Electromagnetic Engineering for Communications in the Built Environment

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***Abstract*—In this paper, two key aspects relating to the electromagnetic engineering of wireless communication systems in built environments are considered. Firstly, the mechanisms by which radio signals propagate in typical built environments are discussed, using results from a comprehensive study of propagation in a representative multi-storey building using the Finite-Difference Time-Domain (FDTD) method. Secondly, the influence of these propagation effects on the reliability and capacity of wireless systems from a user perspective are considered. Strategies for how wireless communication systems engineers might best address the challenges imposed by the propagation process on system deployments are then proposed.**

I. Introduction

The ability to communicate wirelessly within buildings — both with acceptable performance and with sufficient capacity — is becoming increasingly important, as the range of consumer-grade portable devices with broadband wireless functionality proliferates. Although these devices provide amazing functionality, much of this is dependent on being able to achieve broadband internet connectivity which, from a user perspective, is frequently sub-optimal. It can be argued that levels of dissatisfaction have increased as a result of inevitable comparisons with broadband wired systems — the performance of which is taken for granted by many users at present. For wireless systems, the shared nature of the channel and the ability to compensate (where necessary) for the vagaries of radio propagation within buildings is crucial for achieving adequate performance. This situation is further compounded in that buildings are often internally reconfigured during their lifetimes, and details of their construction are frequently only known to limited accuracy.

In this paper, two key aspects relating to the electromagnetic engineering of the built environment for wireless communications will be discussed. In Section II, relevant historical aspects relating to wireless communications in buildings will be presented, together with societal expectations as to what these services should provide. Issues relating to the modelling of radio propagation will then be presented in Section III, and recent developments in this area discussed in Section IV. The challenges imposed by the propagation process on system deployment strategies are presented in Section V, and strategies for how these challenges might be addressed proposed in Section VI.

II. Wireless Communications — History and Societal Expectations

A key concept underpinning the success of cellular communications is that of frequency reuse [1, p58]. Intensive application of this concept in regions of high user density has yielded significant increases in net capacity of systems, as a consequence of decreasing the nominal coverage areas of cells. An unfortunate side-effect of this is that the nominal distances between co-channel transmitters (whether they be at the base stations/access points or mobile stations) are reduced, which increases the levels of co-channel interference. It is well known that the performance of these systems (as typified by those deployed in indoor environments) are limited by the levels of interference encountered.

In recent times, wireless communications infrastructure based on the IEEE802.11a/b/g/n standards [2] have proliferated, and are now a popular means by which users can easily and inexpensively access the internet. However, it can be argued that these systems have not delivered their true potential. User experiences are frequently sub-optimal – usually as a result of inadequate throughput, quality of service or even levels of coverage/connectivity achievable. It is inevitable that many users (either consciously or unconsciously) compare their wireless performance with that of the commonly accessible hard-wired broadband physical layer infrastructure, for which levels of performance significantly outstrip that of systems based on the IEEE802.11 WLAN standards. Despite the technical sophistication of these systems, it must be realised that from societies' perspective, the technical details by which acceptable levels of performance are achieved are unimportant, only that they are achieved.

Wireless communications engineers are fundamentally charged with delivering wireless connectivity that is reliable, high quality, efficient, scalable and inexpensive. It is important to note that while significant technical advances in hardware and software have realised many potential capabilities, much of this has been locked into standards which cannot be changed ‘in the field’. For example, in the case of IEEE802.11, modulation and coding algorithms are fully specified in the relevant standards and cannot be changed — even should some better alternative be identified at a later stage. In practice, the engineer charged with deploying wireless systems has relatively few degrees of freedom. Factors such as access point location, their antennas and channel selection are obvious candidates, but the question remains as to whether these factors offer sufficient degrees of freedom to allow the realisation of an acceptable level of performance. The fundamental questions that those deploying wireless systems must ask are *“What levels of coverage will I get?”*, and *“What levels of interference might I cause to users assigned to the access points I have already deployed?”*. Answering both of these questions requires an understanding of how the physical environment influences the transmissions of both the access points and mobiles. It is well known that significant environmental obstacles (such as steel-reinforced concrete walls and floors) can significantly attenuate the propagating fields, and raises the question as to whether this behaviour might be exploited to benefit performance.

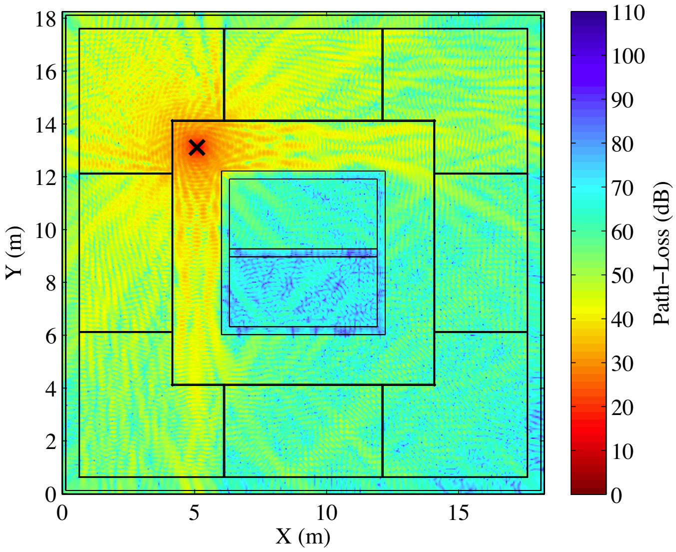

Fig. 1. Path loss estimates on a horizontal slice through the ‘basic’ geometry (from [6]). A 1 GHz vertically-polarised (E_z) field was excited from a source located at $\times$.

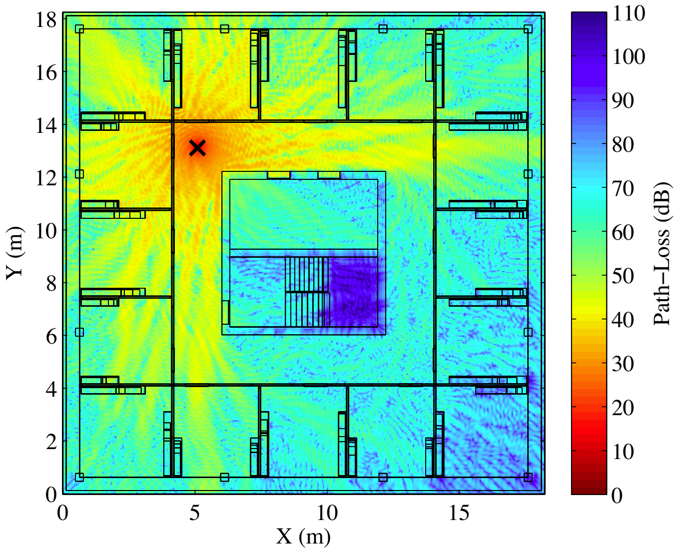

Fig. 2. Path loss estimates on a horizontal slice through the ‘detailed’ geometry (from [6]). A 1 GHz vertically-polarised (E_z) field was excited from a source located at $\times$.

III. Radio Propagation Modelling in Indoor Environments

There have been a significant number of attempts to develop reliable models for radio propagation in indoor environments (e.g, [1], [3], [4]). Broadly speaking, these models can be categorised as either *empirical* (i.e. based primarily on experimental measurement campaigns), *deterministic* (i.e. derived from Maxwell’s equations) or *semi-deterministic* (i.e. based on some relevant deterministic approach but with heuristic corrections which might be determined from additional experimental measurements). Each of these categories have distinct advantages and disadvantages. For example, empirical models can be very efficiently applied in practice but are difficult to apply reliably to environments beyond that which was originally measured. Conversely, deterministic models can be very accurate, but only so long as they have accurate input data. A further disadvantage of a fully deterministic approach is that they can be very cumbersome to apply, given that typical building-scale geometries are electromagnetically very large, and coverage estimates from a range of potential access-point locations might well be required [5], [6].

At all times, the aim of the system deployment engineer is to produce designs which will have an acceptable level of performance in a timely manner — often in the face of considerable uncertainty. It is an unfortunate fact that the physical structure of many buildings is only known to a limited degree of accuracy. What is needed therefore is a modelling approach that is able to capture the key effects which dominate received signal strengths. The semi-deterministic approach advocated herein is to implement an ‘exhaustive’ analysis of a typical range of building environments, and then use the results from this analysis to derive simpler ‘mechanistic’ models which encapsulate the key effects which dominate the propagation process [5], [6]. Fortunately, recent advances in low-cost computing hardware have meant that techniques such as the Finite-Difference Time-Domain (FDTD) method can be used to analyse building-scale obstacles at typical wireless LAN frequencies.

IV. Modelling the Built Environment using the FDTD Method

An extensive study has been made of the School of Engineering Tower at The University of Auckland, New Zealand, using a parallel implementation of the FDTD method [6]. The floor dimensions are 20 m $\times$ 20 m with a centrally-located steel-reinforced concrete services core (containing lifts/elevators and a stairwell). Offices are located on the periphery of the floor, and are separated from the services

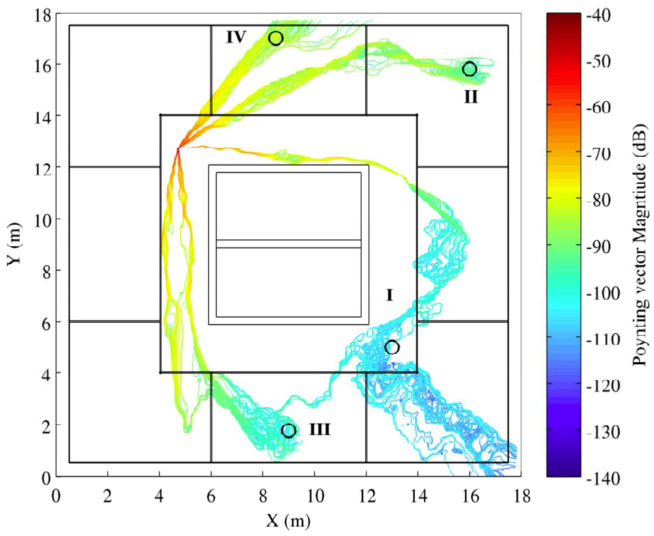

Fig. 3. Streamlines of energy flow for the 'basic' geometry in Fig. 1 (from [6]).

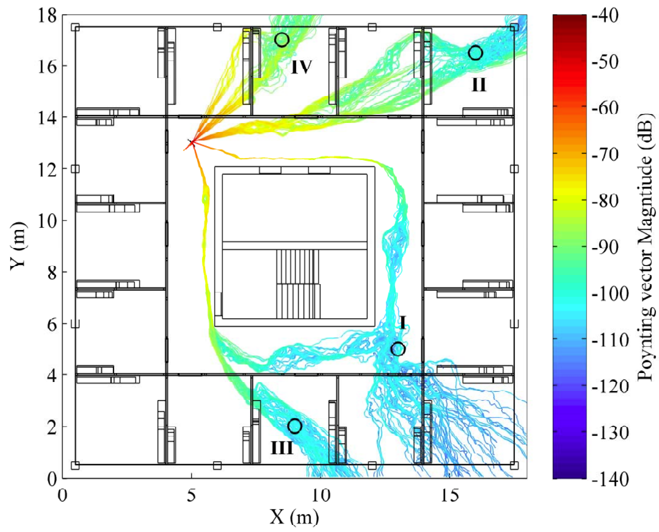

Fig. 4. Streamlines of energy flow for the 'detailed' geometry in Fig. 2 (from [6]).

core by a corridor. The studies reported in [6], [7] have shown that the services core acts as a significant shadowing obstacle, with signal levels in the deep shadow region being heavily influenced by the specific objects encountered by the fields as they propagate. Two specific geometries were considered — the first (denoted 'basic') only included the services core and other fixed walls, whereas the second (denoted 'detailed') also included small-scale environmental clutter such as bookshelves. A 3D FDTD algorithm was implemented and used to solve for fields across three floors of the building. Path loss estimates for both the 'basic' and 'detailed' geometries are shown in Figs. 1 and 2 respectively. These results demonstrate that environmental clutter (caused by small-scale obstacles such as bookshelves, metal screens, etc) can significantly increase the path loss, and should therefore be accounted for in any path loss prediction model.

An added advantage in using the FDTD to assist in the understanding of the propagation process is that the spatially interleaved electric and magnetic field data is both vectorial in form and is sampled on a very fine mesh (typically $\sim \lambda/20$). This information can be used to estimate the time-averaged Poynting vector, defined by

$$\mathbf{S} = \frac{1}{2}\Re\left[\mathbf{E} \times \mathbf{H}^*\right]$$

at every grid point throughout the field lattice. By colocating the $\mathbf{E}$ and $\mathbf{H}$ field components (via spatial averaging), it is possible to define streamlines according to

$$\frac{d\vec{p}(a)}{da} = \mathbf{S}(\vec{p}(a)),$$

which can be used to visualise energy flow.

Examples of this are shown in Figs. 3 and 4 for the 'basic' and 'detailed' geometries respectively. Comparison of these results demonstrate that the central services core is acting as a major shadowing obstacle, but also that the addition of environmental clutter is also having a significant effect. It is therefore important to have reliable estimates of both wall attenuations and the influence of environmental clutter such as bookshelves — especially if a significant number of such obstacles might be encountered (which is frequently the case in regions of deep shadow). It is important to emphasise that the FDTD is not appropriate for routine system planning, but the results from the 'exhaustive' analysis using the FDTD can be used to formulate simpler 'mechanistic' models more suited to system planning applications.

V. High Capacity System Deployment and the Built Environment

In deploying wireless systems, engineers are primarily interested in predicting levels of coverage from potential access point locations. However, it is clear that very high levels of performance will only be possible if levels of co-channel interference can be effectively managed. To quantify the effect of interference, parameters such as the signal-to-(interference+noise) ratio (SINR) are frequently employed. The specific threshold SINR value to give acceptable performance for a given deployment depends on details of the standard (i.e. modulation, coding) being considered. Given these constraints, the question arises as to how the access points might be deployed in a building so as to keep the SINR at all locations throughout the user volume greater than this threshold.

To illustrate these concepts a rudimentary study of a single floor of the Engineering School Tower has been undertaken using a simple wall attenuation model. Similar to the 'basic' geometry in Section IV, the geometry contains a central services core (with wall attenuations of 20 dB) surrounded by a corridor and partitioned offices (with wall attenuations of 3 dB). Received powers are calculated using the free-space model, with the specific attenuations of any intervening walls along the line-of-sight path accounted for. An SINR threshold of 10 dB and frequency of 2.45 GHz is assumed.

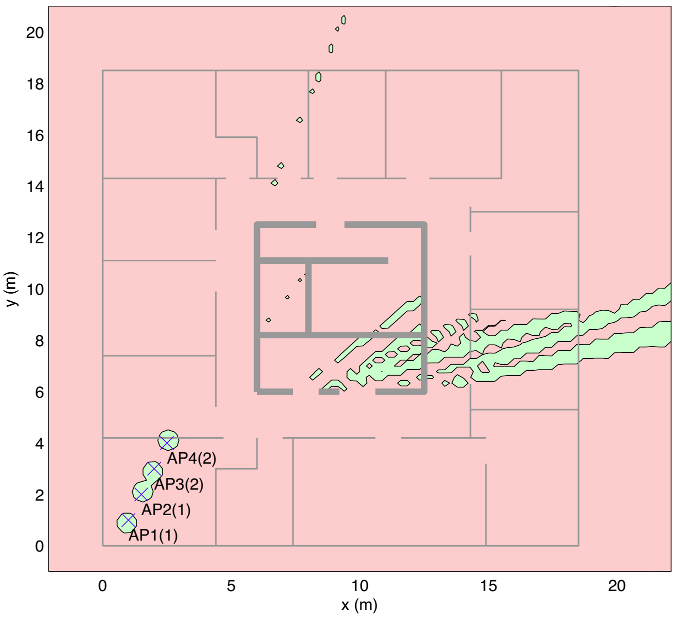

Fig. 5. Initial system deployment.

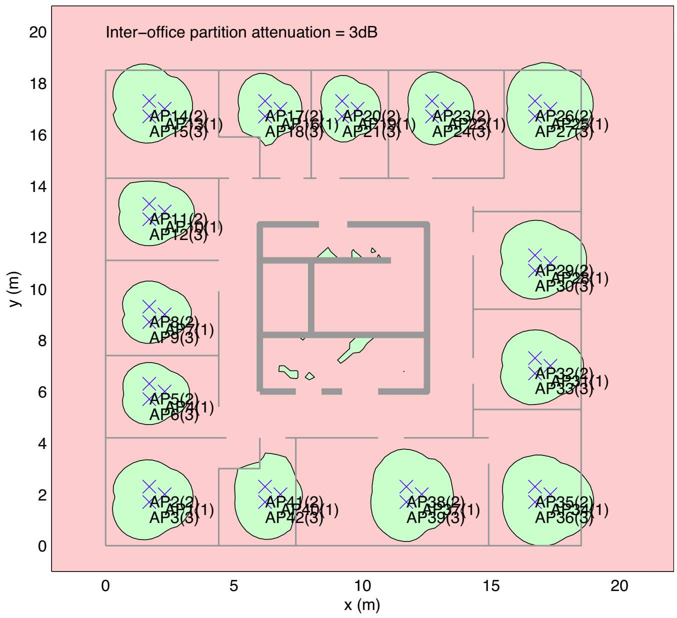

Fig. 7. Very high capacity system — initial deployment.

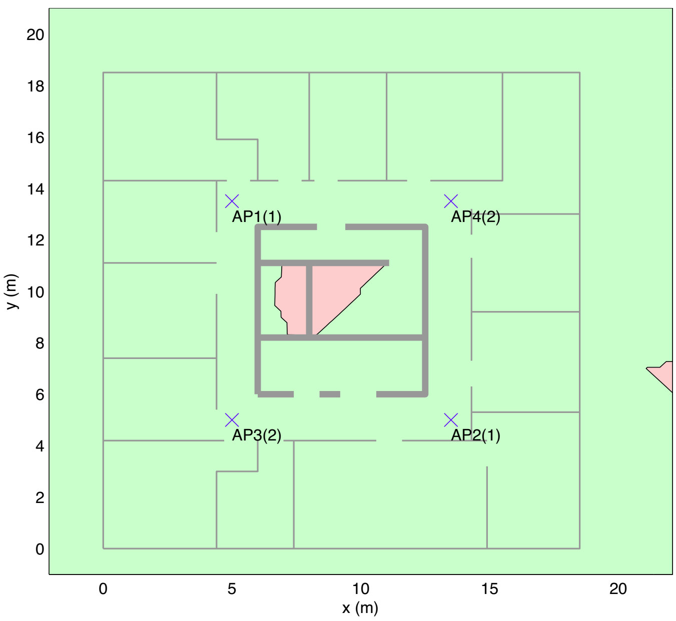

Fig. 6. New system deployment taking advantage of natural shielding provided by the central services core.

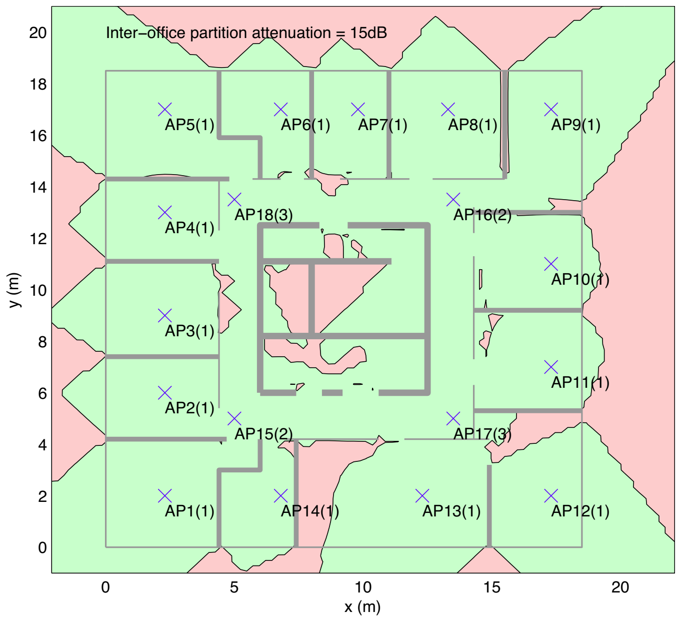

Fig. 8. Very high capacity system — improved deployment.

An initial deployment is shown in Fig. 5, which shows four access points (labelled AP1, AP2, AP3 and AP4) deployed in a highly non-optimal fashion. The notation AP$x(y)$ is used, in which x is an access point identification number and y is a logical channel number[1]. Regions which do not satisfy the downlink SINR threshold are shown in red. In order to increase the area for which a satisfactory SINR can be achieved, it is possible to make use of the natural shielding properties of the central core by locating co-channel base stations on diagonally-opposite corners as shown in Fig. 6. This result suggests that (barring a small area internal to the core) satisfactory performance has been achieved. However, while it is true that high quality (as a result of an acceptable SINR) has been achieved, it can be argued that this deployment is *not* successful as the overall capacity is inadequate due to the small number of access points per square metre of occupied floor area.

The implication of this observation is that the number of access points must been increased significantly if a very high level of capacity is to be achieved. Having done this, the question then arises as to whether *any* perturbation of these

[1]In these examples access points with the same logical channel number are assumed to mutually interfere — those with different logical channel numbers will not.

access point locations might result in a solution that satisfies the global SINR requirement. An extreme case is considered in Fig. 7 which shows the SINR threshold contour for three access points deployed per office — each on different channels. As expected very high levels of co-channel interference are observed, and the only regions in which satisfactory SINR is achieved are very close to the access points in which the desired coverage dominates the interference. Regions away from the access points (i.e. close to the walls and in the corridor) have unacceptable SINR performance.

A solution to this problem is to increase the wall attenuation. For example, increasing the inter-office partition attenuation to a modest 15 dB can realise a workable solution in all of the offices, and if two of the channels (logical channels 2 and 3) are re-allocated to the corridor acceptable performance can be achieved there as well, as shown in Fig. 8. This observation suggests that clever engineering of inter-office partitions might well provide a solution to realise very high capacity wireless services in building environments[2]. This rudimentary study has shown that 15 dB attenuation is adequate, and in reality this might be achieved using a band-stop frequency selective surface (FSS). In fact, previous research has shown that practical inter-room attenuation levels for simple band-stop FSSs are of this order [8], [9]. Using such an FSS would allow system planners to 'control' the transmissions of the indoor wireless systems, but would allow the transmissions of other (out-of-band) systems (such as 3G, television) to pass through unperturbed.

VI. A Contribution to Industry

The influence of the building structure on the transmissions of wireless systems suggests that those responsible for providing the basic 'fabric' of buildings should be cogniscent of the issues faced by wireless system planners. Arguably the provision of wireless connectivity is an aspect of building services engineering that needs to be considered in the building design process — much in the way that lighting and heating requirements are routinely incorporated at present. The results presented in this paper suggest that it is possible to formulate design rules and practices that can have real benefit to all stakeholders, and the question remains as to how this might best be achieved. One approach which is being considered by the UK-based *Wireless Friendly Buildings Forum* [10] is to formulate a wireless *Code of Practice* containing guidelines for practitioners, such as where to place access points,what antenna technology might be optimal, and what environmental modification solutions are applicable. The development of such a code would go a long way to assist all concerned in realising the true benefit that wireless can offer.

VII. Conclusion

Strategies for effective electromagnetic engineering for wireless communications in the built environment will be important if these systems are to realise their full potential. Incredible growth in wireless communications and the development of high performance broadband wired alternatives over the last two decades has resulted in very high user expectations. Decisions made at the time of deployment can significantly influence the performance of wireless services, and so practical strategies for making these decisions are required. Key results from a programme of research into propagation in buildings has yielded useful results. A rudimentary system deployment study has shown that while high quality communications *can* be realised, to simultaneously achieve very high capacities it may be necessary to adopt structural shielding solutions to contain transmissions. Ultimately, it is proposed that this research be contributed towards an industry wireless *Code of Practice*, to provide a practical series of guidelines intended to assist those charged with the deployment of wireless services in built environments.

[2]It can be argued that deploying access points into *every* office in a building will be an excessively expensive solution — however the current popularity of wired internet telephony products (which might, in the future, contain a remotely configurable access point) may well provide a non-invasive and cost effective solution.

References

[1] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Prentice Hall, 2002.

[2] G. R. Hiertz, D. Denteneer, L. Stibor, Y. Zang, X. P. Costa, and B. Walke, "The IEEE 802.11 Universe," *IEEE Commun. Mag.*, vol. 48, no. 1, pp. 62–70, 2010.

[3] W. C. Jakes, *Microwave Mobile Communications*. New York: Wiley, 1974.

[4] J. D. Parsons, *The Mobile Radio Propagation Channel*. Pentech Press, 1992.

[5] A. C. M. Austin, M. J. Neve, G. B. Rowe, and R. J. Pirkl, "Modeling the Effects of Nearby Buildings on Inter-Floor Radio-Wave Propagation," *IEEE Trans. Antennas Propagat.*, vol. 57, no. 7, pp. 2155–2161, 2009.

[6] A. C. M. Austin, M. J. Neve, and G. B. Rowe, "Modelling Propagation in Multifloor Buildings using the FDTD Method," *IEEE Trans. Antennas Propagat.*, vol. 59, no. 11, pp. 4239–4246, 2011.

[7] K. S. Butterworth, K. W. Sowerby, and A. G. Williamson, "Base Station Placement for In-Building Mobile Communication Systems to Yield High Capacity and Efficiency," *IEEE Trans. Commun.*, vol. 48, no. 4, pp. 658–669, Apr. 2000.

[8] G. H. H. Sung, K. W. Sowerby, M. J. Neve, and A. G. Williamson, "A Frequency Selective Wall for Interference Reduction in Wireless Indoor Environments," *IEEE Antennas Propagat. Mag.*, vol. 48, no. 5, pp. 29–37, Oct. 2006.

[9] G. H. H. Sung, "Frequency Selective Wallpaper for Mitigating Indoor Wireless Interference," Ph.D. dissertation, Department of Electrical and Computer Engineering, The University of Auckland, New Zealand, 2006.

[10] "Wireless Friendly Buildings Forum." [Online]. Available: http://www.wfbf.org.uk/