INFLUENCE OF CORRELATED SHADOWING AND BASE STATION CONFIGURATION ON IN-BUILDING SYSTEM CAPACITY

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Abstract: This paper illustrates the impact of base station deployment on the performance of an indoor DS-CDMA system. It is shown that system performance can be altered dramatically by changing the base station configuration. Correlated shadowing is a significant factor contributing to the wide range of performance results. Outage probability analyses indicate that substantial capacity improvements can be achieved at the expense of increased complexity in the base station deployment scheme.

I. Introduction

High capacity in-building systems require three-dimensional frequency reuse. The efficiency of this reuse has been found to be very dependent on the base station positioning within a particular building. However, as the form and construction of the building is typical of many multi-storey office buildings these findings are significant in terms of planning high capacity radio services in such buildings. The paper illustrates the dramatic effect that base station location changes can have on system capacity and performance. The details of the in-building wireless communication system considered in the paper are discussed in Section II. Techniques used for estimating the performance of the in-building communication system are outlined in Section III. An approach for modeling the in-building propagation environment is presented in Section IV. The influence of base station deployment on system performance estimates is investigated in Section V. Finally, in Section VI some conclusions are drawn.

II. System

A number of multiple access schemes have been identified for use in in-building wireless communication systems. The wireless communication system considered in this paper operates in an in-building environment with vertical frequency reuse and uses DS-CDMA with BPSK modulation. The system uses frequency division duplex with two separate frequency bands, one for the downlink and one for the uplink, as shown in Fig. 1.

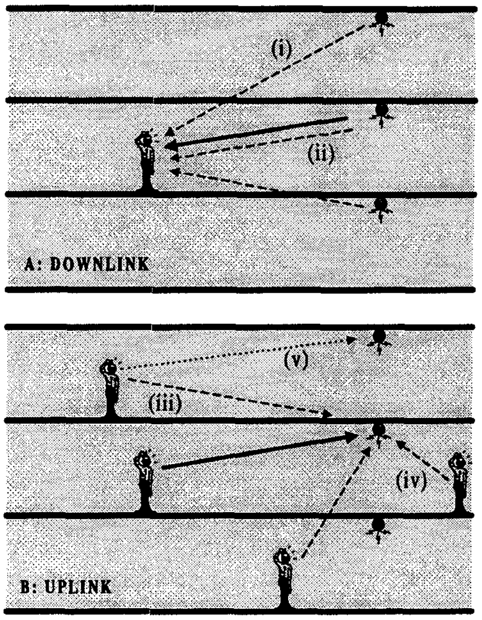


Fig. 1: *Downlinks and uplinks for an in-building DS-CDMA system showing the various sources of interference. Components (i)-(v) are described in the text.*
——— *Desired Signal* — — — *Interfering Signal*

The same frequencies are assumed to be reused on each floor. It is assumed that the sequences used for spreading the spectrum are random, that the received baseband signal has a rectangular pulse shape, and that the system receivers are perfectly synchronised to the desired signal. It is further assumed that the mobile radio system serves K active mobile users randomly located on each floor and that power control is used to compensate for variations in mean signal attenuation[1] due to the path loss and log-normal shadowing associated with each signal received at the base station. The signals are assumed to experience Rayleigh fading on top of the variations in mean signal attenuation. Quantisation errors and errors resulting from the response time in the power control algorithm are modelled by a log-normal variability with σ=2dB [1].

[1] Mean signal attenuation is defined here as the received signal attenuation averaged over a 1m diameter region.

The propagation environment in which the wireless communication system operates is assumed to be identical to the Engineering Tower Block at The University of Auckland where an in-building propagation study was undertaken [2]. The Tower Block is a 12 storey building constructed of reinforced concrete with offices around the outside of a large central structural core (housing a stairwell, lift shafts and services). The dimensions of each floor are 18.5m x 18.5m with an inter-floor spacing, s=2.9m. All floors have a layout very similar to that shown in Fig. 2.

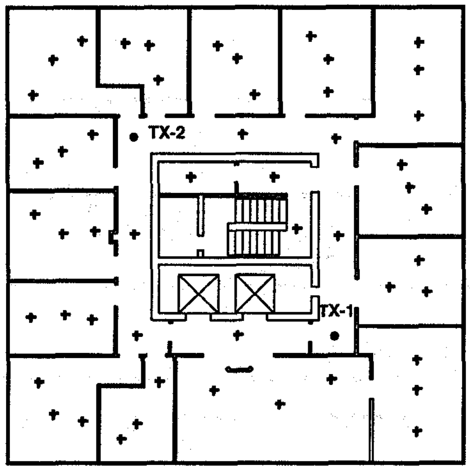


Fig. 2: *Typical floor layout of the Engineering Tower Block.*

The propagation study employed either one or two base stations (transmitters) using omni-directional ceiling mounted discone antennas. The two possible base station locations are shown in Fig. 2 (marked as TX-1 and TX-2). Also shown in Fig. 2 are 53 possible mobile user locations, indicated by +'s. Base stations and mobiles were restricted to these locations as measurements were only made at these locations in the propagation study [2].

Floors more than two levels away from the desired floor (8th floor) are not considered in the system analysis. Thus only the 6th, 7th, 8th, 9th, and 10th floors are included. Fig. 1 illustrates the links considered in the analysis (only one adjacent floor either side of the desired floor is illustrated).

CDMA system performance is interference limited. Consequently, the downlink is limited by interference received at the mobile (downlink interference), and the uplink performance is limited by interference received at the base station (uplink interference), as illustrated in Fig. 1. The interference may be composed of:

- interference from mobile users on other floors:
  (i) inter-floor downlink interference
  (iii) inter-floor uplink interference
- interference from mobile users on the same floor:
  (ii) intra-floor downlink interference
  (iv) intra-floor uplink interference

(Note: component (v) in Fig. 1 is discussed in Section IV)

III. Performance Estimation

The performance of the mobile radio system is obtained in terms of a probability of outage which is estimated over all possible user locations across an entire floor of the building. An outage at any given location is defined to occur when the instantaneous BER exceeds 10^{-2}[1]. As mentioned in Section II, mobile users are assumed to be randomly located at the 53 measurement locations (indicated by +'s in Fig. 2). In the Monte Carlo simulation undertaken, mobile users can be moved in a pseudo-random manner around all possible user locations. For each mobile user location, the BER is compared with the outage threshold. The average of these outages over all random user locations is used to estimate the probability of outage for the entire floor.

A. Downlink

It is assumed that the mobile radio system has a sufficiently large processing gain and serves a sufficient number of users for the instantaneous composite interference at a mobile receiver to be Gaussian distributed. Accordingly, the BER of a received signal at a mobile user located at Cartesian coordinates (x, y) (with the origin located at the base station on each floor) is given by [3]

$$BER_{Mobile}(x,y) = \Phi\left(\frac{1}{\sqrt{\frac{\alpha}{3N}(K-1+\beta)}}\right), \qquad (1)$$

where α is the voice activity factor (assumed to be 0.5), N is the processing gain (assumed to be 511), K is the number of active users on each floor and $\Phi()$ is the complementary Gauss probability integral[3]. The random variable (RV) β, which is dependent on x and y, represents the accumulation of Rayleigh distributed random variables that characterise the signal variability from the desired and interfering floors, namely

$$\beta = K\sum_{\substack{n=-p \\ n\neq 0}}^{p} \frac{u(n)}{u(0)} 10^{0.1(L_{d_d,0}-L_{d_i,n})}, \qquad (2)$$

where $2p$ is the number of floors contributing to inter-floor interference. The RVs $u(n)$ and $u(0)$ represent the Rayleigh signal variability respectively, from the nth interfering floor and the desired floor. $L_{d_i,n}$ and $L_{d_d,n}$ are the mean path losses (dB) for a transmitter and receiver separated by n floors and corresponding three dimensional path lengths d_i and d_d. The approach chosen for estimating mean path loss is outlined in Section IV. The path lengths d_i and d_d are the three dimensional spatial separations between the desired user and the interfering and desired base stations respectively and are given by

$$d_{i \text{ or } d} = \left((|n|\cdot s)^2 + x^2 + y^2\right)^{0.5}, \qquad (3)$$

for the case of d_d, the number of floors between the desired user and the desired base station is zero ($n=0$).

B. Uplink

As for the downlink, it is assumed that the instantaneous composite interference at a mobile receiver is Gaussian distributed. In this case, the BER of the received signal at the base station on the desired floor is given by

$$BER_{Base} = \Phi\left(\frac{1}{\sqrt{\frac{\alpha}{3N}\left(\frac{\psi+\zeta}{\varphi}\right)}}\right), \qquad (4)$$

where φ represents the desired signal and is given by

$$\varphi = u_K(0)P_{des}, \qquad (5)$$

P_{des} is the desired received power in linear units at the desired base station as determined by the power control algorithm and $u_K(0)$ is a Suzuki [4] distributed RV representing the variability of the desired signal (σ=2dB). The Kth user is considered to be the desired user. In (4), ψ represents the composite intra-floor uplink interference and is given by

$$\psi = \sum_{i=1}^{K-1} u_{intra}(0)P_{des}, \qquad (6)$$

where each $u_{intra}(0)$ is a Suzuki distributed RV representing the variability of the interference from the ith intra-floor interferer ($\sigma_i(0)$=2dB $\forall i$). The RV ζ in (4) is the composite inter-floor uplink interference and is given by

$$\zeta = \sum_{\substack{n=-p \\ n\neq 0}}^{p} \sum_{l=1}^{K} P_l(n)u_l(n), \qquad (7)$$

where each $P_l(n)$ and $u_l(n)$ are respectively, the mean power and the Rayleigh variability associated with the interference from the lth user n floors away. $P_l(n)$ is given by

$$P_l(n) = \frac{P_{des}10^{0.1L_{d_{l\,int},0}}}{u_{des}(0)u_{pc}(0)10^{0.1L_{d_{ldes},n}}}, \qquad (8)$$

where d_{lint} and d_{ldes} are the three dimensional separations between the lth interfering mobile user and the base stations on the interfering and desired floors respectively, $u_{des}(0)$ is the Rayleigh variability associated with the signal from the interfering user to their respective base station and $u_{pc}(0)$ is the lognormal variability associated with the power control algorithm (σ_{pc}=2dB). $L_{d_{l\,int},0}$ is the mean path loss between an interfering user and the base station on their floor separated by a path length d_{lint} and $L_{d_{ldes},n}$ is the mean path loss between an interfering user n floors away and the base station on the desired floor separated by a path length d_{ldes}. The approach chosen for estimating mean path loss is outlined in Section IV.

IV. Propagation Modeling

Section III presented techniques for estimating uplink and downlink system performance based on a number of parameters, one of which was mean signal attenuation. This section describes the approach used for estimating the mean signal attenuation between any transmitter and receiver location. This approach is based on data from a 1.8 GHz in-building propagation study undertaken in the Engineering Tower Block at The University of Auckland[2].

The Engineering Tower Block is constructed of reinforced concrete with offices around the outside of a large central structural core housing a stairwell and lift shafts. The study determined the mean path loss for a large number of transmitter and receiver locations within the building. Measurements were made at 53 small areas (1m diameter circles) on one floor of the building with the transmitter located on the same floor, and one and two floors both above and below. Within each small area, measurements were averaged to eliminate fast/multipath fading.

The estimation approach employed consists of a lookup table of mean path losses for all propagation paths over which measurements were made in the tower block. For a transmitter and receiver separated by n floors and corresponding three dimensional path length, d, the mean path loss is defined as

$$L_{d,n}(\text{dB}) = \text{lookup table value}. \qquad (9)$$

Possible values of d and n are constrained to the locations where measurements were made. Unlike statistical models for estimating mean signal attenuation such as that proposed by Seidel [5], this approach makes no assumptions about the signal variability. All variability is inherently included in the actual measurement data with the exception of fast fading. Therefore, between any given transmitter and receiver locations, the mean signal attenuation is known exactly from measurements.

During the propagation study undertaken in the Engineering Tower Block at The University of Auckland a 'key' propagation characteristic was identified, this being correlated shadowing between desired and interfering signals [6].

Correlated shadowing is understood to occur when desired and interfering signals have very similar propagation paths, i.e. encounter the same shadowing obstacles. For example, consider the Engineering Tower Block scenario with base stations located at position TX-1 (see Fig. 2) on every floor. A mobile user on one particular floor will receive a 'desired' signal from the base station on its floor and interfering signals from base stations on all other floors. If positive correlation exists, when the mean signal strength of the desired signal is strong it is likely that the interfering signals will also be strong and vice versa. If negative correlation exists, when the mean signal strength of the desired signal is strong it is likely that the interfering signals are weak and vice versa.

For the Engineering Tower Block, the correlation between a desired signal and an interfering signal separated by zero to two floors was determined for two different scenarios. In scenario I all the base stations were vertically aligned at position TX-1. Scenario II is the same as scenario I but with the desired base station on the 8th floor horizontally transposed to location TX-2 (see Fig. 2). Table 1 shows the results of the correlation analysis [6]. It is important to note that the correlation analysis is not specific to any propagation model.

Table 1: *Engineering Tower Correlation Coefficients*

Floors, n	ρ_n (Scenario I)		ρ_n (Scenario II)	
	above	below	above	below
1	0.93	0.95	-0.40	-0.54
2	0.88	0.70	-0.43	-0.34

For the system model considered in this paper the influence of correlated shadowing is most obvious for the downlink where the desired signal can be correlated with all interfering signals. This means that for the downlink, interfering signals can not be assumed to suffer independent shadowing. For the uplink scenario the influence of correlated shadowing is more subtle and is an artifact of the use of power control. Considering the uplink model illustrated in Fig. 1b, signal components (iii) and (v) may be correlated. For a power controlled system it is assumed that the transmit power of a mobile user is adjusted to compensate for attenuation between the mobile and its "connected" base station. In this particular case, the attenuation is that suffered by signal component (iii). If signal component (v) is correlated with (iii), the effect of inter-floor interference at the co-channel base station is reduced.

It is important to note the significant variations in correlation caused by variations in base station placement. By simply offsetting one base station to the opposite side of the building the correlation coefficients become strongly negative. This suggests that placement of base stations has the potential to have great influence on system performance.

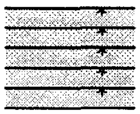
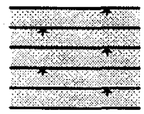
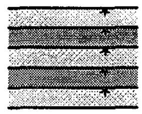
V. Performance Comparisons

In this section a number of system performance estimates are made for both downlink and uplink scenarios using the techniques described in Section III. As mentioned previously, these performance estimates require as an input, estimates of mean signal attenuation. Section IV outlined the significant influence that base station placement can have on the propagation characteristics, in particular on the correlation coefficients. It is important to appreciate how base station deployment and knowledge of correlation characteristics may be used to maximise system performance. The impact of base station deployment on system performance was determined for six different base station deployment scenarios in the Engineering Tower Block environment.

Scenario I consists of one base station per floor aligned vertically at position TX-1 (see Fig. 2). Scenario II is identical to scenario I except that the base stations on the 7th and 9th floors are located at position TX-2. For the remaining scenarios the spectrum allocated to the system is split equally into two separate frequency bands, A and B. The processing gain N is now assumed to be 255. For scenario III there is one base station per floor located at position TX-1, base stations on the 6th, 8th, and 10th floors use frequency band A while the base stations on the 7th and 9th floors use frequency band B. Scenario IV is identical to scenario III except that the base stations on the 6th, 9th, and 10th floors are located at position TX-2. For scenario V there are two base stations per floor located at positions TX-1 and TX-2, frequency band A is allocated to base stations located at TX-1 and frequency band B is allocated to base stations located at TX-2. Scenario VI is identical to scenario V except that on the 7th and 9th floors, frequency bands A and B are swapped between the two base stations.

For each scenario system performance estimates were made for a range of active users per floor (K), between 10 and 30. Mobiles were assumed to only connect to the base station with the minimum mean signal attenuation. Tables 2 and 3 show a comparison of the simulated downlink and uplink outage probabilities for each of the scenarios. The outage probability estimates are for users connecting to a base station on the 8th floor.

Table 2: *Uplink and Downlink outage probability estimates averaged over an entire floor for scenarios I-III.*

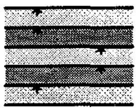
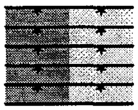
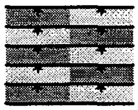
Scenario	**I**	**II**	**III**
			
Users/Floor	**Downlink Outage Probability**		
10	0.0013	0.0049	0.0008
20	0.0031	0.0096	0.0012
30	0.0052	0.0152	0.0023
	Uplink Outage Probability		
10	0.0237	0.0224	0.0380
20	0.0447	0.0469	0.0824
30	0.0679	0.0691	0.1192

The estimates of system performance in tables 2 and 3 are compared using three logical pairings based on increasing levels of system complexity.

Let us first consider the pairing of scenarios I and II which have the minimum system complexity. For scenario I the downlink performance estimates are a factor of three better than those for scenario II while for the uplink there is no appreciable difference between the performance estimates. This suggests that the negative correlation introduced in scenario II by alternating base stations on adjacent floors is detrimental to system performance. Thus for this level of complexity it appears desirable to align base stations vertically to maximise positive correlation and correspondingly, to maximise system performance.

The next pairing consists of scenarios III and IV, here the added complexity of split spectrum is introduced with one base station per floor. For scenario IV the downlink performance estimates are a factor of two better than those for scenario III while for the uplink, the performance estimates for scenario IV are appreciably worse than those for scenario III. It is important to note that the uplink performance estimates for both scenarios III and IV are significantly worse than those for scenarios I and II. However, for the downlink the reverse is true. This suggests that for this level of complexity there are performance gains to be made for the downlink, especially when base stations using the same frequency band are alternated on opposite sides of the building (scenario IV). For scenario IV these downlink performance gains are possible due to mobile users being allowed to connect to any base station. For example, if a mobile user were forced to connect to a base station on the opposite side of the building on the same floor, the interference from co-channel base stations two floors away is likely to result in an outage due to the strong negative correlation between the desired and interfering signals. However, if the mobile were allowed to connect to the most desirable base station (the one with the strongest signal strength) it is likely to connect to the base station on an adjacent floor that is on the same side of the building. This being the case, interference from the adjacent co-channel base station on the opposite side of the building is likely to be negligible due to the strong negative correlation between the desired and interfering signals.

Table 3: *Uplink and Downlink outage probability estimates averaged over an entire floor for scenarios IV-VI.*

Scenario	**IV** 	**V** 	**VI** 
Users/Floor	**Downlink Outage Probability**		
10	**0.0003**	0.0005	**0.0002**
20	**0.0007**	0.0020	**0.0008**
30	**0.0011**	0.0034	**0.0011**
	Uplink Outage Probability		
10	0.0533	**0.0151**	**0.0144**
20	0.1108	**0.0345**	**0.0331**
30	0.1568	**0.0468**	**0.0452**

The last pairing is scenarios V and VI, these scenarios consider not only split spectrum but also incorporate twice as many base stations. For scenario VI the downlink performance estimates are a factor of three better than those for scenario V while for the uplink there is no appreciable difference between the performance estimates. A comparison of the performance estimates for scenario VI with all other scenarios suggests that splitting the spectrum and alternating base stations that use the same frequency band will maximise the system performance for both uplink and downlink. However, the disadvantage of scenario VI is the increased complexity involved with twice as many base stations and spectrum splitting.

It is apparent from these results that base station deployment can have a dramatic effect on estimated system performance. The differences between the results for each of the scenarios are heavily dependent on the correlation characteristics that exist between desired and interfering signals. These results indicate that, depending on the level of complexity the system planner is willing to introduce into a system design, there are certain deployment scenarios that are much more appropriate than others.

The results observed in this study are based on measurements made in the Engineering Tower Block at The University of Auckland [2] and as such are strictly only valid for this building. However, the Engineering Tower Block is typical of many high-rise buildings supported by a concrete structural core. It is therefore expected that the performance trends observed here will be applicable to other buildings of similar construction. It is the authors intention to conduct further measurements in a variety of other buildings and undertake similar analyses.

VI. Conclusions

It has been shown that system performance is heavily dependent on base station configuration and spectrum allocation. This requires serious consideration to be made of the implications of base station location when planning in-building wireless communication systems. Correlated shadowing has been shown to be a significant factor contributing to the wide range of results. With one base station per floor for the downlink it is desirable to alternate base stations and reuse spectrum every other floor while for the uplink alignment is less important with spectrum reused on every floor. With two base stations per floor, each using different spectrum, it is desirable to alternate co-channel base stations on opposite sides of the building on adjacent floors. There are clear advantages in terms of outage probability for more complex systems employing multiple base stations per floor and split spectrum. However, increased system complexity may also mean greater system cost and therefore a compromise between performance and cost may be required.

VII. References

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