Time-domain analysis of measurements on scaled urban models with comparisons to ray-tracing propagation simulation.

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Abstract—This work deals with propagation prediction for wireless communications in urban environments. Its purpose is to clearly distinguish the different field contributions collected by the receiving antenna through a series of wideband frequency measurements and a time domain analysis of the obtained results. The experimental data are then compared to the field predictions given by a ray-tracing electromagnetic wave propagation simulator. The application of this research lies in the modeling of the urban channel for wireless communication systems of the third generation (UMTS) and beyond.

Keywords—Anechoic Chamber, Propagation Predictions, Time-Domain Analysis, Urban Environment, UMTS, Ray-Tracing, Geometrical Theory of Diffraction.

I. INTRODUCTION

IN this paper a time-domain (TD) analysis is carried out to compare measurements with theoretical predictions about propagation in urban environments. The purpose of the TD analysis is to identify the multipath components that actually contribute towards the received field in a selected frequency band. The novelty of this study is that the measurements are conducted inside an anechoic chamber facility, using scaled models of urban environments and appropriate antennas. The advantage of this approach is that all parameters such as physical dimensions of the model and material properties are known with very low tolerances. Therefore, it is possible to make extremely accurate comparisons with the theoretical prediction obtained using a ray-tracing method.

In this paper, the experimental results are compared to the predictions given by the Polygonal Line (PL) simulator, which was described in [1], [2], [3] and compared with other methods in [4]. The results presented here complement those given in [5]. More specifically, the latter is about path-loss analysis at a single frequency, whereas this paper deals with the identification of the contributions from different trajectories by means of wideband measurements and a TD analysis. Since the two studies share the same experimental setup, the reader is referred to [5] for these details. In both papers, great emphasis is given to experiments that closely approach the simplified model of the real world that is analyzed with the theoretical method. In fact, the assumptions of the theoretical method are verified

using the results of these experiments, an operation that is impossible to carry out with field measurements because too many parameters are unknown.

Nevertheless, this approach is not intended to substitute for field measurements, which are still very important, but simply to be used as one of the benchmarks to test new computer simulators and validate propagation models [6].

As it will become clear in the following sections, the close agreement between the predictions and the measurements validates the method of the PL simulator. Preliminary results of this investigation were given in [7], [8], [9], [10].

II. TIME-DOMAIN ANALYSIS

The purpose of the TD analysis is the measurement and identification of the multipath components that actually contribute towards the received field in a selected frequency band. This requires the ability to resolve two closely time spaced multipath components, which we will refer to as *response resolution*, and the ability to locate the peak, in time, of a single multipath component, which we will refer to as *range resolution* [11].

The experiments consist of pulses that are launched from T_x and measured at R_x . The pulses are generated by a Hewlett-Packard HP8510 Network Analyzer (NA) that operates in the frequency domain. The frequency bandwidth of operation determined by the radiation characteristics of the antennas is in the range from 19 GHz to 27 GHz. Within this frequency range interval of 8 GHz, the NA considers 801 equally spaced samples, which results in a time period of 100 ns for the measured waveform. With 801 sample points, the response resolution of the system is 0.25 ns and the range resolution is 0.0625 ns.

For a given scaled model of an urban environment, different configurations are considered. Each configuration is characterized by the positions of the transmitter and receiver with respect to the scaled building model. Given a certain configuration in input, the PL simulator computes the complex value of the EM field for a pre-determined set of frequencies. Both the experiments and the theoretical predictions return results in the frequency domain. The TD analysis was accomplished via post-processing using MATLAB, in order to guarantee full control and identical processing of the two sets of results. For both the measured and the simulated data, the sampling bandwidth in the frequency domain was extended by adding zero samples. The effect of adding zeroes corresponds to creating new samples

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Fig. 1. Time-domain analysis for free space propagation. The curves show the PL simulator prediction (black line), and the measurements for soft (red line) and hard (blue line) polarization, respectively.

that interpolate the TD shape of the pulse. As a result, the pulse shape is less abrupt. This enlargement was limited to 32 GHz, i.e. four times the original frequency interval, in order not to corrupt the measurements too much. Additional details are found in [12].

The measured TD response for the case of free space propagation, after interpolation and normalization, is shown in Figure 1 for hard and soft polarization. The black line represents the impulse used for reference. The mean delay and attenuation of the main peak for this case are also summarized in Table I.

TABLE I
MEAN DELAY AND ATTENUATION OF THE MAIN PEAK

Polarization	Delay (ns)	Attenuation (dB)
Vertical (Hard)	9.72 (± 0.0625)	-26.15 (± 0.2)
Horizontal (Soft)	9.8 (± 0.0625)	-27.2 (± 0.4)

III. SINGLE-BUILDING PROFILE

To verify the accuracy of the PL simulator against the measured data in the case of propagation past buildings, let us start with the simple structure of the single building profile for different significant configurations. For all comparisons, the TD analysis is reported in graphs where the black line represents the PL simulator prediction and the measurement data are represented by red and blue lines for soft and hard polarization, respectively. In addition, the details of each multipath component are presented in a series of tables.

A. Transmitter and receiver below rooftop and at different heights

Let us consider the configuration shown in Figure 2 for the case of soft polarization. In this configuration the R_x is only a few wavelengths from the ground. For this and

Fig. 2. Configuration 1: T_x and R_x below rooftop.

the single-building configuration that follows, the possible trajectories predicted by the PL are:

1. $T_x \rightarrow A \rightarrow B \rightarrow R_x$
2. $T_x \rightarrow A \rightarrow B \rightarrow K \rightarrow R_x$
3. $T_x \rightarrow H \rightarrow A \rightarrow B \rightarrow R_x$
4. $T_x \rightarrow H \rightarrow A \rightarrow B \rightarrow K \rightarrow R_x$

Fig. 3. Configuration 1: Time-domain analysis for soft polarization. The curves show the PL simulator prediction (black line) and the measurements (red line).

The TD analysis for this configuration is shown in Figure 3, which exhibits two peaks. The trajectories responsible for these peaks are easily recognized referring to Table II. In this configuration, the main peak is due to the double diffracted trajectory 1, and the secondary peak to trajectory 2. Notice that, since R_x is only a few wavelengths above the ground plane, the paths $B \rightarrow R_x$ and $B \rightarrow K \rightarrow R_x$ provide similar contributions. The peaks associated with trajectories 3 and 4 are too weak to be

TABLE II
CONFIGURATION 1: COMPARISON BETWEEN MEASURED DATA AND PREDICTIONS GIVEN BY THE PL SIMULATOR

Trj	Measured Delay (ns)	Data Attn (dB)	PL Delay (ns)	Simul Attn (dB)
1	9.920	-43.01	9.929	-42.87
2	10.220	-52.87	10.208	-50.88
3	x	x	10.791	-65.88
4	x	x	11.071	-73.33

detected and they are immersed in the background noise.

B. Transmitter and receiver at grazing aspects of incidence and observation

Fig. 4. Configuration 2: T_x and R_x at grazing incidence.

The configuration shown in Figure 4 is of particular importance because it challenges the ray-tracing algorithms by containing two transition zones. Also, it has the characteristic of being perfectly symmetrical. The experiments were carried out by actually keeping both the transmitter and the receiver slightly below the building rooftop to avoid direct ray contributions. The trajectories are the same indicated in Section III-A.

Fig. 5. Configuration 2: Time-domain analysis for hard polarization. The curves show the PL simulator prediction (black line), and the measurements (blue line).

The TD analysis for this configuration is shown in Figure 5. Taking into consideration the data of Table III, the main peak is associated with the double-diffracted trajectory 1, whereas the secondary peak is due to a combination of both trajectories 2 and 3. In fact, because of the symmetry of the present configuration, trajectories 2 and 3 have equal path-lengths and their contributions are not separable.

When dealing with propagation over buildings, most of the ray tracing models used for wireless network planning consider only R_x -side ground reflection contributions, discarding the T_x -side ones. This choice is acceptable as long as the T_x is located at a much higher height with respect to the R_x , otherwise it leads to a weaker prediction of the received field.

TABLE III

CONFIGURATION 2: COMPARISON BETWEEN MEASURED DATA AND PREDICTIONS GIVEN BY THE PL SIMULATOR.

Trj	Measured Delay (ns)	Data Attn (dB)	PL Delay (ns)	Simul Attn (dB)
1	9.720	-8.40	9.724	-8.42
2	10.795	-24.72	10.839	-29.60
3	"	"	10.839	-31.99
4	x	x	11.953	-48.43

IV. TWO-BUILDING PROFILE

The TD analysis of the multipath components is now applied to the case of the two-building profile. This profile represents the simplest case of rows of parallel buildings. In addition, since the two buildings have exactly the same height, it provides a way to challenge the ray-tracing algorithm because of the intrinsic grazing incidence condition created by this particular shape.

A. Transmitter at grazing incidence

Fig. 6. Configuration 3: T_x at grazing incidence.

Figure 6 shows the geometry for the configuration of the T_x at grazing incidence. For this configuration, the trajectories that provide the most important contributions are:

1. $T_x \rightarrow A \rightarrow B \rightarrow C \rightarrow D \rightarrow R_x$
2. $T_x \rightarrow A \rightarrow B \rightarrow C \rightarrow D \rightarrow K \rightarrow R_x$
3. $T_x \rightarrow H \rightarrow A \rightarrow B \rightarrow C \rightarrow D \rightarrow R_x$

The TD analysis is shown in Figure 7, which corresponds to a hard-polarization case. Hard polarization was chosen because it results in stronger values for the received field and therefore makes the measurements easier.

The main peak of Figure 7 is easily identified with trajectory 1 of Table IV. The agreement with the theoretical prediction is very good both for the main and the secondary peaks. Also, notice that trajectories 2 and 3 provide similar contributions.

TABLE IV

CONFIGURATION 3: COMPARISON BETWEEN MEASURED DATA AND PREDICTIONS GIVEN BY THE PL SIMULATOR.

Trj	Measured Delay (ns)	Data Attn (dB)	PL Delay (ns)	Simul Attn (dB)
1	9.750	-21.25	9.763	-21.36
2	10.655	-35.40	10.680	-36.84
3	10.934	-38.65	10.964	-41.07

Fig. 7. Configuration 3: Time-domain analysis for hard polarization. The curves show the PL simulator prediction (black line) and the measurements (blue line).

B. Transmitter and receiver at grazing aspects of incidence and observation

Fig. 8. Configuration 4: T_x and R_x at grazing incidence.

The grazing incidence configuration, shown in Figure 8, proves once again to be one of the most challenging configurations to analyze with a ray-tracing algorithm. As for the single-building configuration, the experiments were carried out by actually keeping both T_x and R_x below the building

Fig. 9. Configuration 4: Time-domain analysis for hard polarization. The curves show the PL simulator prediction (black line) and the measurements (blue line).

rooftop to avoid direct ray contributions.

The results for the TD analysis are shown in Figure 9. In Table V, notice that the two secondary peaks due to trajectories 2 and 3 are again merged together in a single contribution. Both the main and the secondary peaks are predicted by the PL simulator, even though the agreement with the experiments is not as accurate as in the case of the single building profile.

TABLE V

CONFIGURATION 4: COMPARISON BETWEEN MEASURED DATA AND PREDICTIONS GIVEN BY THE PL SIMULATOR.

Trj	Measured Delay (ns)	Data Attn (dB)	PL Delay (ns)	Simul Attn (dB)
1	9.720	-13.05	9.724	-15.49
2	10.970	-34.80	10.971	-36.84
3	"	"	10.973	-38.15

This behavior is attributed to the fact that the two buildings have exactly the same height (within the mechanical tolerance of the scaled profile). Under conditions of grazing aspects of incidence and observation, diffraction past the edges A , B , C , D of Figure 8 requires a diffraction coefficient of order higher than the second. However, the PL simulator computes the diffraction past the two buildings by cascading the diffraction past A , B with the diffraction past C , D . Each diffraction past a single building is computed using the diffraction coefficients described in [13].

V. THREE-BUILDING PROFILE

The three-building profile is introduced to analyze a more complex situation where there are buildings with different heights and not all surfaces are either horizontal or vertical.

Fig. 10. Configuration 5.

Let us analyze the configuration shown in Figure 10. Though the vertices are no longer all at the same height, the T_x height is chosen to illuminate B while, at the same time, almost creating grazing incidence over the roof of the building to the left. For sake of completeness, we consider both hard and soft polarization. The three main trajectories are:

1. $T_x \rightarrow A \rightarrow B \rightarrow R_x$
2. $T_x \rightarrow A \rightarrow B \rightarrow K \rightarrow R_x$
3. $T_x \rightarrow H \rightarrow A \rightarrow B \rightarrow R_x$

The results of the TD analysis are shown in Figure 11. There is good agreement for the prediction of the main and secondary peaks, as shown in Table VI.

Fig. 11. Configuration 5: Time-domain analysis. The curves show the PL simulator predictions (black lines), and the measurements for soft (red line) and hard (blue line) polarization, respectively.

As expected, soft polarization provides weaker fields than hard polarization. This explains why in Figure 11 the secondary peaks for soft polarization are not so evident as in the case of hard polarization. For both polarizations, the secondary peaks are due to trajectories 2 and 3, whereas the main peaks are due to trajectory 1. Additional trajectories are not presented here because their contributions are weaker than the background noise.

TABLE VI

CONFIGURATION 5: COMPARISON BETWEEN MEASURED DATA AND PREDICTIONS GIVEN BY THE PL SIMULATOR.

Trj	Measured Delay (ns)	Data Attn (dB)	PL Delay (ns)	Simul Attn (dB)
Hard polarization				
1	9.875	-25.40	9.850	-24.29
2	10.785	-31.90	10.832	-33.76
3	10.110	-45.55	11.179	-45.39
Soft polarization				
1	9.845	-35.55	9.850	-33.68
2	10.815	-50.10	10.832	-50.76
3	11.150	-57.25	11.179	-60.40

The last configuration, shown in Figure 12, presents the same profile, but with the tallest building on the transmitter side. For this configuration, the main trajectories

Fig. 12. Configuration 6.

TABLE VII

CONFIGURATION 6: COMPARISON BETWEEN MEASURED DATA AND PREDICTIONS GIVEN BY THE PL SIMULATOR. HARD POLARIZATION.

Trj	Measured Delay (ns)	Data Attn (dB)	PL Delay (ns)	Simul Attn (dB)
Hard polarization				
1	9.720	-13.05	9.724	-15.49
2	10.970	-34.80	10.971	-36.84
Soft polarization				
1	9.720	-13.05	9.724	-15.49
2	10.970	-34.80	10.971	-36.84

Fig. 13. Configuration 6: Time-domain analysis. The curves show the PL simulator prediction (black lines), and the measurements for soft (red line) and hard (blue line) polarization, respectively.

are:

1. $T_x \rightarrow A \rightarrow B \rightarrow R_x$
2. $T_x \rightarrow A \rightarrow B \rightarrow K \rightarrow R_x$

The results for soft and hard polarization are shown in Figure 13 as well as in Table VII. Again, there is good agreement with the theoretical results.

VI. DISCUSSION OF THE RESULTS

The predictions obtained with the PL simulator for the single-building profile are in very good agreement with the measurements for all the configurations that were examined. The experiments with the two- and three-building profiles were focused on locations of the T_x that cause grazing incidence and on R_x at a short distance from the ground. This choice was made in order to better simulate the real world where it is common to have the T_x positioned higher than the R_x , whereas the opposite hardly ever happens.

The experiment results confirm that for all these configurations the contribution of the T_x -side reflected ray is generally not negligible, as it is often comparable in amplitude with the R_x -side reflected ray. Simplified models usually account only for what happens on the R_x -side, without

considering the T_x -side at all. This approximation can be considered acceptable when the base station is higher than the surrounding obstacles, but is definitely too rough in all the other cases.

Most of the experiments concerned grazing incidence conditions, which usually are critical for ray-tracing techniques, because of interaction with the first Fresnel zones. Nevertheless the use of the PL simulator gives results which are in good agreement with the experimental analysis.

VII. CONCLUSIONS

This article presented an experimental study of propagation past scaled building models focusing on the different contributions due to multipath propagation. This study has been carried out to further estimate the accuracy of a two-dimensional ray tracing model for propagation in urban environment described in [1] [2] [3]. In particular, this research has isolated the components of the received signal that are most important according to the configuration of the examined profile with respect to the T_x and R_x .

The limitations of this analysis are mainly due to the fact that it was performed on metallic models. On the other hand, the advantages of carrying out such a set of measurements in an anechoic chamber are evident, as contrasted with field measurements that are influenced by a series of factors, most of which are not easily quantifiable. It would be difficult with field measurements to determine the causes of any disagreement with the predictions. To the best of the authors' knowledge, this is the first time that a study of propagation over buildings is performed in an anechoic chamber. In literature there is only a single paper on measurements on scaled buildings [15], which however are not performed in an anechoic chamber, and that paper addresses horizontal propagation around buildings instead of over buildings.

ACKNOWLEDGMENTS

The authors are indebted to Dr. Thomas D. Monte for his technical assistance and for providing the sector antennas, and are thankful to the National Science Foundation which supported this research under grant ECS-9979413. The authors acknowledge the suggestions of Prof. Rashid Ansari for the signal processing part of the analysis, and thank Art Sawczuk, Walter Schindler and Marian Balaban of the UIC Machine Shop for manufacturing the scaled buildings and related items. Finally, they thank Giuseppe D'Elia for his assistance in the measurements, and the Reviewers for their helpful suggestions.

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