A Ray-Tracing Approach for Indoor/Outdoor Propagation Through Window Structures

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***Abstract*—A ray-tracing approach for indoor/outdoor propagation through windows is proposed. Using both the finite-difference time-domain (FDTD) method and a ray-tracing algorithm, several cases of indoor/outdoor propagation through windows were investigated. It is shown that wave transmission through windows cannot generally be accounted for through a single transmission coefficient parameter. Instead, a full diffraction pattern needs to be accounted for and multiple-ray representation is therefore required. It is also shown that a single window model may be used to calculate transmission through set of windows in a typical building structure as a building block. Results from the implementation of a multiple-ray representation and FDTD simulations showed good agreement. Results were validated for both normal and oblique incident cases. The developed ray-tracing approach, therefore, facilitates the use of the developed window model in available ray-tracing algorithms often used for propagation characterization of urban environments. Simulation results were further validated by conducting measurements on scaled models at 30 GHz. The experimental results agreed well with the simulation data, thus validating the accuracy of the developed ray-tracing model for transmission through windows.**

***Index Terms*—Diffraction, propagation, ray tracing.**

I. Introduction

WITH the rapid growth of wireless communications, cell sizes are getting smaller and therefore, site-specific propagation information is needed for the design of mobile systems. During the past decade, many theoretical and measurement-based propagation models for micro cells in urban environments have been proposed. Studies on outdoor micro-cell propagation are widely reported [1]–[4], and some experimental results are available as well [2]–[4]. Recently, indoor propagation has attracted more and more attention, especially since the development of wireless local area network (LAN) [5], [6], [15] the backbone for the studies on indoor propagation. Overall, most of the models that have been presented are restricted solely to the outdoors or solely to indoor propagation environments. Only a few models [7]–[11] deal with the indoor/outdoor issues and this is usually done through experimental investigation.

Among all site-specific algorithms, ray tracing is one of the most accurate and often-employed method [12], [13]. The ray-tracing method does not only provide path-loss information, but it also provides time delay, angle spread, and polarization information as well, all of which are crucial in developing effective and optimized wireless communication systems. Ray-tracing methods work quite well in either an outdoor or an indoor environment; but when an indoor and an outdoor environment are integrated together, some difficulties arise. One such difficulty is how to treat the composite walls on the exterior of a building. Some experimental results on composite walls can be found in literature [14]. The other main difficulty is how to deal with windows and metal-framed structures. Most windows are around a few to tens of wavelength and therefore, when a plane wave passes through a window, it generates a diffraction pattern that cannot be treated in terms of complex transmission and reflection coefficients. Instead, a complete ray-tracing model needs to be developed to accurately characterize transmission through windows.

This paper focuses its investigation on indoor/outdoor propagation as it relates to window structures. A ray-tracing approach for the indoor/outdoor propagation problem is proposed. Simulations were performed using an finite-difference time-domain (FDTD) code and results for different window sizes will be presented. The FDTD-calculated transmitted field distribution is then represented by an equivalent ray-tracing model to help integrate the results in indoor, outdoor, and other urban propagation models. Some of the theoretical results are compared and verified with experimental measurements on scaled models.

II. Equivalent Ray-Optics Model of Window Structures

As mentioned above, windows are the most popular architectural element and hence can be found in almost every building. Measurements [11] made in front of windows show 6-dB more penetration on average than do measurements made in other parts of the building except windows. Therefore, windows play a crucial role in the ray-tracing problem-solving approach, but they are relatively difficult to analyze, particularly because of their relatively large electrical size. To demonstrate this, a typical window propagation situation was simulated using two-dimensional (2-D) FDTD. The window layout is shown in Fig. 1(a), and the diffraction pattern created by an incident plane wave is shown in Fig. 1(b).

As may be seen in Fig. 1(b), the phenomenon of a plane wave interacting with window structures is very complex (The vertical gray-scale bar corresponds to normalized power.) The transmitted wave is no longer a plane wave after it passes through the window structures. Electromagnetic field strength

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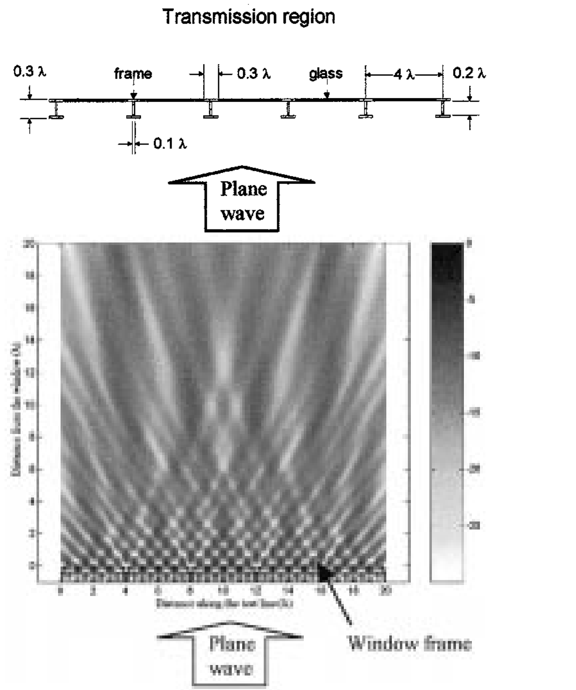


Fig. 1. Interference pattern created when a plane wave passes through the multiple-window arrangement. (a) Plane wave incident on a window-frame structure. (b) Diffraction pattern of incident plane wave (window size: $20\lambda * 21\lambda$).

does not monotonically decay along the direction of propagation. Instead, a diffraction pattern is generated and a new model for describing this transmission through windows needs to be developed.

One straightforward way to solve the aforementioned difficulty with windows is to use electromagnetic numerical methods, such as FDTD. Unlike ray tracing, most electromagnetic numerical methods are time consuming and can only solve electrically small-scale problems—on the order of tens of wavelengths at most on todays' available computers. On the other hand, a standard ray-tracing problem can cover an area greater than a thousand wavelengths. Therefore, it would be advantageous if a ray-tracing model for windows could be developed and integrated with the commonly used ray-tracing codes, which are often used in modeling urban propagation environments. From Fig. 1(b), it may also be noted that extracting ray information from numerical results appears to be very difficult, as the diffraction pattern appears to be rather complex.

One way to overcome this difficulty is by dividing the window structure into more basic building blocks, namely a single window. It is of great interest to investigate if the diffraction pattern from a single window, together with the superposition principle of electromagnetic fields, could be used to reconstruct the total diffraction fields from an arrangement of windows. For example, if a plane wave is directed at five side-by-side windows as in Fig. 1(a), then is it possible that by adding up the vector components of the rays from each building block window at a given point along the test line (see Fig. 1(b), that the total electromagnetic field strength can be accurately determined at that point? This question needs to be answered but before proceeding with this simulation, however,

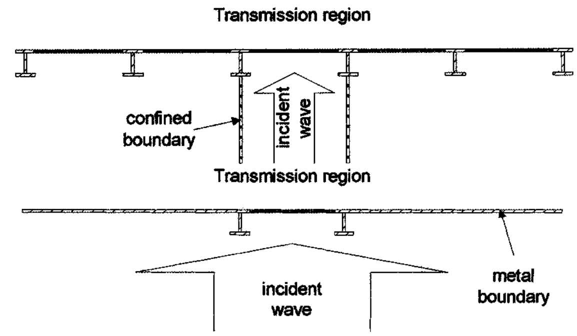


Fig. 2. Two options for obtaining a single window pattern. (a) Option I. (b) Option II.

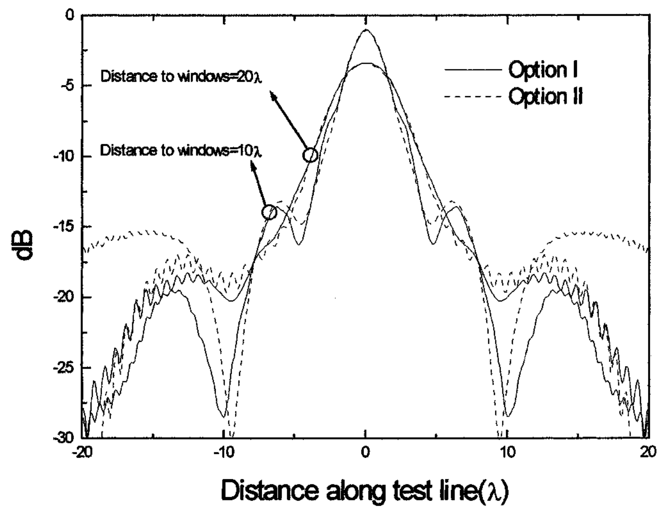


Fig. 3. Diffraction pattern in a single window.

it is necessary to decide the geometry of the basic building block window structure. To this end, we explored the possible use of two geometries as shown in Fig. 2.

Fig. 2 shows two possible approximations for simulating a single-window diffraction pattern. Fig. 2(a) uses confined metal boundaries to guide the incident plane wave to only one window, whereas Fig. 2(b) uses metal boundaries to cover all but one of the windows.

Fig. 3 shows patterns for both options at distances of 10λ and 20λ in the transmission region in the window frame structures shown in Fig. 1(a). Small fluctuations that may be noted on the patterns are introduced by reflections from the absorbing boundary of FDTD. The solid line is calculated by implementing Option I and the dotted line by Option II. When the distance from the windows is chosen to be 10λ, some disagreement appears between these two options, particularly in the side-lobe region. When the distance is chosen to be 20λ instead the difference between these two options decreases, and either option seems to be suitable as a building block. All additional simulations in this paper, therefore, used Option II. Fig. 4 shows the equivalent representation of the calculated electric fields with ray-optics fields. The vertical gray-scale bar corresponds to normalized power. In this case, the diffraction pattern calculated using FDTD was represented by an equivalent ray representation. Each ray includes amplitude, phase, and direction information that are calculated from the FDTD data,

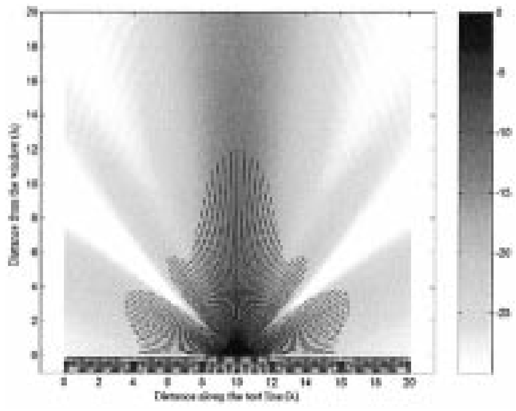


Fig. 4. Ray-optics equivalent representation to the transmitted fields.

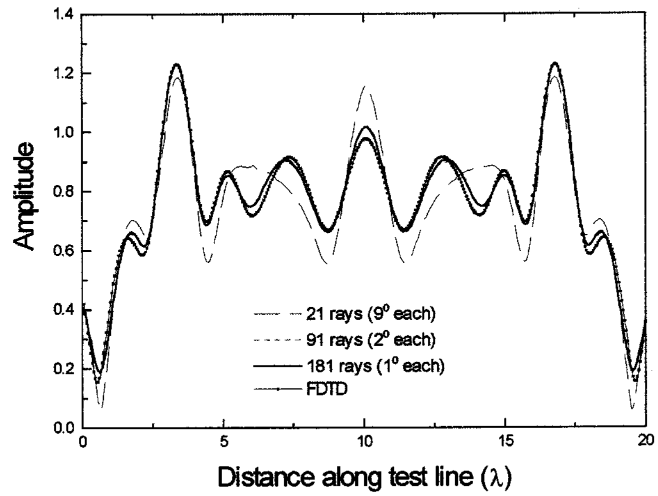


Fig. 5. Accuracy effect for a given number of rays.

and can be easily integrated into existing ray-tracing codes. Basically, each window uses the rays transmitted through it to generate a radiation pattern similar to that of an aperture antenna.

It is important at this stage to verify that the single window model can actually be used as a building block to accurately calculate transmission through an assembly of windows. To this end, we used the single window model to calculate transmission through a set of five windows. Fig. 5 shows comparison between the obtained results from the building block—single window model and the FDTD simulation of the entire system of five windows. As may be seen from Fig. 5, using the single window building block generally provides good results, particularly as far as the main feature of the transmission pattern is concerned. Accuracy of the results can be improved with the improved representation of the transmission from the single window using larger number of rays. All results are calculated at a distance of 20λ away from the window. The dashed line in Fig. 5 represents the ray-tracing result when 21 rays (9° each) are used. The dotted line shows the ray-tracing result when 91 rays (2° each) are utilized. The solid line shows the ray-tracing result when 181 rays (1° each) are utilized. The solid line with rectangular mark in Fig. 5 displays the FDTD result, which is included for comparison. It is clear from Fig. 5 that when the number of rays increases, the accuracy of results improves. It is, however, a tradeoff between accuracy and the speed of the simulation; when the number of rays is doubled, the consumed computer time is also doubled. As can be seen from Fig. 5, the use of 91 rays provides fairly good results and hence this number of rays was used in subsequent calculations.

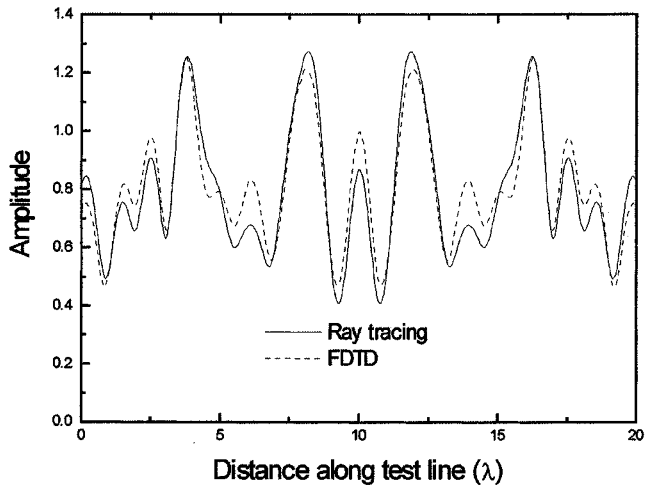
III. Characteristics of the Equivalent Ray-Optics Window Model

As it is, the purpose of this study to develop an equivalent ray-optics model for windows that can be used as a building block in simulating propagation transmission through windows, it is important to simulate and examine in detail some of the more important characteristics of these window models. Parameters such as the effect of the window size and the shape of the metal frame on the diffraction pattern need to be understood; and from the computational accuracy point of view, it is important to determine the effect of the number of rays on the simulation results as well as the accuracy of the developed model versus the distance from the window.

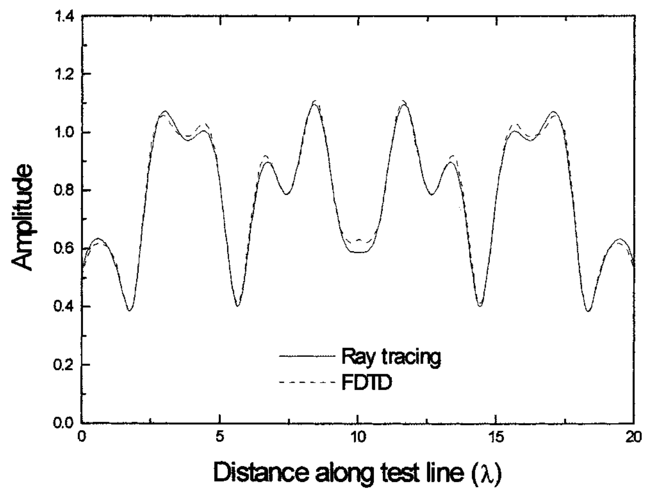
As we have already examined the effect of the number of rays used represent the diffraction pattern on the accuracy of the overall transmission pattern from window, we examine next the accuracy of the ray-optics model versus the distance from the window. Fig. 6 shows comparison between FDTD and the ray-tracing results. The dotted lines represent the FDTD results, while the solid lines depict the ray-tracing results. Figs. 6(a), (b), and (c) contain the results calculated at a distance of $10\lambda, 15\lambda$ and 20λ, respectively. It can be seen in the above results that the ray approximation is fairly accurate when the test position is at a sufficiently large distance from the window. This distance dependence is also a function of the window size. For a smaller window, the necessary separation distance will be less; and for a larger window, the required separation distance will be greater. In the 1.8 GHz communication frequency band, 15λ is equal to 2.5 m, which is a sufficiently short distance, and in many practical situations is smaller than the width of hallways alongside windows. Therefore, the ray-optics equivalent model is valid and can be used in many simulations of practical interest.

Another important parameter that needs to be examined is the effect of the size of the window on the shape of the diffraction pattern. Fig. 7 shows how the pattern changes when the window size changes. The dotted, solid, and dashed lines represent the patterns (function of angle) for window sizes of $3\lambda, 4\lambda$ and 5λ, respectively. It can be seen that as the window size increases, more energy is concentrated in the main lobe; however, this also results in an increase in the number of side lobes. This phenomenon is somewhat similar to patterns generated by an aperture antenna with uniform aperture field distribution. Fig. 8 shows comparison results between the ray-tracing and the FDTD simulations of the electric field distribution at a distance of 15λ from the windows and for different window sizes of 3λ and 5λ. The solid lines depict the ray-tracing results, while the dotted lines display the FDTD results.

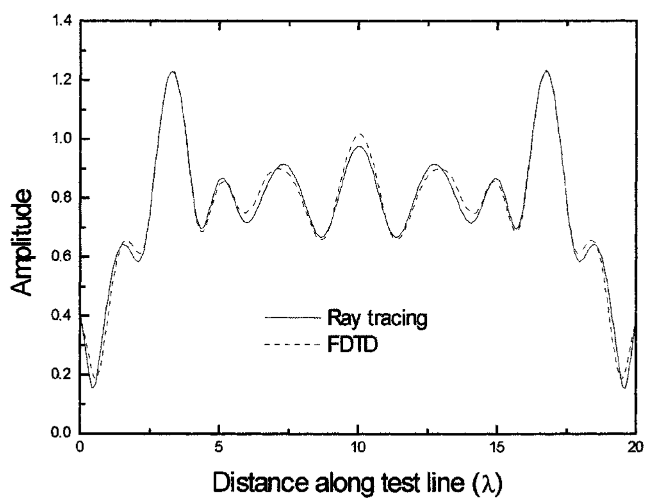
One of the important considerations in characterizing and establishing the ray-optics equivalent model as a building block in simulating indoor/outdoor propagation characteristics is to examine the effect of the type and shape of the metal frame around



(a)



(b)



(c)

Fig. 6. Comparison results at different distances from the window structures. (a) 10λ from windows. (b) 15λ from windows. (c) 20λ from windows.

the window. Fig. 9 shows how the pattern changes when the window frames changed from I-shaped columns to rectangular columns. All other dimensions used in the simulation for Fig. 9 are exactly the same as those in Fig. 5. The results are calculated at a distance of 20λ away from the windows. From Fig. 9,

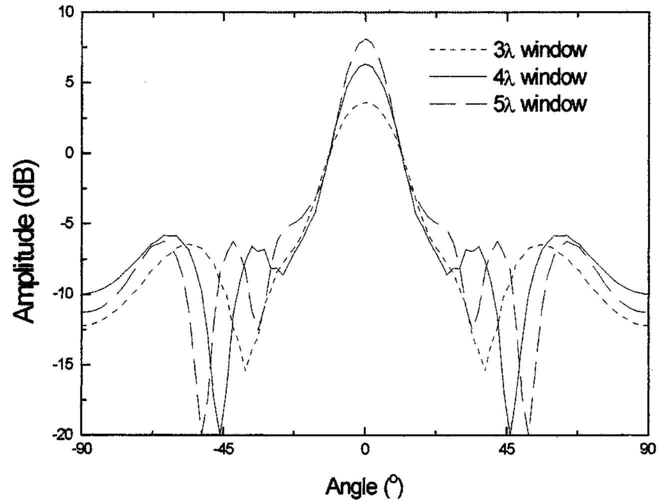


Fig. 7. Window size influence on rays.

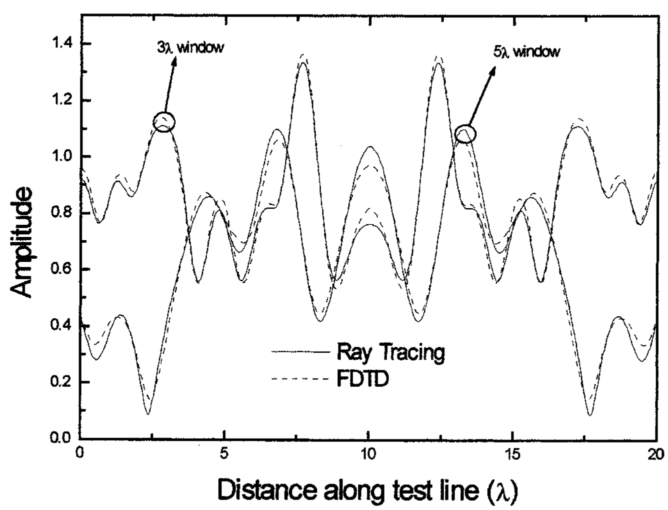


Fig. 8. Comparison results for different window sizes.

it is clear that window frame types play an important role in indoor/outdoor transmission and, hence, different window models need to be developed for different metal-frame shapes.

Finally, it is important to verify the accuracy of the developed ray-optics equivalent window model for the case of oblique incidence. Fig. 10 shows the resulting field patterns at a distance of 15λ from the windows when oblique-incident plane waves at angles of 20° and 40°, respectively, were applied to the windows. These figures confirm that the method proposed in this paper works very well even for the case of oblique incidence.

IV. Comparison With Experimental Results

To verify the accuracy of the ray-optics equivalent transmission model for windows and metal-framed structures, a millimeter-wave scale-model test set, as seen in Fig. 11, was built and used for making comparative measurements. The experimental setup consists of a 20 dB-gain horn antenna used as the transmitter and an open-ended waveguide attached to a 2-D rectangular scanning frame used as the receiver. The window structure is composed of six side-by-side 3mm-by-3mm-square

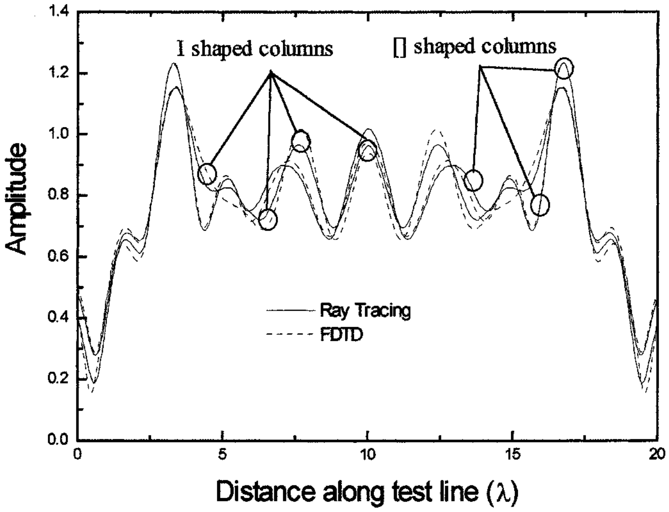
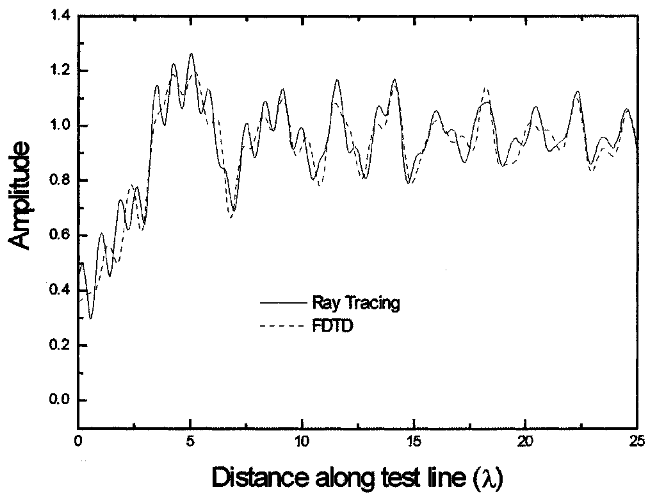
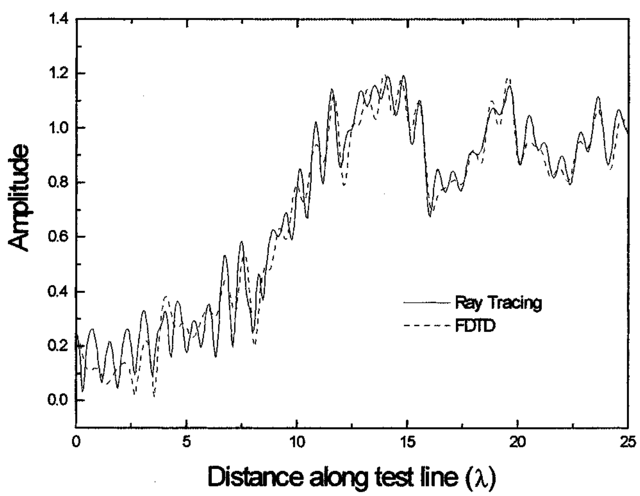


Fig. 9. Effect of window frames on the diffraction pattern.



(a)



(b)

Fig. 10. Validity of the ray-optics equivalent model for the case of oblique incidence. (a) 20° oblique incidence. (b) 40° oblique incidence.

metal rods that are flanked by two metal sheets, so as to ensure that the transmitted signal only passes through the five

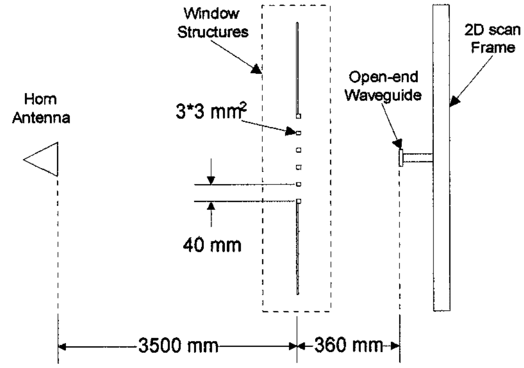


Fig. 11. Layout of scale-model test set. Photograph of the 2-D scanning frame is shown in Fig. 12.

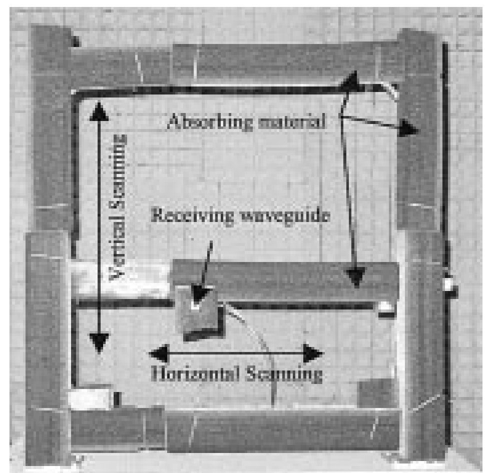


Fig. 12. Photograph of 2-D scanning test frame.

central window frames. The distance between the metal rods is 40 mm, and the test frequency used was 30 GHz. Therefore, the five windows were each 4λ-wide, and there was no glass between the window frames. The distance between the transmitter and the window structure is approximately 3500 mm, and the distance between the window structure and the open-ended waveguide is about 360 mm. The entire setup was placed in a large indoor antenna range at the University of Utah, Salt Lake City, UT.

Fig. 12 shows the 2-D scanning test frame with an open-ended waveguide attached to it. All of the components of the test frame are covered with absorbing material. Fig. 13 shows the window structure, which has been placed in front of the 2-D scanning test frame (the waveguide attached to the test frame can be seen in the background between the metal rods). The six square metal rods in the middle of the window structure are used to represent the window frames, and the pyramid-shaped structures surrounding the waveguide are the cone-shaped absorbing material on the back wall of the antenna range. The outer edges of the window structure were covered with absorbing material to avoid edge diffraction. Although the test set is three dimensional (3-D), both the transmitter and the receiver were placed at the same height, thus the results can be treated as a 2-D measurement. The polarization direction of the H-field is parallel to the window frames. Fig. 14 shows the calibration test results of the

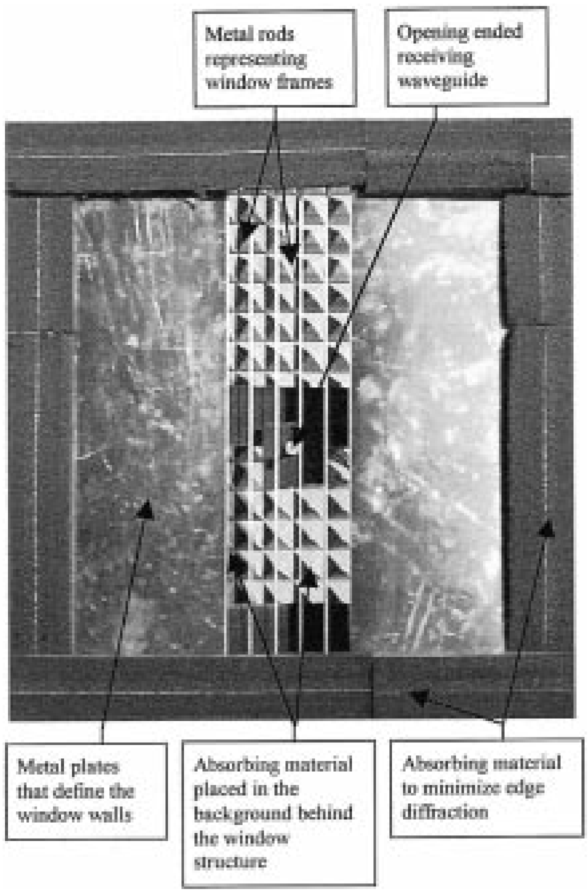


Fig. 13. Photograph of window structure scale model.

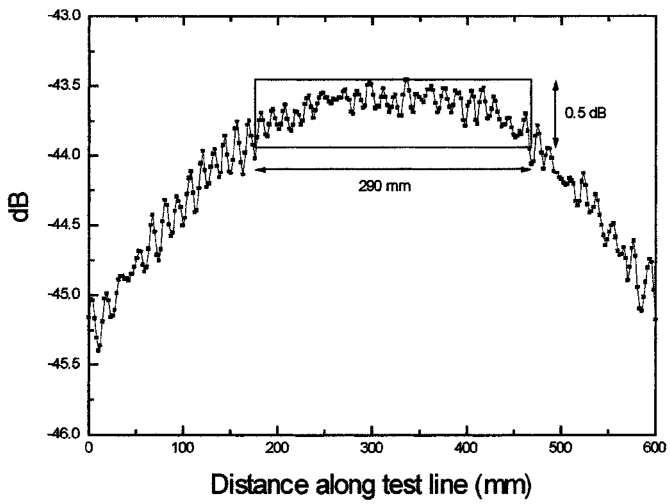


Fig. 14. Calibration test results of horn antenna.

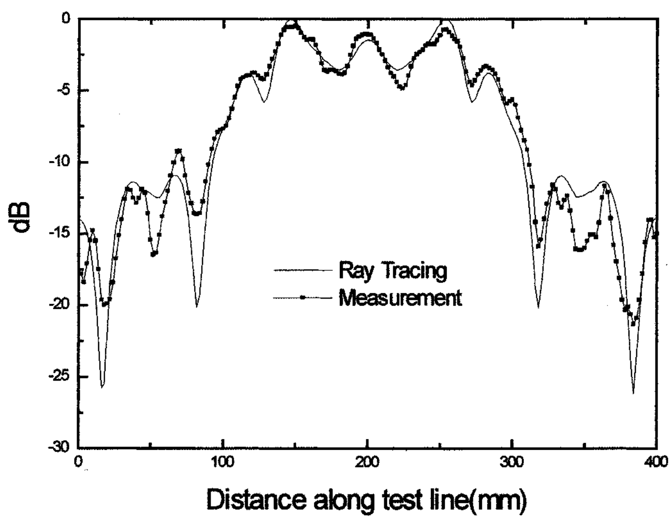


Fig. 15. Comparison of measurement and ray-tracing results.

horn antenna, i.e., transmission without the window structure. From Fig. 14, it can be seen that the radiation pattern is flat (within 0.5 dB vertical range) for about 290 mm along the test line in the central region that will be occupied by the window frames. The ripples in the measurement results can be attributed to the multipath signals in the propagation measurement environment.

Fig. 15 compares measurement results with ray-tracing (simulation) results. The solid line represents the ray-tracing results and the line with rectangular bumps depicts the measurement results. The results have been normalized to the maximum value. Assuming the incident wave to be a plane wave, the line-of-sight region is between 100 mm and 300 mm, which is also the aperture region of the window structure. On both sides of this region are the diffraction regions. Fig. 15 shows excellent agreement between the measurement and the ray-tracing results, thus verifying the accuracy of the ray-optics equivalent window model.

V. CONCLUSION

This paper examined the topic of indoor/outdoor propagation through windows using a new method based on a ray-optics equivalent model. First, the developed model was compared with the more familiar and proven FDTD method. As long as an adequate number of rays was used to represent the diffraction pattern from windows, and as long as the radiation pattern was calculated at a sufficient distance away from the window structures (say 20λ), the ray-optics representation of transmission through windows matched up very well with the FDTD calculations. Characteristics of the model were also examined for varying window sizes, different window frame shapes, and oblique angles of incidence. The ray-tracing method was also compared with the traditional experimental method, which was implemented by building a scale-model test set in an indoor antenna range. The measured results agreed quite well with the calculated results from the ray-tracing method, thus validating the accuracy of the developed model. Overall, this paper concludes that the ray-tracing equivalent model of a metal-framed window model is a valid and useful approach in the development of mobile radio systems that must deal with indoor/outdoor propagation issues. Based on this study, it is also clear that traditional methods that treat transmission through windows through the introduction of a single transmission coefficient are not adequate and, instead, a full ray-tracing model should be used. A complete accounting for a diffraction pattern is clearly required, and the developed ray-tracing equivalent model is suitable for integration with many of the available ray-tracing-based methods for modeling urban propagation environments.

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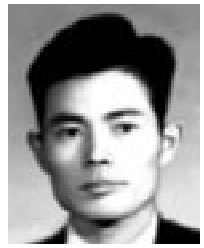

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