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Prediction of Impulse Response in Frequency Domain by Ray Tracing Technique

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1 Introduction

If a reliable deterministic modeling of in-building radio channels is feasible, the method is useful to characterize the channels in various buildings, to estimate performance of the channels, or to design and optimize the channels. A possible route to the goal of this channel simulator is via the use of the ray tracing technique. The ray tracing technique is based on the geometrical optics that approximate the wave propagation phenomenon in a multipath environment. Although many have been reported on a comparison of the ray tracing prediction with the measurements in time domain, prediction in frequency domain has not been widely reported. In this paper, the theory and method to predict the transfer function of in-building radio channels in UHF band by using the ray tracing technique are presented. The method is verified by comparing the prediction with the frequency response measurements performed in a hallway of a high-rise building. Also shown are the estimates of the channel impulse response derived by the inverse Fourier transform of the measured and predicted transfer function. The results show that the destructive phase composition within the time resolution of the measurement system occur at certain antenna location and it can be predicted by the filtered ray tracing prediction. Comparison of the filtered and non-filtered prediction together with the measured results highlights the usefulness of the ray tracing simulation in the frequency domain.

2 Theory and Method

The impulse response $h(t)$ and the transfer function $H(f)$ of a time-invariant multipath radio channel is, respectively, given by

$$h(t) = \sum_{k=1}^{N-1} \alpha_k e^{j\phi_k} \delta(t - t_k), \quad \text{and} \quad H(f) = \sum_{k=1}^{N-1} \alpha_k e^{j\phi_k} e^{-j2\pi f t_k}. \tag{1}$$

where the notation of the parameters are as commonly used [1]. With the ray tracing technique, the k^{th} wideband received signal, E_k, relative to that received at one meter transmitter-receiver (T-R) separation distance is expressed as

$$E_k = \frac{A_t A_r c}{4\pi f r_k} \prod_{l=1}^{L_k} F_{k,l}. \tag{2}$$

where A_t and A_r is the antenna gain for the transmitter and the receiver, respectively, L_k is the number of reflection and/or transmission, $F_{k,l}$ is the Fresnel coefficients, r_k is the length of the ray, and c is the speed of light. By Eqn. 2, the signal amplitude is the function of frequency. However, for a sufficiently narrow frequency span at higher frequency, f can be approximated by the center frequency f_c. Also the Fresnel coefficient can be approximated as constant along the frequency of interest by using the value for the center frequency. Then Eqns. 1 and 2 are associated by

$$\alpha_k = |E_k|, \quad \phi_k = \angle E_k, \quad \text{and} \quad t_k = \frac{r_k}{c}. \tag{3}$$

Unlike the conventional methods to predict the impulse response by the ray tracing technique, we first predict the frequency response by applying the ray tracing parameters to the transfer function, $H(f)$. As it has been recognized by the researchers, for example [2], the finite bandwidth or the limited time resolution of a measurement system should be taken into account when a result of the ray tracing prediction is to be compared to a measurement. Rays that arrive with close time interval may not be detected as distinct paths and may be added vectorially. The advantage of the ray tracing simulation is that we can use the same discrete frequency steps as in the measurement thus retaining the same time resolution. By applying the identical filtering and inverse discrete Fourier transform (IDFT) to both predicted and measured data, the limited time resolution in the measurement system can be incorporated into the ray tracing technique.

3 Measurement and Simulation

The measurement setup is similar to the one reported in [3]. In stead of using dipole antennas, broadband discone antennas were developed and were used to obtain a flat characteristic along the frequency of interest. The antennas are fixed on tripods at 1.7 m height from the floor. With a center frequency of 1.0 GHz and the frequency span of 200 MHz, 801 uniformly spaced frequency samples were measured in the hallway on Level 23 of the UTS's Tower Building. The measurement set-up is as shown in Fig. 1. The transmitter was fixed and the receiver was moved referencing the ruler attached on the floor. The T-R separation was varied between 1 m to 14 m with an increment of 0.5 m.

The measured transfer function was windowed, zero-padded, and then converted into time-domain by the IDFT. Figure 2 shows eleven approximated impulse responses from 1 m to 6 m T-R separation. It can be seen from the figure that the line-of-sight (LOS) path offers the strong initial signal that is followed by reflected signals with associated time delay.

Since the first arrived signal in each impulse response profile corresponds to the direct LOS path, the time delay of the first received signal is linearly related to the T-R separation. Figure 3 shows the time delay of the strongest signal multiplied by the speed of light for each impulse response profile. Two cases indicated by the circles in the same figure represent situations in which the direct LOS signal has less amplitude than that of delayed signals. This phenomenon was consistently observed and can be attributed to the limited time resolution in the measurement system as it was discussed in the previous section. Apart from these two cases, a line ($y = 1.01x + 0.46$) was fitted to the data with in the least square error sense. The offset 0.46 m is equal to 1.53 ns in time, which is considered as a systematic time delay in the measurement system and is incorporated in the prediction.

In the simulation, the geometry of the hallway was simplified as a rectangular box having a 19 m length and 2 m width. A two-dimensional ray launching algorithm described in [4] was used to determine all significant paths on the horizontal plane at the height of the antennas. Three walls were modelled as brick and one wall as reinforced concrete whose conductivities are assumed to be 0.3 and 5.0 [S/m], respectively.

4 Analysis

Figures 4 and 6 show comparison of measured and predicted amplitude transfer function at T-R separation of 3.5 m and 5.5 m, respectively. It can be seen that the certain minima and maxima of the signal are predicted closely. Similar results were obtained for other antenna configurations. Figure 5 and 7 show the estimates of the impulse response given by the measured and predicted transfer functions. Also shown in the same figure is the impulse response amplitude predicted by the time domain ray tracing technique. From the analysis of results, for example Figures 5 and 7, it can be stated that in many cases, the presence of rays as predicted by the simulation have been confirmed by the measured results within an amplitude deviation of approximately 3 dB. In almost all the cases, the time delays of the local maxima of predicted profiles are consistent with those of measured profiles. From Fig. 7, it can be seen that the measured direct LOS signal is attenuated because of the destructive phase composition within the limited time resolution of the measurement system, which has been correctly predicted by the frequency domain ray tracing technique as evident from the same figure. Similar results were obtained at T-R separation of 3.0 m and 6.0 m. The ray tracing simulator failed to predict some delayed signals. These signals are the signals that are reflected from objects excluded in the modelled environment or the signals diffracted from the corners of the hallway.

5 Conclusion

In this paper, a procedure to predict the frequency domain impulse response using the ray tracing technique is proposed. The frequency domain impulse response measurement and simulation have been discussed. Validity of the ray tracing technique in frequency domain analysis has been shown. The simulator can predict the direct line-of-sight signal and most of the significant reflected signal accurately both in time and amplitude. Filtering of ray tracing generated data is shown to closely simulate the destructive phase composition within the system time resolution. The procedure discussed in the paper is applicable to more complex modelling methods using the ray tracing technique, for example to the three-dimensional modelling.

References

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[4] H. Suzuki, A. Mohan, J. G. Wang, and H. Yabe, "Measurement and prediction of two-dimensional fading map in a hallway", *IEICE Trans. on Commun.*, under review.

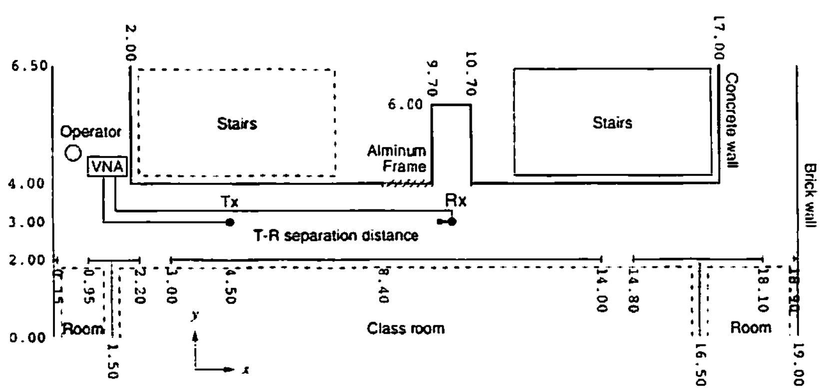

Figure 1: Measurement set-up. Unit [m].

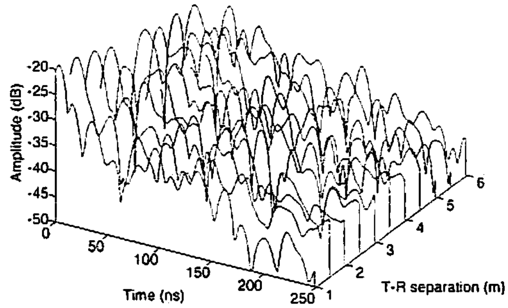

Figure 2: Impulse response profiles.

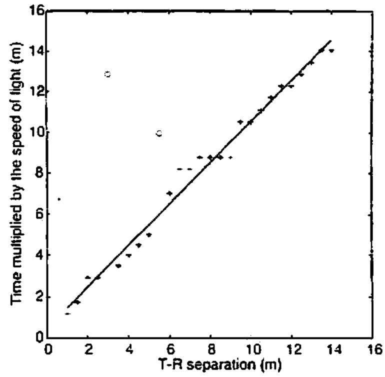

Figure 3: Time delay of the strongest path versus T-R separation. The line fitted to the data is $y = 1.01x + 0.46$.

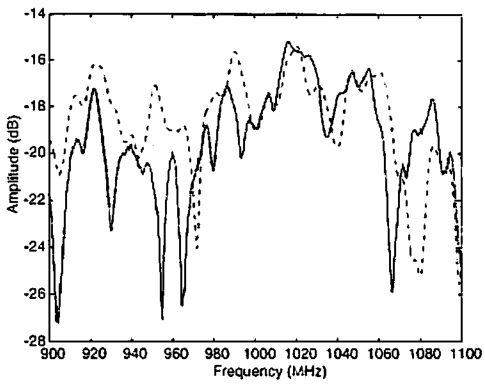

Figure 4: Measured (solid curve) and predicted (dashed curve) amplitude frequency response at 3.5 m T-R separation.

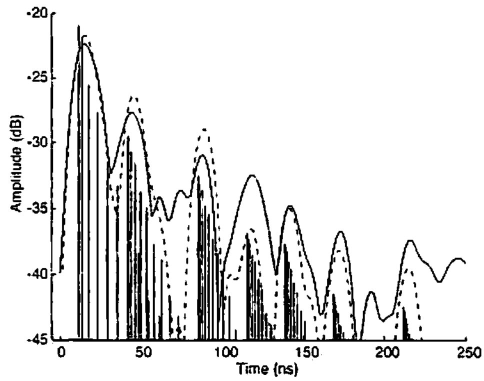

Figure 5: Measured (solid curve), filtered predicted (dashed curve), and non-filtered predicted (solid lines) impulse response profile at 3.5 m T-R separation.

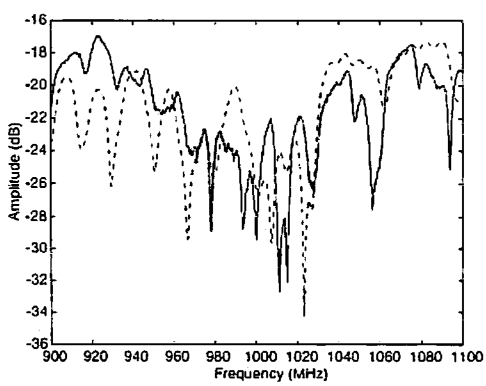

Figure 6: Measured (solid curve) and predicted (dashed curve) amplitude frequency response at 5.5 m T-R separation.

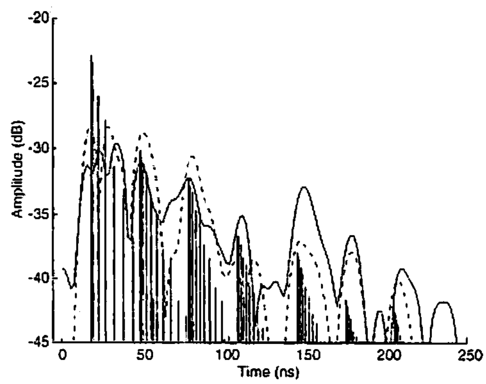

Figure 7: Measured (solid curve), filtered predicted (dashed curve), and non-filtered predicted (solid lines) impulse response profile at 5.5 m T-R separation.