10^8 \) m/s in air). This effect is known as dispersion, and its severity is dependent on the wavelength and direction of propagating waves, as well as the lattice size. The effect of dispersion can usually be reduced by increasing the lattice sampling density. However, higher sampling density means a greater number of grids and therefore more field computations are necessary, which can lead to unrealistically high computational requirements. To reduce the effect of dispersion to an acceptable level without incurring excessive computational burden, the size of lattice (\( \Delta \)) should be a fraction of wavelength as indicated by [15, pp. 109–119]

\[ \Delta < \frac{\lambda_{\text{min}}}{10} \] (3.11)
where $\lambda_{\text{min}}$ is the shortest wavelength of the propagating wave in the modelling domain.

In addition, the time step ($\Delta t$) has a specific bound relative to the lattice size to ensure numerical stability. Based upon the Courant stability limit, the time step should satisfy the criteria as indicated by [15, pp. 133–141]

$$\Delta t < \frac{1}{c \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}}$$

(3.12)

where $c$ is the speed of light in air ($c = 3 \times 10^8$ m/s), and $\Delta x$, $\Delta y$, and $\Delta z$ are the grid discretisation size in the $x$, $y$, and $z$ directions, respectively.

### 3.3.3 Uniaxial Perfectly Matched Layer (UPML)

A significant challenge for the FDTD method is to solve the electromagnetic wave interaction problems in unbounded regions. To overcome this issue, a suitable boundary condition on the outer perimeter of the modelling domain must be introduced so as to effectively extend the FDTD lattice to infinity. Originally, an absorbing material medium created by Berenger, called the perfectly matched layer (PML) [79] was found to be highly effective. The concept of the PML is that plane waves of arbitrary incidence, polarisation, and frequency are matched at the boundary between the absorbing medium and modelling domain so it is reflectionless to all impinging waves. Once the impinging waves are transmitted into the absorbing medium, these transmitted waves will be attenuated according to the spatial loss grading functions. A PML in the form of a uniaxial anisotropic medium having both magnetic and electric permittivity tensors, called the uniaxial perfectly matched layer (UPML) [80], is implemented in this thesis. A UPML was chosen over an original PML is due to the UPML which is based on a Maxwellian rather than a mathematical formulation. As a result, the UPML realises the physical absorbing medium for the FDTD simulation.

Generally, a UPML is established as a 5- or 10-cell thick layer around the modelling domain of the FDTD lattice, and is backed up by a PEC. The parameters of the UPML are scaled according to a power law so that the transmitted waves are gradually attenuated. In particular, the conductivity ($\sigma$) governs the attenuation of the transmitted waves in the UPML, and the real stretch coordinate ($\kappa$) governs the speed of attenuation by scaling the relative permittivity so that the mesh in the UPML behaves like a non-uniform grid. These parameters are scaled by a polynomial grading and given by [15, pp. 305–308]

$$\sigma_x(x) = \left(\frac{x}{d}\right)^m \sigma_{x,\text{max}}$$

(3.13)
where \( d \) denotes the thickness of the UPML, and \( m \) governs the response of attenuation. Usually \( \sigma \) increases from zero at the surface of the UPML \( (x = 0) \) to \( \sigma_{\text{max}} \) at the PEC outer boundary \( (x = d) \). Similarly, \( \kappa \) increases from one at \( x = 0 \) to \( \kappa_{\text{max}} \) at \( x = d \). For a given reflection error estimate, the maximum conductivity \( (\sigma_{\text{max}}) \) at \( x = d \) may be shown to be

\[
\sigma_{\text{max}} = -\frac{(m + 1) \ln [R(0)]}{2\eta d}
\]

where \( \eta \) is the intrinsic impedance of free space \( (\eta = 377 \ \Omega) \), and \( R(0) \) is the desired reflection error. Typically, \( 3 \leq m \leq 4 \), \( R(0) \approx e^{-16} \) for a 10-cell thick UPML, or \( R(0) \approx e^{-8} \) for a 5-cell thick UPML, have been found to introduce a very minimal reflection from the boundary for many FDTD simulations [80].

**Effectiveness of the UPML**

A test environment of a \( 40 \times 40 \)-cell FDTD grid (Fig. 3.3) is used to demonstrate the effectiveness of the UPML. The source is a \( z \)-directed line source (1 GHz) and invariant along the axial direction, and radiates two-dimensional transverse magnetic (TM) waves. In this case, \( \lambda_{\text{min}} = 0.3 \) m and a lattice size of \( \Delta = 0.006 \) m \( (\lambda_{\text{min}}/50) \) and a time step size of \( \Delta t = 10 \) ps \( (\Delta/2c) \) were chosen to further minimise the dispersion. The \( E \) field is probed at point \( A \) as shown in Fig. 3.3 to observe the field strength over 1000 time steps (that is, well past the steady state response). A 10-cell UPML with a polynomial grading parameter \( m = 4 \) is deployed to absorb the outgoing impinging waves.

To quantify the magnitude of the reflected waves from the boundaries observed at point \( A \), the reference solution \( E_{\text{ref}}|_{i,j}^n \) at grid location \((i, j)\) and time step \( n \) is obtained using a larger cell grid \((1200 \times 1200\)-cell FDTD grid\). The reference grid is sufficiently large such that there is no reflection from the outer boundary during the time span of interest. The observation location \((i, j)\) is at the same position relative to the source as in the test environment (Fig. 3.3). The field difference between point \( A \) and the reference location can be quantified as the relative error and is indicated by [15, pp. 322–326]

\[
\text{Rel. error}|_{i,j}^n = \left| \frac{E_{i,j}^n - E_{\text{ref}}|_{i,j}^n}{E_{\text{ref, max}}|_{i,j}^n} \right|
\]

where \( E_{i,j}^n \) is the field value at grid location \((i, j)\) and time step \( n \) in the test grid, and \( E_{\text{ref, max}}|_{i,j}^n \) is the maximum amplitude of the reference field at grid location \((i, j)\), as ob-
Figure 3.3: Test environment with a $z$-directed line source centred in a 2D TM$_z$ FDTD grid. The modelling domain of $0.24 \, \text{m} \times 0.24 \, \text{m} \times 40 \Delta \times 40 \Delta$ is surrounded by the UPML of thickness $d = 10 \Delta$. The $E$ field is probed at point A.

served during the time span of interest.

Fig. 3.4 shows the FDTD simulation results of the reflected wave from the outer boundaries and quantified in terms of the relative error. Results indicate that the maximum relative error is in the order of $10^{-5}$ ($-100$ dB), proving the effectiveness of the UPML.

3.4 Validation of Ray Model

Ray-methods are generally simple and can be computationally efficient. However, their applicability to modern wireless propagation environments must be carefully justified as some of the propagation processes are not strictly ray optical in nature (e.g. the dielectric wedge diffractions [12, 13]). Indoor environments often consist of many dielectric structures, of which the properties (e.g. the thickness and permittivity of the construction materials) are known to have a significant effect on the propagation [63]. For example, the effective reflection coefficient is dependent on the polarisation and incident angle of the incident wave, as well as the material properties and physical thickness of the structure. It is therefore important to ensure that the ray model can represent the observed propagation effects with the dielectric structures appropriately.

In this section, two test cases (A and B) are investigated using a ray model and validated by a FDTD algorithm and experimental measurements. Test Case A considers a finite thickness dielectric slab. In particular, the reflected and transmitted fields are estimated using the ray model, and then compared with that predicted using the FDTD
and Green’s function [65]. Test Case B considers a single room environment, in which the channel impulse response was experimentally measured, and estimated using the 2D FDTD and ray model at several receiving locations. In this case, the impulse response estimated using the ray model and FDTD have both been extended to 2.5D by incorporating an additional isotropic spreading in the third dimension [20]. This extension allows the 2.5D impulse estimates to compare directly against the 3D measured data from the experimental measurements.

### 3.4.1 Test Case A: Dielectric Slab

To assess the ability of ray models in representing the signal reflected from and transmitted through a finite thickness dielectric slab, an environment containing a 2D dielectric slab is considered. As diffraction from the edge of the dielectric slab is not the concern of the investigation, the slab has been effectively extended to infinity by inserting it into the UPML as shown in Fig. 3.5. Transmitter T (indicated by ×) is located 1 m above the dielectric slab. Two 10 m long sampling trajectories A and B (indicated by - - -) were used to observe the reflected and transmitted fields, respectively. Trajectory A is located at the same level as transmitter T (i.e. 1 m above the dielectric slab), and Trajectory B is located at 1 m below the dielectric slab. The setup of this geometry allows the observation of the reflected and transmitted fields for different incident angles ranging from 0° to 78° (corresponding to $x = 0$ m to $x = 10$ m, respectively).

![Figure 3.4: Relative error at point A of the test environment over 1000 time steps for a 10-cell UPML.](image)
**Figure 3.5:** Plan view of the environment containing a single dielectric slab of thickness $t$. This slab has been effectively extended to infinity in the $x$ direction by inserting it into the UPML. Transmitter $T$ is indicated by $\times$, and the receiving trajectories (A and B) are indicated by $\cdots$.

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity $\epsilon$</th>
<th>Conductivity $\sigma$ (mS/m)</th>
<th>Thickness $t$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drywall</td>
<td>$2\varepsilon_0$</td>
<td>0.0</td>
<td>1.0 ($2\Delta$)</td>
</tr>
<tr>
<td>Glass</td>
<td>$6\varepsilon_0$</td>
<td>2.0</td>
<td>0.5 ($1\Delta$)</td>
</tr>
<tr>
<td>Concrete</td>
<td>$6\varepsilon_0$</td>
<td>50.0</td>
<td>30.0 ($60\Delta$)</td>
</tr>
</tbody>
</table>

**Table 3.1:** Material properties of the dielectric slabs investigated for Test Case A.

**FDTD Model**

A 2D TM$_2$ algorithm was implemented to investigate the radio propagation in the geometry shown in Fig. 3.5. Three common building construction materials, namely drywall, glass and concrete were investigated. The material properties of the dielectric slabs under consideration are summarised in Table 3.1. The FDTD simulation domain is $11 \times 3.3$ m, and is surrounded by a UPML [80]. As the highest dielectric constant in the modelling domain is 6 resulting the shortest wavelength $\lambda_{\text{min}} = 0.12$ m ($\lambda_0/\sqrt{6}$), a square lattice $\Delta = 0.005$ m ($\lambda_{\text{min}}/25$) and $\Delta t = 8.3$ ps ($= \Delta/2c$) were chosen to minimise dispersion effect and ensure numerical stability [15, pp. 109–140].

Although indoor wireless systems usually operate in the range $1.8 – 5.8$ GHz, a lower excitation frequency is used for investigations in this thesis to reduce the computational requirements. Nevertheless, the observed effects are expected to be similar to some ex-

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3Precise values of material properties are practically challenging (if possible) to determine. Therefore only common values of material properties have been adopted as in [20], which are adequate for the purpose of investigations in this thesis.
tent and thus useful for providing insights to radio propagation behaviour. A vertically-polarised line source with a centre frequency of 1.0 GHz is used. The reflected and transmitted fields were observed by obtaining the maximum field magnitudes along Trajectories A and B, respectively. These FDTD estimates of the reflected and transmitted fields are then compared with that estimated using the ray model.

**Ray Model**

A 2D ray model has also been formulated to estimate the field strengths along Trajectories A and B shown in Fig. 3.5. For estimating the field above the slab (Trajectory A), hypothesised candidate mechanisms arriving from two different propagating paths including the direct and the reflected paths are considered, namely

\[ E_A = E_{\text{dir}} + E_{\text{refl}} \]  \hspace{1cm} (3.17)

where \( E_{\text{dir}} \) and \( E_{\text{refl}} \) are the field of the direct component and the reflected components, respectively.

The field of the direct component is estimated by [26, pp. 746–752]

\[ E_{\text{dir}} = \left( \frac{A}{\sqrt{d_{\text{dir}}}} \right) e^{-jkd_{\text{dir}}} \]  \hspace{1cm} (3.18)

where \( A \) is a scaling factor used to calibrate the ray model against the FDTD predictions, \( d_{\text{dir}} \) is the distance between a transmitter and a receiver, and \( e^{-jkd_{\text{dir}}} \) accounts for the phase shift due to the length of the direct propagation path \( d_{\text{dir}} \).

The field of the reflected component is estimated by [26, pp. 753–760]

\[ E_{\text{refl}} = \sum_{i=1}^{n} \left( \frac{A}{\sqrt{d_{\text{refl}_i}}} \right) \left( \prod \Gamma_i \right) \tau_i^2 e^{-jkd_{\text{refl}_i}} \]  \hspace{1cm} (3.19)

where \( n \) is the number of the reflected components considered including the paths from the front surface of the slab, and the multiple internal reflections inside the dielectric slab. In this case, a total of twenty reflected components \( n = 20 \) are included to represent the observed reflected field. The parameter \( d_{\text{refl}_i} \) is the total length of the reflected path, \( \Gamma_i \) and \( \tau_i \) are the reflection and transmission coefficients of the slab, respectively, and \( e^{-jkd_{\text{refl}_i}} \) accounts for the phase shift due to the length of the reflected path \( d_{\text{refl}_i} \).
For estimating the field below the slab (Trajectory B), hypothesised candidate mechanisms arriving from the transmitted path are considered, namely [26, pp. 746–752]

\[
E_B = E_{\text{trans}} = \sum_{i=1}^{n} \left( \frac{A}{\sqrt{d_{\text{air}i} + d_{\text{slab}i}}} \right) \left( \prod \Gamma_i \right) \tau_i^2 e^{-jkd_{\text{air}i}} e^{-\gamma d_{\text{slab}i}} \tag{3.20}
\]

where \( n \) is the number of the transmitted components considered. Similarly, a total of twenty transmitted components \( (n = 20) \) are included to represent the observed transmitted field. The parameters \( d_{\text{air}i} \) and \( d_{\text{slab}i} \) are the lengths of the transmitted path in the air and slab, respectively, and \( \Gamma_i \) and \( \tau_i \) are the reflection and transmission coefficients of the slab, respectively. The parameter \( e^{-jkd_{\text{air}i}} \) accounts for the phase shift due to the length of the transmitted path in the air \( d_{\text{air}i} \), and \( e^{-\gamma d_{\text{slab}i}} \) corresponds to the phase shift and attenuation due to the length of the transmitted path inside the slab \( d_{\text{slab}i} \).

Fig. 3.6 illustrates the paths of the direct, reflected, and transmitted components considered. In particular, components arriving at the receiver Rx 1 are the direct and singly-reflected components with the path length of \( d_{\text{dir}} \) and \( d_{\text{refl}} \), respectively. The propagation path of the transmitted component arriving at the receiver Rx 2 has been considered in two segments. Specifically, the path lengths of the transmitted path in the air and inside the slab are correspond to \( d_{\text{air}} \) and \( d_{\text{slab}} \), respectively.

**Comparison of the FDTD and Ray Estimates**

The field strengths along Trajectories A and B are estimated using the ray model described in Eqs. (3.17) – (3.20) for all possible rays, and compared against the FDTD and Green’s function results. Figs. 3.7(a) – (c) show the field magnitude estimates along Trajectories
Figure 3.7: Comparison of the field estimates along Trajectories A and B in the presence of (a) drywall; (b) glass; and (c) concrete slabs.
A and B in the presence of drywall, glass, and concrete slabs, respectively. From the results along Trajectory A, fading is observed for all the cases considered. In any event, if there are at least two or more significant components arriving with similar phases, they will add constructively resulting in a peak. Similarly, if there are at least two significant components arriving out of phase, they will add destructively resulting in a null. Fading observed in this case is due to the relative phase of the direct and reflected components varying with the receiving location.

Results along Trajectory B do not exhibit fading because the relative phases of the transmitted components do not change appreciably in general. The received field strength is observed to decrease with distance because of the longer propagation path length and the incident angle being close to grazing, thus less energy can be transmitted via such a path. It is noteworthy that the received signal can be greatly attenuated due to the significant loss in the concrete.

Overall, good agreement between the FDTD and the ray estimates is obtained with a maximum error of about 1.5 dB for all the cases considered. This demonstrates the validity of ray models in representing radiowave interactions with dielectric objects. In particular, the fading predicted along Trajectory A is in close agreement with that obtained using the FDTD and Green’s function, indicating that the ray model can represent the propagation behaviour in the presence of finite thickness dielectric slabs appropriately.

3.4.2 Test Case B: The Single Room Environment

To examine the transportability of the propagation behaviour from 2D to 3D, the channel impulse response was measured in a standard rectangular room. A photograph, along with the layout of the room are shown in Figs. 3.8(a) and (b), respectively. The dimensions of the room are 6.2 m × 15.7 m. Walls 1 and 2 are both substantially occupied by glass windows with aluminum frames (shown as red), Walls 3 and 4 are both fixed partitions made of drywall (shown as blue), and Walls 5 and 6 are both partition boards with a height of 2.0 m (shown as black). Transmitter T (indicated by □) was located close to the middle of the room, and six receiving locations (indicated by ●) have been considered as shown in Fig. 3.8(b).
Measurement Setup

The channel impulse response was measured using an Agilent E8364A network analyser and two vertically-polarised omni-directional dipoles\(^4\) (shown in Fig. 3.9). The transmission coefficients \(S_{12}\) or \(S_{21}\) were measured in the frequency domain with a 1.2 GHz bandwidth centred at 1.0 GHz. For each receiving location, a sweep of 16001 points was taken and analysed using the inverse Fourier transform (IFT) to estimate the time domain response (i.e. time delay profile). During the experimental measurements, the transmitting and receiving antennas were fixed on a wooden mast at a height of 1.8 m. Most of the furniture in the environment is positioned lower than the transmitting and receiving antennas, thus minimising obstacles present in the direct propagation path.

FDTD Modelling

The single room environment shown in Fig. 3.8(a) was also investigated using a 2D TM\(_z\) FDTD algorithm. The FDTD simulation domain is 6.4 m \(\times\) 15.9 m, and is surrounded by a UPML. A square lattice of \(\Delta = 0.006\) m and a time step of \(\Delta t = 10\) ps are used. Walls 1 and 2 are modelled as glass, whereas Walls 3–6 are modelled as drywall. The

\(^4\)These two dipoles have the same frequency response, and they were made to operate at 1.0 GHz by the Radio Systems Laboratory at the University of Auckland.
properties of these materials are indicated as in Table 3.1. The impulse response was obtained by applying a modulated Gaussian pulse \( s(t) = e^{-(t-t_0)/t_w^2} \sin(2\pi f_0 t) \) with the carrier frequency of 1.0 GHz to the electric field component at the transmitter location in Fig. 3.8(b). The parameters of the pulse are: \( t_w = 1.2 \text{ ns} \), and \( t_0 = 5t_w \text{ s} \), producing a pulse width with a 440 MHz 3-dB bandwidth. The received signal at the receiving locations was then filtered using a zero-phase digital filter for recovering the estimated impulse response of the channel.

**Comparison of Impulse Response Estimates**

To better compare the 2D ray and FDTD results to the 3D measured data, the 2D results have been extended to 2.5D by including an additional isotropic spreading term (i.e. assuming there is no change to the geometry in the z direction). When considering the electric field, the additional spreading term is \( (1/\sqrt{d}) \), where \( d \) is estimated based on the elapsed time \( (d = ct) \). However, this spreading term will only alter the components arriving from the x and y directions (e.g. reflections from the surrounding walls). Components arriving from the z direction (e.g. reflections from the ground and ceiling) which are not considered in the 2D model, might still lead to the disagreement between the estimated and the measured results. Fortunately, components arriving from the vertical plane (i.e. the z direction) are generally found to be of secondary importance due to the longer propagation path length, and therefore greater loss compared to those arriving from the horizontal plane (i.e. the x and y directions). As a result, estimates of the channel impulse response extracted from the components arriving from the horizontal plane could provide useful insight into the propagation, from which the candidate mechanisms could be inferred.
#### 3.4 Validation of Ray Model

![Figure 3.10: Comparison of the estimated and the measured channel impulse responses for receiving location A.](image)

Fig. 3.10 compares the estimated and the measured impulse responses at receiving location A as shown in Fig. 3.8(b). The time delays of the significant components, and the associated surfaces where the reflections take place in the ray predictions are summarised in Table 3.2. Comparison of the FDTD, the ray model, and the measured results show good agreement in the time delay for the direct component (A) and the singly-reflected components from Walls 2, 1, and 4 (corresponding to B, C, and D). It is noteworthy that the doubly-reflected component from Walls 2 and 1 (E) in the FDTD and ray predictions does not appear to match any component in the measured data. This discrepancy might be caused by the poor temporal resolution of the IFT which cannot distinguish multiple components with relatively short time delays. Similar observations can be seen at about 47.8 ns (e.g. F) and 60.4 ns (e.g. G), where multiple reflected components are arriving at similar time, but have not been identified explicitly in the measured data.

The salient feature of the environment (e.g. the location and material properties of the walls) must be provided in order to identify main multipath components. In this single room environment, most of the time delays of the significant components have been matched with those obtained from the measurements, except for one significant component (H) which appears to be missing in both the FDTD and ray predictions. It is suspected that component is reflected from a metal shelf in the room. This may be confirmed experimentally by placing an absorber around the metal shelf to eliminate the multipath component. Similarly, the magnitude of scattered components arriving after 70 ns in the
FDTD do not match with those obtained from the measurement. These discrepancies may be attributed to the fact that the environmental clutter or nearby buildings have not been considered. Comparing the average magnitude of these scattered components (approximately −75 dB) with the direct component (−51 dB), the signal strengths of these scattered components are substantially weaker. This suggests that the impact of excluding scattered components to the overall signal predictions is not significant in this case. However, one may find scattered components can have an influential effect in a complex environment where no particular mechanism is always dominate. Further investigation with regard to the effect of environmental clutter is discussed in Chapter 8.

Overall, good agreement between the measured and the predicted impulse responses in this single room environment was obtained. This suggests that the dominant mechanisms observed in 2D are transportable to 3D provided that the 2D model is adequately representative of the 3D geometry. This means the 2D analysis of a problem is able to provide useful insight into the radiowave propagation process overall. The key advantage of analysing problems in 2D is that excessive computational requirements can be avoided, which is extremely beneficial in investigating electrically-large geometries.

### 3.5 Summary

This chapter has presented the philosophy of mechanistic modelling approach investigated in this thesis. As mechanistic modelling approach is based on ray-methods, which are known to be inaccurate under certain circumstances, a validation process to demonstrate the applicability of the ray models has been provided using the FDTD. Furthermore, the fundamental concept and treatment for the boundary condition of the FDTD method have also been discussed.

<table>
<thead>
<tr>
<th>Component</th>
<th>Delay (ns)</th>
<th>Path gain (dB)</th>
<th>Reflect. Order</th>
<th>Reflect. Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23.5</td>
<td>−51.0</td>
<td>Direct (0th)</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>26.4</td>
<td>−56.3</td>
<td>1st order</td>
<td>Wall 2</td>
</tr>
<tr>
<td>C</td>
<td>35.9</td>
<td>−60.6</td>
<td>1st order</td>
<td>Wall 1</td>
</tr>
<tr>
<td>D</td>
<td>36.5</td>
<td>−61.5</td>
<td>1st order</td>
<td>Wall 4</td>
</tr>
<tr>
<td>E</td>
<td>38.0</td>
<td>−68.6</td>
<td>2nd order</td>
<td>Walls 2 &amp; 1</td>
</tr>
<tr>
<td>F</td>
<td>47.8</td>
<td>−70.8</td>
<td>1st order</td>
<td>Wall 5</td>
</tr>
<tr>
<td>G</td>
<td>60.4</td>
<td>−70.6</td>
<td>2nd order</td>
<td>Walls 5 &amp; 1</td>
</tr>
</tbody>
</table>

Table 3.2: Delays, magnitudes, and reflecting surfaces of the significant components for receiving location A.
Two test cases involving a dielectric slab, and a single room environment have been used to validate the applicability of the ray models. In particular, the electromagnetic wave interactions with finite thickness dielectric slabs, and the transportability of the propagation mechanisms from 2D to 3D were investigated. In the case of the dielectric slab, good agreement between the ray, the FDTD, and the Green’s function field predictions was obtained, suggesting that the ray model is able to represent the propagation behaviour appropriately in the presence of a finite thickness dielectric slab. For the case of the single room environment, the 2.5D predicted and the measured impulse responses were generally in good agreement, suggesting that the dominant propagation mechanisms observed in 2D can be transportable to 3D provided that the 2D model is adequately representative of the 3D geometry. This is of particular importance especially for modelling electrically-large problems where the computational burden can be reduced significantly.

Chapter 4 presents an investigation overview where a detailed radio propagation study is undertaken in a real office environment. In particular, the process of dividing the environment systematically into several canonical geometries is described. These canonical geometries are subsequently investigated in Chapters 5 – 7 using the modelling techniques presented in this chapter.
Chapter 4

Modelling of Single Floor Propagation in an Office Building — Investigation Overview

4.1 Introduction

Chapter 3 has described the philosophy of a mechanistic modelling approach which is intended for use in general system planning. A useful modelling approach which is suitable for such a role should be simple and computationally efficient, while remaining to have a deterministic basis. As ray methods are generally simple and can be computationally efficient, they have been adopted and are used as the fundamental development of mechanistic models. However, ray methods can sometimes be inaccurate due to non-ray optical propagation behaviours (e.g. dielectric wedge diffraction). As a result, a computational electromagnetics approach namely finite-difference time-domain (FDTD) method has been implemented to assess the validity of ray methods. Two test cases including a single dielectric slab and a single room environment have been used to assess the ray model in representing the radio propagation behaviour. In general, the ray predictions are shown to be in good agreement with the FDTD and the measurement results. This suggests that ray models are able to predict useful power estimates of multipath components arriving at a receiving location.

To investigate the feasibility of the mechanistic modelling approach advocated in this thesis, a typical office environment has been chosen as a test site for the indoor propagation study. The aim of the study is to identify dominant mechanisms which have made a significant contribution to the received signal strength in different parts of the environment. This chapter provides an overview of the investigations presented in this thesis. Section 4.2 discusses propagation modelling in the test site with the FDTD method. Due
to the environment being highly complex where many multipath components can arrive in a receiving location, it is challenging to identify the dominant mechanisms exclusively on the basis of the FDTD analyses. To reduce the complexity of the problem, the environment has been divided into a sequence of generic canonical geometries. By investigating these canonical geometries separately using both the FDTD and the ray models, the main contributors to the received signal strength based on the power contribution of each arriving component can be deterministically identified. These canonical geometries can also be extended by including additional partitions and/or environmental clutter, thus making the environment similar to that encountered in practice. Section 4.3 presents the structure of the investigations in Chapters 5 – 7. Specifically, parameters which may affect radio propagation and therefore have been investigated in an open plan office and corridor, a single corner, a double corner and a discrete obstacle geometries are listed. Lastly, Section 4.4 summarises the chapter.

4.2 Propagation Modelling With The FDTD Method

The School of Engineering Tower at The University of Auckland was chosen as a test site for investigating radio propagation in office environments. This building (shown in Fig. 4.1(a)) is constructed from steel-reinforced concrete with a concrete services core in the centre, and is typical of many conventional office buildings. The Engineering Tower is a twelve-level office building with horizontal dimensions of 18.5 m × 18.5 m

Nine of the levels are above street level and three of the levels are below street level.

2Particle board is an engineered wood product manufactured from wood particles, such as wood chips, sawmill shavings, and saw dust.
were generally underestimated. This observation is most evident when transmitting and receiving antennas were located diagonally on the opposite sides of the concrete services core, thereby severely obstructing the direct propagation path. In this case, the propagation of energy to the shadowed region is contributed from transmission through or propagation around the concrete services core, or combination of both. Modelling radio propagation with the FDTD method may provide assistance for gaining insights into the observed propagation phenomena.

### 4.2.1 FDTD Model

Radio propagation in the Engineering Tower has been investigated using a 2D TMx FDTD algorithm. This geometry has not been analysed in 3D due to high computational requirements. Nevertheless, the underpinning propagation phenomena observed in 2D have been shown, to some extent, to be transportable to 3D [20]. The physical model that has been analysed with the FDTD is shown in Fig. 4.2. Apart from small-scale details of the two elevators and stairwell, most of the internal partitions (made from both concrete and drywall/particle boards) have been considered. The concrete services core is modelled as a 6.8 m × 6.8 m hollow concrete block, forming by four 0.3 m thick homogeneous concrete slabs. An additional concrete slab separating the elevators and stairwell, and two elevator doors made from PEC\(^3\) are also included. Internal partitions, creating a corridor and fourteen offices around the concrete services core, are modelled as 1.2 cm thick dielectric slabs. Glass windows on the outside of the building are modelled as 0.6 cm thick dielectric slabs, ignoring the metal frames. The material properties used in the FDTD simulation are listed in Table 4.1.

The FDTD simulation domain is 18.5 m × 18.5 m, and is surrounded by an uniaxial perfectly matched layer (UPML) [80]. A square lattice of \(\Delta = 0.006\) m \((\approx \lambda_{\text{min}}/20)^4\) is used to minimise numerical dispersion [15, pp. 109–119], resulting in a total of approximately 9.5 million mesh cells. Two transmitting antenna locations \((I_1\) and \(I_2\) in Fig. 4.2) were used to investigate the radio propagation behaviour in the building. The transmitting antenna \(I_1\) is placed in a corner office with the coordinates of \((0.93, 17.58)\) m, whereas the transmitting antenna \(I_2\) is placed in an office near the vertical central axis of the floor, with the coordinates of \((8.94, 17.58)\) m. A line source with centre frequency

---

\(^3\)Perfect electric conductor (PEC) by definition has conductivity \(\sigma = \infty\). In the FDTD simulation, it has been assigned to a very large value \(10^7\) S/m, so that it effectively behaves like having infinite conductivity.

\(^4\)As the highest permittivity of dielectric material in the modelling domain is 6 resulting the shortest wavelength \(\lambda_{\text{min}} = 0.12\) m \((\lambda_0/\sqrt{6})\), a square lattice of \(\Delta = 0.006\) m \((\lambda_{\text{min}}/20)\) is seen appropriate for minimising numerical dispersion. This lattice size is also adopted for FDTD investigations carried out in Chapters 5–7.
Figure 4.1: A photograph and Level 6 floor layout of the School of Engineering Tower at The University of Auckland.
4.2 Propagation Modelling With The FDTD Method

Figure 4.2: Stylisation of the Engineering Tower geometry as simulated by the FDTD method. The transmitting antenna locations $I_1$ and $I_2$ are indicated by □.

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity $\epsilon$</th>
<th>Conductivity $\sigma$ (mS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>$6\epsilon_0$</td>
<td>50.0</td>
</tr>
<tr>
<td>Drywall</td>
<td>$2\epsilon_0$</td>
<td>0</td>
</tr>
<tr>
<td>Glass</td>
<td>$6\epsilon_0$</td>
<td>2.0</td>
</tr>
<tr>
<td>PEC</td>
<td>$\epsilon_0$</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

Table 4.1: Material properties used in the FDTD simulations for the Engineering Tower [20].

of 1.0 GHz is used to excite a single $E_z$ field component, and 60,000 time steps\(^5\) were elapsed to ensure that a steady state condition has been reached. The sector-averaged path gain is obtained by taking the spatial average of the steady state response over a $2\lambda \times 2\lambda$ square sector, so as to largely remove the effect of multipath fading. The influence of using different size of spatial-averaging sectors is discussed further in Appendix B.

4.2.2 FDTD Simulation Results

Figs. 4.3(a) and (b) respectively show the mean path gain estimates across the entire floor from the transmitting antennas $I_1$ and $I_2$. The physical model that was simulated with the FDTD is superimposed. For $I_1$, the path gains are between $-40$ dB and $-18$ dB in the lit region (A). In this region, the presence of internal drywall partitions does not appear to attenuate the transmitting wave noticeably. This is supported by the

\(^5\)For a standard desktop with 2.2 GHz CPU and 3.0 GB RAM, it takes 4–5 hours to complete a simulation of 60,000 time steps.
fact that no significant drop in the signal strength was observed when the wave passes through drywall partitions. By contrast, the presence of concrete walls can attenuate the transmitting wave significantly. For example, the path gain was observed to decrease from $-32$ dB to $-48$ dB when the wave passes through one concrete slab. This result suggests that the concrete services core acts as a significant shadowing obstacle, as evidenced by the path gain decreases to $-60$ dB in the deep shadowed region (B).

It is notable that the path gain inside the lower half of the concrete services core (C, $-58$ dB) is smaller than that in the immediately adjacent area in the corridor (D, $-54$ dB). This suggests that the majority of the energy in the shadowed corridor region does not propagate by direct transmission through the concrete services core. Instead, simple diffraction around the concrete services core, or reflections from exterior glass windows may be the dominant energy paths. This is discussed further in Chapter 6, in which the relative importance of these propagation components are assessed. In any event, when diffraction loss around the concrete corner becomes significant or single reflections from exterior glass windows no longer exist (e.g. in region B), the direct transmission through the concrete services core may become dominant. Unfortunately, the path gain contours shown in Fig. 4.3(a) are not able to reveal the dominant components in this scenario due to the highly complicated propagation process.

From the results for the transmitting antenna $I_2$ shown in Fig. 4.3(b), similar observations can be made in the lit region (E), where the signal strengths are generally strong with the path gains varying between $-33$ dB to $-18$ dB. Moreover, the signals are shown to experience significant attenuation from transmitting through the concrete, resulting in the path gains varying between $-58$ dB and $-53$ dB inside the lower half of the concrete services core (F). It is noticeable that the received signal strength in the deep shadowed region (G) is stronger than inside the lower half of the concrete services core (F), suggesting that a direct transmission is not the dominant energy path.

Comparing the results from both the transmitting antennas $I_1$ and $I_2$, the received signal strength in the shadowed region from $I_2$ (G, $-50$ dB to $-40$ dB) is stronger than that from $I_1$ (B, $-60$ dB to $-45$ dB). This difference may be due to $I_1$ being located at the corner, thus reflections from exterior glass windows could be limited by the reflection shadow boundaries. Alternatively, $I_2$ is located near the vertical central axis of the floor, so that reflections from exterior glass windows are able to propagate to the deep shadowed region without transmitting through the concrete services core. These results suggest that the radio propagation in this environment is highly complicated, and the transmitting antenna locations could significantly influence the overall received signal strengths. As
Figure 4.3: Graphs showing the FDTD estimated path gains across the entire floor from transmitting antennas $I_1$ and $I_2$ as indicated by □.
the radio propagation is greatly dependent on the physical layout, it was decided to divide the environment systematically into a sequence of generic canonical geometries which are then separately analysed. This will allow the isolation of propagation mechanisms present in a specific local feature of the environment, hence the dominant mechanisms can be conclusively identified.

### 4.2.3 Canonical Geometries

Figs. 4.4(a) – (d) show the canonical geometries of an open plan office and corridor, a single corner, a double corner, and a discrete obstacle, respectively. In Fig. 4.4(a), the open plan office and corridor are located adjacent to each other and are separated by a solid dielectric slab made from drywall. For the single corner geometry shown in Fig. 4.4(b), a concrete corner which is surrounded by exterior glass windows is considered. This single corner geometry is then extended to the double corner geometry shown in Fig. 4.4(c) by adding additional concrete and glass slabs. Finally, Fig. 4.4(d) shows a combination of two double corner geometries (mirror-images of each other by the horizontal axis), forming a complete typical office layout with a centrally-located discrete obstacle.

As the investigations primarily focus on the radio propagation in large-scale geometries (e.g. building walls), the propagation environment is assumed to be empty (i.e. no furniture is present). Additionally, these canonical geometries are generic in nature, thus it is hypothesised that their combinations could be used to represent many typical indoor environments. This means, the observed propagation phenomena may be transportable to different environments with similar layouts.
Figure 4.4: Graphs showing the generic canonical geometries featuring (a) an open plan office and corridor, (b) a single corner, (c) a double corner, and (d) a discrete obstacle.
4.3 Structure of Investigation

The aim of this thesis is to investigate the feasibility of a mechanistic modelling approach for indoor radio propagation. In particular, the primary objective is to conclusively identify major contributors to the received signal strength in any given location based on the power contribution of arriving components. This section describes the structure of the investigations, and the content in each chapter is summarised in Fig. 4.5.

In this thesis, the investigations have been divided into two parts (A and B). Part A of the investigation (Chapters 5 – 7) provides a comprehensive sequential propagation study of the canonical geometries as shown in Fig. 4.4. It is important to note that both the FDTD and ray methods have been used to identify the dominant mechanisms. Ray methods are particularly attractive for this purpose because the power contribution (in terms of percentage) for each component arriving at any given receiving locations can be computed in a straightforward manner. As ray methods are known to be inaccurate in some situations due to non-ray optical propagation behaviour, Test Environments A – D (shown in Fig. 4.6) are therefore used to validate the ray models for different canonical geometries by comparing with the FDTD results. Because the dominant mechanisms are greatly influenced by the environmental features (e.g. material properties of the walls and floor layouts) and the operating frequency, a systematic investigation strategy has been adopted to conclusively identify how the energy propagates in the environments considered. A detailed investigation procedure for identifying dominant mechanisms is illustrated in Fig. 4.7.

Armed with the knowledge of radio propagation behaviour in the canonical geometries (i.e. large-scale geometries), Part B of the investigation (Chapter 8) proposes several mechanistic models with different complexity for a real office environment described in Chapter 4. The importance of small-scale details, such as the cumulative effects of internal partitions and environmental clutter, are examined. The mechanistic models performances are evaluated by comparing the path gain predictions with the experimental measurements [83]. The trade-off between the model accuracy and complexity is discussed. Finally, a mechanistic model which has shown to best balance the model accuracy and complexity is identified. A comparison against other existing indoor propagation models is also presented to demonstrate the advantages of the mechanistic modelling approach.
A. Radio Propagation Analysis
Identify dominant mechanisms in canonical geometries

Open Plan Office and Corridor
(Chapter 5)
1. Prediction accuracy requirement
2. Material properties of the wall
3. Transmitting antenna location
4. Operating frequency

Single Corner
(Chapter 6)
1. Material properties of the obstacle
2. Presence of glass windows
3. Operating frequency
4. Transmitter-to-corner distance

Double Corner and Discrete Obstacle
(Chapter 7)
1. Presence of inner concrete wall
2. Presence of glass windows
3. Operating frequency
4. Extension to discrete obstacle

B. Application to a Practical Environment
Mechanistic Models and Performance Evaluation
(Chapter 8)
1. Practical issues: internal details and environmental clutter
2. Model accuracy versus complexity
3. Comparison with existing propagation models

Figure 4.5: Structure of the investigation.
Figure 4.6: Graph showing the plan view of Test Environments A – D which are used for validating the ray models formulated in Chapters 5 – 7.
4.3 Structure of Investigation

Figure 4.7: Investigation steps for identifying dominant mechanisms.
4.4 Summary

This chapter has described the physical environment of the Engineering Tower which is chosen as a test site for investigating indoor radio propagation. The Engineering Tower features a concrete services core in the centre of the building and is surrounded by a corridor and offices, which is typical of conventional office environments. The path gains across the entire floor have been estimated using the FDTD method. For simplicity, only the large-scale geometry has been considered in the FDTD simulation. This is thought to be appropriate as the effect of large-scale geometry is largely deterministic, whereas small-scale details (e.g. environmental clutter) are generally random in size and location, therefore have not been modelled. From the FDTD results, the composite field pattern has shown to be complicated, and as a result dominant mechanisms are challenging to be conclusively identified. It was decided to divide the environment into generic canonical geometries based on the local features of the floor layout, which can then be separately analysed. These canonical geometries include an open plan office and corridor, a single corner, a double corner, and a discrete obstacle. The structure of the investigations in this thesis has been presented.
Chapter 5

Propagation in an Open Plan Office and Corridor

5.1 Introduction

Chapter 4 has provided an overview of investigations in a test office building containing a reinforced concrete services core housing elevators, a stairwell, and associated services. A simplified geometry of this test building including only fixed partitions has been modelled with the FDTD to assist in the understanding of the radio propagation process in this environment. The FDTD results have shown that the concrete services core acts as a significant obstacle which complicates the propagation process in the shadowed region. Moreover, the radio propagation is heavily dependent on the local layout of the environment. Due to the complicated composite fields observed in the FDTD results, the dominant energy paths cannot be conclusively identified. For this reason, the environment has been divided systematically into a sequence of generic canonical geometries by gradually increasing the complexity, and modelling in 2D to avoid an unreasonable computational burden. These canonical geometries include (i) an open plan office and corridor, (ii) a single corner, (iii) a double corner, and (iv) a discrete obstacle.

Among all the canonical geometries considered, this chapter investigates the simplest form — the open plan office and corridor geometry. This chapter begins in Section 5.2 by validating the ray model in representing the observed radio propagation effects in a test environment (Test Environment A). In particular, estimates of the local mean are computed based on the superposition of the candidate mechanisms, which are hypothesised as GO rays, and then compared with the FDTD estimates. Section 5.3 assesses the relative importance of the candidate mechanisms with respect to several parameters using the ray model formulated in Section 5.2. These parameters include the prediction accur-
Figure 5.1: Plan view of an open plan office and corridor geometry.

cacy requirements, the material properties, the transmitter locations, and the frequency selection. Lastly, Section 5.4 summarises this chapter.

5.2 Modelling the Open Plan Office and Corridor

The geometry investigated contains three parallel smooth walls\(^1\) (indicated by 1–3), made of three common building materials—drywall (shown in blue\(^2\)), glass (shown in red), and concrete (shown in gray)—forming the open plan office \((y > 1.5 \text{ m})\) and corridor \((y < 1.5 \text{ m})\) as shown in Fig. 5.1. In particular, Walls 1–3 are positioned at \(y = 5.85 \text{ m}\), \(y = 1.5 \text{ m}\), and \(y = 0 \text{ m}\), respectively. Two scenarios (I and II) were investigated with two different transmitter locations (transmitters T1 and T2). During the investigation, receiving locations are distributed on a regular rectangular lattice inside the observation area (bounded by the dashed lines) shown in Fig. 5.1. Scenario I (transmitter T1) was used to examine the propagation behaviour when the transmitter is positioned in the open plan office with the coordinates of \((0, 3.675) \text{ m}\). Scenario II (transmitter T2) was used to examine the propagation behaviour when the transmitter is positioned in the corridor with the coordinates of \((0, 0.75) \text{ m}\).

5.2.1 FDTD Model

The FDTD modelling domain is \(10 \text{ m} \times 5.85 \text{ m}\) in size, and is surrounded by a UPML \([80]\) (Fig. 5.2). A square lattice of \(\Delta = 0.006 \text{ m} \approx \lambda_{\text{min}}/20\) and a time step of \(\Delta t = 10 \text{ ps}\)

\(^1\)Walls are numbered so that the physical paths of the components which arrive at a receiving location can be explicitly stated. Further explanation of the numerical notation is given in Section 5.3.

\(^2\)Different wall materials are shown in distinct colours so that the geometries investigated in Section 5.3 can be easily recognised.
are used to minimise the dispersion effect and ensure numerical stability [15, pp. 109–140]. In the FDTD simulations, the thickness of the wall is strictly modelled by an exact number of FDTD grids. In this case, a minimum thickness of the wall can be only one grid (i.e. physically 6 mm). The material and physical properties of the walls considered are summarised in Table 5.1.

Because this investigation focuses on the propagation in the open plan office and corridor, these walls have been effectively extended to infinity (that is, by inserting the walls into the UPML), thereby assuming propagation effects due to variations in the environmental features outside the modelling domain are not significant for this investigation. A vertically-polarised line source with a centre frequency of 1.0 GHz was used. The local mean is obtained by taking the spatial average of the steady state response over a $2\lambda \times 2\lambda$ square region so as to largely remove the effect of multipath fading (see Appendix B).

### 5.2.2 Ray Model

A 2D ray model has also been formulated to estimate the local mean in the observation area (shown in Fig. 5.1). Hypothesised candidate mechanisms which arrive from two different propagation paths including the direct and the wall reflected paths are considered. An estimate of the local mean can be obtained by assuming the contributions from these
components are uncorrelated and can thus be added on a power basis (in Watts) [20], namely

\[ P_r = P_{dir} + P_{refl} \]  \hspace{1cm} (5.1)

where \( P_r \) is the total received power, \( P_{dir} \) and \( P_{refl} \) are the power of the direct component and the reflected components, respectively.

The power of the direct component is estimated by [26, pp. 746–752]

\[ P_{dir} = \left( \frac{A}{d_{dir}} \right) \kappa \]  \hspace{1cm} (5.2)

where \( A \) is a scaling factor used to calibrate the ray model against the FDTD predictions, \( d_{dir} \) is the distance between the transmitter and receiver, and \( \kappa \) is the attenuation through any obstacle encountered. Notice that \( P \propto 1/d \) rather than \( P \propto 1/d^2 \) is formulated for 2D scenarios.

The power of the reflected components from the walls is estimated by [26, pp. 753–760]

\[ P_{refl} = \sum_{i=1}^{n} \left( \frac{A}{d_{refl_i}} \right) |\Gamma_i|^2 \kappa \]  \hspace{1cm} (5.3)

where \( n \) is the total number of possible singly-reflected components, \( d_{refl_i} \) is the total length of the reflected path, \( \Gamma_i \) is the effective reflection coefficient\(^3\) from a reflecting surface, and \( \kappa \) is the attenuation through any obstacle encountered. Second-order and higher wall reflections have also been considered, but their contributions to the local mean were found to be insignificant and can therefore be neglected.

Fig. 5.3 illustrates the propagation paths of the candidate mechanisms described in Eqs. (5.1)–(5.3) for Scenario I. In this example, both transmitter T1 and receiving location Rx are located in the open plan office. The candidate mechanisms from four propagation paths including the direct and three singly-reflected paths are considered. In particular, the direct component is indicated as \( T \), and the singly-reflected components from Walls 1, 2, and 3 are indicated as \( R_1 \), \( R_2 \), and \( R_3 \), respectively. Among all the reflected components, only the singly-reflected component from Wall 3 (\( R_3 \)) needs to take the extra attenuation into consideration (resulting from the transmission through Wall 2).

\(^3\)The effective reflection coefficient is the coefficient which includes the combined effect of reflection from the front face and multiple internal reflections inside a dielectric wall. A detailed computation of the effective reflection coefficient is included in Appendix A.
5.2 Modelling the Open Plan Office and Corridor

5.2.3 Comparison of the FDTD and the Ray Model Predictions

To ensure all the candidate mechanisms which are present in the environment have been considered appropriately, the local means in the observation area are predicted using the ray model described in Eqs. (5.1)–(5.3) and compared against the FDTD estimates. In this section, comparison of estimates from the ray model and the FDTD in Test Environment A (Fig. 5.3) which consists of three smooth walls and made of glass (Wall 1), drywall (Wall 2), and concrete (Wall 3) for Scenario I is presented. Additional comparison results for other environments investigated in this chapter are included in Appendix C.

Test Environment A

Figs. 5.4(a) and (b) show respectively the ray and the FDTD estimates of the local mean in Test Environment A. For both cases, circular-shaped path gain contours radiating from the transmitter can be observed, suggesting that the direct component dominates other components. When receiving locations are sufficiently far from the transmitter, the lack of circular-shaped path gain contours suggest that a combination of the direct and reflected components is present. The reflected path becomes increasingly important at more distant receiving locations since the incident angle becomes more grazing, and more energy can be reflected via such a path. As a result, reflections from surrounding walls are not negligible.

The error between the ray and the FDTD estimates of the local mean is shown in Fig. 5.4(c). Areas coloured red and blue correspond to the ray model overestimates and
Figure 5.4: Graphs showing the predicted path gains in the observation area using (a) the ray model, (b) the FDTD, and (c) the prediction error (i.e. $P_{ray} - P_{FDTD}$) in Test Environment A for Scenario I. In (c), the colours red and blue indicate overestimation and underestimation of the path gain, respectively.
underestimates the path gain, respectively. Overall, very good agreement for the majority of the receiving locations is obtained, except for a few small regions with an error up to ±3 dB. A higher error in these small regions is likely due to the rapid field variations occur in that local region, and the spatial-averaging process performed on the FDTD results does not remove the multipath fading effect adequately. As a result, contributions from these candidate mechanisms computed based on Eqs. (5.1)–(5.3) becomes less reliable. Fig. 5.5 shows the probability density function (pdf) of the ray prediction error across the entire observation area. Negative and positive errors indicate underestimation and overestimation of the path gain, respectively. The mean error $\mu$ and the standard deviation $\sigma$ of 0.1 dB and 0.5 dB, respectively, suggests that acceptable prediction accuracy\textsuperscript{4} can be achieved for the majority of the receiving locations using the ray model.

### 5.3 Dominant Mechanisms in the Open Plan Office and Corridor

The received power at any given location is generally comprised of a number of components propagating over different paths [9, 26]. The number of mechanisms which need to be considered is dependent on accuracy requirements. For higher accuracy, a greater number of mechanisms need to be included, and thus increased model complexity is necessary. In order to reveal the relative importance of all the components under the situation when a particular mechanism is likely to always dominate, a stringent accuracy requirement

\textsuperscript{4}The acceptable prediction accuracy is dependent on the applications and the environment where a system is intended to operate. This is further discussed in Section 5.3.1.
of 1.5 dB\(^5\) (with respect to the ray model described in Eqs. (5.1)–(5.3)) is used for the investigation, except where specified otherwise.

To eliminate insignificant candidate mechanisms, the power contribution of these candidate mechanisms is assessed in the observation area using the ray model. It is found that the environment can be sub-divided into different regions based on the mechanisms which dominate the received power. In this section, the notation specified in each region represents the dominant mechanisms and the ordering indicates the significance of the mechanisms. For example, the notation \(T|R_3\) means two dominant mechanisms are present in the region, of which the capital letter indicates the propagation process, and the associated subscript indicates the physical propagation path. Therefore, the notation \(T|R_3\) denotes the power of the direct component \((T)\) is larger than the singly-reflected component from Wall 3 \((R_3)\).

In this section, different parameters which can potentially influence the dominant mechanisms in the open plan office and corridor are explored. Sections 5.3.1–5.3.3 investigate the effect of the prediction accuracy requirement, the material properties of the wall, and the choice of transmitter location, respectively, at the frequency of 1.0 GHz. Section 5.3.4 investigates a change of the dominant mechanisms due to different frequencies including 2.4 GHz and 5.8 GHz.

### 5.3.1 Effect of Prediction Accuracy Requirement

In practice, engineers would generally over-design indoor wireless systems with a 4–6 dB safety margin to combat the practical effects of signal variations [84, pp. 283–293]. Therefore, an accuracy requirement of 3 dB (that is half of the total received power) was initially chosen for meaningful system performance estimations. In order to investigate the effect of prediction accuracy requirement in the environment where a particular component is likely to always dominate, more stringent accuracy requirements including 2 dB and 1.5 dB are also examined. The environment contains two parallel walls fabricated of glass (Wall 1) and concrete (Wall 3) with Transmitter T1 (indicated by \(\times\)) is investigated (Fig. 5.6). The operating frequency of 1.0 GHz was used. The characteristics of the dominant mechanisms and the associated modelling implications with regard to the prediction accuracy are discussed.

\(^5\)The selection of accuracy requirements is discussed in Section 5.3.1.
Component Attributes

Figs. 5.6(a) – (c) show the distinct regions in which the received power is contributed by different dominant mechanisms with the accuracy requirement of 3 dB, 2 dB, and 1.5 dB, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole number) of each region to the total area considered. From the contour plots, three distinct regions have been identified and a maximum of two mechanisms are present in all the regions. The notations $T$, $T|R_1$, and $T|R_3$ respectively denote the mechanisms in the corresponding region are the direct component, the direct and singly-reflected component from Wall 1, and the direct and singly-reflected component from Wall 3. In the case of 3 dB prediction accuracy, the results have shown that only one region has been identified, in which the received power is dominated by the direct component. As the prediction accuracy increases, reflections from the nearby walls are observed to become more important. This is evidenced by two additional regions which are dominated by the direct as well as the singly-reflected components from Walls 1 or 3 have now appeared. In particular, the percentage of the total area which also needs to consider wall reflections is increased from 0% to 39% when the prediction accuracy is increased from 3 dB to 1.5 dB.

Implications

There is an inevitable trade-off between model accuracy and complexity. A more accurate model requires more mechanisms to be considered. As a result, more environmental information and computational effort are necessary. In the environment considered, if a prediction accuracy of 3 dB is regarded as acceptable, a model which incorporates the direct component is adequate. The advantage of this one-component model is simple and efficient to implement as only the transmitting and receiving locations are needed for the local mean predictions. However, if higher prediction accuracy is required, a maximum of two mechanisms (i.e. a direct and a singly-reflected components) will need to be included. The drawback of this two-component model is that adequate information about the environment must be provided (i.e. the location and material properties of the walls).

5.3.2 Effect of Material Properties

Propagation of electromagnetic waves is governed, among other things, by the material properties of structures in the propagation environment. In this section, the effect of walls made of common building materials including concrete, glass, and drywall are investigated.

6 The total area is represented by a number of receiving locations in the observation area indicated in Fig. 5.1. During the investigation, receiving locations are distributed in a regular rectangular lattice with a gap of 0.1 m, resulting a total number of 5800 receiving locations.
Figure 5.6: Graphs showing the distinct regions in which the received power is contributed by different dominant mechanisms, and their corresponding percentage contributions to the total area when the accuracy requirement is (a) 3 dB, (b) 2 dB, and (c) 1.5 dB, for Scenario 1 (with transmitter T1, indicated by ×).
The environment considered consists of three parallel walls and is shown in Fig. 5.7. Among the three walls, Walls 1 (glass) and 2 (drywall) are kept the same for all cases, and Wall 3 is changed to concrete, glass, and drywall accordingly. Transmitter T1 and the operating frequency of 1.0 GHz were used in this investigation. The characteristics of the dominant mechanisms and the associated practical implications with regard to the material properties of walls are discussed.

Component Attributes

Figs. 5.7(a) – (c) show the distinct regions in which the received power is dominated by different mechanisms when Wall 3 is made of concrete, glass, and drywall, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole number) of each region to the total area considered. Comparing the cases where Wall 2 (drywall) is absent (Fig. 5.6(c)) and present (Fig. 5.7(a)), the same dominant mechanisms and similar region contours can be observed. Both results indicate that the direct component is the most dominant mechanism, and reflections from the nearby walls only become significant at distant receiving locations (i.e. when the separation distance between transmitting and receiving locations is at least 4.5 m in this case). It is also noticeable that the contours of regions $T|R_1$ and $T|R_3$ are slightly shifted. This is due to the singly-reflected component from Wall 3 ($R_3$) which now has to transmit through Wall 2 twice to reach the receiving location in the open plan office as illustrated in Fig. 5.8. However, a shift of the regions is minimal, suggesting that the transmission loss through Wall 2 is not significant enough to change the dominant mechanisms.

When the material of Wall 3 is changed from concrete to glass, Fig. 5.7(b) shows the region in which the direct component is dominant has increased from 58% to 67%. In addition, the singly-reflected component from Wall 3 is only found to be significant in the corridor (i.e. $y < 1.5$ m). These observations suggest that reflections from the glass are not as strong as from the concrete at 1.0 GHz. When the material of Wall 3 is changed to drywall, Fig. 5.7(c) shows the received power at the majority of the receiving locations is dominated by the direct component (84%), and the singly-reflected from Wall 3 is no longer exists, suggesting that reflection from the drywall is not considerable at 1.0 GHz.

Implications

In practice, propagation modelling in an environment featuring walls mostly made of drywall can be straightforward as the direct component is likely to be dominant in a majority of the receiving locations. This means that provided the attenuation through an obstacle encountered is appropriately estimated, an acceptable prediction accuracy can
Figure 5.7: Graphs showing the regions in which the received power is dominated by different mechanisms, and their corresponding percentage contributions to the total area when Wall 3 is made of (a) concrete, (b) glass, and (c) drywall, for Scenario 1 (with transmitter T1, indicated by ×).
Figure 5.8: Graph illustrating the propagation path of the singly-reflected component from Wall 3 when both transmitter T1 and the receiving location Rx are located in the open plan office. In this case, double transmission through Wall 2 (drywall) is necessary to reach the receiving location Rx.

be achieved in a computationally efficient manner. In contrast, an environment featuring walls mostly made of glass or concrete is somewhat more complicated. This is because of the greater number of mechanisms which can dominate the received power in a receiving location. In this investigation, reflections from both the glass and concrete are shown to be important when receiving locations are sufficiently far from the transmitter. In addition, reflection from the concrete is more significant than that from the glass. Both the glass and concrete are modelled to have the same dielectric constant (i.e. $\epsilon = 6\epsilon_0$), but with different physical thickness. This suggests that other than the material properties, appropriate estimate of the wall thickness is also necessary for identifying the dominant mechanisms, and hence predicting useful local means.

5.3.3 Effect of Transmitter Location

For indoor wireless systems in modern office buildings, it is often found that base stations are deployed in corridor areas. In the literature, propagation studies in corridors have been performed using experimental measurements [30], ray models [44], and a wave guide model [85]. However, the underlying net effects and the influence of corridor walls to the dominant mechanisms in adjacent rooms have not been fully explored. In this investigation, a change of the dominant mechanisms when the transmitter is located in the corridor, rather than the open plan office is examined. Similarly, the environment considered in this investigation is identical to one of the environments investigated in Section 5.3.2, but with the transmitter located in the middle of the corridor (see Fig. 5.9). The operating frequency of 1.0 GHz was used. The characteristics of the dominant mechanisms, and the associated practical implications with regard to the transmitter location are discussed.
Figure 5.9: Graph showing the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution of each region to the total area when the transmitter is located in the corridor (with transmitter T2, indicated by ×).

Component Attributes

Fig. 5.9 shows the distinct regions in which the received power is dominated by different mechanisms, and the corresponding percentage contribution (rounded to a whole number) of each region to the total area when the transmitter is located in the corridor. From the region contour plot, there are two regions in which the received power is dominated by the same mechanisms, but these mechanisms are in different order of significance (i.e. regions T|R₃ and R₃|T). For brevity, the percentage contributions of these two regions to the total area are categorised as one region, and indicated as T|R₃ in the pie chart. Compared to the case when the transmitter is located in the open plan office shown in Fig. 5.7(a), the singly-reflected component from Wall 1 (glass) no longer exists and the received power at more than half of the receiving locations (57%) is dominated by both the direct and singly-reflected component from Wall 3 (concrete). This change is because the angle of the incident wave which hits upon Wall 3 is near grazing, resulting the energy delivered via such a path becomes considerable. In the corridor (i.e. y < 1.5 m), the results suggest that wall reflection is as equally important as the direct component in most receiving locations and should always be considered. This is evidenced by the received power being predominantly contributed by both the direct and singly-reflected component from Wall 3.

Implications

The results of this investigation suggest that received powers can generally be increased when a transmitter is located in the corridor rather than the office. This is consistent with that reported in [85] where the guided wave channeled by the corridor walls is possible to attenuate insignificantly, and re-radiate the energy back into the rooms at the end of the
corridor. Practically this means depending on the requirement of the system, transmitter locations should be planned according to the needs. If maximising the coverage area from a single transmitter is required, it may be preferable to locate the transmitter in the corridor. By contrast, if the coverage area of a transmitter is to be limited to reduce cochannel interference, it may be better to locate the transmitter away from a reflective wall and inside a room where walls and environmental clutter can provide a shielding effect.

5.3.4 Effect of Frequency Selection

Apart from the physical layout of propagation environments, the operating frequency is another parameter which can influence the propagation of energy. Two different frequencies including 2.4 GHz and 5.8 GHz are used to investigate a change of the dominant mechanisms for Scenario II (transmitter T2). The significance of these two frequencies is that they are the Industrial, Scientific, and Medical (ISM) radio bands, which have been widely used to support many Wireless-Fidelity (Wi-Fi) technologies e.g. Wireless Local Area Networks (WLANs). In this section, the accuracy requirement has been changed from 1.5 dB to 3 dB because the investigation is focused on a change of the dominant mechanisms when operating at different frequencies. Specifying a stringent accuracy requirement could lead to overly-complicated contour regions that are dominated by different combination/order of mechanisms, which is not necessary for the purpose of the investigation. As the effect of prediction accuracy requirement has been previously discussed in Section 5.3.1, 3 dB prediction accuracy is seen to be appropriate for indoor applications in general. The characteristics of the dominant mechanisms and the associated practical implications with regard to the frequency selection are discussed.

Component Attributes

Figs. 5.10(a) – (c) show the distinct regions in which the received power is dominated by different mechanisms at the frequencies of 1.0 GHz, 2.4 GHz, and 5.8 GHz, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole number) of each region to the total area considered. At 1.0 GHz, Fig. 5.10(a) shows that the received power in the majority of the locations is contributed by the direct component (82%). The results also indicate that the singly-reflected component from Wall 3 (concrete) is only significant at distant receiving locations (i.e. at least 5 m away from the transmitter in this case). Reflections from Wall 2 (drywall) can generally be disregarded as the region where they are significant is physically very small (less than 1% of the total area).
Figure 5.10: Graphs showing the distinct regions in which the received power is dominated by different mechanisms, and their corresponding percentage contributions to the total area at the frequencies of (a) 1.0 GHz, (b) 2.4 GHz, and (c) 5.8 GHz, for Scenario II (transmitter T2, indicated by ×).
The significance of the reflected components is shown to increase with the frequency. This observation is most prominent and evidenced by the singly-reflected component from Wall 1 which is absent at 1.0 GHz but becomes one of the mechanisms present at 2.4 GHz (22%) and 5.8 GHz (49%). Similarly, the physical size of the region where the singly-reflected component from Wall 2 is significant has increased from less than 1% to 6% and 14% at 2.4 GHz and 5.8 GHz, respectively. It is noteworthy that the significance of the direct component has decreased dramatically at 5.8 GHz. In this case, the direct component is no longer always dominant. Sometimes, the direct component does not exist at certain parts of the open plan office. It is also interesting to note that the change of mechanism is observed in the corridor where the singly-reflected component from Wall 2 (drywall) now dominates that from Wall 3 (concrete) at 5.8 GHz.

**Implications**

The dominant mechanisms can be influenced by the operating frequency. When operating at a lower frequency, a direct component is the dominant mechanism which contributes most of the received power and needs to be considered. As the frequency increases, the number of the dominant mechanisms which contribute significantly to the received power also increases. In the open plan office and corridor geometry, a maximum of two dominant mechanisms are seen to present in all the receiving locations. These two mechanisms are a direct and a singly-reflected component from the nearby walls. The question arises as to which reflected component should also be included in addition to the direct component, so that useful estimates of the local mean can be obtained. Practically, the challenge is to identify which wall would support a significant reflection at the intended operating frequency. Such an identification requires the wall reflectivity to be assessed, in which appropriate estimates of wall parameters namely the material properties and the physical thickness are necessary.

**5.4 Summary**

This chapter has identified dominant mechanisms which govern the energy propagation in an open plan office and corridor geometry. Several parameters including the prediction accuracy requirement, the material properties of walls, the transmitter location, and the frequency selection have been investigated. It has been shown that there is an inevitable trade-off between the model accuracy and complexity. For a higher prediction accuracy, a greater number of mechanisms need to be considered, and therefore more detailed information on the environment is necessary. Fortunately in any situation, the consideration of two mechanisms seen to be adequate for estimating the local mean in an open plan office and corridor geometry. These two mechanisms are a direct component
and a singly-reflected component from the nearby walls. Therefore, a practical challenge is to determine which reflecting surface is able to support a significant reflection in the frequency of operation. In particular, the reflectivity of walls which are present in the environment need to be assessed. Moreover, good estimates of wall parameters (e.g. the material properties and the physical thickness of walls) are required for such an assessment.

Chapter 6 adopts a similar investigative approach to identify dominant mechanisms at a single corner geometry. In particular, the investigation focuses on the effects of the physical structures, the transmitter-to-corner distance, and the operating frequency.
Chapter 6

Propagation in the Presence of a Single Corner

6.1 Introduction

Chapter 5 has described the investigative approach in this thesis and identified the dominant mechanisms which govern the propagation of energy in an open plan office and corridor geometry. It was shown that the number of mechanisms which need to be considered is greatly dependent on the prediction accuracy required. The inclusion of a direct component and a singly-reflected component were shown to be adequate for predicting the local mean, which in turn can be used to estimate useful system performance. Moreover, the significance of reflected components was shown to be dependent on the material properties and the distance between transmitter and reflecting surfaces, as well as the operating frequency. As a result, good estimates of physical structures such as the material properties and the thickness of walls may be needed to accurately identify the dominant mechanisms.

This chapter investigates radio propagation in a single corner geometry, in which a subset of the receiving locations are shadowed by a significant shadowing obstacle. This investigation is of great importance in practice as receiving locations are often shadowed by obstacles in indoor environments. As a result, assessing the relative importance of propagation mechanisms in different parts of the shadowed region can provide valuable assistance for estimating the local means, and hence useful system performance estimation. Section 6.2 describes the single corner geometry considered and how it has been modelled using the FDTD and the ray model. Test Environments B and C were used to ensure that the candidate mechanisms have been correctly identified and estimated. Section 6.3 reports a series of studies which investigate the effects of material properties, exterior glass
windows, frequency selection, and transmitter-to-corner distance. Finally, Section 6.4 summarises this chapter.

6.2 Modelling the Single Corner

The geometry investigated in this chapter is extended from the open plan office and corridor geometry considered in Chapter 5. Two walls were added creating a L-shaped corner, which is surrounded by exterior glass windows (Fig. 6.1). From Fig. 6.1, it shows that the L-shaped corner is formed by two concrete walls (indicated by 2 and 3). Parallel to one of the concrete walls is the internal partition made of drywall (indicated by 1) forming a 1.5 m wide corridor. The open plan office (i.e. \( y > 1.5 \) m) is adjacent to the corridor. This environment is surrounded by exterior glass windows (indicated by 4 and 5). It should be noted that these walls are numbered from 1 to 5 (which are hereafter be referred to as Walls 1–5, respectively, in this chapter), so that a propagation mechanism which is supported by a particular wall in this generalised environment can be clearly specified.

Transmitter T3 is 3.3 m from the corridor junction and 1.1 m away from Wall 2 with the coordinate of \((0, -3.3)\) m. During the investigation, the receiving locations are fixed and distributed on a regular rectangular lattice inside the observation area (bounded by the dashed lines shown in Fig. 6.1). The setup of this geometry is used to examine the propagation behaviour when a subset of the receiving locations are shadowed by the significant environmental obstacle. In this case, the direct component would have to transmit through at least two walls (Walls 2 and 3) to reach the majority of the receiving locations.

6.2.1 FDTD Model

The FDTD modelling domain is 14.35 m \(\times\) 9.3 m, and is surrounded by a UPML [80] (Fig. 6.2). Since the aim of this chapter is to examine the relative importance of components which propagate around or transmit through a single corner to reach a receiver, the discussions here only focus on the propagation behaviour in the observation area (i.e. bounded by the dashed lines in Fig. 6.2). A square lattice of \(\Delta =0.006 \) m \((\approx \lambda_{\min}/20)\) and a time step of \(\Delta t = 10 \) ps are used to minimise dispersion and ensure numerical stability [15, pp. 109–140]. Similar to Chapter 5, three building materials namely drywall, glass, and concrete are represented in the colours blue, red, and gray, respectively, and their material properties are specified in Table 5.1. These walls have been effectively extended to infinity by inserting the walls into the UPML as shown in Fig. 6.2, thereby assuming propagation effects due to variations in the environmental features outside the
modelling domain are not significant to this investigation.

A vertically-polarised line source (indicated by $\times$) with a centre frequency of 1.0 GHz was used. The local mean is obtained by taking the spatial average of the steady state response over a $2\lambda \times 2\lambda$ square region so as to largely remove the effect of multipath fading. A detailed explanation for the choice of spatial-averaging sector is described in Appendix B.

### 6.2.2 Ray Model

A 2D ray model has also been formulated to estimate the local mean in the observation area (shown in Fig. 6.1). Hypothesised candidate mechanisms arriving from four different propagating paths including the direct, wall reflected, corner diffracted, and combined reflected-diffracted paths are considered. An estimate of the local mean can be obtained by assuming the contributions from these arriving components are uncorrelated and can thus be added on a power basis (in Watts) [20], namely

$$P_r = P_{\text{dir}} + P_{\text{refl}} + P_{\text{diff}} + P_{\text{refl/diff}}$$

where $P_r$ is the total received power, $P_{\text{dir}}$, $P_{\text{refl}}$, $P_{\text{diff}}$, and $P_{\text{refl/diff}}$ are the power of the direct, the reflected, the diffracted, and the reflected-diffracted components, respectively.
The power of the direct component is estimated by [26, pp. 746–752]

\[ P_{\text{dir}} = \left( \frac{A}{d_{\text{dir}}} \right) \kappa \]  

(6.2)

where \( A \) is a scaling factor used to calibrate the ray model against the FDTD predictions, \( d_{\text{dir}} \) is the distance between the transmitter and receiver, and \( \kappa \) is the attenuation through any obstacle encountered.

The power of the reflected components from the walls are estimated by [26, pp. 753–760]

\[ P_{\text{refl}} = \sum_{i=1}^{n} \left( \frac{A}{d_{\text{refl}_i}} \right) \left( \prod |\Gamma_i|^2 \right) \kappa \]  

(6.3)

where \( n \) is the total number of possible doubly-reflected components, \( d_{\text{refl}_i} \) is the total length of the reflected path, and \( \Gamma_i \) is the effective reflection coefficient\(^1\). Third-order and higher wall reflections have also been considered, but their contributions to the sector mean were found to be insignificant and can therefore be neglected.

The power of the diffracted component around the corner is estimated by [26, pp. 765–769]

\[ P_{\text{diff}} = \left( \frac{A}{d_{\text{diff}}} \right) |D|^2 \kappa \]  

(6.4)

where \( d_{\text{diff}} \) is the total length of the diffracted path, and \( D \) is the diffraction coefficient computed according to the Uniform Theory of Diffraction (UTD) [49].

\(^1\)The effective reflection coefficient is the coefficient which includes the combined effect of reflection from the front face and multiple internal reflections inside a dielectric wall. A detailed computation of the effective reflection coefficient is included in Appendix A.
The power of the combined reflected-diffracted/diffracted-reflected components are estimated by [26, pp. 753–760, 765–769]

\[ P_{\text{refl\_diff}} = \sum_{i=1}^{n} \left( \frac{A}{d_{\text{refl\_diff}i}} \right) \left( \prod |\Gamma_i|^2 \right) |D_i|^2 \kappa \] \hspace{1cm} (6.5)

where \( n \) is the number of possible reflected-diffracted/diffracted-reflected components (up to second-order reflections and first-order diffraction), and \( d_{\text{refl\_diff}i} \) is the total length of the reflected then diffracted or the diffracted then reflected path.

The UTD is formulated based on the high frequency asymptotic techniques to approximate diffraction around a perfect conducting wedge as a ray [49]. The applicability of the UTD in indoor environments can sometimes be questionable because common building walls are generally made of dielectric materials (e.g. concrete, glass, and drywall). Additionally, research to date has shown that to accurately model diffraction around/through dielectric wedges requires a heuristic modification of the UTD formulation, suggesting that is non-ray optical in nature (e.g. [12, 13]). Nonetheless, the UTD is adopted here as there is no computationally efficient solution for dielectric wedge diffractions that is regarded as appropriate/reliable for the purpose of this investigation. Therefore, the applicability of the UTD is validated with the FDTD results throughout the investigation.

Fig. 6.3 illustrates the propagation paths of the candidate mechanisms described in Eqs. (6.1)–(6.5). In this example, the receiving location Rx is placed in the open plan office. The candidate mechanisms from six different propagation paths including the direct (\( T \)), the diffracted (\( D \)), up to doubly-reflected (i.e. \( R_3 \) and \( R_5R_4 \)), and up to doubly-reflected then diffracted (i.e. \( R_3D \) and \( R_5R_3D \)) paths are considered. It is important to note that for the sake of clarity, only one of the propagation paths from each propagation category is depicted. For example, the doubly-reflected component from Walls 4 and 3 (\( R_4R_3 \)) has also been considered but the propagation path has not shown in Fig. 6.3. In this particular example, transmission through Wall 1 occurs for all the paths depicted and therefore the extra attenuation resulting from this must be considered.

### 6.2.3 Comparison of the FDTD and the Ray Model Predictions

To ensure all the candidate mechanisms have been identified and modelled correctly, the ray model described in Eqs. (6.1)–(6.5) is used to estimate the local means in the observation area by including rays which are the potential significant contributors to the received power and compared against the FDTD estimates. In this section, the comparison results in two test environments (Test Environments B and C) having the absence and
Figure 6.3: Illustration of the propagation paths for the candidate mechanisms considered in the presence of a single corner.

the presence of exterior glass windows (shown in Figs. 6.4(a) and (b), respectively) which are used to demonstrate the applicability of the ray model. Additional results for other environments investigated in this chapter are included in Appendix C.

Test Environment B: Exterior Glass Windows Absent

Figs. 6.5(a) and (b) show the ray and the FDTD estimates of the local means in the observation area, respectively, for the environment containing the concrete corner only (Fig. 6.4(a)). From both results, the path gain in the region where the direct component does not have to transmit through the concrete walls is about $-30$ dB. When a receiving location is shadowed by the concrete corner (i.e. area to the right of the incident shadow boundary ISB, shown in Fig. 6.6), the path gain decreases rapidly. This is because components that are either transmitted through or diffracted around the concrete corner have been severely attenuated.

The error between the ray and the FDTD estimates of the local mean is shown in Fig. 6.5(c). Overall, good agreement is obtained, except for the area in the vicinity of the ISB where the ray model tends to overestimate the path gain. The error is likely to be caused by a diffracted ray estimated based on a perfect conducting wedge which is not an appropriate approximation for the dielectric wedge considered. Nonetheless, a maximum error is approximately 6 dB, and the physical size and the geographical location are relatively small and localised. As a result, it will not severely impact the overall performance of the ray model. Fig. 6.7 shows the probability density function (pdf) of the ray prediction error across the entire observation area. Negative and positive
errors indicate underestimation and overestimation of the path gain, respectively. The
mean error $\mu$ and standard deviation $\sigma$ of 0.3 dB and 0.2 dB, respectively, suggesting
that acceptable prediction accuracy$^2$ has been achieved in the majority of the receiving
locations.

**Test Environment C: Exterior Glass Windows Present**

Figs. 6.8(a) and (b) show the ray and the FDTD estimates of the local mean in the observa-
tion area, respectively, for the environment contains the concrete corner which is fully
surrounded by exterior glass windows (Fig. 6.4(b)). From both results, similar observa-
tions can be made as that in Test Environment B. In particular, the path gain is about
$-30$ dB provided that the concrete corner is not in the direct path, and the path gain
decreases substantially when the receiving location is shadowed (i.e. area to the right of
the ISB). However, for the receiving locations situated in the deep-shadowed region, the
path gains are seen to remain largely the same. This is evidenced by the area bounded by
the two reflection shadow boundaries (i.e. RSB and RISB, shown in Fig. 6.6) where the
path gain remains approximately $-45$ dB, suggesting that reflection from exterior glass
windows may have an important role in delivering energy to the heavily shadowed region.

The error between the ray and the FDTD estimates is shown in Fig. 6.8(c). Good
agreement is obtained, except for the areas in the proximity to the ISB and RISB where
the ray model tends to overestimate the path gain. This phenomenon is similar to that
observed in Test Environment B, and is thought to be caused by an inappropriate approx-

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$^2$The acceptable prediction accuracy is dependent on the applications and the environment where a
system is intended to operate. This has been discussed in Section 5.3.1.
Figure 6.5: Graphs showing the predicted path gains in the observation area using (a) the ray model, (b) the FDTD, and (c) the prediction error (i.e. $P_{\text{ray}} - P_{\text{FDTD}}$) in Test Environment B. In (c), the colours red and blue indicate overestimation and underestimation of the path gain, respectively.
6.3 Dominant Mechanisms in the Presence of the Single Corner

To conclusively identify dominant mechanisms which govern the propagation of energy in the presence of a single corner, the power contribution of candidate mechanisms is assessed in the observation area using the ray model described in Eqs. (6.1)–(6.5). The number of mechanisms which need to be considered is dependent on the prediction accuracy required. As discussed in Section 5.3.1 that prediction accuracy of 3 dB (with respect to the ray model) is adequate for estimating useful system performance in practice, and is thus used for all the investigations in this chapter. Sections 6.3.1, 6.3.2, and 6.3.4 investigate the effects of the material properties of the corner, exterior glass windows, and transmitter-to-corner distances, respectively, at operating frequency of 1.0 GHz. Section 6.3.3 investigates a change of the dominant mechanisms when operating at different frequencies including 2.4 GHz and 5.8 GHz.

Figure 6.6: Shadow boundaries for the single corner geometry with transmitter T3 indicated by ×. Incident, reflection, and combined incident and reflection shadow boundaries are indicated by ISB, RSB, and RISB, respectively.
Effect of Corner Material Properties

The presence of a shadowing obstacle may weaken the received signal strengths, which in turn degrades the system performance and limits the coverage area of a transmitter. In practice, reducing the coverage area of a transmitter is not always undesirable. This is because many independent indoor wireless systems are often deployed in a close proximity, resulting in cochannel interference which can also introduce a detrimental effect to the system performance. With a strategic placement of transmitter around shadowing obstacles, a level of cochannel interference may be minimised. It is therefore of interest to investigate propagation behaviour in the presence of shadowing obstacles which have different characteristics.

The environments considered in this section contain a corner (formed by Walls 2 and 3) which is made of drywall, glass, or concrete, and are shown in Figs. 6.10(a)–(c), respectively. It is important to note that exterior glass windows (Walls 4 and 5) have not been included as the investigation focuses on the relative importance of components that diffract around or transmit through the corner. Transmitter T3 and a frequency of 1.0 GHz were used. The characteristics of the dominant mechanisms and the associated implications with regard to corner material properties are discussed.

Component Attributes

Figs. 6.11(a)–(c) show the distinct regions in which the received power is dominated by different mechanisms when the corner is made of drywall, glass, and concrete, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole num-
Figure 6.8: Graphs showing the predicted path gains in the observation area using (a) the ray model, (b) the FDTD, and (c) the prediction error (i.e. $P_{ray} - P_{FDTD}$) in Test Environment C. In (c), the colours red and blue indicate overestimation and underestimation of the path gain, respectively.
Propagation in the Presence of a Single Corner

![Probability density function (pdf) of the prediction error across the entire observation area for Test Environment C. Negative and positive errors indicate underestimation and overestimation of the path gain, respectively.](image)

Figure 6.9: Probability density function (pdf) of the prediction error across the entire observation area for Test Environment C. Negative and positive errors indicate underestimation and overestimation of the path gain, respectively.

In the presence of the drywall and glass corners, results have shown that the received power in the observation area is dominated by the direct component. Although the diffracted component has appeared to be significant in the vicinity of the ISB in the presence of the glass corner, the physical size of such a region is very small (3%) and can therefore be safely omitted. In the presence of the concrete corner, results have shown that two mechanisms are dominant in different parts of the observation area. As expected, the direct component is the dominant mechanism if a LOS path exists. As the receiver crosses to the right of the ISB and shadowed by the concrete corner, the diffracted component becomes dominant because the direct component now suffers significant attenuation. However, the diffraction loss has shown to increase rapidly as the receiver moves further into the deep-shadowed region. As a result, a change of the dominant mechanism has been observed where the direct component now dominates the diffracted component. The singly-reflected component from Wall 1 has also been observed to be significant just around the corner, but the physical size of the region is very small (less than 1%), thus has been classified as others.

Implications

Propagation modelling in an environment consisting of a shadowing obstacle which is made of low dielectric constant materials (i.e. drywall) or physically thin walls (i.e. glass) is straightforward because the majority of the energy is transmitted through directly. Provided that the attenuation through any obstacle encountered is appropriately esti-

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3The total area is represented by a number of receiving locations in the observation area indicated in Fig. 6.1. During the investigation, receiving locations are distributed in a regular rectangular lattice with a gap of 0.1 m, resulting a total number of 5800 receiving locations.
6.3 Dominant Mechanisms in the Presence of the Single Corner

Figure 6.10: Graphs showing the plan view of the environments investigated in which the corner is made of (a) drywall, (b) glass, and (c) concrete. Transmitter T3 is indicated by ×, and the observation area is bounded by ---.

mated, an acceptable prediction of the local mean can be made accurately and efficiently. In contrast, a shadowing obstacle which is made of lossy and/or highly reflective material (i.e. concrete) can potentially complicate the propagation process. This is because the dominant mechanism is now dependent on the geometrical relationship between the transmitter, receiver, and shadowing obstacle. Results have shown that the direct and the diffracted components are dominant in different parts of the shadowed region, suggesting that the concrete corner can act as a significant shadowing obstacle. This means predicting the received power in the region where the diffracted component is dominant, one must be cautious due to the non-ray optical behaviour.

6.3.2 Effect of Exterior Glass Windows

Most modern office buildings are enclosed by glass windows for lighting and aesthetic purposes. Although glass is usually physically thin and optically transparent, research to date has shown that reflections from the glass can have an important role in influencing
Figure 6.11: Graphs showing the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution of each region to the total area when the corner is made of (a) drywall, (b) glass, and (c) concrete. Transmitter T3 is located at \((0, -3.3)\) m.
6.3 Dominant Mechanisms in the Presence of the Single Corner

energy propagation in indoor environments (e.g. [20, 24]). This phenomenon is particularly apparent when the receiving locations are shadowed by the environmental obstacle, thus a direct component is not always dominant. In this section, the progression of the environments investigated consider Wall 4, Wall 5, and both Walls 4 and 5 present shown in Figs. 6.12(a) – (c), respectively. Of interest here is to examine the effect of each wall and their combined effect as a whole. The characteristics of the dominant mechanisms and the associated implications with regard to exterior glass windows are discussed.

Component Attributes

Figs. 6.13(a) – (c) show the distinct regions in which the received power is dominated by different mechanisms with the presence of Wall 4, Wall 5, and both Walls 4 and 5, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole number) of each region to the total area considered. It is evident that the regions are more complicated than the case without Walls 4 or 5 present (shown in Fig. 5.9) as more
mechanisms are now present. The commonality for all the cases considered is that the direct component is dominant when a LOS path exists. From the results when only Wall 4 is present (Fig. 6.13(a)), a triangular-shaped region which is bounded by the incident and reflection shadow boundaries (ISB and RSB indicated in Fig. 6.6) can be observed, suggesting that the presence of the singly-reflected component from Wall 4 is limited by the concrete corner. Although the combination of the dominant mechanisms has become complicated when the singly-reflected component from Wall 4 no longer exists (i.e. to the right of the RSB), most of the regions require the mechanism to diffract around the corner and then reflect from the glass. This is evidenced by the received power in most of these regions is jointly dominated by the diffracted then singly-reflected component from Wall 4 ($DR_4$).

With Wall 4 removed and included Wall 5, Fig. 6.13(b) shows the complexity of the region has reduced. This is because the glass reflection tends to dominate provided that the significant obstacle is not in the propagation path. In this particular case, the area where the glass reflection is limited by the concrete corner is relatively small. As a result, the singly-reflected component from Wall 5 ($R_5$) is appeared to dominate in a significant numbers of receiving locations. Diffraction is found to be significant only in the vicinity of the incident shadow boundaries. This is evidenced by the diffracted component ($D$) and singly-reflected then diffracted component ($R_5D$) being the dominant mechanisms in the area around the ISB and RISB (indicated in Fig. 6.6), respectively.

With both Walls 4 and 5 present, Fig. 6.13(c) shows that a triangular-shaped region has reappeared, but now dominated by the singly-reflected components from Wall 4 and Wall 5 ($R_4$ and $R_5$). Similar to the finding from the previous case, the singly-reflected component is dominant provided that the propagation path is not obstructed by the shadowing obstacle. When the receiving location places in the deep-shadowed region, the combined effect of Walls 4 and 5 becomes important. This observation is supported by the doubly-reflected component from both exterior walls ($R_3R_4$) being the most dominant mechanism in the region. It is also noteworthy that apart from the region where a LOS path exists, the direct component is no longer found to be significant in the shadowed region.

**Implications**

Generally, the results obtained suggest that reflections from exterior glass windows should always be considered for estimating the received signals in the shadowed region as they tend to dominate. However, the existence of reflected components can be limited by the shadowing obstacle. Therefore, the locations and material properties of exterior glass
Figure 6.13: Graphs showing the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution of each region to the total area with the presence of (a) Wall 4, (b) Wall 5, and (c) both Walls 4 and 5. Transmitter T3 is located at $(0, -3.3)$ m.
windows and potential shadowing obstacles should be carefully considered. In any case when solely reflected components are severely attenuated via transmission through a significant shadowing obstacle, combined mechanism of reflection and diffraction becomes dominant. In this case, the model is expected to be more complicated as both reflection and diffraction computations are required. In addition, the diffraction computation around a dielectric wedge requires a heuristic modification to the UTD formulation as it is non-ray optical in nature [12,13], hence reliable estimates can be challenging to obtain.

6.3.3 Effect of Frequency Selection

Apart from the geometry and materials in the propagation environment, the dominant mechanisms are also dependent on the operating frequency. The results in Section 6.3.2 have shown that reflections from the glass can have a significant contribution to the received power in some of the shadowed regions. To demonstrate the effect of the frequency on the reflected components, both the transmitter Tx and receiver Rx are setup to be 2 m away from the dielectric wall of thickness $t$ and 5 m apart (Fig. 6.14). The dielectric wall with the material properties specified in Table 5.1 is extended to infinity in the $x$ direction, thus the effect due to other environmental variations beyond the modelling domain can be neglected. For calculating an effective reflection coefficient from the dielectric wall, a total of twenty rays are considered as this was shown to be adequate to represent the observed reflected field (see Section 3.4.1). These twenty rays include one reflected from the front face, and nineteen internal reflected rays from the dielectric wall. The illustration of the reflected ray path from the front face (Path A), and the first-order internal reflected ray path from the dielectric wall (Path B) are shown in Fig. 6.14. A detailed computational method for an effective reflection coefficient from a dielectric slab is presented in Appendix A.

Fig. 6.15 shows the magnitude of the effective reflection coefficient with respect to frequency for the geometry setup shown in Fig. 6.14. It is evident that for a physically thin dielectric wall (e.g. drywall or glass), the effective reflection coefficient from such a surface increases with the frequency. Furthermore, the magnitude of the effective reflection coefficient from the glass is always higher than the drywall. For a physically thick dielectric wall (e.g. concrete) on the other hand, the magnitude of the effective reflection coefficient can vary significantly from 0.13 to 0.88. This is because the internal reflected components of the concrete wall are contributing constructively and destructively with that from the front face. In this particular example, the results show that the magnitude of the reflection coefficient from the concrete is higher than that from the glass or drywall at the frequencies below 1.73 GHz (A). Between frequency bands of 1.73 GHz (A) and 2.87 GHz (B), and 3.57 GHz (C) and 5.44 GHz (D), the magnitude of the reflection
6.3 Dominant Mechanisms in the Presence of the Single Corner

![Figure 6.14](image)

**Figure 6.14:** A geometry for demonstrating a change of the effective reflection coefficient with respect to the frequency. Paths A and B depict the reflected ray path from the front face and the first-order internal reflected ray path from the dielectric wall, respectively.

![Figure 6.15](image)

**Figure 6.15:** Effective reflection coefficients from the dielectric wall with different material properties.

...coefficient from the glass is higher than that from the concrete.

To what extent the characteristics of the dominant mechanisms may change due to the choice of frequency is therefore the main interest of the investigation in this section. The environment under consideration consists of a concrete corner which is surrounded by glass windows (Fig. 6.12(c)). Three different frequencies including 1.0 GHz, 2.4 GHz, and 5.8 GHz are investigated. The characteristics of the dominant mechanisms and the associated implications with regard to frequency selection are discussed.
Component Attributes

Figs. 6.16(a) – (c) show the distinct regions in which the received power is dominated by different mechanisms, and the percentage contributions (rounded to a whole number) of each region to the total area at 1.0 GHz, 2.4 GHz, and 5.8 GHz, respectively. Fig. 6.16(a) is the result from Section 6.3.2, but is repeated here. From all the cases considered, results have shown that the direct component (18%) is only dominant when a LOS path exists. As expected, the component which involves diffraction in the propagation process has observed to become less important at the higher frequency, due to the higher diffraction loss. This phenomenon is evidenced by the percentage of the total area which is dominated by the solely diffracted ($D$) and the jointly diffracted components (i.e. $R_5D$ and $DR_4$) are 27% and 8% at 1.0 GHz and 5.8 GHz, respectively. It is also noteworthy that the significance of the doubly reflected component has increased significantly with the frequency. In particular, the received power which is dominated by the doubly reflected component from Walls 5 and 4 ($R_5R_4$) has shown to be 16%, 22%, and 44% at 1.0 GHz, 2.4 GHz, and 5.8 GHz, respectively. In addition, the doubly reflected component has shown to dominate over the singly reflected component.

Implications

Generally, the dominant mechanisms which govern the propagation of energy in a single corner geometry are observed not to change appreciably with frequency. Reflections from the glass are shown to be the significant contributors to the received power in the shadowed region regardless of a change in frequency. This finding is consistent with that shown in Fig. 6.15 where the magnitude of the reflection coefficient from the glass increases significantly with frequency. Although lower-order reflections are often thought to dominate higher-order reflections as the propagation path length is shorter, the results however suggest that second-order glass reflections can dominate first-order glass reflections at 5.8 GHz. This means in practice, geometries which can support higher-order reflections may be as crucial as that supporting lower-order reflections particularly at higher frequencies.

Other than reflection, diffraction around the corner is also found to be significant in the vicinity of the shadow boundaries at the lower frequency. However, the physical size of such a region is relatively small in comparison to the total area, and the location is very localised. From a modelling point of view, the diffracted component can therefore be neglected with a reduced prediction accuracy in the area close to the shadow boundaries.
Figure 6.16: Graphs showing the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution of each region to the total area at (a) 1.0 GHz, (b) 2.4 GHz, and (c) 5.8 GHz. Transmitter T3 is located at (0, −3.3) m.
6.3.4 Effect of Transmitter-To-Corner Distance

For designing reliable indoor wireless systems, potential shadowing obstacles and their impacts on the overall received signal strengths must be identified and carefully assessed. Shadowing obstacles are generally part of the structural partitions which are dependent on the construction method. Without physically modifying the environment (e.g. by deploying metal shields [86] or frequency selective surfaces [87] on the walls), the significance of the shadowing effect can be altered by the transmitter placement around the shadowing obstacle. In this section, a change of the dominant mechanisms with respect to the geometrical relationship between the transmitter and the obstacle is investigated. In particular, two transmitter locations which are both 1.1 m away from the adjacent wall and the distance to the corner junction of 6.0 m and 9.0 m, with the coordinates of (0, –6.0) m and (0, –9.0) m, respectively, were used. The characteristics of the dominant mechanisms and the associated implications with regard to transmitter-to-corner distance are now discussed.

Component Attributes

Figs. 6.17(a) and (b) show the distinct regions in which the received power is dominated by different mechanisms when the transmitter-to-corner distance is 6.0 m and 9.0 m, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole number) to the total area considered. Comparing the cases with the transmitter located at 3.3 m (shown in Fig. 6.13(c)) and 6.0 m from the corner, the area where the received power is solely dominated by the direct component has decreased (i.e. from 18% to 10%). This is because the area where a LOS path exists is decreased, and the singly-reflected component from Wall 2 becomes increasingly important due to the incident angle is near grazing. It is notable that the triangular-shaped region which is dominated by the singly-reflected components has reduced and shifted towards the left as the transmitter moves away from the corner. This suggests that the corner can be used to limit the existence of the dominant mechanisms. As the receiving locations moved into the shadowed region, up to second-order glass reflections are observed to be the dominant mechanisms. This observation can be supported by the singly-reflected component from Wall 5 (21%) and doubly-reflected component from Walls 5 and 4 (32%) are the dominant mechanisms in the majority of the receiving locations in the shadowed region. Similarly, the combined mechanism of diffraction and reflection is only found to be significant in the close proximity to the incident shadow boundaries.

With the transmitter further away from the corner (i.e. 9.0 m from the corner), the shadowed region is increased. Fig. 6.17(c) shows that the general shape of the regions
Figure 6.17: Graphs showing the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution of each region to the total area when the transmitter-to-corner distance is (a) 6.0 m, and (b) 9.0 m.
remains approximately the same, but has been shifted towards the left. In this case, the direct component is no longer the only dominant mechanism present in any given receiving location. This is expected as the singly-reflected component from Wall 2 becomes increasingly important and comparable to the direct component as the incident angle is near grazing. In the shadowed region, similar observations can be made with the previous cases where up to second-order reflections are seen to be the dominant mechanisms. It is noteworthy that when the reflections from the exterior glass windows no longer exist, the combined mechanism of reflection and diffraction becomes dominant. This is evidenced by up to doubly-reflected and then diffracted components (i.e. \( R_5D \) and \( R_2R_5D \)) being the dominant mechanisms when the receiving locations are outside the double reflection shadow boundary (i.e. in the region on the upper right corner of Fig. 6.17(c)).

**Implications**

In the shadowed region, the results have shown that the energy predominantly propagates via the reflected path from exterior glass windows. In particular, up to second-order reflections are observed to be significant provided that the shadowing obstacle is not in the propagation path. Practically this means the base stations should be deployed so that the doubly-reflected components from the nearby glass windows can be supported in the area where a reliable communication link is required. If however a good received signal for several areas of particular concern (e.g. offices or conference rooms) cannot be achieved simultaneously, the deployment of an additional base station should be considered. By contrast, no further action is required if a good received signal cannot be achieved in a less important area (e.g. inside restrooms or elevators).

**6.4 Summary**

This chapter has identified dominant mechanisms which govern the energy propagation in an environment containing a potential shadowing obstacle — a single corner. The investigations are focused on the effects of the corner material properties, the presence of exterior glass windows, the operating frequency, and the geometrical relationship between a transmitter and a corner. In the absence of exterior glass windows, the material properties of the corner have been found to be influential on the dominant mechanisms. The results suggested that the concrete corner acts as a significant shadowing obstacle, whereas the drywall or glass corners allow most of the energy to transmit through directly. Practically this means that propagation process is expected to be complicated only when a receiving location is shadowed by a concrete corner. In the presence of exterior glass windows, the received signal strengths in the shadowed region can be enhanced. This is because a significant portion of the energy can be delivered alternatively via reflections with a
negligible loss. In particular, up to second-order reflections are found to be significant provided that the shadowing obstacle is not in the propagation path. In any event when a reflected path is severely attenuated by an obstacle encountered, a majority of the energy will be delivered via a combined reflected-diffracted path.
Chapter 7

Propagation in the Presence of a Double Corner and a Discrete Obstacle

7.1 Introduction

Chapter 6 has identified the significant contributors to the received signal strength in the presence of a single corner. In this geometry, the energy has to propagate around the corner and/or transmit through to reach the receiving locations. In the absence of exterior glass windows which can support the propagation of energy to the shadowed region, it was shown that the dominant mechanisms are dependent on the corner material properties. If the corner is formed by walls which are highly lossy, then both the direct and the diffracted components need to be considered to estimate the local mean accurately. In the presence of exterior glass windows, a significant portion of the energy has shown to be delivered via reflections. This phenomenon becomes more prominent at higher frequencies. Overall, the results have suggested that none of the components are universally dominant in the shadowed region. As a result, five components namely a direct, up to doubly-reflected, a diffracted, and combined reflected-diffracted components need to be included to achieve high prediction accuracy.

This chapter extends the investigation and introduces a discrete obstacle which is located at the centre of the propagation environment. The discrete obstacle is a rectangular-shaped hollow concrete block which houses lifts, a stairwell, and associated services. In this chapter, radio propagation in two canonical geometries namely a double corner and a discrete obstacle have been investigated. For the double corner geometry, the energy can either transmit through or propagate around a double corner to reach a receiver on the opposite side of the discrete obstacle. It is assumed that the discrete obstacle is elongated, thus the energy that propagates from the other side of the discrete obstacle is insignificant and can therefore be neglected. For the discrete obstacle geometry, the
obstacle has been modelled as a square-shaped hollow concrete block hence the energy that propagates around both side of the discrete obstacle needs to be considered. As the propagation environment becomes complicated, it is possible that components which propagate via different paths may be dominant in different parts of the shadowed region. The objective of the investigations is to assess the relative importance among various components arriving at the receiving locations.

Section 7.2 describes the double corner and the discrete obstacle geometries considered and how they have been modelled using the FDTD and a ray model. Particularly, the FDTD and the ray path gain predictions for Test Environment D are compared to ensure the candidate mechanisms have been correctly identified and estimated. Section 7.3 reports a series of investigations which consider variations in both the physical features and the choice of frequency in the double corner geometry. Subsequently, the investigation considers the discrete obstacle geometry and examines how the dominant mechanisms change at different operating frequencies. Finally, Section 7.4 summarises this chapter.

7.2 Modelling the Double Corner and the Discrete Obstacle

The illustrations of double corner and discrete obstacle geometries that are investigated in this chapter are shown in Figs. 7.1(a) and (b), respectively. It should be noted that the double corner geometry is similar to the discrete obstacle geometry, except the discrete obstacle is modelled to have an infinite extension. In addition, the discrete obstacle is formed by the combination of four concrete walls and can be used to represent a hollow concrete block. The double corner geometry is extended from the single corner geometry investigated in Chapter 6. The addition of two concrete walls (Walls 6 and 7) forms the discrete obstacle with an internal concrete wall. This environment is then surrounded by exterior glass windows (Walls 4, 5, and 8).

Fundamentally, the discrete obstacle geometry is made up by two double corner geometries which are mirror-images of each other with respect to the $x$ axis. However, it is noted that the mirror-image of Wall 1 which should be located at $x = -8.3$ m has not been included. The purpose of this setup is to examine the relative importance of components that propagate around the discrete obstacle through different layouts of the propagation environment. Again, the environment is surrounded by exterior glass windows (Walls 4, 5, 8, and 10). As the layout of the discrete obstacle geometry is similar to a typical single-floor office environment, the propagation phenomena observed can be
used to gain insights into the radio propagation in practice.

Similar to Chapters 5 and 6, the receiving locations are fixed and distributed on a regular rectangular lattice inside the observation area (bounded by the dashed lines in Fig. 7.1). Transmitter T3 is 3.3 m and 1.1 m away from the corridor junction and Wall 2, respectively, with the coordinate of \((0, -3.3)\) m. From this setup, the propagation of energy can be observed for receiving locations which are significantly shadowed by the environmental obstacle. Particularly, the relative importance of components that transmit through the obstacle or propagate around can be quantified.

### 7.2.1 FDTD Model

The FDTD modelling domains for the double corner and the discrete obstacle geometries are respectively \(18.5\text{ m} \times 12.65\text{ m}\) and \(18.5\text{ m} \times 18.5\text{ m}\), and are surrounded by UPML [80] (see Fig. 7.2). As the objective of the investigation is to identify the dominant mechanisms in the deeply-shadowed region, the observations presented will focus on the observation area (i.e. bounded by the dashed lines in Fig. 7.2). A square lattice of \(\Delta = 0.006\text{ m} \approx \frac{\lambda_{\min}}{20}\) and a time step of \(\Delta t = 10\text{ ps}\) are used to minimise dispersion and ensure numerical stability [15, pp. 109–140]. For consistency, three common building materials including drywall, glass, and concrete are represented in the colours blue, red, and gray, respectively, and their material properties are specified in Table 5.1. For the double corner geometry, Walls 2 and 5–8 have been effectively extended to infinity by inserting the walls into the UPML as shown in Fig. 7.2(a), thereby assuming propagation effects due to variations in the environmental features outside the modelling domain are not significant to this investigation. In contrast, the entire propagation environment of the discrete obstacle geometry has been included in the FDTD modelling domain as shown in Fig. 7.2(b). In this case, components that propagate through exterior glass windows are attenuated by a UPML, thus effectively extending the modelling domain to infinity.

A vertically-polarised line source (indicated by \(\times\)) with a centre frequency of 1.0 GHz was used. The local mean is obtained by taking the spatial average of the steady state response over a \(2\lambda \times 2\lambda\) square region so as to largely remove the effect of multipath fading (as discussed in Appendix B).

### 7.2.2 Ray Model

A 2D ray model has also been formulated to estimate the local mean in the observation area. Hypothesised candidate mechanisms arriving from three different propagating paths including a direct, wall reflected, and combined reflected-diffracted paths are considered.
Figure 7.1: Plan view of an example environment consists of (a) a double corner, and (b) a discrete obstacle.
Figure 7.2: FDTD model for (a) a double corner geometry, and (b) a discrete obstacle geometry. Transmitter T3 is indicated by $\times$, and the observation area is bounded by $\ldots\ldots$. 
Since a singly-diffracted component does not exist and a doubly-diffracted component suffers a significant attenuation, the purely diffracted paths are therefore not considered further in this investigation. An estimate of the local mean can be obtained by assuming the contributions from these arriving components are uncorrelated and can thus be added on a power basis (in Watts) [20], namely

\[ P_r = P_{\text{dir}} + P_{\text{refl}} + P_{\text{refl\_diff}} \]  
\[ \text{(7.1)} \]

where \( P_r \) is the total received power, \( P_{\text{dir}}, P_{\text{refl}}, \) and \( P_{\text{refl\_diff}} \) are the power of the direct component, the reflected components, and the reflected-diffracted components, respectively.

The power of the direct component is estimated by [26, pp. 746–752]

\[ P_{\text{dir}} = \left( \frac{A}{d_{\text{dir}}} \right) \kappa \]  
\[ \text{(7.2)} \]

where \( A \) is a scaling factor used to calibrate the ray model against the FDTD predictions, \( d_{\text{dir}} \) is the distance between the transmitter and receiver, and \( \kappa \) is the additional attenuation through any obstacles encountered.

The power of the reflected components from the walls are estimated by [26, pp. 753–760]

\[ P_{\text{refl}} = \sum_{i=1}^{n} \left( \frac{A}{d_{\text{refl}_i}} \right) \left( \prod \left| \Gamma_i \right|^2 \right) \kappa \]  
\[ \text{(7.3)} \]

where \( n \) is the total number of up to triply-reflected components, \( d_{\text{refl}_i} \) is the total length of the reflected path, and \( \Gamma_i \) is the effective reflection coefficient\(^1\) from a reflecting surface.

The power of the combined reflected-diffracted/diffracted-reflected components are estimated by [26, pp. 753–760, 765–769]

\[ P_{\text{refl\_diff}} = \sum_{i=1}^{n} \left( \frac{A}{d_{\text{refl\_diff}_i}} \right) \left( \prod \left| \Gamma_i \right|^2 \right) |D_i|^2 \kappa \]  
\[ \text{(7.4)} \]

where \( n \) is the number of reflected-diffracted/diffracted-reflected components (up to second-order reflections and first-order diffraction), \( d_{\text{refl\_diff}_i} \) is the total length of the reflected-then-diffracted or the diffracted-then-reflected path, and \( D \) is the UTD diffraction coefficient\(^1\)

\(^1\)The effective reflection coefficient is the coefficient which includes the combined effect of reflection from the front face and multiple internal reflections inside a dielectric wall. A detailed computation of the effective reflection coefficient is included in Appendix A.
Fig. 7.3 illustrates the propagation paths of the candidate mechanisms considered in the double corner geometry. In this example, transmitter T3 and the receiving location Rx are located on the different side of the discrete obstacle. The candidate mechanisms from six different propagation paths including the direct (T), up to triply-reflected (i.e. $R_4$, $R_5R_4$, and $R_5R_4R_8$), and up to doubly-reflected then diffracted (i.e. $DR_4$ and $R_5R_4D$) paths are considered. For the discrete obstacle geometry, the number of the candidate mechanisms (except the direct component) is doubled as the same propagation processes (i.e. reflections from exterior glass window, and combined reflected-diffracted/diffracted-reflected components) can also be supported around the other side of the discrete obstacle. It should be noted that reflections from Wall 1 has not been considered. This is because the reflection angle from the surface is very close to normal, and the material is nearly electromagnetically transparent. As a result, the power of reflected components from Wall 1 is not significant and can therefore be safely ignored.

7.2.3 Comparison of the FDTD and the Ray Model Predictions

To ensure all the candidate mechanisms have been identified and modelled correctly, the local means in Test Environment D (Fig. 7.1(b)) are predicted using the ray model described in Eqs. (7.1) – (7.4) and compared with the FDTD estimates. Figs. 7.4(a) and (b) show respectively the ray and FDTD estimates of the local mean inside the discrete

\footnote{The appropriateness of using the UTD in indoor environments has previously been discussed in Section 6.2.2.}
obstacle and in the observation area for Test Environment D. From both results, the path gains inside the discrete obstacle have shown to be in the range from $-45 \text{ dB}$ to $-40 \text{ dB}$, except the immediate vicinity of Wall 2 where the path gain is between $-34 \text{ dB}$ and $-30 \text{ dB}$. This abrupt change of the path gain is thought to be caused by the artifact of the spatial-averaging process, in which a subset of the data was sampled outside the discrete obstacle. As a result, the path gain predictions are likely to be overestimated. Similar observations can also be made in the immediate vicinity of Wall 6, where the path gains appear to be higher than other receiving locations in the observation area.

It should also be noted that there are triangular-shaped path gain contours which can be seen in the ray predicted results. This observation is due to the reflection shadow boundaries which limit the singly-reflected components to reach the receiving locations in the deep shadowed region. Similar observations can also be made in the FDTD results, but the triangular-shaped path gain contours are no longer visible. This can be explained by the fact that the drywall partition (i.e. at $x = 8.3 \text{ m}$) has not been considered. As a result, the energy propagates around the lower half of the discrete obstacle has shown to be stronger than that around the upper half. From the phenomenon observed, it suggests that the majority of the energy propagates around the discrete obstacle rather than transmits directly through.

The error between the ray and the FDTD estimates of the local mean is shown in Fig. 7.4(c). Areas coloured red and blue correspond to locations where the ray model overestimates and underestimates the path gain, respectively. Overall, good agreement for the majority of the receiving locations is obtained. In particular, the error inside the discrete obstacle is small, indicating that the direct component which transmits through the concrete wall has been accurately estimated. In contrast, the path gains are overestimated in the vicinity of Wall 6. As explained earlier this is thought to be caused by the artifact of the spatial-averaging process, and the impact is observed to be more prominent due to the received power being weaker compared to that inside the discrete obstacle. It is not straightforward to remedy this without compromising the spatial-averaging process. Fortunately, such an area is small and localised, thus will not have a severe impact on the overall predictions. Fig. 7.5 shows the probability density function (pdf) of the ray prediction error across the entire observation area. Negative and positive errors indicate underestimation and overestimation of the path gain, respectively. The mean error $\mu$ and standard deviation $\sigma$ of $-0.6 \text{ dB}$ and $0.9 \text{ dB}$, respectively, suggest that acceptable prediction accuracy has been achieved in the majority of the receiving locations.

\[ \text{3The acceptable prediction accuracy is dependent on the applications and the environment where a system is intended to operate. This has been discussed in Section 5.3.1.} \]
7.2 Modelling the Double Corner and the Discrete Obstacle

Figure 7.4: Graphs showing the predicted path gains inside the concrete core and in the observation area using (a) the ray model, (b) the FDTD, and (c) the prediction error (i.e. $P_{ray} - P_{FDTD}$) in Test Environment D. In (c), the colours red and blue indicate overestimation and underestimation of the path gain, respectively.
7.3 Dominant Mechanisms in the Presence of the Double Corner and the Discrete Obstacle

To conclusively identify dominant mechanisms governing the propagation of energy in the presence of the double corner or the discrete obstacle geometries, the power contribution of the candidate mechanisms is assessed in the observation area using the ray model described in Eqs. (7.1) – (7.4). As the discrete obstacle geometry is effectively formed by two double corner geometries, the radio propagation studies are primarily conducted in the double corner geometry. The observations/results are then integrated into the discrete obstacle geometry. As in Chapter 6, a prediction accuracy of 3 dB is used to determine the dominant mechanism with respect to the ray model. Sections 7.3.1 and 7.3.2 investigate the effect of the internal structure of the discrete obstacle and exterior glass windows at 1.0 GHz, respectively. Section 7.3.3 examines changes of the dominant mechanisms due to different operating frequencies. Lastly, Section 7.3.4 investigates how the dominant mechanisms vary at 1.0 GHz, 2.4 GHz and 5.8 GHz in the discrete obstacle geometry.

7.3.1 Effect of Internal Structure

The internal structure of discrete obstacles can be highly variable in both layout and materials. For example, the concrete services core in the School of Engineering Tower shown in Fig. 4.1 contains lifts, a stairwell, and associated services which make modelling propagation challenging. Generally, the internal structure is likely to scatter the energy, resulting in an additional attenuation of the propagation signal.
In this investigation, a concrete wall is used to represent the internal structure of the discrete obstacle. In the effect, the direct component which propagates through the discrete obstacle will suffer significant attenuation caused by the concrete wall. Two environments which consider either the absence or the presence of the concrete wall shown in Figs. 7.6(a) and (b) are investigated. Apart from Wall 3, all other walls have been extended to infinity \((y \to -\infty)\), so that the relative importance among components which transmit through or propagate around the concrete core can be isolated. Transmitter T3 and a frequency of 1.0 GHz were used. The characteristics of the dominant mechanisms and the associated practical implications with regard to the internal structure of the discrete obstacle are discussed.

**Component Attributes**

Figs. 7.7(a) and (b) show the distinct regions in which the received power is dominated by different mechanisms when the internal concrete wall is absent and present, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole number) of each region to the total area\(^4\) considered. In the absence of the internal concrete wall, the observation area can largely be divided into two regions. The received power in one of the regions is dominated by the direct component (59%), and the other is dominated by the doubly-reflected component from Walls 5 and 4 (33%). It is clear that reflections from exterior glass windows will dominate if shadowing obstacle is not blocking in the reflected path. The combined reflected-diffracted component is found to be significant in the vicinity of the reflection shadow boundary, but the physical size of

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\(^4\)The total area is represented by a number of receiving locations in the observation area indicated in Fig. 7.6. During the investigation, receiving locations are distributed in a regular rectangular lattice with a gap of 0.1 m, resulting a total number of 3944 receiving locations.
the region is small (7%).

In the presence of the internal concrete wall, three significant regions can be identified. The region which is dominated by the doubly-reflecte component from exterior glass windows \((R_3R_4)\) remains largely the same. This result is consistent with that observed in the previous case (i.e. in the absence of the internal concrete wall) in which the energy propagated around the obstacle will dominate. By contrast, the region in which the direct component dominates has shown to decrease appreciably (i.e. from 59% to 32%) due to the additional loss resulting from transmission through the internal concrete wall. This leads to the transition area which is dominated by combined reflected and diffracted components to increase significantly (i.e. from 7% to 23%).

Implications

In practice, a detailed physical description of the discrete obstacle can be challenging to obtain due to lack of accessibility. Fortunately, the results have suggested that the energy which propagates around the discrete obstacle are dominant regardless of its internal structure. The dominant components including a direct, a doubly-reflecte, and combined reflected-diffracted components need to be considered for estimating local means. If simplicity of a model is the primary concern, the combined reflected-diffracted component can be discarded at the expense of reduced power prediction accuracy in the area near the reflection shadow boundary. The physical size of such an area with suboptimal prediction accuracy is directly influenced by the significance of the discrete obstacle.

7.3.2 Effect of Exterior Glass Windows

In Section 6.3.2, reflections from exterior glass windows were found to have significant contributions to the received power in the shadowed region. In this section, the environment investigated considers the double corner geometry which is fully surrounded by exterior glass windows as shown in Fig. 7.8. This environment is similar to that investigated in Section 7.3.1, but with the presence of an additional glass window (Wall 8). This setup permits a triply-reflecte component from exterior glass windows to propagate to the deep shadowed region where the direct component was found to be dominant (Fig. 7.7(b)). The purpose of this investigation is to examine a change of the dominant mechanisms if another potential significant contributor to the received power exists. Transmitter T3 and a frequency of 1.0 GHz were used. The characteristics of the dominant mechanisms and the associated implications with regard to the effect of exterior glass windows are discussed.
Figure 7.7: Graphs showing the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution of each region to the observation area when the internal concrete wall is either absent or present. Transmitter T3 is located at (0, −3.3) m.
Figure 7.8: Plan view of the double corner geometry which is fully surrounded by exterior glass windows. Transmitter T3 is indicated by ×, and the observation area is bounded by ---.

Component Attributes

Fig. 7.9 shows the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution (rounded to a whole number) of each region to the total area considered when the discrete obstacle is fully surrounded by exterior glass windows. The results have shown that the received power in the region which is previously dominated by the direct component is now contributed by the triply-reflected component from exterior glass windows ($R_3R_4R_5$). The received power in other regions such as those dominated by the doubly-reflected component (36%), or the combined reflected-diffracted component (13%) are observed to remain largely the same. The region where the direct component has shown to be significant is very small and of secondary importance (i.e. region $R_3R_4R_5|T$ is only contributed 2% of the total area), suggesting that the direct component can be neglected in this case.

Implications

Although a triply-reflected component generally propagates a longer distance than a direct component does, the results have shown that the triply-reflected component is dominant. This means that nearby reflecting surfaces can be important, and reflections from these surfaces are likely to be dominant provided that no significant obstacle blocks the reflected paths. In practice, furniture and other objects (known as the environmental clutter) could scatter the propagating energy, and this effect is likely to be prominent when the propagation path is long. Therefore, identifying the dominant mechanisms may also
need to include the environmental clutter. Further investigation which adopts a heuristic approach to include such an effect is conducted in Chapter 8.

### 7.3.3 Effect of Frequency Selection

As discussed in Section 6.3.3, the signal strength of a reflected/transmitted component from/through a dielectric wall is dependent on the operating frequency. Again, this section examines the change of the dominant mechanisms at other frequencies including 2.4 GHz and 5.8 GHz in the environment shown in Fig. 7.8. The characteristics of the dominant mechanisms and the associated implications with regard to the choice of frequency are discussed.

**Component Attributes**

Figs. 7.10(a)–(c) show the distinct regions in which the received power is dominated by different mechanisms at the frequencies of 1.0 GHz, 2.4 GHz, and 5.8 GHz, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole number) of each region to the total area considered. Fig. 7.10(a) is the same as in Fig. 7.9 and is repeated here for comparison. The results show that the triply-reflected component from Walls 5, 4, and 8 ($R_5R_4R_8$) becomes increasingly dominant at higher frequencies. This is evidenced by the region in which the received power is dominated solely by the triply-reflected component is 35%, 69%, and 99%, at 1.0 GHz, 2.4 GHz, and 5.8 GHz, respectively. On the other hand, the direct ($T$) and combined reflected-diffracted ($R_5R_4D$) components become less important at higher frequencies. For example at 2.4 GHz, Fig. 7.10(b) shows that they are not regarded as significant in any region.
This is because both the penetration and diffraction losses increase with the frequency, hence the reflected components become relatively more significant. Furthermore, the area in which these two components are previously dominant at 1.0 GHz is now dominated by the triply-reflected component.

At 2.4 GHz and 5.8 GHz, Figs. 7.10(b) and (c) show that a subset of the receiving locations which was dominated by the doubly-reflected component \((R_5R_4)\) at 1.0 GHz is now also dominated by the triply-reflected component \((R_5R_4R_8)\), despite an additional reflection loss. This is thought to be caused by the reflection loss of the doubly-reflected component that is higher than for the triply-reflected component. As a result, the effect of distance dependent loss becomes less influential to the dominant mechanisms. This observation is consistent with that found in the single corner geometry investigated Section 6.3.3, where higher-order reflections dominate lower-order reflections at higher frequencies.

**Implications**

In a double corner geometry which is fully surrounded by exterior glass windows, reflections are shown to be dominant and need to be considered at 1.0 GHz. Although a combined reflected-diffracted component is also found to be significant in the vicinity of the shadow boundary, the physical size of such a region is relatively small. In practice, combined reflected-diffracted component could be neglected with the consequence of power predictions being less accurate in the region around the shadow boundary.

As the frequency increases, reflections from exterior glass windows become increasingly dominant. From a modelling point of view, the model complexity is likely to be reduced at higher frequencies while retaining an acceptable prediction accuracy. In particular, the local mean estimates can be made by considering only the doubly- and triply-reflected components from the glass provided that no significant obstacle is in the propagation path. Additionally, geometries which can support higher-order reflections are equally important as they can support lower-order reflections. In some situations, higher-order reflections can even dominate lower-order reflections as shown in Figs. 7.10(b) and (c).

**7.3.4 Extension to the Discrete Obstacle**

The investigation of radio propagation in a double corner geometry has been extended to a discrete obstacle geometry by including two additional walls (i.e. Walls 9 and 10) shown in Fig. 7.1(b). As the energy can also propagate around the other double corner of the discrete obstacle, the other set of the candidate mechanisms which have the same
Figure 7.10: Graphs showing the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution of each region to the total area at (a) 1.0 GHz, (b) 2.4 GHz, and (c) 5.8 GHz. Transmitter T3 is located at (0, −3.3) m.
propagation process are expected to arrive at a receiving location. For example, doubly-reflected components from Walls 5 and 4 ($R_5R_4$) and Walls 5 and 10 ($R_5R_{10}$) both need to be considered due to a symmetry in the propagation environment. Of interest here is to observe the change of the dominant mechanisms in the deep shadowed receiving locations at different frequencies.

Component Attributes

Figs. 7.11(a) – (c) show the distinct regions in which the received power is dominated by different mechanisms in the discrete obstacle geometry at 1.0 GHz, 2.4 GHz, and 5.8 GHz, respectively. The associated pie charts indicate the percentage contribution (rounded to a whole number) of each region to the total area considered. It should be noted that regions which are dominated by components propagating via similar propagation paths have been regarded as the same region. For example, the region in which the received power is dominated by the triply-reflected component from Walls 5, 4, and 8 ($R_5R_4R_8$) is treated as the same as that dominated by the triply-reflected component from Walls 5, 10, and 8 ($R_5R_{10}R_8$), and is thus indicated by $R_5R_4(R_{10})R_8$. Similarly, the region in which the received power is dominated by the doubly-reflected component from Walls 5 and 4 then diffracted around the corner ($R_5R_4D$) is treated as the same as that reflected from Walls 5 and 10 then diffracted around the corner ($R_5R_{10}D$), and is thus indicated by $R_5R_4(R_{10})D$.

At 1.0 GHz, Fig. 7.11(a) shows that the received power at more than half of the locations is dominated by the doubly-reflected components (64%). When the propagation path of the doubly-reflected component is blocked by the discrete obstacle, the triply-reflected components from the glass become dominant. This is evidenced by the area which is dominated by the triply-reflected component from Walls 5, 4, and 8, or Walls 5, 10, and 8 (i.e. $R_5R_4(R_{10})R_8$) is in a quasi triangular shape due to the double reflection shadow boundaries. Similar to the results shown in Fig. 7.10(a), the combined reflected-diffracted component (i.e. $R_5R_4(R_{10})D$) is dominant near the double reflection shadow boundaries. Likewise, such a region is physically small and localised.

The triply-reflected components become prominent at higher frequencies. This is evidenced by that the region which is dominated by the triply-reflected components increases from 20% to 61% when the operating frequency increases from 1.0 GHz to 2.4 GHz. It is noteworthy that the region which is dominated by the doubly-reflected component from the lower half of the environment (i.e. $R_5R_{10}$) remains the same at higher frequencies. By contrast, the dominant mechanisms from the upper half of the environment has changed to the triply-reflected components at higher frequencies due to an additional loss caused by Wall 1.
Figure 7.11: Graphs showing the distinct regions in which the received power is dominated by different mechanisms, and the percentage contribution of each region to the total area in the central core geometry at (a) 1.0 GHz, (b) 2.4 GHz, and (c) 5.8 GHz. Transmitter T3 is located at (0, −3.3 m).
Implications

Due to the symmetrical layout, the dominant mechanisms including the doubly- and triply-reflected components which propagates around both side of the discrete obstacle can arrive at a receiving location and need to be considered at 1.0 GHz. As the operating frequency increases, the transmission loss through obstacles also increases. Although the energy which propagates around the discrete obstacle remains to dominate over that transmission through, the environmental layout is shown to have a significant influence on the dominant energy paths. For instance, if a reflected component which has transmitted through several internal partitions to reach a receiver, the accumulative loss is likely to be significant. In that case, the received signal strength is likely to be weak and can thus be neglected.

7.4 Summary

This chapter has investigated the propagation of energy which transmits through or propagates around the double corner of the discrete obstacle to reach a receiver. The effects of the internal structure of the discrete obstacle, exterior glass windows, and operating frequencies on the dominant mechanisms have been examined. The results have shown that reflections from exterior glass windows are the main energy contributors regardless of the internal structure of the discrete obstacle. This is because the concrete walls which form the discrete obstacle are highly lossy, and as a result the energy that propagates around will dominate. As the operating frequency increases, the significance of reflections also increases. Therefore, a propagation model that considers up to triply-reflected components may be sufficient for acceptable mean path loss predictions.

The investigation has also been extended to the discrete obstacle geometry where the energy can also propagate around another double corner to reach the other side of the discrete obstacle. Due to the symmetrical layout, reflections from the other side of exterior glass windows have also shown to be dominant and need to be considered. As the operating frequency increases, internal partitions have shown to cause an increased attenuation to the reflected components. Therefore, a detailed physical layout and the operating frequency must be considered in order to accurately identify the dominant mechanisms in this geometry.
Chapter 8

Mechanistic Models and Performance Evaluation

8.1 Introduction

Chapters 5–7 have suggested dominant propagation mechanisms in an open plan office and corridor, a single corner, and a double corner geometries, respectively. It is likely that combinations of these geometries can be used to represent indoor environments, in which dominant mechanisms can be inferred. While only the basic architecture of the environments have been considered, including additional internal details (e.g. partitions and environmental clutter) might be expected to change the dominant propagation mechanisms and therefore the received signal strengths.

In this chapter, the mechanistic models are proposed based on the results in Chapters 5–7 for the Engineering Tower that is described in Chapter 4. In order to evaluate the performance of the mechanistic models, the path gain predictions are compared with the experimental measurements [83]. As the environment contains several internal partitions (mostly made of drywall) and is relatively cluttered, the detailed floor layout and the effect of environmental clutter have also been considered. The model accuracy, complexity, and efficiency for mechanistic models are compared with existing propagation models (i.e. the ITU-R [37], the Ericsson [38], the log-distance [8], and the COST 231 multi-wall [40] models). The outcome of this chapter not only provides insights into underlying propagation behaviour, but the mechanistic models developed for the test site are also justified.

Section 8.2 describes the propagation measurement campaign and the mechanistic characterisation of the Engineering Tower. Two environmental models with simplified and detailed floor layouts have been used for investigating a level of environmental detail required to achieve an acceptable accuracy. In addition, a heuristic approach for
characterising the effect of environmental clutter has also been proposed. The prediction performance is obtained by comparing with the measurements. It is noted that there can be more than one dominant mechanism in a receiving location. For this reason, Section 8.3 presents the performance of the Mechanistic models (A1–F1 and A2–F2), each model has considered a different number of mechanisms. This investigation provides guidance for selecting appropriate mechanisms in the balance of model accuracy and complexity. Section 8.4 compares the Mechanistic model D1 with existing indoor propagation models, namely the ITU-R, the Ericsson, the log-distance, and the COST 231 multi-wall models. Particularly, the comparisons are focused on the model accuracy, complexity, and computational efficiency. Lastly, Section 8.5 summarises this chapter.

8.2 Propagation Study in the Engineering Tower

Because the description of the environmental model is limited, an error in the estimates of the mean received signal strength is inevitable. To quantify the level of error, the path gain predictions in the Engineering Tower are compared with the experimental measurements. In this section, two different environmental models — termed Simplified and Detailed — are proposed for both the ray and the mechanistic predictions. The simplified model includes only the essential partitions for forming the central concrete core and the internal corridor, whereas the detailed model includes the majority of the partitions present in the environment. The purpose of using two environmental models is to investigate the required detail of the environment for achieving an acceptable prediction accuracy.

From Chapters 5–7, significant contributors to the mean received power in different canonical geometries have been suggested. Based on these results, comprehensive mechanistic models for the Engineering Tower can be formulated. It should be noted that the observed dominant mechanisms are based on the 2D modelling of the canonical geometries, therefore the validity of the mechanistic model should be assessed to ensure the 2D mechanisms are transportable to 3D. Section 8.2.1 reports the narrowband measurements which have been conducted in the Engineering Tower. Section 8.2.2 describes the mechanistic models for predicting the path gains across the entire floor. Section 8.2.3 compares the ray and mechanistic path gain predictions using both the simplified and detailed environmental models against the experimental measurements. Section 8.2.4 quantifies the effect of environmental clutter (e.g. book shelves, desks, and file cabinets) and discusses its impact on the overall mean received signal strengths.
8.2.1 Narrowband Measurements and Results

Measurement Setup

Narrowband measurements were conducted at 1.8 GHz in Level 6 of the Engineering Tower at The University of Auckland [83]. Fig. 8.1(a) shows the floor layout, the transmitting (Tx, indicated by □) and receiving (indicated by ●) antenna locations. The transmitting antenna was located at the junction of the corridor, and a total of 55 receiving locations were measured across the entire floor. It should be noted that a significant number of the receiving locations were in the corridor (a total of 23 locations), whereas only 2–3 receiving locations were inside each office (giving a total of 30 locations inside the offices). This is because Level 6 of the building consists of primarily academic staff offices, most offices contain at least a desk, metal bookshelf (usually with many books) and file cabinet. As a result, measurements taken inside the offices were necessarily restricted. During the experimental measurements, both the vertically-polarised transmitting and receiving discobee antennas were positioned approximately 1.6 m from the floor. The path gain was measured by averaging the instantaneous received powers to remove the effects of multipath fading. This is obtained by rotating the receiving antenna around a 1 m diameter circular locus.

Measurement Results

Fig. 8.1(b) shows the measured path gain contours in Level 6 of the Engineering Tower with the floor plan superimposed. It should be noted that the contours are interpolated from the 55 measured locations indicated by ●. Although the contours appear to be smooth, in reality an abrupt drop of the path gain can be expected when the propagating wave transmits through a highly lossy wall or obstacle. In the corridor area where a line-of-sight (LOS) path exists, and in the nearby offices (labelled “A” in Fig. 8.1(a)) where the direct component would have to transmit through a drywall to reach the receiver, the path gain is between $-55$ dB and $-40$ dB. For the offices which are further down but still adjacent to the corridor (labelled “B”), the path gain has decreased appreciably to between $-75$ dB and $-65$ dB. This is likely due to more partitions and potentially more environmental clutter on the propagation path to cause additional attenuation. When receivers are located around the corners behind the central concrete core, the path gain has further reduced. For example, the path gain in offices labelled as “C” and the adjacent corridor area is between $-95$ dB and $-85$ dB. This suggests that the central concrete core causes a severe shadowing effect, which is consistent with the observation made from the FDTD simulations in Section 4.2.2.
Figure 8.1: Graphs showing (a) the floor layout, and (b) the measured path gain in Level 6 of the Engineering Tower. The transmitting and receiving antennas locations are indicated by □ and ⋄, respectively.
8.2.2 Mechanistic Modelling of the Engineering Tower

To determine the required environmental detail for achieving the acceptable accuracy, Simplified and Detailed environmental models have been proposed for the path gain predictions, as shown in Figs. 8.2(a) and (b), respectively. The simplified model includes four 0.3 m thick concrete walls forming a hollow concrete core in the centre. With the addition of another concrete wall inside the concrete core, the inner area has been divided into two. Specifically, the upper area houses the two elevators, whereas the lower area houses the stairwell and associated services. Four 1.2 cm thick partitions fabricated of drywall are added, creating a corridor around the concrete core and dividing the remaining space into four open plan offices. This environment is surrounded by glass windows which are 0.6 cm thick.

Similarly, the detailed model comprises all the partitions as that in the simplified model, but the open plan offices area are further divided into fifteen individual offices. Comparing the detailed model with the actual floor layout shown in Fig. 8.1(a), they are now similar to a significant extent. As the characteristics of the walls do not change appreciably between 1.0–1.8 GHz [37], the same material properties which are used for the investigations at 1.0 GHz were adopted (Table 5.1).

Based on the transmitting antenna location, the floor has been divided into three regions, named Regions I, II, and III. In particular, a generic canonical geometry can be used to represent each region. For example, Region I (shaded yellow) is the area where a direct propagation path may be blocked by partitions made of drywall, and can thus be represented by an open plan office and corridor geometry as investigated in Chapter 5. A direct and a singly-reflected component from the concrete are found to be the dominant mechanisms, and therefore need to be considered when calculating the path gain.

Region II (shaded pink) is the area where receiving locations are shadowed by a significant obstacle, and can thus be represented by a single corner geometry as investigated in Chapter 6. Due to the complicated propagation process in this geometry where no particular component is always dominant, the five most dominant propagation components have been considered. These components include the direct, singly- and doubly-reflected, combined reflected-diffracted, and purely diffracted components.

Region III (shaded blue) is the area where components are transmitted through a concrete wall into the concrete core. In this case, a direct transmitted component is found to be adequate for predicting the received signal strengths. To summarise the dominant mechanisms (in Regions I, II, and III) that are used for the mechanistic model predictions, Table 8.1 describes the dominant mechanisms included and their notations for each region.
Mechanistic Models and Performance Evaluation

Figure 8.2: Graphs showing the simplified and detailed environmental models for path gain predictions in the Engineering Tower. The transmitting antenna (Tx) is indicated by □.

8.2.3 Comparison of Predicted and Measured Results

Chapters 5–7 have shown that the majority of mechanisms can be represented as rays. Fundamentally, mechanistic models are similar to ray models, except that only significant contributors to the mean received signal strengths have been considered. For this reason, it is appropriate to compare both the ray and mechanistic models predictions with the measurements. The purpose of this double comparison is to ensure that the prediction errors are not attributed by the misidentification of the dominant mechanisms. Similarly, the simplified and detailed environmental models shown in Figs. 8.2(a) and (b) are also used for the ray model predictions. The components considered in ray models for Regions I, II, and III are described in Eqs. (5.1)–(5.3), Eqs. (6.1)–(6.5), and Eq. (7.2), respectively.

To compare with the measurements, 2D results have been extended to 2.5D by considering isotropic spreading in the third (vertical) dimension. This assumes there are no

<table>
<thead>
<tr>
<th>Region</th>
<th>Dominant Mechanisms Included</th>
<th>Notations</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>Direct propagation and single reflection from the concrete wall</td>
<td>$T, R$</td>
</tr>
<tr>
<td>II</td>
<td>Direct propagation, single and double reflections from glass windows, combined reflection and diffraction, and pure diffraction</td>
<td>$T, R, R^2, RD, D$</td>
</tr>
<tr>
<td>III</td>
<td>Direct transmission</td>
<td>$T$</td>
</tr>
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Table 8.1: Summary of the dominant mechanisms included in each region for path gain predictions across the entire floor of the Engineering Tower.
changes to the geometry in the vertical plane as discussed in Section 3.4.2. However, in order to make a meaningful comparison with the measurements, a calibration factor between 2.5D and 3D in free space is also included. In this case, the calibration factor\(^1\) is found to be 0.0133 in electric field at the frequency of 1.8 GHz. For both the ray and mechanistic path gain predictions, receiving locations have been distributed in a regular rectangular lattice with spacing of 6 cm, resulting a total of 94864 receiving points\(^2\).

**Predictions Using The Simplified Model**

Figs. 8.3(b) and (c) show respectively the ray and mechanistic path gain predictions with the simplified floor layout superimposed. For comparison, the measured path gain contours shown in Fig. 8.3(a) is repeated here. As expected, similar observations can be made from both the ray and mechanistic predicted contours, where the path gain in Region I is between $-55$ dB and $-40$ dB in the corridor, and between $-65$ dB and $-45$ dB in the open plan offices. In the transition area between Regions I and II, an abrupt decrease in power can be seen. This is due to the direct component suffering severe attenuation from transmission through the concrete walls. Generally, the path gain in Region II is between $-80$ dB and $-65$ dB. Except for the area where glass reflected component is no longer exists, the path gain is approximately $-85$ dB. In Region III, the path gain predictions from both the ray and mechanistic models are the same since both consider only the direct transmitted component.

Figs. 8.3(d) and (e) show the comparison between the ray and mechanistic predictions with the measurements. Due to the limited resolution of the data set, the error contours for the entire floor are therefore interpolated from the 55 measured locations (indicated by ●). The areas coloured red and blue represent overestimation and underestimation of the received power, respectively. Apart from the corridor area in Region I, the path gain in a majority of the locations is generally overestimated by 10– 20 dB. Figs. 8.4(a) and (b) show the probability of error occurrence based on the 55 measured locations for the ray and mechanistic models, respectively. From both results, similar means $\mu$ (7 dB and 6.6 dB) and standard deviations $\sigma$ (both 6.6 dB) of the prediction error are obtained. Additionally, a large spread of prediction error ranging from $-8$ dB to 20 dB is observed.

\(^1\)The calibration factor is obtained by comparing the free space offset between 2.5D and 3D that is computed from the Friis equation [25, p.71].

\(^2\)The computational time required for the mechanistic predictions is approximately 15 minutes. Comparing with the FDTD simulations (4-5 hours) described in Section 4.2.1, the time required for meaningful estimates of path gain is significantly reduced. This is only for the indication of computational time required for each method. They should not be compared directly as the density of receiving locations for ray-based methods can be much coarser than for the FDTD method.
These results suggest two possible reasons to cause overestimation of the path gain. First, the simplified model includes inadequate internal details (i.e. partitions between offices), which in turn underestimates the actual attenuation when the propagating wave transmits through several internal partitions. Second, environmental clutter (e.g. books, shelves, and desks in the offices) which can potentially scatter or absorb the energy have not been considered. Fortunately, the floor layout of the building provides an exact location of internal partitions, allowing internal details to be considered in an appropriate manner. To eliminate uncertainty introduced by an overly simplistic description of the environment, the detailed model (shown in Fig. 8.2(b)) which incorporates the majority of internal partitions has also been used to predict path gain for the entire floor.

Predictions Using The Detailed Model

For simplicity, it is assumed that transmission loss through one internal partition (made of drywall) is 1.0 dB/partition irrespective of incident angles. To predict the power of an arriving component at a receiving location, both the propagation distance and the number of internal partition transmissions need to be considered as illustrated in Fig. 8.5. In this example, the singly-reflected component from the glass not only experiences the distance-dependent loss from the actual propagation distance \( d \), but also suffering an additional 6 dB loss from transmission through six internal partitions.

Comparing the predicted path gains using the detailed model in Figs. 8.6(b) and (c) with that using the simplified model in Figs. 8.3(b) and (c), it is evident that the path gain has decreased by up to 5 dB and 10 dB in Region I (office area only) and Region II (both corridor and office area), respectively. The inclusion of internal details has a greater influence on the path gain predictions in Region II because arriving components are required to transmit through more partitions. Path gain predictions for the corridor area in Region I, and inside the concrete core in Region III remain the same, as there is no change to the geometry in the propagation path.

Figs. 8.6(d) and (e) compare the path gain predictions with the measurements, when the detailed model is used. The areas coloured red and blue represent overestimation and underestimation of the received power, respectively. Although adding internal details improves the prediction accuracy, the path gains in a majority of the locations are still overestimated by 5–10 dB. From the 55 measured locations, Figs. 8.7(a) and (b) show that the ray and mechanistic mean prediction errors are improved by 1.6 dB and 1.8 dB, respectively, and the standard deviations \( \sigma \) remain approximately the same (i.e. improved less than 1 dB).
Figure 8.3: Graphs (a) – (c) showing the measured and the predicted path gains (PG) across the entire floor when the simplified environmental model is used, while (d) and (e) comparing the measured (PG\textsubscript{m}) and the predicted (PG\textsubscript{p}) path gains where Error = PG\textsubscript{p} − PG\textsubscript{m}. In (d) and (e), the areas coloured red and blue indicate overestimation and underestimation of PG, respectively. The transmitting antenna is indicated by □, and receiving antennas are indicated by ●.
In reality, internal partitions are generally consisted of two sheets of drywall attached to wooden frames with an air gap in between. Although internal partitions here have been modelled as solid homogeneous dielectric slabs with permittivity \( \epsilon = 2\epsilon_0 \), this cannot solely account for the difference between the measured and predicted results. It can be supported by the fact that the power overestimation is largely comparable in Regions I and II, irrespective of the number of partitions on the propagation path. Up to this point, though the results have shown that adding internal details can improve the prediction accuracy by 5–10 dB, however the path gains are still overestimated by 5–10 dB in a majority of the locations. This may be due to the cumulative effect of environmental clutter which have not been considered.

### 8.2.4 Presence of Environmental Clutter

In reality, books, shelves, and desks (hereafter referred to as environmental clutter) can potentially scatter or absorb the energy, thus reduce the received power. Objects regarded as environmental clutter are usually random in size, position, and properties, hence modelling their presence in a deterministic manner is challenging. Moreover, precise inclusion of environmental clutter could make the geometry too site-specific. For these reasons, an heuristic approach which accounts for the effect of environmental clutter has been adopted.

#### Quantifying the Effect of Environmental Clutter — An Heuristic Approach

To incorporate the clutter effect in a straightforward manner and without adding a considerable computational burden, an heuristic approach which incorporates a clutter coefficient \( \alpha \) has been used. This approach assumes that components with any segment...
of the propagation path in the cluttered part of the environment (i.e. in the offices or the concrete core) can be attenuated. This means in addition to the distance-dependent and partitions transmission losses, components also suffer an extra attenuation caused by environmental clutter. In this case, clutter attenuation is modelled using a clutter coefficient $\alpha$ (dB/m), and is directly proportional to the total propagation distance. The power of a component (in Watts) which suffers from clutter attenuation based on the total propagation distance is estimated by

$$P_{\text{clutter\_total}} = \left( \frac{A}{d_{\text{total}}^2} \right) 10^{\left( \frac{\alpha d_{\text{total}}}{10} \right) \kappa}$$

where $A$ is the scaling factor used to account for the effects of frequency and antenna gains, $d_{\text{total}}$ is the total propagation distance, $\alpha$ is the clutter coefficient, and $\kappa$ is the total transmission loss through partitions.

This is likely to be appropriate to a certain extent as the energy of a component with longer propagation distance is more likely to be absorbed or scattered, thus yielding a higher attenuation. It should be noted that components with clutter-free propagation paths do not suffer clutter attenuation. In this case, those are components that propagate along the corridor in Region I without entering the offices.

**Prediction Results With Environmental Clutter**

Fig. 8.8 shows the ray and mechanistic path gain predictions across the entire floor, when the clutter coefficient $\alpha$ of 0.4 dB/m, 0.6 dB/m, and 0.8 dB/m are considered. The
(a) Measurements

(b) Ray model

(c) Mechanistic model

(d) Ray prediction error

(e) Mechanistic prediction error

Figure 8.6: Graphs (a) – (c) showing the measured and the predicted path gains (PG) across the entire floor when the detailed environmental model is used, while (d) and (e) comparing the measured (PGm) and the predicted (PGp) path gains where Error = PGp − PGm. In (d) and (e), the areas coloured red and blue indicate overestimation and underestimation of PG, respectively. The transmitting antenna is indicated by □, whereas the receiving antennas are indicated by •.
detailed environmental model is used and also superimposed on the path gain prediction contours. It is evident that the path gains in the corridor area in Region I are similar for all the clutter coefficients considered. This is because a majority of the received power is contributed by the direct component which has a clutter-free propagation path. As expected, the path gain in most of the locations is decreased when the clutter coefficient is increased. Comparing Regions I and II, it is notable that the path gains have generally decreased more rapidly in Region II as the clutter coefficient increases. This observation is due to the fact that arriving components in Region II have longer propagation distances, and thus experiencing higher clutter attenuation.

**Comparisons of Predicted and Measured Results**

Fig. 8.9 shows the prediction errors between the predicted and measured path gains when the effect of environmental clutter have been considered. Comparing the error contours of environmental clutter which has been neglected in the model (shown in Figs. 8.6(d) and (e)) with that incorporated the clutter coefficient of 0.4 dB/m, the prediction accuracy has improved considerably. For example, the prediction error in the offices in Region I is between 10 – 15 dB when environmental clutter is neglected. Modelling clutter effects with a clutter coefficient of 0.4 dB/m improves the prediction error to 5 – 10 dB in the same area. Moreover, the prediction accuracy has improved significantly in Region II where the error is now 0 – 5 dB (5 – 15 dB when clutter is neglected) in a majority of the locations.

As the clutter coefficient increases to 0.6 dB/m, the prediction accuracy has further improved. A maximum prediction error in the offices in Region I is now less than 10 dB, and the area with a small error (shaded green) has generally increased. In Region II, it is evident that a considerable number of locations have a small error or the power is slightly
underestimated. As in the previous case, the path gains in the transition area between Regions I and II are also underestimated. As expected, increasing the clutter coefficient further ($\alpha = 0.8 \text{ dB/m}$) improves the prediction accuracy in Region I, but the path gains in a large number of the locations in Region II are now underestimated.

Fig. 8.10 shows the probability of error occurrence for three different clutter coefficients considered. For the clutter coefficient of 0.4 dB/m, the means and standard deviations are approximately $1-2 \text{ dB}$ and $6 \text{ dB}$, respectively, suggesting that the received power in general is slightly overestimated. On the other hand, the results for the clutter coefficient of 0.8 dB/m have shown that the received power is slightly underestimated and the errors are varied significantly. It has appeared that the effect of environmental clutter in the Engineering Tower can be modelled more appropriately with the clutter coefficient $\alpha$ of 0.6 dB/m, where the errors are centred near zero with the standard deviations of $6-7 \text{ dB}$.

Notice that one should not directly compare the performance of the ray model and the mechanistic model based on the results shown in Fig. 8.10. This is because the clutter coefficients are estimated heuristically which may not truly represent the environment presented. The resultant path loss may be favoured to one model or another in terms of prediction accuracy.

It is assumed that components which propagate into or via the cluttered part of the environment (i.e. the offices) to reach receiving locations are scattered or absorbed by environmental clutter. For simplicity, the attenuation is approximated based on the total propagation distances. However, the clutter attenuation can sometimes be overestimated if a substantial segment of the propagation path is in fact clutter-free (i.e. in the corridor). Predictions in Region II are particularly susceptible to such an overly simplistic approximation as some components are mostly propagated along the corridor to reach the receiving locations. To investigate the improvement of the prediction accuracy when a detailed propagation path is modelled, cluttered and uncluttered paths have been considered explicitly. This means the clutter attenuation is only applied to propagation segments which are in the cluttered part of the environment.

**Incorporating Attenuation For Cluttered Paths Only**

The clutter coefficient $\alpha$ of 0.6 dB/m has shown to be appropriate for characterising clutter in the environment considered, and thus is adopted. The power of a component (in Watts) which suffers an additional attenuation from propagation in the cluttered part of the environment only is estimated by

$$P_{\text{clutter partial}} = \left( \frac{A}{d^2_{\text{total}}} \right) 10^{(\alpha d_{\text{total}}/10)} K.$$  (8.2)
where $A$ is the scaling factor used to account for the effects of frequency and antenna gains, $d_{\text{total}}$ is the total propagation distance, $\alpha$ is the clutter coefficient, $p$ is a fraction of the total propagation distance which is in the cluttered part of the environment, and $\kappa$ is the total transmission loss through partitions.

Figs. 8.11(a) and (b) respectively show the path gain estimates and prediction errors when compared with the measurements. Comparing the prediction error contours with that incorporates the clutter attenuation based on the total propagation distance shown in Fig. 8.9(b), similar observation can be made where the path gains in Region II are mostly underestimated. Likewise, the probability of error in the 55 measured locations shown in 8.11(c) remains largely the same, where the mean prediction error is close to zero and the standard deviation is 6–7 dB.

Considering an additional clutter attenuation in only the cluttered part of the environment in Region II does not improve the prediction accuracy significantly. This is thought to be caused by components with a substantial uncluttered segment in their propagation path are not the dominant mechanisms for contributing the received power in the locations. For example, Fig. 8.12 shows that both the diffracted component ($D$) or the combined reflected then diffracted component ($RD$) propagate mostly in the corridor to reach the receiving location. On the other hand, the doubly-reflected component ($R^2$) from the glass propagates through the offices, and therefore suffers from substantial clutter attenuation. In this case diffraction loss around the corner is so significant, the diffracted components (i.e. $D$ and $RD$) are therefore not the dominant components. As a result, the prediction accuracy has not been notably improved.

\section*{8.3 Prediction Accuracy Versus Model Complexity}

In any given receiving location, the mechanisms which should be considered are somewhat dependent on the required model performance. As summarised in Table 8.1, there is more than one mechanism which may need to be considered for predicting path gains in Regions I and II. In this section, the Mechanistic models ($A_1 - F_1$, and $A_2 - F_2$) with different permutations for Regions I and II are therefore used to investigate the trade-off between the model accuracy and complexity. In Region III, the direct transmitted component is always included, as it is the only mechanism required to adequately predict the received power in the region.

Table 8.2 gives an indication of the model performance by progressively excluding the candidate mechanisms in Regions I and II. Particularly, the Mechanistic models $A_1 - F_1$ exclude the candidate mechanisms in Region II only, whereas the Mechanistic models $A_2 -$
Mechanistic Models and Performance Evaluation

$\alpha$ (dB/m) | Ray model | Mechanistic model
---|---|---
| ![Graph](image1) | ![Graph](image2) | ![Graph](image3) |
(a) 0.4

| ![Graph](image4) | ![Graph](image5) | ![Graph](image6) |
(b) 0.6

| ![Graph](image7) | ![Graph](image8) | ![Graph](image9) |
(c) 0.8

**Figure 8.8:** Graphs showing the path gain predictions of the ray and mechanistic models for the clutter coefficient $\alpha$ of 0.4 dB/m, 0.6 dB/m, and 0.8 dB/m. The transmitting antenna is indicated by $\Box$. 
8.3 Prediction Accuracy Versus Model Complexity

\[ \alpha \text{ (dB/m)} \]

Ray model

Mechanistic model

(a) 0.4

(b) 0.6

(c) 0.8

\[ Error = |4P_y^p - 4P_y^m| \]

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Table 8.10: Probability of the prediction error occurrence at the 55 measured locations (indicated by • in Fig. 8.9(a)) of the ray and the mechanistic models for the clutter coefficient $\alpha$ of 0.4 dB/m, 0.6 dB/m, and 0.8 dB/m.

<table>
<thead>
<tr>
<th>$\alpha$ (dB/m)</th>
<th>Ray model</th>
<th>Mechanistic model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 0.4</td>
<td><img src="image" alt="Ray model 0.4 dB/m" /></td>
<td><img src="image" alt="Mechanistic model 0.4 dB/m" /></td>
</tr>
<tr>
<td>(b) 0.6</td>
<td><img src="image" alt="Ray model 0.6 dB/m" /></td>
<td><img src="image" alt="Mechanistic model 0.6 dB/m" /></td>
</tr>
<tr>
<td>(c) 0.8</td>
<td><img src="image" alt="Ray model 0.8 dB/m" /></td>
<td><img src="image" alt="Mechanistic model 0.8 dB/m" /></td>
</tr>
</tbody>
</table>

Figure 8.10: Probability of the prediction error occurrence at the 55 measured locations (indicated by • in Fig. 8.9(a)) of the ray and the mechanistic models for the clutter coefficient $\alpha$ of 0.4 dB/m, 0.6 dB/m, and 0.8 dB/m.
### 8.3 Prediction Accuracy Versus Model Complexity

<table>
<thead>
<tr>
<th>Ray model</th>
<th>Mechanistic model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Ray model" /></td>
<td><img src="image2.png" alt="Mechanistic model" /></td>
</tr>
<tr>
<td><img src="image3.png" alt="Ray model error" /></td>
<td><img src="image4.png" alt="Mechanistic model error" /></td>
</tr>
<tr>
<td><img src="image5.png" alt="Ray model probability" /></td>
<td><img src="image6.png" alt="Mechanistic model probability" /></td>
</tr>
</tbody>
</table>

**Figure 8.11:** Graphs showing (a) the path gain estimates, (b) the prediction error, and (c) the probability of the error occurrence for both the ray and mechanistic models which consider an additional attenuation in the cluttered part of the environment only.
Figure 8.12: Illustration of the propagation paths for the diffracted ($D$), combined reflected then diffracted ($RD$), and doubly-reflected ($R^2$) components when a receiving location is in Region II. In this example, both components $D$ and $RD$ have paths which are substantially uncluttered (i.e. in the corridor), whereas component $R^2$ has most of the propagation path in the cluttered part (i.e. in the offices) of the environment.

F2 exclude the candidate mechanisms in both Regions I and II that are listed in Table 8.1. For example, the Mechanistic model A1 includes all the candidate mechanisms. The Mechanistic models B1 and C1 include only four candidate mechanisms in Region II with $D$ and $RD$ being excluded, respectively. The Mechanistic models D1, E1, and F1 include three, two and one candidate mechanisms, respectively. Similarly, the Mechanistic models A2 – F2 respectively include the same candidate mechanisms as that in the Mechanistic models A1 – F1 in Region II, but only include the direct component $T$ in Region I.

For the Mechanistic model A1, results indicate that the mean error $\mu$ of $-0.2$ dB, standard deviation $\sigma$ of $5.4$ dB, maximum negative error of $-18.9$ dB, and maximum positive error of $10.8$ dB are obtained across the entire floor. Additionally, $34.5\%$ and $70.1\%$ of the predictions with the error less than $3$ dB and $6$ dB, respectively, suggesting that a substantial number of locations ($35.6\%$) have the prediction error between $3$ – $6$ dB. As the number of the candidate mechanisms incorporated decreases, the performance of the model degrades. However, this behaviour has not indicated in the performance statistics evidently as it is only changing the predictions in Region II. When observing the error contours across the entire floor for the Mechanistic models A1 – F1 shown in Fig. 8.13, degradation in the prediction accuracy can be visibly seen.
Furthermore, a notable change in the prediction accuracy shown by the error contours can be observed for the Mechanistic models D1 and E1. In particular, the percentage of the prediction error less than 6 dB (from 66.5% to 59.6%) and the mean (from −0.6 dB to −1.1 dB) are degraded when the number of the candidate mechanisms considered in Region II is reduced from three to two. This suggests a minimum of three mechanisms namely $T$, $R$, and $R^2$ should be included in Region II. Incorporating more candidate mechanisms does not improve the overall error mean and standard deviation significantly in this case. Similar trends can also be observed for the Mechanistic models A2–F2, except for the Mechanistic model D2 has the mean prediction error of −1.7 dB. If this is regarded as acceptable, incorporating only a direct component in Region I is adequate for predicting the path gain. However, a more complicated model (considering more candidate mechanisms) may still be necessary if more receiving locations with an error less than 3 dB in Region I must be achieved.

8.4 Comparison With Other Propagation Models

Currently, there are a number of indoor propagation models which have been used in system planning [8, 37, 38, 40]. Particularly, semi-empirically based propagation models are popular as they are generally simple and computationally efficient, which is of great importance in practice. In this section, existing propagation models including the ITU-R [37], the Ericsson [38], the log-distance [8], and the COST 231 multi-wall [40] models are applied to the Engineering Tower. Additionally, the Mechanistic model D1 described in Section 8.3 and the ray model are also applied to the same environment. The model performances are compared, and the trade-off between model accuracy, complexity, and efficiency are also discussed.

ITU-R Model

The Radiocommunication Sector of the International Telecommunication Union (ITU-R) has carried out several propagation measurements in residential, office, and commercial environments [37]. The measurement results suggest that the floor penetration loss should be accounted for explicitly, whereas the path loss between transmitting and receiving antennas on the same floor can be included implicitly by changing the path loss exponent $n$. Additionally, path loss variation with the frequency is assumed to be the same as in free space. The path gain formulation is given by [37, p. 3]

$$PG_{\text{dB}} = -(20 \log(f) + 10n \log(d) + L_f(n_f) - 28)$$  \hspace{1cm} (8.3)
### Table 8.2: Model performance statistics with different candidate mechanisms considered in Regions I and II

<table>
<thead>
<tr>
<th>Region</th>
<th>Model</th>
<th>Neg. Error</th>
<th>95% CI</th>
<th>Model Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Region I**
  - Model 1: 
    - Max Error: 3.8
    - 95% CI: [-3.2, 2.2]
    - Neg. Error: 53.7
  - Model 2: 
    - Max Error: 3.6
    - 95% CI: [-3.6, 1.0]
    - Neg. Error: 70.5
  - Model 3: 
    - Max Error: 3.9
    - 95% CI: [-1.7, 2.1]
    - Neg. Error: 64.0

- **Region II**
  - Model 4: 
    - Max Error: 4.0
    - 95% CI: [-2.5, 1.5]
    - Neg. Error: 74.8
  - Model 5: 
    - Max Error: 4.1
    - 95% CI: [-0.5, 3.0]
    - Neg. Error: 74.0

- **Region III**
  - Model 6: 
    - Max Error: 4.2
    - 95% CI: [-2.0, 1.0]
    - Neg. Error: 74.0
  - Model 7: 
    - Max Error: 4.9
    - 95% CI: [-1.3, 1.9]
    - Neg. Error: 72.0

- **Region I**
  - Model 8: 
    - Max Error: 4.0
    - 95% CI: [-1.9, 2.9]
    - Neg. Error: 71.0
  - Model 9: 
    - Max Error: 4.0
    - 95% CI: [-0.5, 3.5]
    - Neg. Error: 69.6

- **Region II**
  - Model 10: 
    - Max Error: 4.0
    - 95% CI: [-0.5, 3.5]
    - Neg. Error: 69.4
  - Model 11: 
    - Max Error: 4.0
    - 95% CI: [-1.8, 1.9]
    - Neg. Error: 70.1

- **Region III**
  - Model 12: 
    - Max Error: 4.0
    - 95% CI: [-1.8, 1.9]
    - Neg. Error: 70.1
  - Model 13: 
    - Max Error: 4.0
    - 95% CI: [-0.5, 3.5]
    - Neg. Error: 69.6

- **Model Performance**
  - **T1**: 
    - Max Error: 3.9
    - 95% CI: [-3.5, 7.3]
    - Neg. Error: 74.8
  - **T2**: 
    - Max Error: 3.6
    - 95% CI: [-3.6, 0.5]
    - Neg. Error: 74.0

- **Mechanistic Models and Performance Evaluation**
Figure 8.13: Comparison of the measured path gain ($P_{G_m}$) and predicted path gain ($P_{G_p}$) for the Mechanistic models A1–F1, where $\text{Error} = P_{G_p} - P_{G_m}$. The transmitting and receiving antennas locations are indicated by □ and ●, respectively.
Mechanistic Models and Performance Evaluation

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Lower limit of path loss (dB)</th>
<th>Upper limit of path loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &lt; r &lt; 10</td>
<td>$30 + 20 \log(d)$</td>
<td>$30 + 40 \log(d)$</td>
</tr>
<tr>
<td>10 ≤ r &lt; 20</td>
<td>$20 + 30 \log(d)$</td>
<td>$40 + 30 \log(d)$</td>
</tr>
<tr>
<td>20 ≤ r &lt; 40</td>
<td>$-19 + 60 \log(d)$</td>
<td>$1 + 60 \log(d)$</td>
</tr>
<tr>
<td>40 ≤ r</td>
<td>$-115 + 120 \log(d)$</td>
<td>$-95 + 120 \log(d)$</td>
</tr>
</tbody>
</table>

Table 8.3: Ericsson indoor propagation model [84, p. 286]

where $f$ is the frequency (MHz), $n$ is the path loss exponent, $d$ is the direct path length, and $L_f(n_f)$ is the floor penetration loss which varies with the number of penetrated floors $n_f$. Based on the ITU-R recommendations, the path loss exponent $n = 3$ is found to be appropriate between 1.8 GHz to 2.0 GHz in office environments [84, p. 285], and is therefore used for predicting path gain in the Engineering Tower. In this case, the floor penetration loss $L_f(n_f)$ equals zero as both the transmitting and receiving antennas are on the same floor.

**Ericsson Model**

The Ericsson model is derived from propagation measurements which were conducted at around 900 MHz [38]. The path loss predictions are random and normally distributed between the two limits as indicated in Table 8.3 [84, p. 286] to account for the shadowing effect. It is noted that the path loss exponent increases from 2 to 12 as the distance increases, indicating a rapid power drop for a distant receiving location. In the Engineering Tower, the path loss exponent is mostly between 2 to 4 as the building is in a square shape, and the separation distances between transmitting and receiving antennas are mostly within 20 m in this case. To extend the Ericsson model for use at 1800 MHz, an extra path loss of 8.5 dB at all distances is added [84, p. 286].

**Log-Distance Path Loss Model**

The log-distance path loss model is a radio propagation model that predicts the path loss a signal encounters inside a building. The mean path loss increases exponentially with distance. Additionally, shadow fading caused by obstructions in buildings is assumed to be log-normally distributed, and is determined from experimental measurements. The mean path gain is given by [8]

$$PG(dB) = - \left( PL_0 + 10n \log\left(\frac{d}{d_0}\right) - X_g \right)$$

(8.4)

where $PL_0$ is the free space path loss at a reference distance $d_0$ (normally $d_0$ is 1 m for indoor environments), $n$ is the path loss exponent, $d$ is the separation distance between
the transmitter and receiver, and \( X_g \) is a zero-mean log-normally distributed random variable with standard deviation \( \sigma \) in decibels. Both parameters \( n \) and \( X_g \) are obtained from the measured data, and are based on a simplified characterisation of the environment (e.g. building type and transmission frequency). The database collected from extensive measurements in several buildings suggests that \( n = 3 \) and \( \sigma = 7 \) dB are appropriate for office environments at 1.8 GHz [8], and are therefore used for path gain predictions in the Engineering Tower.

**COST 231 Multi-Wall Model**

The COST 231 multi-wall model was developed by the European Cooperation of Scientific and Technology Research [40]. In addition to free space loss, wall and floor attenuation are considered explicitly. The wall attenuation is modelled to be directly proportional to the number of walls penetrated. The floor attenuation on the other hand is more complex as the loss increases more slowly for a propagating wave passing through second and more floors. The path gain formulation of the COST 231 multi-wall model is given by [84, p. 285]

\[
PG (dB) = - \left( L_{FS} + L_c + \sum_{i=1}^{W} L_{wi}n_{wi} + L_f n_f^{(n_f+2)/(n_f+1)-b} \right)
\]

(8.5)

where \( L_{FS} \) is the free space loss for the direct path between the transmitter and receiver, \( n_{wi} \) is the number of walls crossed by the direct path of type \( i \), \( w \) is the number of wall types, \( L_{wi} \) is the penetration loss for a wall of type \( i \), \( n_f \) is the number of floors crossed by the path, \( b \) and \( L_c \) are the empirically derived constants, and \( L_f \) is the loss per floor. The floor loss (the last term in Eq. (8.5)) equals zero for the case when both the transmitter and receiver are on the same floor. The common wall penetration losses \( L_w = 3.4 \) dB for light walls and \( L_w = 6.9 \) dB for heavy walls at 1.8 GHz [84, p. 285], and are therefore used to model the penetration loss through drywall and concrete, respectively.

**Path Gain Prediction Results**

Figs. 8.14(a) – (f) respectively show the path gain predictions across the entire floor using the ITU-R, Ericsson, log-distance, COST 231 multi-wall, Mechanistic D1, and ray models. For the ITU-R, Ericsson, and log-distance models predictions, the received power decreases exponentially with propagation distance. Additionally, internal details have not been explicitly considered, thus the contours remain in a circular shape. By contrast, the COST 231 multi-wall model shown in Fig. 8.14(d) considers walls which are on the direct propagation path, and incorporates the wall attenuation accordingly based on wall type. As a result, an abrupt decrease in the signal strengths is observed when a propa-
gating wave passes through a wall. This phenomenon is particularly visible in the area on the opposite diagonal of the concrete core where a direct component would have to transmit through at least three concrete walls to reach the receiving locations. Path gain contours for the Mechanistic model D1 shown in Fig. 8.14(e) and the ray model shown in Fig. 8.14(f) are similar. Specifically, an abrupt change of the power in the transition area between Regions I and II, and the diagonal corner on the opposite side of the concrete core can be observed. This is due to components which propagate on low loss paths which no longer exist in the region. For example, the rapid drop in the received power in Region II is due to the singly-reflected component from the glass which suffers significant attenuation from transmission through the concrete.

Comparisons of Predicted and Measured Results

Figs. 8.15(a)–(f) compare the predicted path gains with the measurements shown in Fig. 8.1(b). Due to the limited data set, the error contours are interpolated based on the 55 measured locations for the entire floor. Areas coloured red and blue correspond to locations where the predicted power is overestimated and underestimated, respectively. It is evident that the path gains are generally overestimated for the models which do not take internal details into consideration explicitly. For example, the ITU-R, Ericsson, and log-distance models overestimate the path gains by 10–20 dB when receiving locations are shadowed by the central concrete core. Furthermore, the path gains are also overestimated by 5–10 dB when several internal partitions (made of drywall) are in the direct propagation path.

On the other hand, model predictions which take internal details into consideration appear to be in better agreement with the measurements. This is evidenced by the prediction accuracy for the COST 231 multi-wall model, Mechanistic model D1, and ray model which are significantly improved. Particularly, the prediction errors for the COST 231 multi-wall model and the Mechanistic/ray models are 5–10 dB and −5–0 dB, respectively, in a majority of the locations in Region II. Generally, COST 231 model overestimates the received power. This may be because the true concrete wall attenuation is higher than that estimated (6.9 dB/wall), suggesting good estimates of wall attenuation are essential for achieving acceptable prediction accuracy. It should be noted that the Mechanistic model D1 and ray model prediction errors in Region II are generally small, except for areas immediate to the corners (i.e. the transitions between Regions I and II).

Figs. 8.16(a)–(f) show the probability of error occurrence for the 55 measured locations (indicated by • in Fig. 8.15) across the floor. It is evident that the prediction errors vary significantly for models which have not taken internal details into considera-
Comparison With Other Propagation Models

Overall, the average mean and standard deviation are 5.0 dB and 7.6 dB, respectively, indicating the predicted power is generally overestimated with a large variation. In contrast, the prediction errors have been shown to be normally distributed with a mean close to zero when internal details have been considered. The overall average mean and standard deviation are respectively 0.9 dB and 5.0 dB, which suggests that including internal details in the model can improve the prediction accuracy considerably.

There is an inevitable trade-off between model accuracy, complexity, and efficiency, especially when modelling a complicated environment. A more accurate model requires more physical internal details, therefore higher computational complexity may be necessary. Table 8.4 summarises the prediction accuracy for different propagation models, and provides a qualitative indication of their computational requirements. It is clear that models which do not consider the presence of the partitions explicitly tend to overestimate the path gains in this case. If a mean error of 4–6 dB and approximately 50% of the area with an error less than 6 dB is regarded as acceptable, the ITU-R, Ericsson, or log-distance models would be adequate for the path gain predictions. An advantage of using these models is that predictions can be made efficiently, which can be very useful in practice.

However, if a larger area (e.g. 70%) with the error less than 6 dB is required, physical details of the environment (e.g. floor layout and material properties of the partitions) should be considered. Though the prediction accuracy has improved significantly, modelling the environment into detail may drastically increase the computational burden. It should be noted that both the Mechanistic model D1 and COST 231 model require moderate physical details and computational complexity for the path gain predictions, but the Mechanistic model D1 outperforms the COST 231 model. For example, the mean prediction error for the Mechanistic model D1 (−0.6 dB) is closer to zero than the COST 231 model (2.9 dB). Furthermore, the Mechanistic model D1 is formulated with a deterministic basis, in which the predictions are made based on the actual dominant propagation mechanisms. By contrast, the COST 231 model is formulated without a physical basis by assuming a direct component is the dominant mechanism. This assumption has shown to be not always valid for indoor environments as there are frequently obstructions between transmitting and receiving antennas. If an obstacle is highly lossy, a significant amount of the receiving energy may propagate around rather than transmitting directly through the obstacle. In addition, the prediction accuracy of the COST 231 model is dependent on an estimation of the wall attenuation obtained from measurements, suggesting the model transportability may be limited. It should be noted that including more mechanisms does not improve the prediction accuracy significantly. For example, the ray model has the
mean error of 0.5 dB, standard deviation of 5.2 dB, and 70.2% of the area with an error less than 6 dB, which are similar to that obtained using the Mechanistic model D1.

8.5 Summary

This chapter has proposed a propagation model for predicting the path gains in the Engineering Tower. In particular, the model formulation is based on the dominant mechanisms which are identified from the canonical geometries investigated in Chapters 5–7. To evaluate the performance and applicability of the mechanistic model, the path gain predictions across the entire floor have been compared with the measurements. Two environmental models—termed Simplified and Detailed—have been used. Specifically, the simplified model includes only a basic architecture of the environment (i.e. concrete core and glass windows only), whereas the detailed model considers a majority of the partitions in the floor layout (i.e. also including internal partitions between offices). It was found that adding internal details improves the prediction error by 5–10 dB, suggesting that the received power can be influenced by both the building architecture as well as internal partitions. Furthermore, the presence of environmental clutter (e.g. bookshelves and desks) was found to reduce the received power considerably (5–10 dB). This suggests that indoor propagation is not only governed by the floor layout and material properties of partitions, but that environmental clutter can also have a significant influence.

In any given receiving location, the dominant mechanisms can sometimes be more than one. For this reason, the Mechanistic models (A1–F1 and A2–F2) with different permutations have been investigated. Considering both the model accuracy and complexity, the Mechanistic model D1 which incorporates the direct and singly-reflected component from the concrete for Region I (the open plan office and corridor scenario), the direct and up to doubly-reflected components from the glass windows for Region II (the single corner scenario) was found to be appropriate. Comparisons with existing propagation models have also been performed. The results show that models which do not consider internal details tend to overestimate the received power (with an average mean error of 5.0 dB). In contrast, models which include internal details were shown to have higher prediction accuracy (with an average mean error of 0.9 dB). Additionally, considering more components in the model does not improve the accuracy significantly.
Figure 8.14: Graphs showing the path gain predictions using the existing and proposed indoor propagation models for the Engineering Tower. The transmitting antenna is indicated by □.
Figure 8.15: Comparison of the measured path gain ($P_G_m$) and the predicted path gain ($P_G_p$) for the Engineering Tower, where $\text{Error} = P_G_p - P_G_m$. The transmitting and receiving antennas locations are indicated by $\square$ and $\bullet$, respectively.
Figure 8.16: Probability of the prediction error occurrence at the 55 measured locations (indicated by • in Fig. 8.15(a)) for different propagation models.
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Complexity</th>
<th>Physical Details</th>
<th>Computational</th>
<th>Error &gt; 6 dB</th>
<th>Negative Error (dB)</th>
<th>Positive Error (dB)</th>
<th>Max. Error (dB)</th>
<th>H</th>
<th>0.3</th>
<th>0.5</th>
<th>0.7</th>
<th>0.9</th>
<th>1.1</th>
<th>1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate</td>
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<td>0.0</td>
<td>-1.3</td>
<td>-1.6</td>
<td>-0.9</td>
<td>-0.6</td>
<td>1.1</td>
<td>2.2</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
</tr>
<tr>
<td>Moderate</td>
<td>Moderate</td>
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<td>2.3</td>
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<td>2.7</td>
<td>2.9</td>
<td>3.1</td>
<td>3.3</td>
</tr>
<tr>
<td>None</td>
<td>Low</td>
<td>70.0</td>
<td>1.7</td>
<td>-1.4</td>
<td>-1.6</td>
<td>-0.9</td>
<td>-0.6</td>
<td>1.1</td>
<td>2.2</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
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</tr>
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<td>72.2</td>
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<tr>
<td>None</td>
<td>Low</td>
<td>72.2</td>
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<td>2.3</td>
<td>2.5</td>
<td>2.7</td>
<td>2.9</td>
<td>3.1</td>
<td>3.3</td>
</tr>
</tbody>
</table>

**Table 8.4:** Model performance statistics and a qualitative indication of computational requirements for different path gain prediction models.
Chapter 9

Implications for Engineering Design

9.1 Introduction

In Chapters 5 – 7, the dominant mechanisms in canonical geometries including an open plan office and corridor, a single corner, a double corner and a discrete obstacle have been identified. Based on these results, the mechanistic models for the Engineering Tower (which was used as a test site) have been formulated. In Chapter 8, the performance of a mechanistic model was evaluated by comparing with existing indoor propagation models and the experimental measurements. The comparison results have shown that the mechanistic model can outperform models which do not include internal details of the environment such as the ITU-R, the Ericsson, and the log-distance models. In addition, considering only dominant mechanisms has shown to be adequate for achieving acceptable prediction accuracy.

In this chapter, the practical implications of using mechanistic models for engineering design are discussed. Section 9.2 discusses the applicability of mechanistic models in different environmental conditions (i.e. different layouts and wall materials) and frequencies. In addition, the assistance provided by mechanistic models in system planning is considered. Sections 9.3 and 9.4 explain the practical limitations and possible extensions of this research, respectively. Lastly, Section 9.5 summarises this chapter.

9.2 Applicability of Mechanistic Models

This thesis has investigated and isolated the dominant mechanisms in generic canonical geometries. The purpose of mechanistic models is to provide assistance for deploying indoor wireless systems with a required level of performance. It should be noted that a useful engineering model does not necessarily mean “to predict to an extremely high precision”, but to be able to identify regions in which prediction can only be made with
reduced confidence. Furthermore, a useful engineering model should be simple and with a physical basis. Due to indoor layouts and construction materials being highly variable and wireless systems usually operating in different frequency bands, these variations pose several challenges for modelling indoor propagation. In this section, applicability of mechanistic models and implications for system deployment strategies are discussed.

9.2.1 Applicability

Buildings can be categorised into different types e.g. residential houses, office and factory buildings [88]. Among all the building types, careful system deployment in office buildings could arguably be most important as demands of high capacity and reliability for wireless systems are often required. For this reason, this thesis has investigated radio propagation in a single-floor office environment.

Layouts

Although building layouts are highly variable, most typical office environments may have common environmental features. Depending on the relative position between the transmitter and the receiver, the floor area can be divided into regions which contain an open plan office and corridor, a single corner, or a double corner and discrete obstacle(s) that have been investigated in Chapters 5–7, respectively. In the line-of-sight (LOS) situation or when there is no significant obstacle in the direct propagation path, a direct and a singly-reflected components will dominate. In comparison to a full ray or FDTD method, accurate predictions in open plan offices and corridors can be made efficiently as only a maximum of two components need to be considered.

Conversely, when there is a significant obstacle in the direct propagation path, it is likely that part of the energy will propagate around the obstacle, and part will transmit through to reach the receiving locations. In this situation, the radio propagation process can become complicated as no component is universally dominant. It is likely that the direct and up to doubly-reflected components from exterior glass windows can have a significant contribution to the received signal strength in the moderately-shadowed region. In the heavily-shadowed region, up to triply-reflected components from exterior glass windows can be significant and therefore need to be considered. If however high prediction accuracy is necessary, additional components such as the diffracted and combined reflected-diffracted components may also need to be included.
9.2 Applicability of Mechanistic Models

Materials
There are different types of internal walls ranging from drywall (“nearly” electromagnetically transparent) to concrete (highly lossy) which are commonly used in building construction. Propagation modelling in environments featuring walls mostly made of drywall or glass can be straightforward, as the direct component is likely to be dominant in the majority of the receiving locations. On the contrary, environments featuring walls mostly made of concrete are somewhat more complicated as multipath effects are expected to be more severe. As a result, mechanistic models may perform less well in this type of environment, particularly in heavily-shadowed regions. It should be noted that good estimates of transmission loss through different types of internal walls are necessary for accurate power predictions.

Frequencies
Indoor wireless communications operate at several different frequency bands. In this thesis, radio propagation at the unlicensed frequency bands including 1.0 GHz, 2.4 GHz, and 5.8 GHz have been investigated. From the analyses, the significance of reflections from exterior glass windows have been shown to increase as the operating frequency increases. In addition, transmission and diffraction losses increase with the frequency, and as a result the significance of the direct and diffracted components diminishes at higher frequencies. It is possible that only reflections need to be considered at higher frequencies, and therefore mechanistic models incorporating only these components are expected to be computationally efficient.

9.2.2 System Deployment Strategies
Depending on the nature of the wireless systems and the propagation environments, the system deployment strategies used to achieve the required system performance can vary considerably. In this section, three aspects including the coverage, accuracy, and reliability of wireless communications are discussed.

Coverage
In the situation when there is only one base station in a single floor office environment, the primary concern is to maximise the coverage area in order to accommodate all users on the floor. In this case, mechanistic models can be used to determine the optimal base station location such that the total area which meets the system performance requirement is maximised. As mechanistic models consider only dominant mechanisms, an iteration process which tests several possible base station locations can be achieved efficiently. In
reality, a base station has a limited transmitting power, and therefore a limited coverage area. As a consequence, the received signal strength in some areas would not be sufficient for a wireless system to operate. These areas are hereafter referred to as **coverage holes**. These coverage holes are likely to be distant from a base station or heavily-shadowed by a significant obstacle. Typically, a base station is deployed so that coverage holes are at locations where the received signal strength is not a concern (e.g. the bathroom or lift shaft). If however a coverage hole at important areas (e.g. offices or conference rooms) is unavoidable, methods such as (i) increasing the transmission power, (ii) improving the receiver sensitivity, or (iii) deploying an additional base station may be necessary to provide service to the coverage holes.

For the case when two or more base stations using the same frequency spectrum are deployed in close proximity, system performance may suffer from cochannel interference. One way to reduce the level of cochannel interference is to ensure that at any given receiving location, the power of the **dominant signal components** (i.e. from the desired base station) is sufficiently greater than the power of the **dominant interfering components** (i.e. from the undesired base stations). This can be achieved by placing the base stations sufficiently apart or use environmental shadowing obstacles to block interfering signals. For example, the concrete services core in the Engineering Tower investigated in Chapter 8 has been shown to cast a significant shadow across the floor. By deploying two base stations at the opposite corner of the concrete services core, it has shown that the level of cochannel interference is minimised. Hence the system performance (i.e. the outage probability) can be improved [89].

**Accuracy**

There is an inevitable trade-off between the model accuracy and complexity. A more accurate mechanistic model requires more mechanisms to be considered. As a result, more environmental information and computational effort are necessary. Rather than formulating a highly complicated propagation model which attempts to provide high precision path loss predictions everywhere in the environment, it is arguably more useful to achieve good predictions only in these areas where high accuracies are necessary. For example, accurate predictions in areas where the received signal strengths are weak is more important than the area where the signal strengths are strong. This is because in the situation when the received signal strength is strong (e.g. in the LOS situation), the wireless system would be able to operate to the required standard regardless of a large power prediction error. On the other hand when the received signal strength is weak (e.g. in the deep shadowed region), the system performance is more susceptible to the nature of radio propagation and the level of the interfering signals.
Reliability

The appropriate system deployment strategy is dependent on the purpose of buildings and services. For example, highly robust wireless systems are required in health care facilities where additional safety margin would be necessary. Of note is the observation that mechanistic models often under predict the received signal strength as fewer components are considered compared to a full ray model. As a result, a wireless system which is deployed based on mechanistic predictions is inherently a conservative design in terms of coverage. In any event when the structure of a significant shadowing obstacle (e.g. the internal structure of a lift shaft) cannot be determined, an extra precaution is needed for ensuring that a system operates to a required performance standard. For instance, if mechanistic models cannot confidently predict the received signal strength in a heavily shadowed office area, an additional base station is recommended to improve quality of signal reception. However, the additional cost for setting up another base station is required. Furthermore, these two systems should be carefully engineered so that co-channel interference at locations on the boundary between two systems is minimised.

9.3 Practical Limitations

Fundamentally, mechanistic models of the type considered in this thesis are based on ray theory which is a high frequency asymptotic technique. As long as the dimensions of the objects which the wave propagated through or around are large compared to the wavelength, the approximation is generally accurate. A limitation to the ray theory, and therefore to the mechanistic models, is that they are likely to be inaccurate for estimating the non-ray optical propagation phenomenon e.g. dielectric wedge diffraction. Although several studies (e.g. [12, 13]) have tried to overcome this issue by heuristically modifying the standard UTD coefficients (which are accurate for perfectly conducting wedges [49]), these formulations are not generalised and therefore have a limited range of applications. For this reason, a standard UTD rather than a heuristic UTD is used in this thesis to estimate scattered fields from dielectric wedges. As a consequence, mechanistic predictions in areas where diffracted fields are significant are likely to be less accurate. For example, a maximum of 6 dB error is observed near the incident shadow boundary in the presence of a single corner shown in Fig. 6.5(c).

Throughout the investigations in this thesis, building walls have always been modelled as homogeneous dielectric slabs. Particularly, reflection from the front face and nineteen internal multiple reflections of the slab are considered to represent the overall reflection effect introduced by a building wall. In reality, building walls are often inhomogeneous and sometimes contain complex structures which may complicate the scattering process.
of radio propagation. In any given case when the embedded complex structure causes a significant change the propagation behaviour compared to the homogeneous slab case, estimates of the reflected field from building walls will be less accurate. This is most likely to occur when propagation paths are short [66].

Mechanistic models generally under predict the received signal strength as fewer components are considered. When used for estimating the system performance such as the signal-to-interference ratio (SIR), the SIR may be over-predicted if the interfering signal is underestimated. As a consequence, the system will not have an adequate safety margin to combat the effect of interference. If the system is particularly susceptible to interference, it is likely that the deployed system will not be able to perform to the required standard. Therefore, system planners should always aim to deploy a wireless system with a SIR higher than required to ensure a better system reliability in actual operation.

9.4 Future Recommendations

Apart from the practical limitations presented in Section 9.3 that can be further improved to enhance the performance of mechanistic models, this section outlines potential future developments of this research.

Multifloor Environments

This thesis has focused on the investigation of radio propagation in single-floor office environments. Scenarios where both transmitting and receiving antennas are located on the same floor have been considered. In practice, inter-floor communications between transceivers or other independent wireless systems operate in the same radio channel may cause harmful cochannel interference, and degrades the system performance. Therefore, it is important to investigate the inter-floor radio propagation. Recently, Austin et al. [19–21] have adopted a similar approach advocated in this thesis to identify the dominant mechanisms between floors. It was found that diffraction along exterior building walls and reflections off nearby buildings have significant contributions to the mean received power when the transmitter and receiver are separated by several floors. However, detail analyses on the presence of dominant mechanisms across the entire floor on adjacent levels have not yet being conducted. Hence, to better understand how the radio energy propagates inside buildings, an integral study that considers both the intra-floor and the inter-floor radio propagation is recommended as an extension to this thesis.
Higher Level Models

The ray-based models can be computationally efficient, but they cannot accurately model the scattering effects caused by internal complex structures embedded inside building walls. In the literature, a significant number of investigations have been directed to characterisation of complex walls using numerical methods, e.g. [58, 59, 65, 66]. The results obtained can be highly accurate as detail modelling of complex structure has been included. The effects of complex walls are usually presented in terms of transmission and reflection coefficients which could be integrated into ray-based models in a form of look-up table in respect to angle of incidence. While the computational efficiency of the resultant models remains largely the same, the prediction accuracy is likely to improve significantly.

Inclusion of Environmental Clutter

Throughout the investigations in the canonical geometries proposed in Chapters 5–7, it is assumed that the presence of environmental clutter (e.g. furniture and fixtures) will not have a significant effect on the dominant energy paths, and therefore has not been considered. This assumption is valid when the object is relatively small and does not severely block the propagation path. However when several physically-large objects (e.g. bookshelves) block the dominant energy path, the accumulative effects may need to be considered. Although not much work has been directed to the characterisation of environmental clutter in indoor propagation modelling, results presented in Section 8.2.4 and experimental measurements conducted by other researchers [37, p. 15] have suggested that environmental clutter can potentially affect indoor propagation characteristics. Therefore, a possible extension to this research is to investigate the effect of environmental clutter in greater details, with a specific focus on identifying changes it may incur on the dominant propagation mechanisms.

Transportability

It is hypothesised that a typical office environment can be represented by a combination of several canonical geometries proposed in this thesis. Based on the dominant propagation mechanisms observed in the canonical geometries, a mechanistic model which predicts the mean path loss for the given environment has been formulated. The Engineering Tower has been chosen as a test site for assessing the feasibility of the mechanistic modelling approach. In Chapter 8, the mechanistic models have demonstrated the capability to provide acceptable prediction accuracy while remain computationally efficient. However, the degree of transportability to other environments needs to be justified. Further verification of dominant mechanisms in other environments with different characteristics would be valuable for the future development of mechanistic models.
9.5 Summary

In this chapter, the applicability of mechanistic models and their roles in engineering design have been discussed. When applying a mechanistic model in an environment, the floor layout, internal partition materials, and operating frequency have to be considered simultaneously. Mechanistic models are expected to perform best (in terms of the prediction accuracy and computational efficiency) when receivers are not shadowed by significant obstacles. This is due to particular mechanisms being universally dominant in a majority of the receiving locations. When receivers are shadowed by significant obstacles, the radio propagation process becomes complicated as no particular component is always dominant. As a result, mechanistic models are expected to be less accurate and less computationally efficient in these cases.

The materials from which internal partitions are made in the propagation environment can influence the dominant energy paths, and therefore may affect the performance of mechanistic models. In the environment when most of the internal partitions are nearly electromagnetically transparent (e.g. drywall) or physically thin (e.g. glass), only the direct component needs to be considered and therefore the mechanistic model is expected to be simple and efficient. On the contrary, reflections from exterior glass windows need to be included when most of the internal partitions are highly lossy (e.g. concrete). Furthermore, the significance of glass reflections increases with the frequency. As a result, mechanistic models need to consider both direct transmission and reflections to achieve acceptable predictions.

To demonstrate the use of mechanistic models, an example application to determine the optimal base station locations depending on the system requirement has been discussed. If there is more than one base station deployed on the same floor, the level of harmful cochannel interference should be minimised. It is noted that mechanistic models usually underestimate the level of interference as fewer components from the undesired base stations are considered compared to a full ray model. As a result, additional safety margin(s) should always be included in system planning to achieve an acceptable system performance in the actual operation. In contrast, mechanistic models are suitable for use in engineering robust wireless systems where only one base station is deployed on the floor.

Lastly, several possible future directions for this research have been discussed. Radio propagation in multifloor environments should be investigated, so that the effects of other systems which operate in the same frequency spectrum in close proximity can be estimated. The prediction accuracy of ray-based models can be improved by incorporating
the effects of complex walls and environmental clutter in the model. At the same time, the transportability of mechanistic models to other environments with different characteristics from the test site used in this thesis should be further justified.
Chapter 10

Conclusions

The proliferation of indoor wireless communication services has led to increased levels of cochannel interference which can degrade system performance. While emerging wireless technologies aim to improve quality of service and establish seamless connectivity, a good system deployment strategy is the key to combat cochannel interference and thus achieve optimal system performance. Therefore, propagation models which can efficiently yet reliably predict signal strengths from both desired and interfering devices are required. Many studies have attempted to develop propagation models for such a role. Unfortunately, they are found to either lack transportability or be computationally intensive, and are thus not suitable for use in system planning. For this reason, innovative indoor propagation modelling approaches are required.

This thesis has investigated the feasibility of mechanistic modelling approaches which aim to improve computational efficiency over existing propagation models while retaining the physical underpinning of the propagation process. For several propagation components arriving at a given receiving location, the basis of this approach is to consider only the significant contributors (which are known as the dominant mechanisms) to the received signal strength. A significant advantage with this approach is that the model would be able to efficiently estimate useful output parameters (e.g. local mean) for evaluating the system performance. Moreover, dominant mechanisms explain the physical phenomena observed in practice and are therefore more likely to be transportable to other environments.

Ray methods are the foundation of mechanistic models due to the simplicity in their canonical applications. However, they are known to be inaccurate when the propagation process is non-ray optical in nature (e.g. dielectric wedge diffraction). For this reason, a 2D FDTD method was implemented to validate the applicability of ray models. Two test cases including 1) a finite thickness dielectric slab and 2) a single room environment
have been used to validate the ray models in representing the electromagnetic wave propagation. For the case of the finite thickness dielectric slab, good agreement among the FDTD, the Green’s function, and the ray estimates for the reflected and the transmitted fields was obtained. A maximum error of 1.5 dB was observed, suggesting that the ray model is able to represent the propagation effects appropriately. For the case of the single room environment, a 2.5D ray model was implemented to allow direct result comparison with that obtained from the impulse measurement. In general, good agreement has been achieved, suggesting that the dominant propagation mechanisms identified from a 2D model may be transportable to the explicit 3D environment.

To assess the feasibility of mechanistic modelling approaches, a typical office environment has been chosen as a test site for the indoor propagation study. This environment contains a centrally-located discrete obstacle where the energy has to either transmit through or propagate around to reach receivers on the other side of the obstacle. The primary objective of the study is to identify the dominant mechanisms which govern the energy propagation. Initially, an attempt was made to use the FDTD method to achieve this objective. However, a plurality of multipath components in shadowed regions makes such an identification challenging. Therefore, the environment has been systematically divided into a sequence of generic canonical geometries including an open plan office and corridor, a single corner, a double corner, and a discrete obstacle. This thesis has performed a detailed analysis in each canonical geometry using both the ray and the FDTD methods. The dominant mechanisms in each specific layout have been conclusively identified.

For the case of an open plan office and corridor geometry, it has been shown that there is an inevitable trade-off between the model accuracy and complexity. To obtain a higher prediction accuracy, a greater number of mechanisms must be considered, and therefore more detailed information of the environment is necessary. Regardless of the wall material properties, the transmitter location, and the operating frequency investigated, the dominant mechanisms have always been found to be either the direct transmission, the singly-reflected component from the nearby walls, or the combination of both mechanisms. Reflections have been observed to be more prominent when the transmitter is located in the corridor rather than inside the open plan office. Additionally, as the operating frequency increases, reflections have appeared to be more significant. Overall, the consideration of two components are shown to be adequate to estimate the local mean accurately. However, detailed physical information such as the material properties and the thickness of the walls are required.
In the situation when the presence of a single corner causes shadowing to a subset of receiving locations, the propagation process becomes complicated. This thesis has investigated two different cases including both the presence and the absence of exterior glass windows which can support the propagation of energy to the shadowed region. For the case when the exterior glass windows are absent, the dominant mechanisms have been shown to be dependent on the corner material properties. If the corner is formed by walls which introduce insignificant loss or are physically thin, then direct transmission will dominate. If the corner is formed by walls which are highly lossy, part of the energy will transmit through the corner, and part will diffract around. In this situation, the received signal strength in the shadowed region is likely to be weak, and both the direct and the diffracted components must be considered in order to estimate the local mean accurately.

When the exterior glass windows are present, the received signal strength in the shadowed region may be enhanced. This is because a significant portion of the energy can be delivered via reflections. In particular, up to second-order reflections were found to have significant contribution to the received power. This phenomenon becomes more prominent at higher frequencies. In any event when a reflected component is severely attenuated by the obstacles encountered, the majority of energy will be delivered via a combined reflected-diffracted path. Overall, the results have shown that none of the components is universally dominant. In order to achieve high prediction accuracy, several different components including a direct, up to doubly-reflected, a diffracted, and combined reflected-diffracted components must be considered. Neglecting any of these components may lead to a reduced prediction accuracy in the area where the components are dominant.

In the situation when the energy can either transmit through or propagate around a double corner of a discrete obstacle to reach a receiver, the dominant mechanisms are found to be largely the same regardless of its internal structure. This is because the concrete walls which form the discrete obstacle are highly lossy, and as a result the energy that propagates around will dominate provided that there is no significant obstacle on the propagation path. In particular, a direct, up to triply-reflected, and combined reflected-diffracted components are found to be significant at different parts of the receiving locations. As the operating frequency increases, the significance of reflections was observed to increase. It is likely that only the components which propagate around the double corner need to be considered at higher frequencies (e.g. 5.8 GHz). Similarly for the case when the energy can also propagate around another double corner to the other side of the discrete obstacle, these components will dominate. As the operating frequency increases, internal partitions have shown to cause an increased attenuation to the reflected components. Therefore, a detailed description of the physical layout may be needed to
conclusively identify the dominant mechanisms.

Based on the dominant mechanisms identified from the canonical geometries investigated, this thesis has formulated several mechanistic models that consider different combinations of mechanisms for the test environment. To evaluate the performance of the mechanistic models, the path loss predictions have been compared with the measurements. A simplified environmental model which includes only the basic architecture, and a detailed environmental model that considers the majority of the partitions have both been used to serve this purpose. Moreover, a heuristic approach for characterising the effect of environmental clutter has been proposed. It was found that internal partitions and environmental clutter can each reduce the received signal strength by 5 – 10 dB, suggesting that they both need to be considered.

Among all the mechanistic models formulated, the one that demonstrates an optimal balance between the model accuracy and complexity has been identified. The performance of the mechanistic model has been evaluated by comparing with the existing propagation models including the ITU-R, the Ericsson, the log-distance, the COST 231 multi-wall, and the ray models. The comparison results have shown that the mechanistic model outperforms the models which do not take internal details into consideration. Moreover, no significant improvement in the prediction accuracy was observed when incorporating excessive insignificant components.

While the performance of the mechanistic model for an office environment has been evaluated in this thesis, the applicability of mechanistic models and their possible roles in engineering design have also been discussed. As mechanistic models are based on high frequency asymptotic techniques, the inherent limitations include a suboptimal prediction accuracy for the computation of non-ray optical behaviour (e.g. dielectric wedge diffraction) and complex wall reflection (e.g. reinforced concrete walls). As fewer interfering components are considered, mechanistic models may overestimate the signal-to-interference ratio. As a consequence, an unacceptable system performance may result due to an inadequate protection margin. Future research for the development of mechanistic models could (i) extend propagation study to multifloor environments, (ii) develop higher level models, (iii) incorporate the effect of environmental clutter, and (iv) examine model transportability to other environments.

As the demand for high performance indoor wireless systems grows, the development of propagation models which are able to provide efficient and reliable system deployment strategies will become increasingly important. Eventually, mechanistic modelling
approaches are likely to play an important role in the engineering of future indoor wireless communication systems.
Appendix A

Computation of Effective Reflection Coefficients

When an incident wave propagating in one medium impinges upon a second medium with different electrical properties (e.g. from medium \(a\) to medium \(b\)), the wave is partially reflected and partially transmitted. The electric field intensity of the reflected and the transmitted waves may be related to the incident wave using the Fresnel reflection coefficient [90, pp. 308-313]. The Fresnel reflection coefficient is computed based on the incident wave impinging on the front surface of the second medium. It is assumed that the second medium is infinite in extension, thus that the transmitted field will not be reflected back from the back surface of the second medium (e.g. Fig. A.1(a)). In any event when the second medium is physically thin and/or relatively low loss (e.g. Fig. A.1(b)), estimating the reflected field observed in the first medium using the Fresnel reflection coefficient may not be appropriate. This is because multiple internal reflections that occur inside the second medium will also contribute to the reflected field observed in the first medium.

This appendix describes the computation of an effective reflection coefficient which is used to estimate the reflected field observed for the ray model formulated in this thesis. The effective reflection coefficient incorporates the effect of both the front surface and the multiple internal reflections of the second medium, and is obtained by modifying the Fresnel reflection coefficient.

The 2D ray model formulated in this thesis considers only transverse-magnetic (TM) components which have electric fields perpendicular to an incident plane. Suppose that media \(a\) and \(b\) in Fig. A.1(b) represent air and a dielectric slab, respectively, the reflected component from the front surface of the dielectric slab (shown in blue) is estimated by

\[
E_{\text{front}} = \left( \frac{A}{\sqrt{d_1}} \right) \Gamma_1 e^{-jkd_1}
\]  

(A.1)
where $A$ is the divergence factor for GO reflection, $d_1$ is the propagation path length, and $e^{-jkd_i}$ accounts for the phase shift due to propagation along path length $d_1$. The parameter $\Gamma_1$ is the Fresnel reflection coefficient for nonmagnetic dielectrics and is computed by [90, p. 312]

$$\Gamma_1 = \frac{\cos \theta - \sqrt{\frac{\epsilon_b}{\epsilon_a}} - \sin^2 \theta}{\cos \theta + \sqrt{\frac{\epsilon_b}{\epsilon_a}} - \sin^2 \theta}$$

where $\theta$ is the angle of incidence with respect to normal as shown in Fig. A.1(b), $\epsilon_a$ and $\epsilon_b$ represent the permittivity of medium $a$ and medium $b$, respectively.

The total reflected field observed in medium $a$ which considers a reflected component from the front surface (shown in blue) and multiple internal reflections inside the dielectric slab (only one of the internal reflections has been depicted and shown in red) is estimated by

$$E_{total} = \sum_{i=1}^{n} \left( \frac{A}{\sqrt{d_i}} \right) \left( \prod \Gamma_i \right) \tau_i^2 e^{-jkd_i}$$

where $n$ is the number of the reflected components considered including the paths from the front surface, and multiple internal reflections inside the dielectric slab. The parameter $d_i$ is the total length of the reflected path, $\Gamma_i$ and $\tau_i$ are the reflection and transmission coefficients of the dielectric slab, respectively, and $e^{-jkd_i}$ accounts for the phase shift due
to the length of the reflected path $d_i$.

Fig. A2 demonstrates the relationship between received signal strength and number of reflected components off the three different dielectric slabs (drywall, glass, and concrete) considered in this thesis. The material properties are specified in Table 5.1. In this result, transmitter and receiver with a separation of 5 m are placed at 2 m from each respective dielectric slab (Fig. 6.14). It is shown that the effects of higher order internal reflections are insignificant, and for this particular instance an $n = 5$ is adequate for a reasonably well estimation of the received signal strength. Fig. A3 further demonstrates the effects of material properties on the number of reflected components required, including relative permittivity, thickness, and conductivity. Despite the number of reflected components required is slightly sensitive to the material properties, an $n = 10$ is adequate for an acceptable reflected field estimation. In this thesis, a total of twenty reflected components ($n = 20$) are therefore included to conservatively represent the reflected field strength.

As the angle of incidence and the material properties of dielectric slabs can significantly influence the reflected field, they are used as the input parameters to extract an additional contribution of multiple internal reflections to the observed reflected field. A modification factor, $F$ which is used to modify the Fresnel reflection coefficient is incorporated to consider the net effect of multiple internal reflections. The modification factor, $F$ is computed by

$$ F = \frac{E_{total}}{E_{front}} $$

(A.4)

where $E_{total}$ is the total reflected field including that from the front surface and multiple internal reflections of the dielectric slab (described in Eq. (A.3)), and $E_{front}$ is the reflected field from the front surface of the dielectric slab only (described in Eq. (A.1)). In this thesis, an effective reflection coefficient from a finite thickness dielectric slab is therefore computed by using a modified Fresnel reflection coefficient (i.e. $\Gamma_1 F$).
Figure A.2: Graph of the reflected field strength when different numbers of internal reflections are considered.
Figure A.3: Graph of the reflected field strength when different numbers of internal reflections are considered for different material properties.
Appendix B

FDTD Spatial-Averaging Sectors

This appendix describes the spatial-averaging process used to remove the effect of multipath fading in the FDTD results. Generally, it is not of interest to measure the instantaneous power as it is greatly dependent on the fine scale of the physical environment. When conducting path loss measurements, the received signal strength at a point in space is obtained by rotating the receiving antenna around a few wavelength diameter circular locus. In a similar sense, the FDTD results presented in this thesis have been averaged over a spatial-averaging sector, $s$. In this appendix, the effect of using different size of sectors is investigated. From the results, an appropriate size of spatial-averaging sector is nominated.

The test environment investigated in Chapter 4 is used to demonstrate the effect of spatial-averaging sectors. Figs. B.1(a)–(d) and Figs. B.2(a)–(d) respectively show the path gain estimations from the transmitting antennas $I_1$ and $I_2$, when different spatial-averaging sectors, $s$ are used. From the results of $s = 0$ (i.e. the instantaneous power), fading patterns can be seen in the lit region for both transmitting antenna locations. This is due to the phase of two or more components (with comparable magnitudes) that are added constructively and destructively. Furthermore, the wave guiding effect along the corridor is evident. In the shadowed region, the multipath components have shown to be prominent and resulted in a rapid signal fluctuation.

When the FDTD results are averaged over the spatial-averaging sector $s$ of size $\lambda \times \lambda$ (i.e. $\pm 0.5\lambda = 15$ cm from both vertical and horizontal directions as illustrated in Fig. B.3), the effect of multipath fading is diminished. In this case, the path gain contours have become smoother compared to the case of $s = 0$. However, the fading patterns can still be visibly seen, suggesting that the effect of multipath fading have not been sufficiently removed. For the case when the spatial-averaging sector $s$ of $2\lambda \times 2\lambda$ (i.e. $\pm \lambda = 30$ cm from both vertical and horizontal directions) is used, the path gain contours have
Figure B.1: Graphs showing the FDTD estimated path gains across the entire floor from transmitting antennas $I_1$ (indicated by □) when different spatial-averaging sectors, $s$ are used.

became smooth as the multipath fading effect is eliminated. Further increasing the spatial-averaging sector $s$ to $3\lambda \times 3\lambda$ (i.e. $\pm 1.5\lambda = 45$ cm from both vertical and horizontal directions) does not significantly change the path gain contours observed. Therefore, the spatial-averaging sector $s = 2\lambda \times 2\lambda$ has been chosen to process the FDTD results in this thesis.
Figure B.2: Graphs showing the FDTD estimated path gains across the entire floor from transmitting antennas \( I_2 \) (indicated by □) when different spatial-averaging sectors, \( s \) are used.

(a) \( s = 0 \)  
(b) \( s = \lambda \times \lambda \)  
(c) \( s = 2\lambda \times 2\lambda \)  
(d) \( s = 3\lambda \times 3\lambda \)

Figure B.3: An illustration of the spatial-averaging sector, \( s \) which is used to obtain the mean received signal strength at point A. In this example, the spatial-averaging sector \( s = \lambda \times \lambda \) is used. The received signal strength at point A is computed based on the average of all the data points bounded by the red dashed box.
Appendix C

Additional Results For Chapters 5 – 6

This appendix presents the additional results for the investigations described in Chapters 5 and 6. The purpose of this appendix is to validate the ray models which are formulated to identify the dominant mechanisms in the canonical geometries. Specifically, the ray and the FDTD estimates of the path gains across the area of interest are compared. The additional results for Chapter 5 are shown in Figs. C.1–C.3, whereas the additional results for Chapter 6 are shown in Fig. C.4.
**Figure C.1:** Graphs showing the ray and the FDTD estimates of the path gains and their difference in the geometry investigated in Section 5.3.1. Areas coloured red and blue in the error plot indicate overestimation and underestimation of the path gain, respectively.
Figure C.2: Graphs showing the ray and the FDTD estimates of the path gains and their difference in the geometry investigated in Section 5.3.2. Areas coloured red and blue in the error plot indicate overestimation and underestimation of the path gain, respectively.
Figure C.3: Graphs showing the ray and the FDTD estimates of the path gains and their difference in the geometry investigated in Section 5.3.3. Areas coloured red and blue in the error plot indicate overestimation and underestimation of the path gain, respectively.
Figure C.4: Graphs showing the ray and the FDTD estimates of the path gains and their difference in the geometry investigated in Section 6.3.2. Areas coloured red and blue in the error plot indicate overestimation and underestimation of the path gain, respectively.
Appendix
References


REFERENCES


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