IMPLICATIONS OF PROPAGATION MODELING ON THE DESIGN OF A DS-CDMA IN-BUILDING MOBILE COMMUNICATION SYSTEM

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Abstract: This paper investigates the implications of propagation modeling on the design of a DS-CDMA in-building mobile communication system. Two modeling approaches are considered, namely a floor-averaged propagation model and a localised area model that considers individual propagation paths for a range of potential mobile user locations. Results show that overall system performance estimates are heavily dependent on the model used to describe the building's propagation characteristics and suggest that the former approach leads to a rather pessimistic prediction of system performance when compared with the later. This suggests that unnecessarily conservative design would be likely if the former approach was utilised as part of a system planning process.

I. Introduction

With the recent rapid growth in demand for wireless communications it is becoming increasingly important to develop new and more efficient systems for handling greater capacity requirements. Consequently, the radio systems engineer is faced with a number of challenges. Among these is the provision of a system that will allow many wireless systems and users to coexist in a relatively small area while maintaining spectral efficiency, system throughput, and channel quality.

A consequence of the rapid growth in the cellular market is the demand for in-building wireless mobile communications systems where high concentrations of potential users coexist, such as within high-rise office buildings. Direct Sequence Code Division Multiple Access (DS-CDMA) has shown considerable promise for use in cellular communication networks [1-3] and more recently for in-building systems [4]. It has also recently become a standard (IS-95) for cellular communication systems [5].

Previous research on CDMA system performance has mainly concentrated on outdoor (macro/micro) cellular systems. Somewhat less research has looked at indoor (pico) cellular systems. Previous work undertaken for both outdoor and indoor environments has seldom considered the variable nature of the propagation environment, but rather, has assumed the propagation characteristics to be relatively homogeneous. However, this variability is particularly significant when considering the performance of picocellular systems, as the indoor propagation environment has been found to be rather more variable than the macro-cellular case [6-10]. More recently it has been shown that there are significant variations in performance estimates between different buildings due to their dissimilar propagation characteristics [11]. This suggests that the propagation characteristics of a particular building must be known before an efficient mobile radio system can be deployed.

In this paper, we investigate the performance of a DS-CDMA in-building mobile communication system. The paper extends on [11] to consider the influence of building propagation modeling on system performance estimation. Two different approaches are considered for modeling of the propagation characteristics observed in a 1.8 GHz indoor propagation study carried out in the School of Engineering at The University of Auckland. A summary of the results of the propagation study are presented in this paper.

II. Propagation Study and Modeling

A 1.8 GHz indoor propagation study was undertaken at The University of Auckland within the 12 storey School of Engineering tower block [12]. The study investigated the mean path loss for a large number of transmitter and receiver locations within the building.

Measurements were made in academic staff offices on floors 5-10 of the tower block. All floors had an internal structure very similar to that illustrated in Fig. 1. The offices are located around the outside of the building with an internal corridor separating the offices from a central structural core which contained a stairwell, lifts, and services. The office walls were constructed with a mix of wood and plasterboard while the central core was constructed with very solid reinforced concrete. The floors were also constructed with reinforced concrete.

Measurements were made in 53 small areas (1m diameter circles, indicated with +'s in Fig. 1) on the eighth floor of the

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building with the transmitter located on the same floor (marked by Tx), and also 1 and 2 floors above and 1 to 3 floors below. Within each area measurements were averaged to eliminate fast fading.

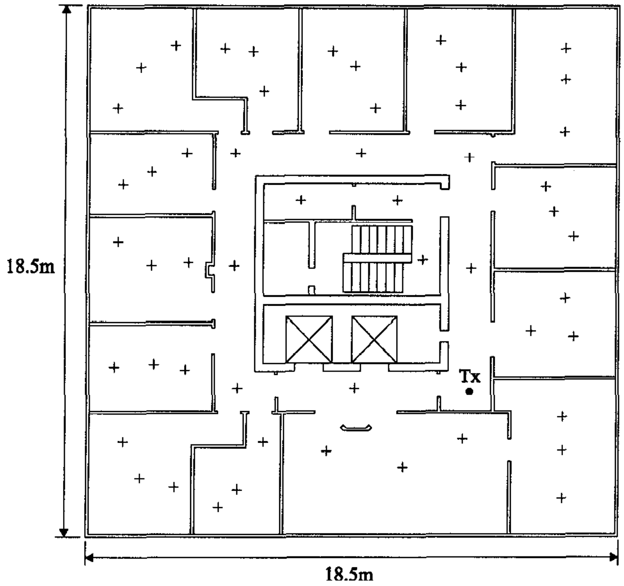

Fig. 1: *Internal structure of the engineering tower block.*

Two approaches were considered for estimating the mean local area pathloss at some point across the floor. The first approach is a floor averaged model that considers the statistics for entire floors of the building. The second is a localised model that considers individual propagation paths for a large number of potential mobile user locations within the building.

A. Floor Averaged Model

This approach is identical to that proposed by Seidel [9]. The mean path loss, $L_{d,n}(dB)$, for a transmitter and receiver separated by n floors and corresponding three dimensional path length, $d(m)$, is given by

$$L_{d,n}(dB) = B + 10 \cdot \gamma_n \cdot \log_{10}(d) + FAF_n\,, \tag{1}$$

where B is a reference path loss, FAF_n is the cumulative floor attenuation and γ_n is the pathloss exponent. Both FAF_n and γ_n are dependent on the number of floors, n, separating the transmitter and receiver.

The parameters for this model for the engineering tower block were determined from the measurement data and are outlined in Table 1. When n=0 the transmitter and receiver are on the same floor. Positive and negative values of n refer respectively, to floors above and below the desired floor. The signals are assumed to suffer log-normal shadowing, the severity of which is modeled by σ.

Table 1: *Engineering tower propagation parameters*

Floors(n)	FAF_n *(dB)*	σ_n *(dB)*	γ_n
0	0	9.6	4.8
±1	16.0	9.8	4.8
±2	22.1	8.5	4.8
-3	29.0	7.9	4.8

The parameters in this model are average values over entire floors of the building. Consequently, any performance estimates that employ this model can only be expected to provide estimates of system performance averaged across an entire floor.

B. Localised Model

This approach consists of a lookup table of mean path losses for all propagation paths over which measurements were made in the engineering tower block. The mean path loss is defined as

$$L_{d,n}(dB) = \textit{lookup table value}\,, \tag{2}$$

where d and n are as before but must correspond to only the locations where measurements were made. Unlike the floor averaged model the signals are not assumed to suffer log-normal shadowing as this effect is included in the path loss measurements.

By not fitting a propagation model to the measured data no assumptions are made about the propagation mechanisms between transmitter and receiver. Therefore, between any given transmitter and receiver locations, the pathloss is known exactly from measurements.

III. CDMA Mobile Radio System

The mobile radio system under consideration here operates in an indoor environment with vertical frequency reuse and uses a DS-CDMA scheme to spread the spectrum of a BPSK modulated signal. The system uses frequency division duplex with two separate 15 MHz frequency bands, one for the downlink and one for the uplink (see Fig. 2). The same frequencies are assumed to be reused on each floor. It is assumed that the antennas at the base stations and the mobile users are isotropic, that the sequences used for spreading the spectrum are random, that the received base-band signal has a rectangular pulse shape, and that the system receivers are perfectly synchronised to the desired signal. It is futher assumed that the mobile radio system serves K active mobile users per floor and that power control is used to compensate for 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 log-normal shadowing. Quantisation errors and errors resulting from the response time in the power control algorithm are modeled by a log-normal variability with a σ=2dB [13].

The indoor environment is assumed to be identical to the engineering tower block where the propagation study was undertaken. The dimensions of the floor are square (18.5m x 18.5m) with an inter-floor spacing, s=2.9m. Each floor has one ceiling mounted base station offset from the center that serves the mobile users on that floor. Fig. 1 shows the location of the base station (marked by a Tx). Only the two floors immediately adjacent to the desired floor are considered in the analysis. Fig. 2 illustrates the system model.

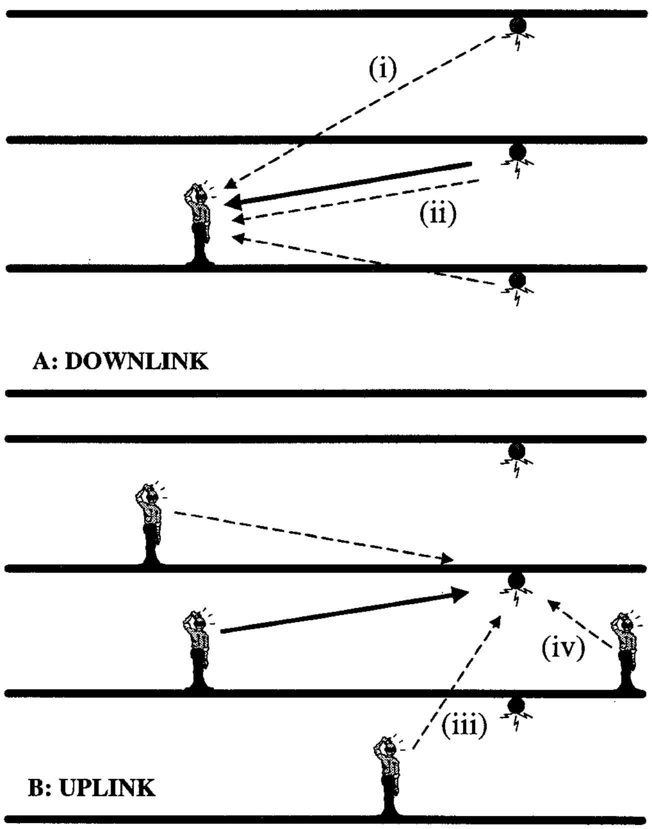

Fig. 2: *Downlink and uplink system models for an in-building CDMA system showing the various sources of interference. Components (i)-(v) are described in the text.*

——————— *Desired Signal*
– – – – – – – – – *Interfering Signal*

The performance of CDMA systems are interference limited. Consequently, the downlink is limited by interference received at the mobile user (downlink interference), and the uplink performance is limited by interference received at the base station (uplink interference), as illustrated in Fig. 2. 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

IV. Performance Estimates

The performance of the mobile radio system is measured in terms of the average bit error rate (BER) of the received signal. In this paper the BER is averaged over the variability of the composite received signal and the spatial distribution of the mobile users in the system. The mobile users are assumed to be randomly located at any one of the 53 positions where propagation measurements were made in the engineering tower (indicated by crosses in Fig. 1).

A. Downlink Performance

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 [10]

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

where α is the voice activity factor (assumed to be 0.5), N is the processing gain (assumed to 511), K is the number of active users on each floor and $\Phi(..)$ is the complementary Gauss probability integral [10]. The random variable (RV) β represents the incoherent accumulation of independent Suzuki distributed random variables that characterise the signal variability from the interfering floors, namely

$$\beta = K\cdot\sum_{\substack{n=-p\\ n\neq 0}}^{p}\frac{u(n)}{u(0)}\cdot 10^{0.1\left(L_{d_i,n}-L_{d_d,0}\right)}, \tag{4}$$

where $2p$ is the number of floors contributing to inter-floor interference. The RVs *u(n)* and *u(0)* represent the Suzuki signal variability respectively , from the *nth* interfering floor and the desired floor (σ=0 for the localised model). The variables d_i and d_d are the three dimensional spatial separation between the desired user and the interfering and desired base stations respectively and are given by

$$d_{i,d} = \left(\left(|n|\cdot s\right)^2 + x^2 + y^2\right)^{0.5}, \tag{5}$$

for the case of d_d, the number of floors, $n=0$.

In this paper an outage is defined to occur when the calculated BER exceeds 10^{-2} [13] . By means of Monte Carlo simulation the mobile user can be moved in a pseudo random manner around the possible user locations. At each location, comparison of the calculated BER with the outage threshold will yield the probability of outage when averaged over all the positions considered.

B. Uplink Performance

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

$$BER_{Base} = \Phi\left(\frac{1}{\sqrt{\frac{\alpha}{3\cdot N}\left(\frac{\psi+\zeta}{\varphi}\right)}}\right), \tag{6}$$

where φ represents the desired signal and is given by

$$\varphi = u_K(0)\cdot P_{des}. \tag{7}$$

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 distributed RV representing the variability of the desired signal (σ=2dB). In Eqn. 6, ψ represents the composite intra-floor uplink link interference and is given by

$$\psi = \sum_{i=1}^{K-1} u_i(0)\cdot P_{des}, \tag{8}$$

where each $u_i(0)$ is a Suzuki distributed RV representing the variability of the interference from the *i*th intra-floor interferer ($\sigma_i(0)$=2dB $\forall i$). The RV ζ in Eqn. 6 is the composite inter-floor uplink interference and is given by

$$\zeta = \sum_{\substack{n=-p\\ n\neq 0}}^{p} \sum_{l=1}^{K} P_l(n)\cdot u_l(n), \tag{9}$$

where each $P_l(n)$ and $u_l(n)$ are respectively, the mean power and the Suzuki variability associated with the interference from the *l*th user *n* floors away (σ=0 for the localised model). $P_l(n)$ is given by

$$P_l(n) = 10^{0.1(10\cdot\log(u_l(0)\cdot P_{des}) - L_{d_{l\,\mathrm{int}},0} - L_{d_{ldes},n})}, \tag{10}$$

where d_{lint} and d_{ldes} are the three dimensional separations between the *l*th interfering mobile user and the base stations on the desired and interfering floors respectively, $u_l(0)$ is the Suzuki variability associated with the desired user's signal (σ=2dB).

The process for determining the outage probability is essentially the same as that used for the downlink.

V. Results and Discussion

In this study two Monte Carlo simulations of a DS-CDMA mobile radio system have been undertaken for both the uplink and downlink. Two different approaches to modeling the in-building propagation environment have been considered. The first simulation used a floor averaged propagation model to predict the mean local area signal strength. The second, used a floor averaged propagation model.

Simulated downlink and uplink outage probabilities versus the number of active mobile users per floor (K) are shown in Figs. 3 and 4 respectively, for the two different modeling approaches outlined in section II.

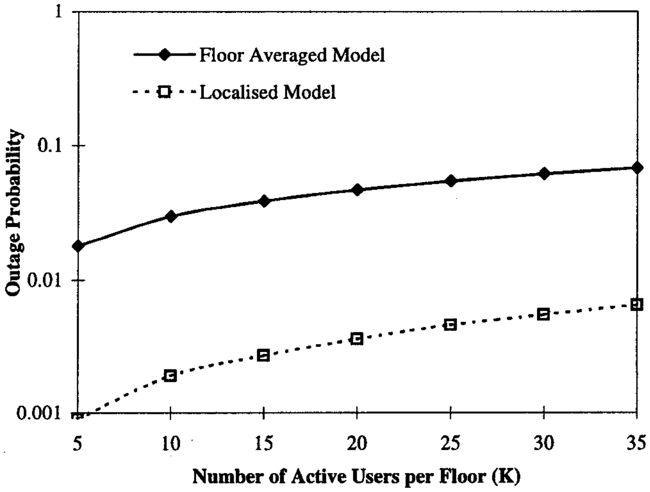

Fig. 3: *Mobile radio system downlink performance.*

The most significant thing to note from Figs. 3 and 4 is the significant difference in predicted outage probabilities between the floor averaged and localised modeling approaches. This is particularly obvious in Fig. 3 where there is more than an order of magnitude difference in predicted outage probabilities.

The localised model uses data for the actual propagation measurements over the paths considered in the simulation. For this reason, it is assumed that the simulation using the localised model will predict outage probability with the greater accuracy. If this is true, the floor averaged model appears to significantly over estimate the probability of outage.

If we consider an acceptable outage probability to be 0.01 or 1%, an estimate of the potential capacity in terms of the tolerable number of active users per floor can be made. Referring to Figs. 3 and 4, the estimated system capacity for the floor averaged approach would be less than 5 active users for the downlink and close to 1 for the uplink. For the localised approach the estimated capacity would be greater than 35 active users for the downlink and close to 5 active users for the uplink. Clearly the floor averaged modeling approach significantly underestimates potential system capacity.

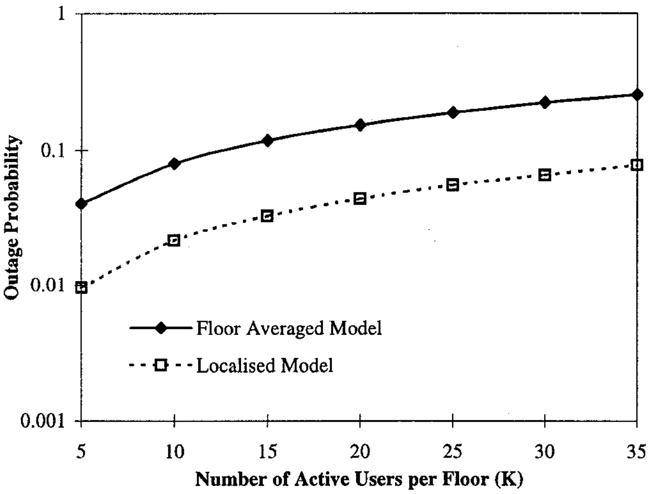

Fig. 4: *Mobile radio system uplink performance.*

Significant differences in the system performance estimates suggest that the floor averaged model lacks some essential information about the propagation environment. Analysis of the data from the propagation study showed that significant correlated shadowing existed between desired and interfering signals [12]. Some initial work has been undertaken that considers the influence of correlated shadowing on system performance estimates. Initial findings suggest that correlated shadowing can explain the large differences in performance estimates found here. In addition it is likely that correlated shadowing would influence the downlink performance more than the uplink. This is because all signals received at a mobile user (downlink scenario) are likely to be correlated, whereas, for the uplink, correlation will only influence power-controlled signals.

VI. Conclusions

The performance of a DS-CDMA in-building mobile communication system has been considered using two different approaches to modeling an in-building propagation environment. Results show that overall system performance estimates are very dependent on the model used to describe the building's propagation characteristics and suggest that the floor averaged approach leads to a rather pessimistic prediction of system performance when compared with the localised approach. This suggests that unnecessarily conservative design would be likely if the floor averaged approach was utilised as part of a system planning process. It has also been suggested that correlated shadowing may be a significant factor involved in the large differences observed.

VII. References

[1] W. C. Y. Lee, "Overview of Cellular CDMA", *IEEE Trans. Vehic. Tech.*, Vol. 40, No. 2, 1991, pp. 291-302.

[2] K. S. Gilhousen, *et al.*, "On the Capacity of a Cellular CDMA System", *IEEE Trans. Vehic. Tech.*, Vol. 40, No. 2, 1991, pp. 303-312.

[3] R. Padovani, "Reverse Link Performance of IS-95 Based Cellular Systems", *IEEE Personal Commun.*, Vol. 1, No. 3, pp. 28-34, 1994.

[4] D. L. Schilling, L. B. Milstein, "Broadband CDMA for Indoor and Outdoor Personal Communications", *Proc. PIMRC'93*, Yokohama, pp. 104-108, 1993.

[5] TIA/EIA/IS-95, "Mobile station-base station compatibility standard for dual-mode wideband spread spectrum cellular system", *Telecomm. Industry Assoc.*, July 1993.

[6] D. A. Hawbaker and T. S. Rappaport, "Indoor Wideband Radiowave Propagation at 1.3 GHz and 4.0 GHz", *Electron. Lett.*, Vol. 26, No. 21, 1990, pp. 1800-1802.

[7] H. Hashemi, "The Indoor Radio Propagation Channel", *Proc. IEEE*, Vol. 81, No. 7, 1993, pp. 943-968.

[8] S. Y. Seidel, S. Rappaport, J. Feuerstein, and K. L. Blackard, "The Impact of Surrounding Buildings on Propagation for Wireless In-Building Personal Communications System Design", in *Proceedings 42nd Vehicular Technology Conference,* Denver, CO., 1992, pp. 814-818.

[9] S. Y. Seidel and T. S. Rappaport, "914 MHz Path Loss Prediction Models for Indoor Wireless Communications in Multifloored Buildings", *IEEE Trans. Ant. & Prop.*, Vol. 40, No. 2, 1992, pp. 207-217.

[10] A. J. Motley and J. M. P. Keenan, "Personal Communication Radio Coverage in Buildings at 900 MHz and 1700 MHz", *Electron. Lett.*, Vol. 24, No. 12, 1988, pp. 763-764.

[11] K. S. Butterworth, "Outage Probability Simulation of a DS-CDMA In-Building Mobile Communication System", in *Proc. Conf. PGSIET,* Christchurch, New Zealand, 1996, pp. 450-455.

[12] K. S. Butterworth, K.W. Sowerby and A. G. Williamson, "1.8 GHz Indoor Wideband Propagation Study at The University of Auckland," *School of Engineering Report No. 569, The University of Auckland,* Nov. 1996.

[13] A. M. Viterbi, A. J. Viterbi, "Erlang Capacity of a Power Controlled CDMA System", *IEEE J. Select. Areas Commun.*, Vol. 11, No. 6, pp. 892-900, 1993.