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Performance estimation for indoor wireless systems using FDTD method

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A three-dimensional implementation of the finite-difference time-domain method is used to estimate the down-link outage probability of a direct-sequence code division multiple access system operating in a multi-storey office building in the presence of co-channel interference. The numerical analysis is supported by experimental measurements and good agreement is found for the outage probability. Both simulation and measured results indicate that vertically aligned co-channel base stations have lower outage than a vertically staggered configuration, which is explained by examining the correlation between the desired and interfering signals.

Introduction: Achieving reliable performance within highly confined areas, such as multi-storey buildings, remains a challenge for contemporary wireless systems. Co-channel interference from neighbouring systems is significant, as transmit powers are relatively high, frequency reuse separations are generally shorter, and unlike outdoor deployments, three-dimensional (3D) reuse strategies are possible [1]. Furthermore, predicting the system performance for indoor environments is complicated by the large variability in building layout, architectural styles, and building materials. Currently, empirical models based on experimental measurements are widely used, e.g. [2, 3]. However, many of the parameters in these models lack an electromagnetic basis and can vary considerably between buildings, and thus often require further tuning measurements (which can be time-consuming and expensive) [2]. To investigate the factors limiting system performance, a 3D model of a multi-storey office building is analysed using the finite-difference time-domain (FDTD) method. The FDTD method has been shown to accurately model radiowave propagation within and around buildings, e.g. [4–7]. However, the previous research has largely focused on characterising propagation mechanisms, and not on the system performance. This Letter focuses on how the FDTD method can be applied to directly estimate the outage probabilities of a direct-sequence code division multiple access (DS-CDMA) system in the presence of co-channel interference.

FDTD channel model: The simulation model consists of three floors ($18 \times 18 \times 9$ m) and contains approximately three billion mesh cells, with a spatial discretisation $\Delta = \lambda/30 = 0.01$ m and time step $\Delta t = 18.3$ ps. Fig. 1*a* shows the building floor plan – a hollow concrete services shaft contains the elevators and stair wells, and the remaining space is divided into offices with dry-wall partitions. Multiple transmitter locations (hereafter referred to as base stations) throughout the building are considered and the received power averaged over $(3\lambda)^3$ sectors to estimate the local mean by removing the effects of small-scale fading [8]. Mobile users operating in the building are assumed to connect to the base station on their current floor, and signals arriving from other co-channel base stations are treated as interference. Of particular interest are configurations where the base stations are vertically aligned or staggered, as previous experimental findings have suggested that the vertical configurations can have a significant impact on the down- and up-link system performance [1, 2].

Outage probability: DS-CDMA is a spread spectrum technique, where users are separated in signal space using orthogonal spreading codes. Therefore, the desired signal for one user will appear as noise-like wideband interference to every other user. CDMA systems are resilient to narrowband interference, but the cumulative effects of this wideband interference will degrade system performance. In digital systems an outage is assumed to occur if the instantaneous bit error rate (BER) is above a certain threshold, assumed here to be 10^{-3}. In a down-link DS-CDMA system, the BER can be approximated as a Gaussian function of the total co-channel signal-to-interference ratio [9]. The DS-CDMA processing gain introduces a receiver protection margin, r_p, and the outage probability is found by determining the probability that the power of the desired signal is less than the interfering signal multiplied by r_p. The outage probability of a DS-CDMA system in the presence of N co-channel interfering systems can thus be expressed [10] as

$$p_{\text{out}} = 1 - \int_0^\infty p(I_1) \cdots \int_0^\infty p(I_N) \int_{\sum_{i=1}^N I_i r_p}^\infty p(w) \mathrm{d}w \mathrm{d}I_N \cdots \mathrm{d}I_1 \quad (1)$$

where $p(w) = (1/A)\exp(-w/A)$ and $p(I_i) = (1/B_i)\exp(-I_i/B_i)$ are the exponentially distributed desired and ith interfering-signal powers, respectively; A is the mean desired signal and B_i is the mean of the ith interferer. As indoor environments are often cluttered, the incident wave is locally scattered around the receiver, and an exponential distribution to characterise the multi-path fading is appropriate. The resulting expression for the outage probability is given by

$$p_{\text{out}} = 1 - \prod_{i=1}^{n} \frac{\Lambda_i}{\Lambda_i + r_p} \quad (2)$$

where Λ_i is the desired-signal/interfering-signal ratio, $\Lambda_i = A/B_i$. Consequently, higher outage is expected in locations where the desired and interfering signals have comparable magnitude.

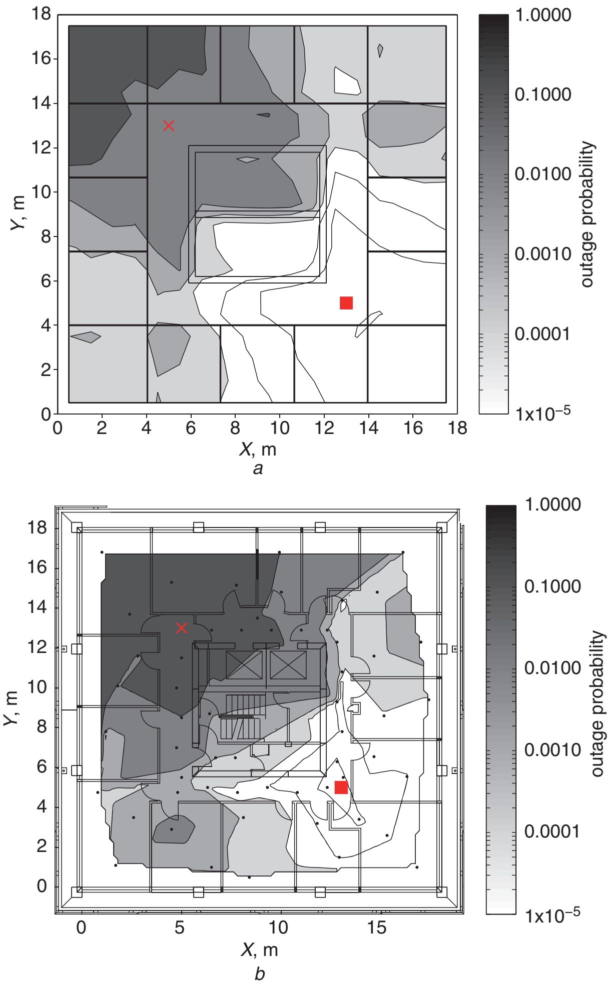

Fig. 1 *Density plots for outage probability for vertically staggered configuration (location of desired and interfering base stations are marked by ■ and ×. respectively)*

a FDTD simulations (1 GHz)
b Experimental measurements (1.8 GHz)

Fig. 1*a* shows a density map of the DS-CDMA outage probability computed from the FDTD simulation results using (2) for a vertically staggered base-station configuration: the desired base station is located at ■ on floor 2, whereas the interfering base stations are located at × on the floors immediately adjacent (1) and (3). This represents the limiting/worst-possible case as it is assumed frequencies are reused on each floor. Regions close to the desired base station are observed to have low outage ($< 10^{-5}$), and outage is highest in regions directly above or below the interfering base stations (reaching a maximum of 0.32). In this scenario, while users operating in regions shadowed by the services shaft may receive sufficient power from the desired base station, the high levels of interference from base stations operating on the adjacent floors will significantly increase the BER and outage probability. However, when the base stations are vertically aligned the outage probabilities are in the range $10^{-5} - 10^{-4}$, and remain relatively constant across the entire floor.

To confirm the FDTD findings, experimental measurements of the path loss (at 1.8 GHz) were used to compute the outage probability using (2). Multiple transmitters were deployed throughout the building and the 3λ sector-averaged power was recorded at 52 locations across the floor. Fig. 1*b* shows a density plot of the measured outage probability across the floor, for the case when two base stations on immediately adjacent floors are vertically staggered. It should be noted that, although Figs. 1*a* and *b* show a smooth variation, the outage will change abruptly at material interfaces. The simulated outage probability generally agrees well with the experimental measurements, and also indicates that the frequency difference between the simulations (1.0 GHz) and measurements (1.8 GHz) does not have a significant impact. Similar results were observed for other base-station configurations.

Correlated shadowing: For both the FDTD simulations and experimental measurements, vertically aligning the co-channel base stations is observed to introduce significant positive correlation between the desired and interfering signals, whereas by contrast staggered base stations display a strong negative correlation. Fig. 2 shows a scatter plot of the desired-signal strength and the corresponding interfering-signal powers for vertically aligned and staggered base stations. The correlation between a pair of desired and interfering base stations can be quantified by [2]

$$\rho = \frac{\sum_k \left(L_{dk} - \overline{L_{dk}}\right)\left(L_{ik} - \overline{L_{ik}}\right)}{\sqrt{\sum_k \left(L_{dk} - \overline{L_{dk}}\right)^2}\sqrt{\sum_k \left(L_{ik} - \overline{L_{ik}}\right)^2}} \tag{3}$$

where L_{dk} (dB) and L_{ik} (dB) are the sector-averaged path losses between the user location (k) and the desired and interfering base stations, respectively. The correlation coefficients computed from the simulations and measurements are as shown in Table 1.

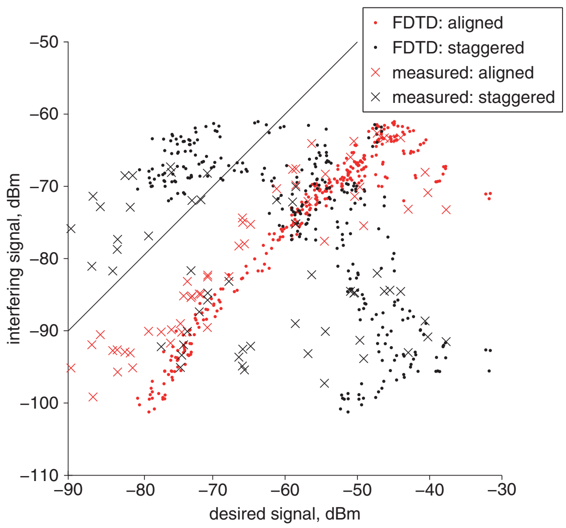

Fig. 2 *Scatter plot of measured and simulated signal strengths for vertically aligned and staggered base stations*

Table 1: Correlation coefficients for different base station configurations

	ρ_{aligned}	$\rho_{\text{staggered}}$
FDTD	0.94	− 0.70
Measured	0.85	− 0.62

The correlation coefficients agree within 10%. Positive correlation can occur when the desired and interfering signals travel over similar propagation paths and encounter the same shadowing obstacles [1, 11]. For the vertically aligned scenario, the FDTD simulation results show that both the desired and interfering signals follow the same general propagation path, namely, diffraction and reflection around the central services shaft. This introduces a strong positive correlation, as shown in Fig. 2. However, the interfering signals experience an additional 10–15 dB attenuation, introduced by the concrete floors. This isolation ensures the outage probability remains low across the floor. By contrast, when the base stations are vertically staggered on opposite sides of the building, the FDTD simulations show that the increased path loss due to diffraction and reflection around the shaft results in negative correlations between the desired and interfering signals.

Conclusion: The results show that a relatively simple FDTD model of a multi-storey building, consisting of concrete floors and dry-wall internal partitions, is sufficient to accurately estimate the outage probability for different base-station configurations. The FDTD simulation results are compared against experimental measurements conducted in a typical multi-storey office building. The strong positive and negative correlations present in the measurements of the sector-averaged signal strength – introduced when the base stations are vertically aligned or staggered, respectively – are well predicted by the FDTD simulations, which also provide an insight into the propagation mechanisms responsible for this phenomenon.

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One or more of the Figures in this Letter are available in colour online.

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