ON THE INVESTIGATION OF RADIOWAVE PROPAGATION MECHANISMS FOR FUTURE WIRELESS COMMUNICATIONS SERVICES PLANNING

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Abstract — A research project on radiowave propagation modelling for future wireless communications services being undertaken within the Radio Systems Group at The University of Auckland, New Zealand is described. A programme of experimental measurements of scaled building models (at appropriately scaled frequencies) is being performed to gain insight into the mechanisms by which radiowaves propagate in real environments. Several results are presented to illustrate the use of the technique.

I. INTRODUCTION

The global move towards mobile wireless communications is necessitating the development of efficient spectrum utilisation strategies. Effective spectrum sharing is a key issue, and requires an understanding of the mechanisms by which radiowaves propagate in real environments. Knowledge of these mechanisms has the potential to provide system planners with channel modelling tools that are not only reliable and efficient but which also have a firm deterministic basis. To identify significant propagation mechanisms, an understanding of the electromagnetic nature of radiowave propagation in the intended operating environment is required.

An effective propagation modelling tool that is useable in system planning must (a), provide accurate estimates of the required output parameter values[1]; (b), require limited information on the physical environment; and (c) be computationally efficient. In recent times, a number of contributions using analytical electromagnetic methods have appeared in the literature. Several techniques have been employed, including both physical optics [1, 2] and ray-methods [3–6]. Ray-methods have been used successfully for a number of years for terrestrial propagation modelling [7], but they are known to be inaccurate in some situations [5]. Many of the alternatives (such as those based on physical optics) provide greater accuracy but are both complex and computationally intensive and are thus not well suited to use in general system planning. It is likely that no specific electromagnetic technique will provide a complete solution to the problem — rather, a hybrid model will be required.

This paper reports research into deterministic propagation modelling for future wireless communications services. Theoretical model validation is being achieved using a novel approach involving the characterisation of scaled-models of environmental obstacles at appropriately scaled frequencies in a propagation range. Several results are presented to illustrate the versatility of this approach.

II. DETERMINISTIC PROPAGATION MODELLING

Up until the late 1980s, propagation models developed for application in dispatch/cellular system design inevitably had some empirical basis. Extensive programmes of experimental field trials had been performed worldwide — the data from which was used to develop models to assist planners in system design. However, it was becoming clear that system planning was requiring an increasingly deep understanding of propagation effects. As systems have become more sophisticated to meet requirements, so too has the need for models that accurately represent the propagation characteristics of the intended operating environment. Empirical models, while implicitly incorporating all significant effects in a given situation, may be quite unreliable when extrapolated for use in environments other than those in which the original measurements were performed. This situation has not been helped by the use of subjective environmental classifications such as “urban” and “suburban”.

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[1] Typical parameters include, for example, the area mean, local mean variability, and delay spread.

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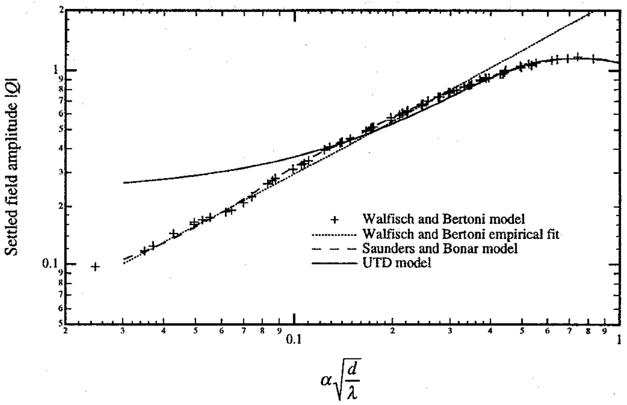

Figure 1: Variation in settled field amplitude for Walfisch and Bertoni, Saunders and Bonar and UTD formulations.

The empirical trend in propagation modelling was changed in 1988 with the publication by Walfisch and Bertoni [1] of an electromagnetic model (based on physical optics) for propagation over multiple rows of buildings. This contribution is notable in that it postulated a deterministic multiple diffraction mechanism by which the fields propagate. The results obtained clearly show that this mechanism is representative, and can account for the fourth law distance dependency of path loss observed in many experimental studies worldwide. A subsequent study by Saunders and Bonar [2] based on the method originally proposed by Vogler [8] obtained similar results.

At approximately the same time the Radio Systems Group at The University of Auckland commenced a research programme using deterministic electromagnetic methods to model propagation in built-up environments. In this study, the group concentrated on assessing the feasibility of using ray-based electromagnetic methods (specifically the *Uniform Theory of Diffraction* (UTD)) in cellular propagation modelling [3–6]. This study identified bounds of applicability for certain environmental geometries. For example, predictions for the settled field amplitude as a function of the environmental factor[2] $\alpha\sqrt{d/\lambda}$ for propagation over an array of multiple diffracting 'screens' is shown in Fig. 1 (from [5]). Predictions for UTD, Walfisch and Bertoni, and Saunders and Bonar formulations are shown, and the divergent behaviour of the UTD formulation for $\alpha\sqrt{d/\lambda} < 0.1$ can be clearly seen. The bound $\alpha\sqrt{d/\lambda} = 0.1$ is a quantitative limit beyond which the ray formulation is no longer sufficient to describe the propagation process. (Further details can be found in [5].)

At that stage, it was clear that deterministic electromagnetic methods would have a role to play in the engineering of future wireless systems, but it was unclear as to exactly what this role might be. Ray-methods were an obvious candidate for future propagation models, but they were known to be inaccurate in some situations [5]. Furthermore, it was becoming clear that no specific electromagnetic technique would provide a unified solution — rather, a hybrid model would be required. Such a model would need to provide accurate predictions of the required planning parameters, require a minimum of information about the physical environment, and be efficient to implement.

To ensure prediction accuracy, an electromagnetic model must accurately portray the propagation processes occurring in the real environment. In principal, accuracy can be verified by comparing model predictions with those derived from experimental measurements. However, it is difficult to validate these predictions using experimental measurements performed in real environments, as it is virtually impossible to eliminate unwanted scattering effects. A novel alternative is to build scaled-models of individual environmental obstacles and then investigate their scattering characteristics in a propagation range at correspondingly scaled frequencies. This method, which has been developed in the United Kingdom at The University of Birmingham [9], is currently being investigated within the Radio Systems Group at The University of Auckland.

III. SCALED PROPAGATION MODELLING AND MECHANISM IDENTIFICATION

In the research programme to date, a number of fundamental propagation scenarios have been identified and corresponding "comprehensive"[3] ray-based electromagnetic models developed. These scenarios are physically simple, and although the level of physical complexity present in real environments is not represented, it is likely that the mechanisms that dominate received signal characteristics (and thus parameters of interest to system planners such as the area mean, local mean variability and delay spread) are similar. Therefore, simplified "mechanistic" propagation models (which could be used to obtain estimates of the required planning parameters) can be obtained by extracting the dominant components from the "comprehensive" models. These "mechanistic" models will represent the dominant effects occurring in a given situation, while retaining a firm deterministic basis.

To assess the accuracy of the "comprehensive" models, a scaled propagation modelling facility has been constructed and is illustrated in Fig. 2. This facility comprises (i) a *propagation range* (a semi-anechoic chamber with an aluminium floor) and (ii) a *microwave measurement system.* This system consists of a vector network analyser (a Hewlett-Packard model HP8510C) together with associated

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[2] $\alpha\sqrt{d/\lambda}$ is proportional to the elevation angle of the incident field relative to the screen array.

[3] These ray-based models are termed "comprehensive" as they account for the contributions of all significant ray-paths in a given situation. The resulting received signal power is calculated from the phasor addition of these contributions.

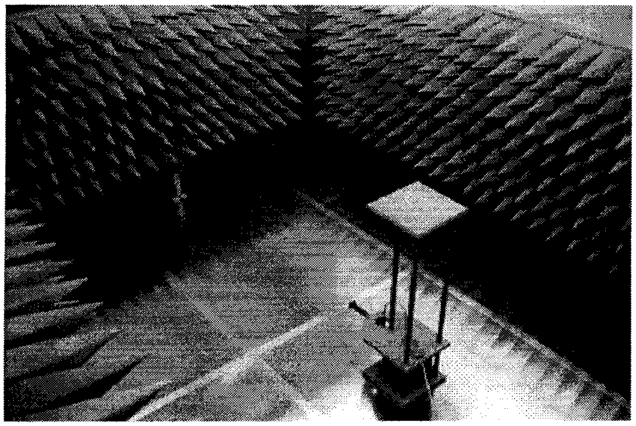

Figure 2: X-band (8.2–12.4 GHz) scaled propagation modelling facility at The University of Auckland.

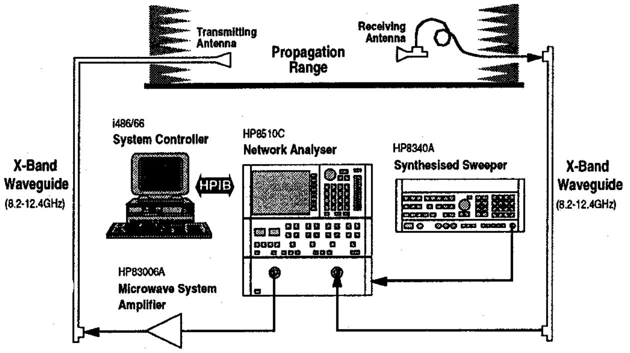

Figure 3: Block diagram of measurement system.

waveguide and data acquisition hardware as illustrated in Fig. 3. As configured, this system is capable of performing swept frequency measurements of complex amplitude (i.e. both amplitude and phase) across the frequency range 8.2 GHz - 12.4 GHz[4]. This data can subsequently be used to estimate the impulse response of the scenario under investigation (using the network analyser time domain option).

IV. RESULTS

A. *Case Study A — The "Two-Ray" Scenario*

To assess the performance of the facility, a simple "two-ray" scenario (illustrated in Fig. 4) has been exhaustively tested. In this scenario, the transmitting antenna aperture[5] is located at height h_t (m) above the ground plane. The receiving antenna aperture is located a horizontal distance d (m) from the transmitting antenna at a height h_r (m). In the geometry of Fig. 4, two principal components can be identified, namely (i) a direct component; and (ii) a ground-reflected component. It can be shown that the received power P_r (W) is given by

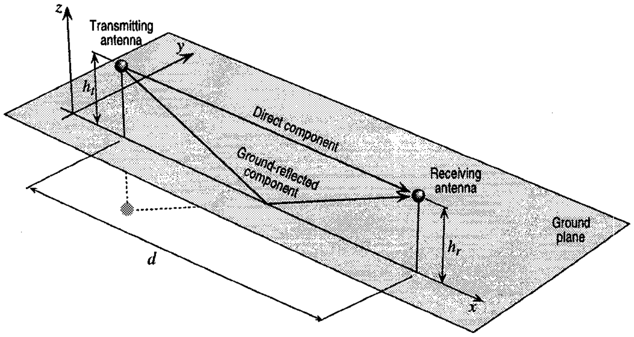

Figure 4: The "two-ray" scenario.

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\begin{aligned}
P_r &= \frac{P_t}{4k^2}\left|\frac{e^{-jkl_{dir}}}{l_{dir}} + \frac{e^{-jkl_{ref}}}{l_{ref}}\right|^2 \qquad (1)\\
\text{where}\quad l_{dir} &= \sqrt{(h_t - h_r)^2 + d^2}\\
\text{and}\quad l_{ref} &= \sqrt{(h_t + h_r)^2 + d^2}
\end{aligned}
$$

The lengths l_{dir} and l_{ref} (m) are the direct and ground-reflected component path lengths respectively, P_t (W) is the transmitted power and k $(= 2\pi/\lambda)$ is the wavenumber. Isotropic radiators have been assumed in the derivation of this expression[6].

To illustrate the behaviour of this model, consider an experiment where $h_t = 0.525$ m, $h_r = 0.519$ m and $d = 1.5$ m. The frequency f is swept from 8.2 GHz to 12.4 GHz. Results for path gain as a function of frequency f are shown in Fig. 5. The effects of constructive and destructive interference between the direct and ground-reflected components with changing frequency can be seen.

The corresponding time domain response for the geometry of Fig. 4 is shown in Fig. 5(b). The direct and ground-reflected components can be clearly seen at 5.1 ns and 6.2 ns respectively. (These results compare very well with the theoretical delays of 5.0 ns and 6.1 ns respectively.) Smaller components arriving at delays ≥ 19 ns are also evident, and are thought to be caused by reflections from the ceiling above

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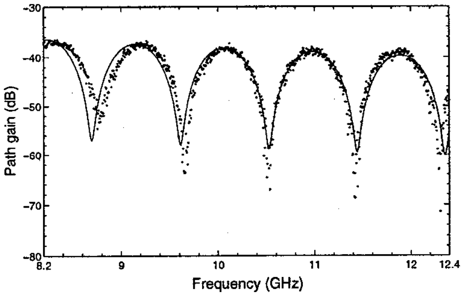
[4] This frequency range corresponds to an approximate scaling ratio of 10 (relative to a 'real' system operating at 1 GHz).

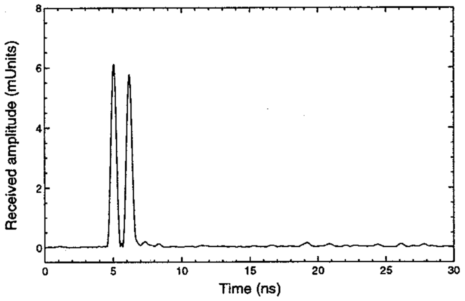
[5] Open-ended waveguide aperture antennas were used in all experiments reported in this paper.

[6] The frequency domain results were used to estimate the effective gain of the transmitting and receiving aperture antennas. The gain was calculated as half the difference (in dB) between the predictions of equation (1) and the experimental results, and was found to be 6.3 dBi. The corrected results are shown in Fig. 5(a).



(a) Frequency domain

— Theoretical predictions
Experimental measurements



(b) Time domain

Figure 5: Frequency and time domain responses for the "two-ray" scenario.

the range. These components are responsible for the noise-like ripple on the frequency domain response in Fig. 5(a). Although not shown in Fig. 5(a), the time domain gating facility of the HP8510C has been shown to be effective in suppressing these unwanted components.

B. *Case Study B — The "Half Street" Scenario*

The "half street" was chosen as the next logical scenario to investigate. The geometry of this scenario is identical to that of the "two-ray", except for the inclusion of a side obstacle — in this case a flat rectangular aluminium wall. This obstacle has dimensions h_s (m) by w_s (m) and is located at (x_s, y_s) (m) relative to the transmitting antenna as shown in Fig. 6. Seven components have been considered in the analysis, namely (i) a direct component; (ii) a ground-reflected component; (iii) a side obstacle reflected component; (iv) a side obstacle/ground-reflected component; (v) a left edge diffracted component; (vi) a right edge diffracted component; and (vii) a top edge diffracted component. The complex amplitudes of these various components are calculated using a computer-based ray tracing tool.

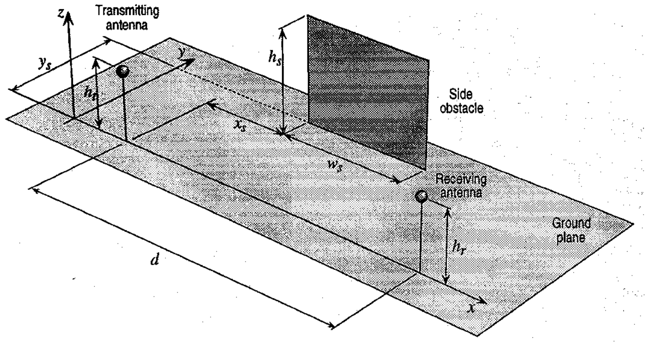
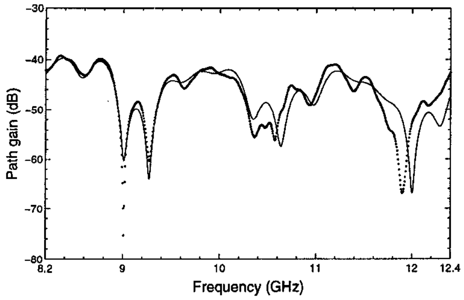


Figure 6: The "half street" scenario.

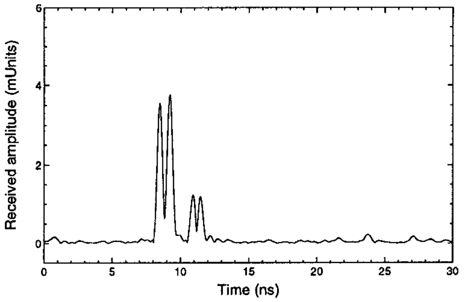
An experiment where h_t = 0.525 m, h_r = 0.526 m, d = 2.5 m, x_s = 0.75 m, y_s = 1.0 m, w_s = 1.0 m and h_s = 0.8 m has been investigated. The frequency f is swept from 8.2 GHz to 12.4 GHz. Results for theoretical path gain as a function of frequency f are shown in Fig. 7(a), together with experimentally measured results (obtained using a 0 ns $\rightarrow$ 15 ns gate on the HP8510C Network Analyser). Good agreement between theory and experiment is seen, especially at lower frequencies. The slight frequency offset at higher frequencies is thought to be due to obstacle placement errors in the propagation range. The corresponding time domain response for the geometry of Fig. 6 is shown in Fig. 7(b). The direct, ground-reflected component, side obstacle reflected and side obstacle/ground-reflected components can be clearly seen at delays of 8.5 ns, 9.2 ns, 10.9 ns and 11.5 ns respectively. (These results compare reasonably well with theoretical delays of 8.3 ns, 9.0 ns, 10.7ns and 11.2 ns respectively.) It is interesting to note that the reduced amplitude of the side obstacle reflected and side obstacle/ground-reflected components is largely due to the finite H-plane beamwidth of the aperture antennas. The three edge diffracted components considered were found to have little effect on the final result. This result is not unexpected since the receiving antenna is well clear of the reflection shadow boundaries of all diffracted components considered.

The overall received signal is thus dominated by the direct and ground reflected components. As a consequence of their uncorrelated nature, a "mechanistic" estimate of the local mean (for this case) can be obtained simply as the power sum (in W) of these two components. Since this case study has considered a static scenario, this result is not surprising. A more complicated result would be anticipated if the receiving antenna was moved with respect to the transmitting antenna. For example, moving the receiving antenna into the shadow region of the illuminating source will cause diffraction to become the dominant propagation



(a) Frequency domain

— Theoretical predictions
Experimental measurements



(b) Time domain

Figure 7: Frequency and time domain responses for the "half street" scenario.

mechanism. The approach being taken in the project reported in this paper has the ability to identify when these mechanism shifts occur.

V. CONCLUSIONS

To a significant extent, earlier wireless systems (such as dispatch and macrocellular systems) were able to be planned using empirically-based propagation modelling tools. As efficient spectrum utilisation is becoming increasingly important, so too is the need for a greater understanding of the propagation mechanisms. Empirical modelling tools will always have a role to play in the planning process. However, it is likely that deterministic propagation modelling techniques will be necessary if future wireless systems are to realise their full potential.

The modelling technique described in this paper can provide considerable insight into the mechanisms of propagation. This insight is derived from the development of electromagnetic formulations and subsequent experimental validation from measurements of scaled building models in both the frequency and time domain. From a systems perspective, "mechanistic" electromagnetic solutions derived from knowledge of these propagation mechanisms have the potential to make a valuable contribution in the design tool arsenal of future wireless systems planners.

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