Modeling the Effects of Nearby Buildings on Inter-Floor Radio-Wave Propagation

Andrew C. M. Austin, *Student Member, IEEE*, Michael J. Neve, *Member, IEEE*, Gerard B. Rowe, *Member, IEEE*, and Ryan J. Pirkl, *Student Member, IEEE*

***Abstract*—Two buildings (A and B) have been modeled and analyzed with a 2D TE_z implementation of the finite-difference time-domain (FDTD) algorithm in order to identify and characterize the mechanisms allowing signals to propagate between floors, specifically reflection and scattering from nearby buildings. Results have been extended to 2.5D by assuming isotropic spreading in the third dimension. In both scenarios considered, reflections from surrounding buildings are found to increase the average received power on adjacent floors—up to 9.7 dB and 32 dB for Buildings A and B respectively. Measurements of the impulse response in Building A, made with a sliding correlator channel sounder, show a number of long-delay pulses, which can be attributed to specific reflection paths. Based on these findings, a simple two-component propagation model to predict the sector-average signal strengths is proposed and validated against measurements of the received power. The direct component is modeled as free space with a 22 dB/floor attenuation factor, and the reflected component is modeled as free space with reflection/transmission coefficients of 0.5. The RMS prediction error for this model is 3.2 dB.**

***Index Terms*—Finite-difference time-domain (FDTD) methods, indoor radio communication, modeling, numerical analysis, radio propagation.**

I. Introduction

The burgeoning growth in wireless communication services has led to increased levels of radio frequency interference. Indoor wireless systems are particularly susceptible to this, as all transmitters and receivers are usually in close physical proximity. As interference adversely affects system capacity and reliability [1], there is a need to understand and characterize the mechanisms governing the propagation of radiowaves inside buildings. While the problem of interfering transmitters on the same floor has been examined previously [2], the propagation mechanisms that support inter-floor interference are not as well understood. This is of particular importance in office buildings where the same frequency channels may be reused on adjacent (or nearly adjacent) floors.

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A. C. M. Austin, M. J. Neve, and G. B. Rowe are with the Department of Electrical and Computer Engineering, The University of Auckland, Auckland, New Zealand (e-mail: acm.austin@ieee.org).

R. J. Pirkl is with the Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA.

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Inter-floor propagation has been investigated through experimental measurements [3] and ray methods, specifically geometrical optics (GO) and the uniform theory of diffraction (UTD) [4]–[6]. However, these investigations have all been concerned with isolated buildings or floors, where the received power is dominated by two components: direct penetration through the floors and diffraction at the floor edges or window frames [5], [7]. As more floors are penetrated, external paths are thought to contribute more toward the received power, because internal paths are significantly attenuated. In dense urban environments, nearby buildings in close proximity can potentially reflect strong signals back onto lower floors. Complicating the problem, the outside face of modern buildings can be cluttered and electromagnetically rough, which may cause local scattering. Previous measurement studies have shown that nearby buildings can increase the received power on lower floors [8], [9]. A simplified radar-cross-section model was proposed in [8], however it is noted that this model is not applicable when the buildings are close, such that the far-field approximation is violated.

The finite-difference time-domain (FDTD) method is well suited to modeling propagation in the presence of inhomogeneous dielectric objects with complicated physical geometry. While the main disadvantage of using the FDTD method to solve electrically large problems is excessive computational requirements, recent advances in processing capabilities are making its application to the indoor propagation problem tractable. For example, the FDTD method has been used to predict the coverage area from base stations operating in the lower ISM bands [10]–[12], while [13] also examined propagation characteristics at 5.8 GHz. None of these references simulated the channel impulse response; however [13] extracted time-delay data from simulations using sinusoidal excitation.

Accurate propagation models that can predict relevant statistical parameters, such as the signal-to-interference ratio (SIR), are essential to the development and successful implementation of future wireless systems. Currently, empirical models based on experimental data are popular [3], but these require many measurements, can be site specific, do not explain the physical phenomena observed, and thus cannot be easily generalized. Indoor environments can be very complex, and a more thorough understanding of radio-wave propagation can be gained through an electromagnetic approach [14]. However, fully electromagnetic methods, such as the FDTD, are inappropriate for day-to-day use, due to complexity and the requirement for detailed knowledge of the physical geometry and layout. Therefore, in this paper, we are also developing mechanistic models appropriate for system planning. These mechanistic models are derived from the FDTD results, while retaining the accuracy of their electromagnetic foundations.

The FDTD implementation is detailed in Section II, which also discusses a method to generalize the 2D results to 2.5D by assuming isotropic spreading in the third dimension. Section III examines wideband and narrowband simulation results—from which a two-component mechanistic propagation model is proposed in Section IV. Section V validates this mechanistic model against narrowband measurements of the path gain. Comparisons are also made between the FDTD simulated impulse response and wideband data. Section VI briefly discusses applicability of the model and implications of the results for the deployment of digital communication systems in buildings, while Section VII summarizes our findings.

II. FDTD Analysis

The two buildings considered in this study are typical 1960s reinforced concrete multifloor structures. Building A is surrounded by two sets of multistory buildings (referred to as Buildings I and II in this paper) between 8 m and 20 m away. Building B is isolated on all faces, except for a single story lecture hall 4 m away on the ground floor; this has a sheet-metal roof. To determine the effect nearby buildings have on the strength of received signals, the FDTD method has been used to simulate TE_z mode propagation in simplified 2D geometries, shown in Fig. 1(a) and (b); these consider a vertical "slice" through each problem consisting of dielectric slabs with metal bars representing the reinforced concrete floors. The external details, such as the windows, ledges and hanging panels were also modeled.

A. Simulation Setup

The FDTD simulation space is surrounded by a uniaxial perfectly matched layer (UPML) [15]. A single, vertically-orientated electric field component in the 2D lattice, acts as the transmitter. This creates a radiation pattern similar to a Hertzian dipole. Therefore, more energy is directed azimuthally (toward the surrounding buildings), than through the floors. The concrete floors are modeled as homogeneous, lossy, dielectric slabs (0.3 m thick) with permittivity $\epsilon = 6\epsilon_0$, and conductivity $\sigma = 50$ mS/m [10]. The metal reinforcing bars have been modeled as $\sigma = 10^7$ S/m blocks with 0.04 m square cross-section spaced 0.5 m apart. The glass windows are 5 mm thick and modeled as dielectric slabs with $\epsilon = 6\epsilon_0$, and $\sigma = 2$ mS/m. The metal roof is modeled as a 10 mm thick sheet with $\sigma = 10^7$ S/m.

Numerical dispersion is minimized by ensuring the lattice density is at least 12 cells/$\lambda_{\min}$ [15]. For 4.5 GHz simulations, the lattice size is 0.002 m, the time step $3.3\dot{3}$ ps, and the total time simulated is 200 ns (60 000 time steps). It should be noted that on a 1.86 GHz Intel Xeon processor, the CPU-time for these problems is in excess of 30 days. At a center frequency of 1.0 GHz the lattice constraints can be relaxed to 0.005 m, which decreases CPU-time to 80 hours and allows an extension in the total time simulated to 400 ns, i.e., total path lengths up to 120 m.

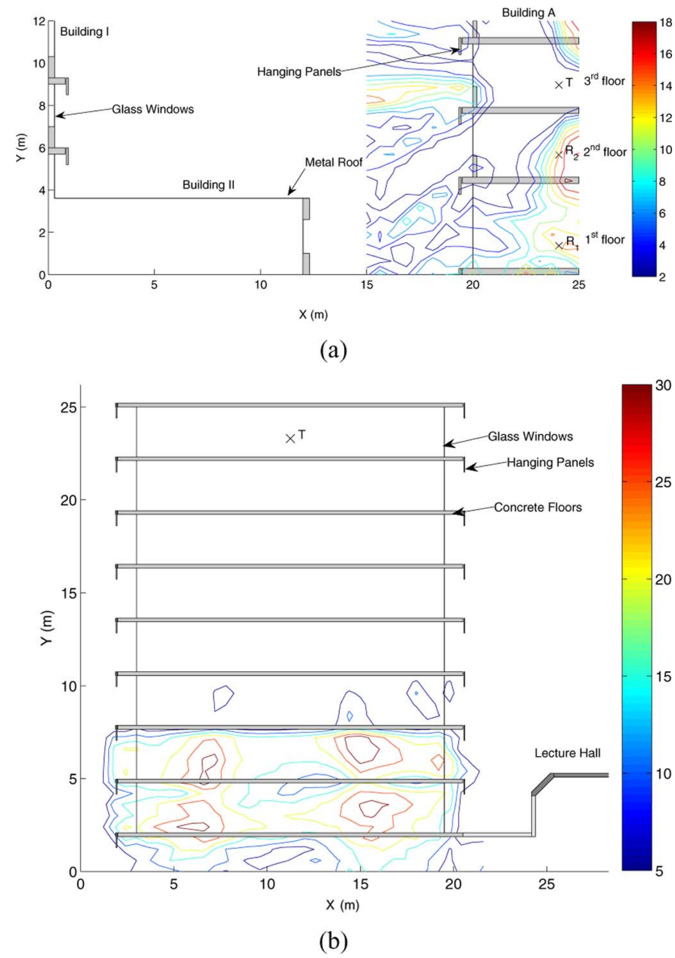

Fig. 1. The problem geometries simulated with the FDTD method. (a) Three floors of building A with the surrounding buildings. The transmitter T and the sampling points R_1 and R_2 are shown. (b) Building B and the metal roof lecture hall; the transmitter is located on the top floor. Overlaid are contour plots showing the increase in sector-averaged received power (in dBm) when the surrounding buildings are included in the simulation model.

B. Extension to Three Dimensions

Three dimensional geometries have not been analyzed with the FDTD method because of the unrealistically high computational requirements. However, 2D simulation results can be extended to 2.5D by considering isotropic spreading in the third dimension. This assumes there are no changes to the geometry in the third dimension. For the electric field, the additional divergence term is $(1/(\sqrt{d}))$, where d is approximated from the total elapsed time, $d = ct$. This correction term will overestimate the distance, and hence attenuation, for paths passing through the concrete floors, as the propagation velocity decreases inside the concrete. However the distance travelled in the floors (0.9 m) is small compared to the free space distance (10 m), and thus the approximation has been observed to result in a maximum error of 0.3 dB/floor penetrated. Diffraction at an edge also spreads the original wavefront in the third dimension, and this will provide additional paths for double-diffracted components which are not considered in the 2D model—however, these are typically much smaller and can be safely ignored.

III. Simulation Results

Both wideband and narrowband simulation results from Buildings A and B indicate substantial levels of power are reflected by nearby structures. Reflected signals dominate, as the penetration loss through the floors is high, whereas the reflected paths are largely free-space. The simulations were conducted at center frequencies of 1.0 and 4.5 GHz, and results show increasing the frequency does not significantly change the findings, as the reflection and transmission coefficients of the dielectric materials do not change substantially over this frequency range. This section presents the results obtained when exciting the lattice with a 1.0 GHz center frequency pulse—Section V compares the 4.5 GHz simulation results to measurements conducted at that frequency.

A. Increase in Received Power

The steady-state magnitude was measured by multiplying the pulse data (with the additional 2.5D divergence term applied) with a 1.0 GHz Cissoid. The electric fields were averaged over $2\lambda \times 2\lambda$ sectors to remove small scale fading and converted to power. The increase in received power was computed by comparing the received power when the surrounding buildings were removed from the simulation model. Fig. 1 presents contour plots showing the increase in received power (in dBm) for buildings A and B when the surrounding buildings are modeled.

When the structures surrounding Building A are included in the FDTD model, the sector-averaged received power is increased by up to 18 dB, as shown in Fig. 1(a). There is little change on the third floor; however on lower floors the signal strength increases—4.0 dB across the second floor and 9.7 dB across the first floor. Similarly, Fig. 1(b) shows the received power is increased by up to 32 dB on the lower two floors of Building B when the transmitter is located on the top floor. The increase in received power is most pronounced in the center of the building, where the interference pattern created by the multifloor structure is known to produce a weaker signal [7]. The received power on higher floors remains unaffected by reflections from the Lecture Hall. The results from these two buildings indicate that the strength of the reflected signal is dependent on the distance to the nearby structure.

B. FDTD Simulated Impulse Response

The impulse response in Building A was measured by applying a modulated Gaussian pulse $p(t) = e^{-((t-t_0)/t_w)^2} \sin(2\pi f_0 t)$ to the vertical electric field component at T in Fig. 1. The pulse parameters are: $t_w = 0.4$ ns and $t_0 = 5t_w$ s, producing a pulse with a 470 MHz 3-dB bandwidth. The E_y component of the electric field was sampled on each floor (R_1 and R_2 in Fig. 1), directly under the transmitter. The baseband impulse response was recovered by non-coherent demodulation of the received signals.

Fig. 2 shows the baseband impulse response at R_1 and R_2 with the 2.5D spreading term applied. In each location a number of distinct pulses are visible, but these can be grouped into three sets—marked A, B, and C on Fig. 2(a). By examining the evolution of the pulse, and by computing path-length from the time-delay, it is possible to associate each pulse with a distinct path. Pulse set A represents the signal traveling directly through the floors, while pulse sets B and C represent single and double reflections at the face of Building I. As shown in Fig. 2(b) on the lower floors the received signal is increasingly dominated by pulses arriving on long delay paths (pulses B and C). The smaller pulses between A, B and C represent diffraction from the corner of Building II (since no direct reflection path is possible).

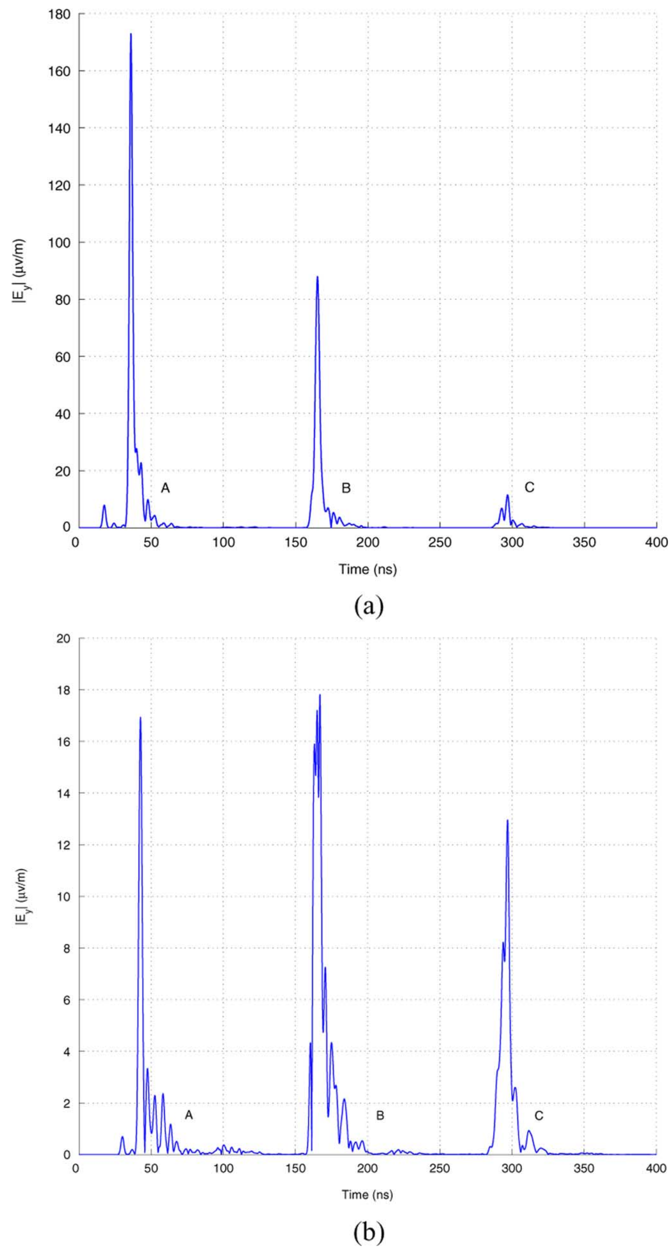

Fig. 2. Simulated impulse responses at positions (a) R_2, single floor separation and (b) R_1, two floor separation.

The fraction of the total received power arriving on each component, with the additional 2.5D spreading factor applied, is estimated in Table I. An additional floor was added to the simulation model to continue the trend. The power arriving on a particular path is calculated by summing the squared electric field over the appropriate time interval; the fraction by dividing this value by the total received power at that location. The time intervals are identified through inspection, and as time delays

TABLE I
PERCENTAGE OF POWER ARRIVING ON EACH COMPONENT

		Floor 1	Floor 2	Floor 3
Direct	(A)	93.1%	54.7%	2.5%
Reflections	*Total*	6.9%	45.1%	93.2%
	Single Bounce (B)	6.9%	37.4%	90.8%
	Double Bounce (C)	0.0%	7.7%	2.4%
Diffraction		0.0%	0.2%	4.3%

are sufficiently spread, overlaps are avoided. The components reflected at the face of the surrounding buildings have been divided into single (B) or double (C) reflections.

For a single floor separating the transmitter and receiver the majority of received power arrives through the floor, while only 6.9% arrives on reflected paths. As more floors separate the transmitter and receiver, the relative strengths of reflected pulses increases. On the second floor, 45.1% of the total received power is reflected, and on the third floor, only 2.5% is due to floor penetration. The majority of the reflected power arrives on single-bounce paths, with double-bounce reflections delivering at most 7.7% of the total power. It must also be noted that diffraction at the corner contributes a maximum 4.3% of the total received power on the first floor, and is negligible on higher floors. This indicates diffraction does not make a major contribution in this environment. As the reflected paths remain external to the building, they are largely free space—resulting in similar amplitudes on lower floors.

IV. DEVELOPMENT OF A MECHANISTIC MODEL

The results presented in Section III indicate the power arriving on adjacent floors in a multistory building is dominated by the component penetrating through the floors and the component reflected by nearby buildings. Based on these findings, a simplified GO-based, mechanistic model to predict path gains on adjacent floors is proposed. The results have also indicated that double-reflections and edge diffraction can increase the received power; however their contribution is inconsequential enough to be excluded from consideration in the mechanistic model. Thus the model consists of two components, both of which are based on the Friis equation [16]. For the computation of spatially averaged power the two components can be treated as uncorrelated and are added together on a power basis, as shown by

$$\mathrm{PG}_{\mathrm{total}} = \mathrm{PG}_{\mathrm{direct}} + \mathrm{PG}_{\mathrm{reflected}}\ (\mathrm{W}). \quad (1)$$

The path gain of the direct component is estimated by

$$\mathrm{PG}_{\mathrm{direct}} = \left(\frac{\lambda}{4\pi d_d}\right)^2 \kappa^{2n}\ (\mathrm{W}) \quad (2)$$

where d_d is the distance between the transmitter and receiver when the wave penetrates through the floors, n is the number of floors penetrated and κ is the (linear) attenuation through a single floor. Measurement and simulation results indicate κ (in log-units) is approximately 22 dB/floor, and is consistent with observations made by other researchers [4]–[6]. The path gain of the component reflected back from the surrounding buildings is estimated by

$$\mathrm{PG}_{\mathrm{reflected}} = \sum_{b=1}^{B} \left(\frac{\lambda}{4\pi d_b}\right)^2 \prod |\Gamma|^2 \prod |\tau|^2\ (\mathrm{W}) \quad (3)$$

where B is the number of adjacent buildings parallel to an external face, d_b is the distance between the transmitter and receiver when the wave reflects from surrounding building b, Γ is the reflection coefficient at the building face and τ is the transmission coefficient through the glass windows. Measurements and simulations indicate transmission through two sets of glass windows and reflection at a glass-fronted building reduces the received power by 18 dB. This can be modeled by reflection and transmission coefficients of 0.5.

V. EXPERIMENTAL VALIDATION OF THE MECHANISTIC MODEL

The mechanistic model, (1)–(3) and the wideband FDTD results have been validated against experimental measurements made on the lower three floors of Building A.

A. *Narrowband Comparison*

The mechanistic model proposed in (1)–(3) has been used to predict path gains on the lower three floors of Building A. Measurements were taken at 4.5 GHz with bi-conical antennas. The transmitting antenna was located 4 m from the windows and the receiving antenna at 20 locations on each floor. The received power was averaged over 9λ sectors to remove small-scale fading. Fig. 3 compares the sector average path gain measurements with values predicted by the mechanistic model. The RMS error between the path gains predicted by the mechanistic model and measurements is 3.5 dB for one floor separation and 2.8 dB for two floor separations, indicating a high degree of prediction accuracy is possible with the mechanistic model. Predictions of the sector-averaged path loss have also been computed with Seidel's "Floor Attenuation Factor" path-loss model [3] and compared against experimental measurements; as shown in Fig. 3, it greatly underestimates the received power. The Seidel model was developed from experimental measurements at 914 MHz, though validity to 5 GHz was proposed on the basis of comparisons with other measurement studies. The 1.0 m reference path loss was measured to be 54.6 dB at 4.5 GHz; the distance dependency exponent (3.27) and the floor attenuation factors (12.9 and 18.7 dB) were taken from Seidel's data [3].

B. *Wideband Comparison*

The simulation findings in Section III-B were confirmed with experimental measurements made on the lower three floors of Building A. The impulse response was measured using a sliding correlator channel sounder with a 511-bit PN sequence clocked at 800 MHz. The center frequency of the system was 4.5 GHz and the 3 dB signal bandwidth was approximately 700 MHz. The theoretical dynamic range for the system is 43.33 dB [17], while in practice it is approximately 30 dB. To express the results in path gain, and to remove the linear system response, the raw data was calibrated against free-space measurements made in an anechoic chamber. The measurements were time-averaged

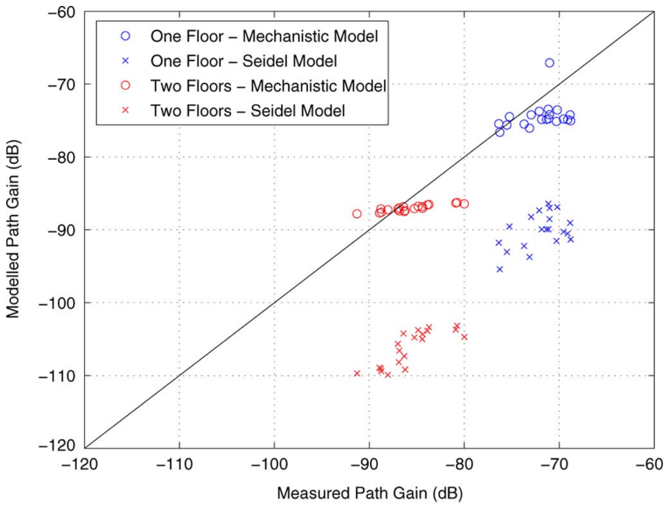

Fig. 3. Scatter plot of the measured and predicted path gains for 40 sectors in Building I. The RMS error for all data-points is 3.2 dB.

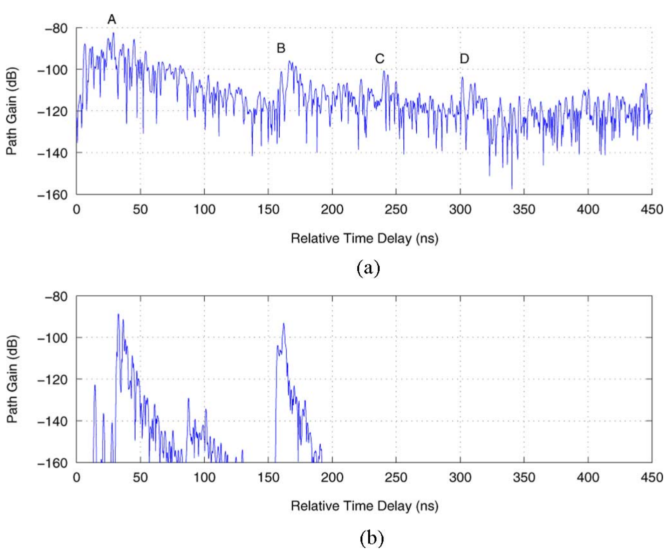

Fig. 4. Comparisons between the (a) experimentally measured and (b) FDTD simulated impulse response for one floor separation.

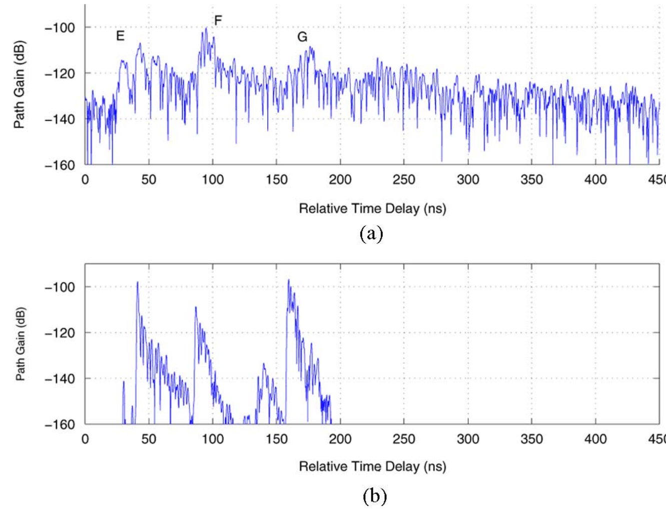

Fig. 5. Comparisons between the (a) experimentally measured and (b) FDTD simulated impulse response for two floor separation.

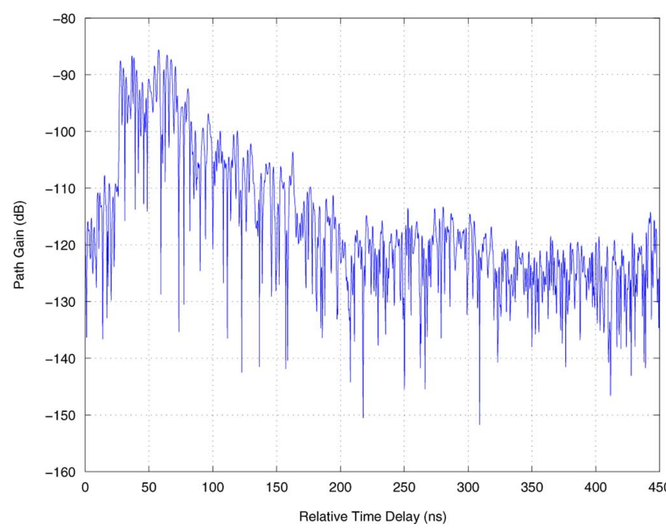

Fig. 6. Impulse response measured at the front face, where there are no surrounding buildings.

to minimize the effects of time-varying scatterers in the environment. Wideband antennas were used: a vertically-orientated bicone as the transmitter and a pyramidal horn as the receiver. The horizontal and vertical 3-dB beamwidths of the horn antenna were 10°. By taking measurements with a directional receiving antenna, only signals arriving in the beamwidth will contribute. Significantly, this will limit the effect of signals arriving from other directions and allows a valid comparison with the 2.5D simulation results.

The transmitter was located on the third floor, and the impulse response measurements were taken on the first and second floors. Both antennas were vertically aligned and positioned 4.0 m from the windows and 1.0 m above the floor—identical to the FDTD simulation setup. The measurements were repeated at the front face of Building I (where there are no nearby buildings). The measured impulse response on the first and second floors at the back face are shown in Figs. 4(a) and 5(a). The salient features have been labeled. For comparison, the 4.5 GHz FDTD simulation results (with 700 MHz 3-dB pulse bandwidth) are shown beneath in Figs. 4(b) and 5(b)—there are differences in the signal magnitude (up to 10 dB) between the simulations and the measurements, however, there is generally good agreement in the time-domain. For both sets of measurement data the noise floor (and dynamic range) of the system is 35 dB below the maximum peak—approximately -115 dB and -135 dB. The measurements have a higher noise floor and lower dynamic range than the FDTD simulations; however the dominant pulses are clearly visible. Furthermore, Fig. 6 shows the impulse response measured for a single floor separation when the horn antenna was directed outwards, toward the street, and no long delay paths were observed.

In Fig. 4(a) there are two distinct sets of pulses, identified by A and B and these are centered at 35 and 165 ns. These correspond to the components of the signal traveling through the floor and reflected by Building I respectively. This is supported by FDTD results and the time difference—indicating an excess path length of 39 m—agrees well with reflection from Building

I, 20 m away. The smaller pulses at 240 and 310 ns (identified by C and D) are thought to be caused by higher order reflections since time delays agree well with FDTD simulations, but, as these are close to the noise floor, no conclusions can be drawn. In Fig. 5(a) three sets of pulses—identified by E, F, and G and centered at 45, 90, and 170 ns, respectively—are observed. These correspond to direct penetration, diffraction at Building II and reflection at Building I respectively. The temporal alignment with the FDTD simulation results in Fig. 5(b) is good; however the magnitudes of some components are different.

The differences between the simulations and measurements are largest when two floors separate the transmitter and receiver—for a single floor separation, the differences are much smaller, approximately 3 dB. This suggests that much of the error is introduced by not including some features of the first floor environment in the FDTD simulation. The first floor environment is heavily cluttered by industrial equipment (motor/generators, gantry cranes etc.), which was not included in the FDTD model—these will scatter the energy and lower the peak power arriving on a single component. Furthermore, the detailed scatter on the roof of Building II (metal rain gutters) was not modeled in the FDTD simulations. It must also be noted that expanding the FDTD results to 2.5D will underestimate the distance travelled (and thus overestimate the received power) when the wave travels through a dielectric material.

VI. Discussion

It is observed that reflections from nearby buildings can increase the averaged received power of adjacent floors by 9.7 dB, compared to the case when no adjacent buildings are present. After two floor separations the reflected signals are of similar magnitude to those penetrating the floors. This could have significant implications for in-building wireless systems. If frequencies are reused on adjacent floors, reflections provide low-loss paths which will increase the level of co-channel interference, lowering the SIR and thereby reducing system performance.

The mechanistic model outlined in (1)–(3) is appropriate when adjacent buildings are present to support reflection onto lower floors and when construction materials and building styles are similar. Other paths, both internal (e.g., propagation down stairwells and lift shafts) and external (e.g., diffraction at floor edges) have not been considered in this paper, as the adjacent building reflections dominate the received signal. However, in the absence of surrounding buildings, other mechanisms will need to be considered. More general models, such as Seidel and Rappaport's empirical distance-dependency model, can predict the sector-averaged path gains in a multistory building with an RMS error of 5.8 dB [3]. As the Seidel model is based on experimental measurements its transportability to other buildings (in which measurements were not taken) is uncertain [18]. Empirical propagation models do not allow system designers to predict the received power for all types of buildings without the need for calibration measurements [3]. As the mechanistic model outlined in this paper is based on physical phenomena it could be applied in other buildings with a higher degree of confidence.

VII. Conclusion

2D models of large buildings in dense urban environments have been analyzed with the FDTD method. Results indicate that reflections from nearby buildings can have a significant role in delivering power to lower floors. As more floors are penetrated, FDTD simulations indicate the proportion of power arriving via external reflection paths increases significantly—up to 93.2% after two floor separations. The strength of the penetrating component becomes substantially weaker passing through each floor, while the strength of the reflected component remains largely the same. 2D simulation results have been extended to 2.5D by introducing isotropic spreading in the third dimension. This allows the FDTD simulations to be compared directly against experimental data collected with a sliding correlator channel sounder. The measured impulse responses agree well with the simulations, and time delays also match the expected path lengths. Both simulations and measurements show reflections from nearby buildings can increase the received signal by over 10 dB.

A mechanistic model to predict the sector-averaged power on lower floors separates out the component contained within the building perimeter and the component reflected at the face of an external building. For the computation of spatially averaged power these two components can be treated as uncorrelated. The components have been modeled as free space with appropriate attenuation and reflection/transmission coefficients. A comparison against measurements show an RMS error of 3.2 dB, indicating a high degree of accuracy is achievable.

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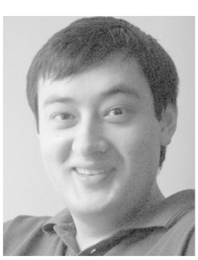

Andrew C. M. Austin (S'06) was born in Auckland, New Zealand, on August 1, 1985. He received the B.E.(Hons.) degree in electrical and electronic engineering from the University of Auckland, in 2007, where he is currently working toward the Ph.D. degree.

His research interests are in the areas of radiowave propagation, mobile communications and computational electromagnetics.

Mr. Austin was awarded a New Zealand Tertiary Education Commission Bright Futures Top Achiever Doctoral Scholarship in 2007.

Michael J. Neve (M'91) was born in Auckland, New Zealand, on October 29, 1966. He received the B.E. (Hons.) and the Ph.D. degrees from the University of Auckland, in 1988 and 1993, respectively.

From May 1993 to May 1994, he was Leverhulme Visiting Fellow at the University of Birmingham, U.K. During this time, he was involved with radiowave propagation research using scaled environmental models. From May 1994 to May 1996, he was a New Zealand Science and Technology Postdoctoral Fellow within the Department of Electrical and Electronic Engineering, University of Auckland where, from May 1996 to December 2000, he was a part-time Lecturer/Senior Research Engineer, and is currently a Senior Lecturer and Director of Graduate Studies in the Department of Electrical and Computer Engineering. In 2004 he was a Visiting Scientist at the CSIRO ICT Centre in Sydney, Australia. His present research interests include radiowave propagation modeling in cellular/microcellular/indoor environments, the interaction of electromagnetic fields with man-made structures, cellular system performance optimization and antennas.

Dr. Neve was jointly awarded a 1992/1993 Inst. Elect. Eng. Electronics Letters Premium for two publications resulting from his doctoral research.

Gerard B. Rowe (M'84) received the B.E., M.E., and Ph.D. degrees from the University of Auckland, Auckland, New Zealand, in 1978, 1980, and 1984 respectively.

He joined the Department of Electrical and Computer Engineering, University of Auckland, in 1984 where he is currently a Senior Lecturer. He is a member of the Department's Radio Systems Group and his (disciplinary) research interests lie in the areas of radio systems, electromagnetics and bioelectromagnetics. Over the last 20 years he has taught at all levels and has developed a particular interest in curriculum and course design. Currently, his educational research activity is concentrated on the secondary-to-tertiary transition and on the development of course concept inventories.

Dr. Rowe is a member of the IET, the Institution of Professional Engineers of New Zealand (IPENZ), ASEE, STLHE, and AaeE. He was the joint recipient of the 1993 Inst. Elect. Eng. Electronics Letter Premium Award for the papers "Assessment of GTD for Mobile Radio Propagation Prediction" and "Estimation of Cellular Mobile Radio Planning Parameters Using a GTD-based Model" which he coauthored. He has received numerous teaching awards from his institution. In 2004 he was awarded a (National) Tertiary Teaching Excellence Award in the Sustained Excellence in Teaching category and in 2005 he received the Australasian Association for Engineering Education award for excellence in Engineering Education in the Teaching and Learning category.

Ryan J. Pirkl (S'06) received the B.S. and M.S. degrees in electrical engineering from the Georgia Institute of Technology, Atlanta, in 2005 and 2007, respectively, where he is currently working toward the Ph.D. degree.

His research interests are radio wave propagation, RF engineering, and analytical electromagnetics.