Propagation Prediction Models for Wireless Communication Systems

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Invited Paper

***Abstract*—A comprehensive review of the propagation prediction models for terrestrial wireless communication systems is presented in this paper. The classic empirical models are briefly described and the focus is placed on the application of ray-tracing techniques to the development of deterministic propagation models. Schemes to increase the computational efficiency and accuracy are discussed. Traditional statistical models are also briefly reviewed for completeness. New challenges to the propagation prediction are described and some new approaches for meeting these challenges are presented.**

***Index Terms*—Channel characterization, delay spread, path loss, propagation prediction model, ray tracing, wireless communications.**

I. Introduction

HEINRICH Rudolf Hertz observed in 1886 [1] the transmission of electromagnetic waves and, hence, realized the long-debated Maxwell's predictions of wave propagation. The first milestone on the road to wireless communications, however, was realized by Guglielmo Marconi who conducted his famous experiments from 1894 to 1901. Marconi demonstrated in 1901 that the radio wave could provide continuous contact with ships sailing the English Channel [2]. After that, two-way radio communications and broadcasting systems were developed in the 1930s and 1940s. In the 1960s and 1970s, the cellular concept was developed in Bell Laboratories, Holmdel, NJ [3].

The first generation of wireless mobile communication systems appeared in the 1980s and was based on analog technology with FM modulation. Examples of first-generation cellular systems are the Nordic Mobile Telephone (NMT) and Advanced Mobile Phone System (AMPS).

In the early 1990s, the second-generation (2G) digital cellular systems were developed with varying standards. Examples include the Goupe Special Mobile [(GSM), now Global System for Mobile Communications)] in the U.K., IS-54/136 and IS-95 in the U.S., and the Personal Digital Cellular (PDC) in Japan. In general, the 2G systems have improved spectral efficiency and voice quality.

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The third generation (3G) of wireless communications are currently being developed in different regions of the world. The 3G systems will provide multimedia services and satisfy more requirements such as applications and communications "anytime and anywhere" [4]. To this end, wide-band and broad-band radio technologies will be necessary. The examples of 3G standards are International Mobile Telecommunications 2000 (IMT-2000), CDMA-2000, and NTT DoCoMo W-CDMA systems.

Although the 3G will begin service in 2001/2002 and reach full deployment by 2005, the fourth-generation (4G) systems are currently being discussed [5]. The 4G system will provide an all-IP network that integrates several services available at present and provides new ones, including broadcast, cellular, cordless, WLAN, and short-range communication systems.

The general trend in the development of wireless communication is the use of higher data rates (broader frequency band), propagation in more complex environments, employment of smart antennas, and use of multiple-input multiple-output (MIMO) systems.

A. Importance of Propagation Prediction

Before implementing designs and confirming planning of wireless communication systems, accurate propagation characteristics of the environment should be known. Propagation prediction usually provides two types of parameters corresponding to the large-scale path loss and small-scale fading statistics. The path-loss information is vital for the determination of coverage of a base-station (BS) placement and in optimizing it. The small-scale parameters usually provide statistical information on local field variations and this, in turn, leads to the calculation of important parameters that help improve receiver (Rx) designs and combat the multipath fading. Without propagation predictions, these parameter estimations can only be obtained by field measurements which are time consuming and expensive. The following subsections provide a brief description of deterministic models, statistical models, and challenges facing the development of accurate and sufficiently general propagation prediction models.

B. Empirical, Theoretical, and Site-Specific Models

The path-loss prediction models can be roughly divided into three types, i.e., the empirical, theoretical, and site-specific models. Empirical models are usually a set of equations derived from extensive field measurements [6], [7]. Empirical models are simple and efficient to use. They are accurate for environments with the same characteristics as those where the measurements were made. The input parameters for the empirical models are usually qualitative and not very specific, e.g., a dense urban area, a rural area, and so on. One of the main drawbacks of empirical models is that they cannot be used for different environments without modification, and sometimes they are simply useless. For example, the empirical model for macrocells cannot be used for indoor picocells. The output parameters are basically range specific, not site specific.

Site-specific models are based on numerical methods such as the ray-tracing method [8], [9] and the finite-difference time-domain (FDTD) method. The input parameters can be very detailed and accurate. The disadvantages of the site-specific methods are the large computational overhead that may be prohibitive for some complex environments.

Theoretical models are derived physically assuming some ideal conditions. For example, the over-rooftop diffraction model is derived using physical optics assuming uniform heights and spacing of buildings. Theoretical models are more efficient than the site-specific models and more site-specific than the empirical models [10].

C. Statistical Models

Small-scale propagation parameters are usually characterized by some statistics, such as rms delay spread, coherence bandwidth, Doppler spread, and coherence time. These parameters directly affect the design of Rxs and affect estimated values of the bit error rate. They also facilitate simulations of communication systems and provide performance measure of quality of service (QoS).

Due to the length limitation of this paper, the review of this rich research area will be very brief. Readers are referred to the references for detailed information on specific areas of interest.

D. Challenges to the Propagation Modeling

Wireless communication channels are inherently frequency dispersive, time varying, and space selective, although only one or two of these dependencies will appear in some cases.

The fast evolution of wireless communications has lead to the use of higher frequency bands, smaller cell sizes, and smart antenna systems, making the propagation prediction issues more challenging.

In macrocells, since the transmitting antenna is usually located on a high tower, simple empirical and statistical models are widely used with satisfactory accuracy. As for the microcells and especially for picocells, the height of the transmitting antenna may be lower than the average height of the buildings in the regions involved. In this case, the geometry of the buildings and terrains will greatly affect the propagation of the radio waves, causing wide shadow regions. The outdoor radio wave propagates through reflections from vertical walls and ground, diffractions from vertical and horizontal edges of buildings, and scattering from nonsmooth surfaces, and all possible combinations. There is no *general* empirical and statistical model that can be used for prediction of these complicated propagation environments.

Smart antenna systems exploiting space diversity require information on the angle of arrival of the multipath in addition to the usual parameters such as path loss and delay spread. A MIMO system uses the multipath to provide higher capacity [11], [12], completely different from the classical systems where multipath is considered harmful. All these new systems involve space-time and space-frequency channel models.

To deal with the new complex propagation environments, site-specific models have been developed based on ray-tracing techniques. In a basic ray-tracing algorithm, the main task is to determine the trajectory of a ray launched from a transmitting antenna. This procedure involves the calculation of the intersection of a ray with a surface (in three-dimensional (3-D) cases) or a ray with an edge segment (in two-dimensional (2-D) cases). The computation time might be huge or even beyond the capability of present computers if the propagation environment is large and/or complex. The computation efficiency is then the biggest obstacle against the application of ray-tracing methods. An efficient ray-tracing procedure is also important for improving the prediction accuracy since more types of rays—such as reflected, transmitted, diffracted and scattered rays and their combinations—can be taken into account.

The accuracy of propagation prediction involves many aspects. These include the accuracy of locations and sizes of buildings and accurate knowledge of the electric parameters of walls and other objects involved. Trees, large posts, traffic, and pedestrians in outdoor cases and furniture in indoor cases can also influence the results and make a difference. Recently, accurate characterization of complex wall structures including metal-framed windows is receiving attention due to the requirement of a more accurate prediction of the indoor/outdoor propagation mechanism. To meet these challenges, existing prediction methods should be modified and improved, and new procedures and techniques have to be developed.

E. Objective

This paper will first give a brief review of widely used empirical and simplified theoretical propagation models. These models are mainly used for macrocells and microcells. Then a detailed review will be given on the research and application of that ray-tracing method that is gaining importance for propagation simulation of microcells and picocells. Some full-wave prediction methods will also be briefly described. It should be pointed out that we will focus on the deterministic prediction models for path loss. Due to the length limitation of this paper, statistical models for multipath fading will only be very briefly included.

The readers are encouraged to read some review papers [13]–[19] and books [20]–[27] to complement the brief review included in this paper.

II. Empirical and Theoretical Models

A. Definition of Path Loss and Free-Space Propagation

The path loss at a point $\mathbf{r}$ is defined as the ratio of transmitted power at $\mathbf{r}_0$, $P_t(\mathbf{r}_0)$, over the received power at $\mathbf{r}$, $P_r(\mathbf{r})$. For free-space propagation, the path loss can be simply expressed as [26]

$$L(\mathrm{dB}) = 10 \log \frac{P_t(\mathbf{r}_0)}{P_r(\mathbf{r})} = -10 \log \left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2} \right] \quad (1)$$

where G_t and G_r are the gains of the transmitting antenna (Tx) and receiving antenna (T_r), respectively, d is the distance between T_x and R_x, and λ is the wavelength in free space.

B. Okumura Model and Hata Model

The Okumura model [6] is an empirical model based on extensive measurements made in Japan at several frequencies in the range from 150–1920 MHz (it is also extrapolated up to 3000 MHz). Okumura's model is basically developed for macrocells with cell diameters from 1 to 100 km. The heights of the BS antenna are between 30–1000 m. The Okumura model takes into account some of the propagation parameters such as the type of environment and the terrain irregularity. The basic prediction formula is as follows:

$$L_{\mathrm{mean}}(\mathrm{dB}) = L_{\mathrm{free}} + A_{m,u}(f, d) - G(h_{te}) - G(h_{re}) - G_{\mathrm{correction}}$$

where L_{mean}(dB) is the median value of the propagation path loss, L_{free} is the free-space path loss, and can be calculated using (1), A_{mu} is the median attenuation value relative to free space in an urban area, $G(h_{te})$ and $G(h_{re})$ are the height gain factors of BS and mobile antennas, and G_{correct} is the correction factor due the environment. A_{mu} and G_{correct} are determined by looking up curves derived from measurements. $G(h_{te})$ and $G(h_{re})$ are calculated using simple formulas.

Terrain information can be qualitatively included in the Okumura model. For example, the propagation environments are categorized as open area, quasi-open area, and suburban area. Other information such as terrain modulation height and average slope of terrain can also be included. Illustrative examples using the Okumura model can be found in, e.g., [26], [27].

The Hata model [7] is a formula-based Okumura model (graphics-based) and can be used more effectively. The frequencies range from 150 to 1500 MHz. It has been extended to cover the frequency band from 1500 to 2000 MHz in the COST 231 project [19].

C. Over-Rooftop Models

Over-rooftop models are typical theoretical models [10], [28] that are more precise than the Okumura model for the description of the urban environments. Based on the physical optics and some assumptions made for the geometry of the buildings and heights of BS antennas, formulas are derived that give the average received signal for mobiles at street level. Typical assumptions are that the heights of the buildings are equal and the spacing between the buildings is identical.

In over-rooftop models, the path loss in decibels is the sum of free-space loss and the so-called excess loss (L_{ex}). The excess loss is further divided into two parts $L_{\mathrm{ex}} = L_{\mathrm{ex1}} + L_{\mathrm{ex2}}$, i.e., the diffraction of the fields at the rooftop before the mobile down to the street level, and the reduction of the field at this rooftop as a result of propagation over the previous rows of buildings.

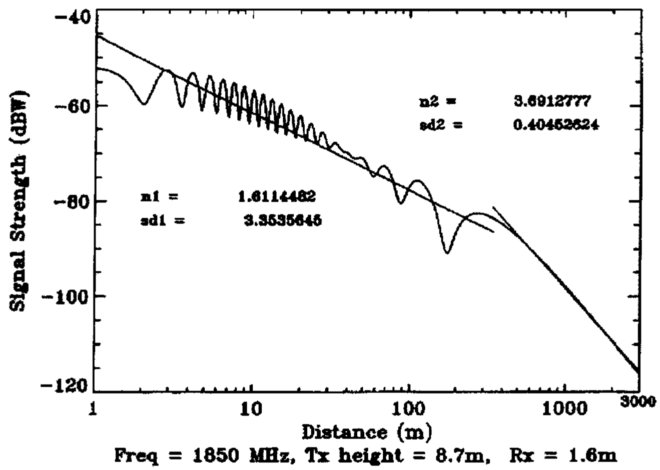

Fig. 1. Multiple slope regression fit to the two-ray model [37].

Saunder and Bonar [29], [30] also investigated the over-rooftop propagation for the case of arrays of buildings. In [29], more general situations are taken into account, e.g., the short-range case where the method in [10] gives incorrect results. In [30], efforts were made to extend the existing model to deal with more realistic situations, i.e., the building heights and spacing are irregular. Ikegami *et al.*, using a single diffraction mechanism, also studied the over-rooftop propagation [31].

Vogler [32] proposed another over-rooftop method for buildings with variant heights and spacing. Bertoni's method [10], [28] and Vogler's formulation were combined in [33] so that an efficient and accurate prediction model for rooftop propagation is obtained. Other improvement of over-rooftop propagation models can be found in [34].

A comparison between several over-rooftop propagation models for two types of building profiles is presented in [35], i.e., buildings with equal heights and uniform spacing, and buildings with irregular heights and spacing. It is found that the two building profiles have their own merits and will give more accurate results if properly used for different environments (including building geometry, antenna heights relative to average building heights, etc.).

D. Two-Slope Model for Microcellular Environments

This model is measurement based and is used for line-of-sight (LOS) propagation in an urban area. The model is based on a two-ray propagation mechanism, i.e., the LOS ray and the reflection ray from the ground [36], [37]. This model is characterized by the fact that a break point exists that clearly separates the different properties of propagation in near and far regions relative to the BS, as shown in Fig. 1. Using regression analysis of the measured data in the San Francisco Bay area, it is shown that the slope before the break point is less than two, while the slope after the break point is greater than two [37].

The two-ray model for LOS propagation was extended in [38] to take into account the effects of traffic and high obstacles such as posts. It is shown that when the heights of traffic and some obstacles are included in the model, better accuracy can be obtained compared with the experimental results.

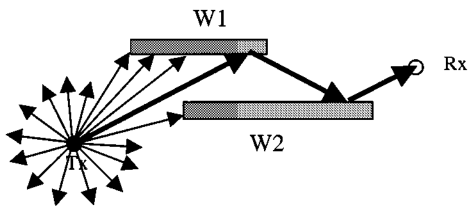

Fig. 2. Ray launching procedure. It is shown that some rays are launched from the Tx and reflected by the walls. It is also shown that at the end of the process, a fewer number of rays may be received by the Rx.

E. Other Models

Rustako *et al.* [36] proposed a six-ray model for an urban LOS area that was shown to be accurate compared with measured results. These rays are the direct (LOS) ray, the ground-reflected rays, two rays with one-wall reflection, and two rays with double-wall reflections.

Lee proposed an area-to-area model [25] for flat-terrain regions. A set of nominal conditions is assumed and, when the realistic situation is different from the assumptions, correction factors are calculated and included in the prediction formula.

Other models can be found in [39]–[42] and, specifically, for indoor prediction models, the reader is referred to [17], [18], [43]–[56].

III. RAY-TRACING MODELS

Ray theory emerged as a highly promising procedure for providing an accurate site-specific means to obtain useful simulation results [8], [9], [57], [58]. It should be noted that the ray-tracing method also serves as a starting point for statistical modeling [59]–[62]. According to the ray optics and the uniform theory of diffraction (UTD), propagation mechanisms may include direct (LOS), reflected, transmitted, diffracted, scattered, and some combined rays, which, in fact, complicates and, in many realistic propagation environments, slows down the calculation procedure. In this section, some of the more commonly used ray-tracing methods will be briefly described.

A. Shooting-and-Bouncing Ray (SBR) Launching Algorithm

The basic procedure of a ray-tracing method is the SBR algorithm [63]. First, a ray is launched from the transmitting antenna (Tx), then the ray is traced to see if it hits any object or is received by the receiving antenna. When an object is hit, reflection, transmission, diffraction, or scattering will occur, depending on the geometry and the electric properties of the object. When a ray is received by a receiving antenna, the electric field (power) associated with the ray is calculated. A schematic of the SBR method is shown in Fig. 2.

This algorithm has some fundamental issues that need to be considered. The first is how to launch a ray. The second is how to determine if a ray hits an object. Third, if there are several possible objects that can be hit by the ray, how is it determined which one is really hit? The fourth is how to determine whether a ray is received. In the following, ray launching and reception criteria as well as ray intersection with an object will be reviewed.

1) Ray Launching Model and Reception Criteria: A ray is actually a ray tube and is usually a cone, as shown in Fig. 3 [8], [64]–[66]. When ray cones are used to cover the spherical wavefront at the receiving location, these cones have to overlap [8]. When ray tubes [see Fig. 3(b)] are used, the spherical wavefront can be covered without the overlapping of ray tubes.

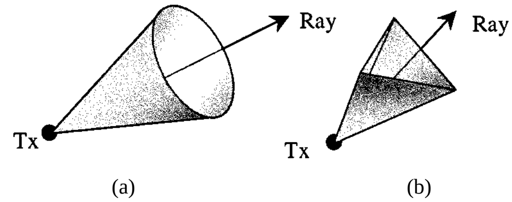

Fig. 3. Ray cone and ray tube. (a) Ray cone. (b) Ray tube.

To determine whether a ray is received or not by a receiving antenna, one has to check if the receiving point is inside the ray cone or tube. If yes, the ray will be received; otherwise, it will not. For the ray-cone scheme, the reception test can be easily carried out by using a reception sphere centered at the receiving point with radius equal to $\alpha d/\sqrt{3}$ [8], where α is the angle between two adjacent rays and d is the total length of the ray.

Since ray cones are overlapped, when a receiving point is located in the overlapping area between the ray cones, the Rx will then receive two rays and ray double counting occurs [67]. This gives errors, and some procedures are proposed to deal with this issue [67], [68].

2) Intersection Test of a Ray With an Object: To determine if a ray hits an object, one has to test the intersection of a ray with the object. This is a classic problem in computational geometry and graphics [69]. A naive SBR method tests all the objects to determine whether a ray hits an object. When the number of objects is large, the testing can be very time consuming and inefficient. It is pointed out in [70] that intersection testing can consume more than 90% of CPU time for a naive SBR algorithm.

B. Image Method

The image method is a simple and accurate method for determining the ray trajectory between the transmitter (Tx) and Rx. Fig. 4 shows the basic idea of the image method. For this simple case, the image of Tx due to $W1$ is first determined ($\mathrm{Tx1}$ in Fig. 4). Then the image of $\mathrm{Tx1}$ due to $W2$ is calculated ($\mathrm{Tx2}$). Connecting Rx and $\mathrm{Tx2}$, one can find a reflection point ($P2$) on $W2$. Another reflection point ($P1$) is the intersection point of $W1$ with the line connecting $P2$ and $\mathrm{Tx1}$.

The image method is accurate, but suffers from inefficiency when the number of walls involved is large and reflection times are high. For realistic applications, special techniques such as the hybrid and acceleration methods have to be used to reduce the computation time.

C. Hybrid Method

Tan *et al.* [71] proposed a hybrid method combining the image and SBR methods. The SBR method is used to quickly identify a possible ray trajectory from Tx to Rx. When the trajectory is found, a series of walls involved can be determined. The exact reflection positions can then be accurately found by the image method. This method has the advantages of the SBR (efficient) and image (accurate) methods.

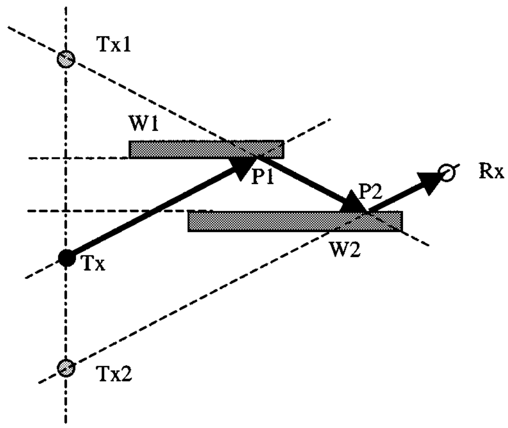

Fig. 4. Illustration of the image method.

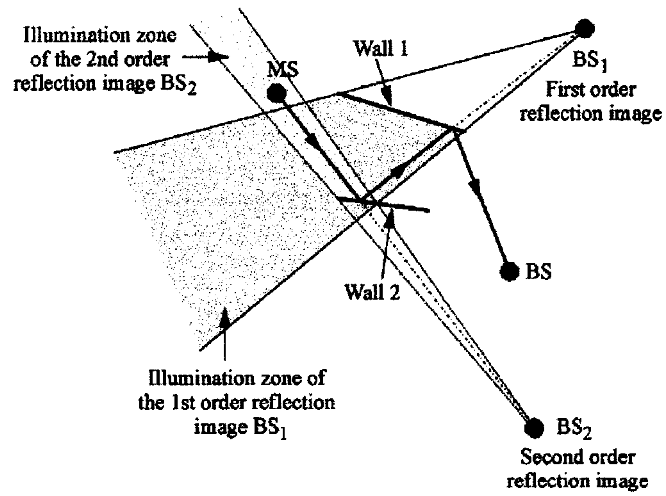

Fig. 5. Image generation and the illumination zones of the images: the basic concept and path tracing using illumination zones [76].

D. Acceleration of Ray-Tracing Algorithms

The ray-tracing method is simple and is most widely used in the area of site-specific propagation prediction. However, the ray-tracing method can be very computationally inefficient. This is why there are many publications focusing on the acceleration of the ray-tracing algorithms. There are several ways to achieve the acceleration. The first is to reduce the number of objects on which actual ray-object intersection will be performed. The second is to accelerate the calculation of the intersection test. All acceleration methods concern the preprocessing of the propagation environments and/or the positions of Tx and/or Rx. In this section, we will provide a brief summary of these efforts.

1) Angular Z-Buffer (AZB) [70], [72]: This method is based on the light buffer technique used in computer graphics. The basic idea is to divide the space into angular regions according to a source point. The source point can be a Tx or an image of it related to a reflection plane. When a ray is launched from the source point, only those objects located in the angular region containing the ray need to be tested for ray intersection. This method can accelerate the ray-tracing algorithm, but, when multiple reflections are needed, the preprocessing is not easy. This is because there are many source points (including the Tx and a large number of its images) and an AZB should be established for each of them.

2) Ray-Path Search Algorithm: Based on the idea that ray-tracing routines should be applied only to those areas where rays are likely to exist, the ray-path search algorithm in [73] and [74] employs the visibility graph to limit the intersection test. The visibility graph contains several layers. The first layer includes all objects visible to the Tx (for LOS rays). The second layer contains objects visible to the first layer (for transmitted, reflected, and diffracted rays). Further layers are of similar recursive relationship. Since the determination of visibility between two objects is not easy, acceleration methods such as bounding boxes are employed for establishing the visibility graph.

When a ray is launched from the Tx, only those objects in the first layer of the visibility graph need to be tested for the first intersection. To determine the nth intersection of the ray, only objects in the nth layer need to be tested, thus leading to saving of computation time.

This method has similar drawbacks to the AZB method, i.e., when interaction levels are high, the establishment of the visibility graph will be much more time consuming and complicated.

A similar procedure for the image method is presented in [75]–[77]. This technique generates an image table for each BS location. These images take into consideration the various wall reflections, transmissions, and edge diffractions. To further accelerate the ray-tracing procedure, accurate "illumination zone" concepts are used to restrict each image to an illuminated area. Thus, only objects inside the illumination zone need intersection testing. Fig. 5 shows the illumination zone concept, where BS_1 is the image of the BS with respect to Wall 1, and BS_2 (second-order image) is the image of BS_1 with respect to W2. The mobile station (MS) is in the illumination zone of BS_2.

In [78], an efficient method for visibility list construction is developed. This method is especially designed for a large number of receiving points. Some unnecessary repetition calculations are avoided by using a so-called "point-to-area" algorithm. A dynamic calculation of the visibility list is used to accelerate the 3-D ray-tracing procedure.

3) Dimension Reduction Method: To achieve efficient ray-tracing procedures and retain acceptable accuracy, ray-tracing algorithms may be carried out in nonfull 3-D geometries. Examples of this approach may include the 2-D/two-and-one-half dimensional (2.5-D) method, the vertical plane launch (VPL) method, and so on. The following is a brief summary of some of these methods.

a) 2-D/2.5-D Method: When the heights of buildings in a region are much larger than the height of the Tx, the main propagation is a lateral one. In this case, the complex 3-D environment can be approximated by much simpler 2-D structures and a significant saving in computation time can be achieved. Rizk *et al.* [79] presented a 2-D ray-tracing modeling method for microcellular environments. Based on the image method, the obtained prediction results compared well with measurement data.

b) VPL Method: The VPL technique is proposed in [9]. The usual 2-D ray tracing is used in the horizontal plane.

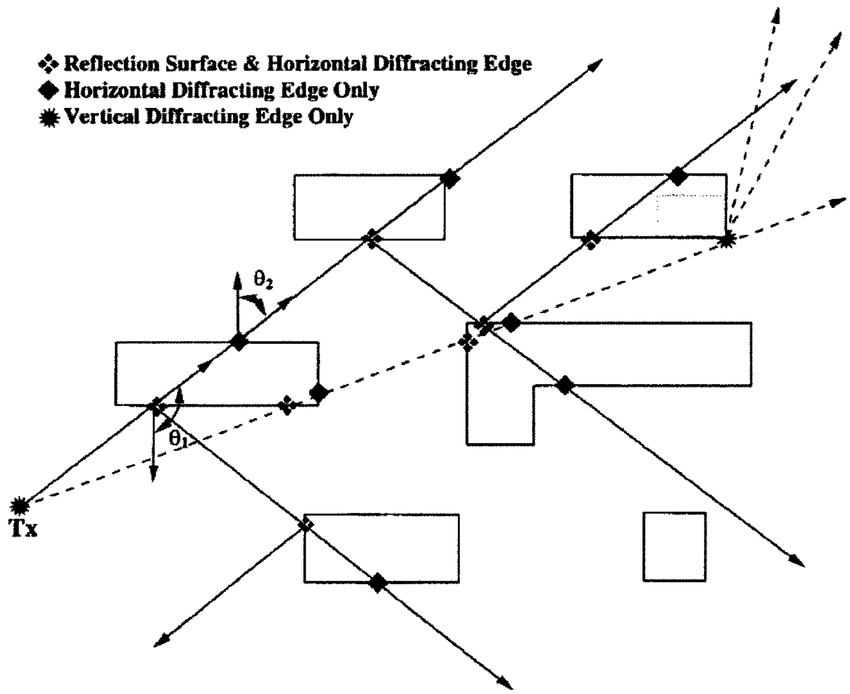

Fig. 6. Schematic illustration of the ray-launching procedure in the VPL method [9].

Each ray in the 2-D case represents a vertical propagation plane. When a ray hits a vertical wall, specular reflection from the vertical wall and diffraction from the rooftop horizontal edge can occur. When the ray hits a vertical edge, diffraction also occurs. The over-rooftop diffraction creates two vertical propagation planes, one in the same direction as the incident ray and the other in the direction of reflection. Diffraction from the vertical edge creates a new source and many new rays in 2-D planes should be launched. These rays are further traced in a similar manner until some criteria are reached. Fig. 6 is a schematic illustration of the VPL method [9].

Rizk *et al.* [80] compared the results using lateral, full-3-D, and VPL methods. It is found that when the average building heights are around the Tx height, VPL can give very good predictions.

4) Space-Division Method: The space-division method is widely used in computer graphics. The basic idea is to first create a grid (usually rectangular) in the propagation environment, and then establish a lookup table registering objects residing in each grid cell. When a ray is launched, it is traced in the grid. For each grid the ray is traversing, the lookup table is checked to see if any objects reside in the grid. If yes, the ray is tested for intersection with these objects. If any object is hit, a reflected (or diffracted) and/or a transmitted ray will be created and the new rays will be further traced.

The space-division method can give fast ray traversing and efficient ray tracing. This is due to the fact that the algorithm for traversing the grid can be fast and the intersection test is performed only on a small number of objects. Two types of space-division methods that have been applied to propagation in urban environments will be summarized in the following subsections.

a) Rectangular Division: The rectangular division method has the advantage that the ray traversing in the grid is very fast [81]. Yun *et al.* [82] developed an efficient ray-tracing method employing the fast ray-traversing algorithm for rectangular grid [81]. Different from the usual space-division method, the new method requires that the wall should be exactly located on the grid lines to acquire best efficiency.

The new method labels each grid cell according to the room (or building) identification number, i.e., cells in the same room have the same identifications.

When a ray is traversing from one grid cell to another, and the label of the new cell is different from the previous cell, the wall between the two cells will be hit. In this case, the intersection test that is used in usual space-division methods is completely avoided. As a result, a significant reduction in CPU time is expected. Specifically, the CPU time for the new method was shown to be around 15% of that of the visibility method for a realistic indoor environment [82].

b) Triangular Division: In [83] and [84], triangular division methods were proposed. It is shown that a great improvement in CPU time was also achieved when using this method. In [84], the triangulation strategies are described in detail, and a ray-traversing algorithm is developed. It should be pointed out that the most important feature of the triangular grid method developed in [84] is that, when finding the segment hit by the ray, only two cross products of two vectors need to be calculated.

Fig. 7 shows the basic ray-traversal procedure. When a ray, i.e., $\boldsymbol{u}$, from the source P_0 is leaving the first intersection edge AB in the triangle ABC, we need to determine which edge, i.e., AC or BC, will be hit next. We can build a unit vector $\boldsymbol{v}$ from the intersection point o on AB and pointing to C, the opposite vertex to edge AB. The sign of the cross-product between $\boldsymbol{u}$ and $\boldsymbol{v}$ then determines the edge to be hit. If the sign is positive, the ray hits BC; otherwise, the edge AC will be hit.

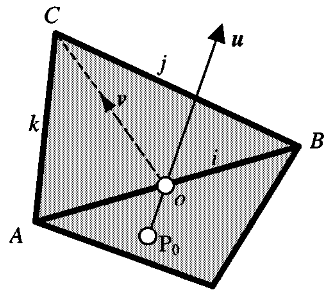

Fig. 7. Determination of the edge to be hit by a ray.

It is shown in [85] that the CPU time for the triangular grid method is about 30% of that of the visibility method for an indoor environment. The triangular grid method was also used to calculate the path loss of Munich City, and the results were compared with the measured results provided by the COST 231 project. It is shown that the average error standard deviation is 7.2 and is very good compared with other results in the COST 231 project [86]. Estimates of the saving in CPU time were very significant and more than an order of magnitude [87].

E. Improvement of Accuracy of Ray-Tracing Algorithms

The ray-tracing method can provide site-specific predictions. Due to the fact that the environmental database may not be accurate and the materials of the objects in the region of interest may not be known, the ray-tracing method can only provide approximate results for realistic propagation environments.

Another factor affecting the accuracy of the ray-tracing procedure is the incomplete account for all kinds of rays. This is because the more rays taken into account, the more computation time will be needed, leading to unacceptable efficiency. Examples of techniques used to improve the accuracy of ray-tracing algorithms are described in the following sections.

1) Additional Ray Mechanisms—Effect of Diffractions: Diffractions from vertical and horizontal edges of buildings are important contributions to the received power. The over-rooftop propagation is mainly due to diffractions from the horizontal edges.

Methods for calculation of diffraction coefficients for metal or materials with finite conductivity were developed [88]–[91]. A comparison among the perfectly absorbing wedge (PAW) method, UTD, and UTD heuristic methods can be found in [79]. It is found that errors given by these three methods are comparable.

Rizk *et al.* [92] proposed a method to include the slope diffraction from wedges to improve the accuracy of calculation of the diffracted field in transition regions using classical UTD. Several decibels (approximately 6 dB) of improvement can be achieved.

The diffraction from building corners (wedges) is taken into account in [93]. New diffraction coefficients for objects with finite conductivity are developed [94]. The artificial dip in the usual diffraction calculation is removed. Comparison with FDTD shows that the results of the new method are of good accuracy.

2) Ray-Launching Models: In the SBR method, the detection of reception of rays depends on how these rays are launched. When ray cones are used, it is usually assumed that the angles between adjacent rays are equal. This is true if the spherical wavefront is approximated by a regular icosahedron and rays are launched from each of the vertices of the icosahedron. Since the number of the vertices of the icosahedron is 12, the number of rays launched is usually too few to get satisfactory accuracy. To launch more rays, the icosahedron is tessellated, but the angles between adjacent rays will no longer be equal. Fortunately, the difference between these angles is not significant [8] and, in practice, they are assumed to be equal.

It is pointed out earlier in this paper that the ray-cone model has the double-counting problem [67]. Several methods have been proposed to reduce or avoid its effect. In [67], a method of distributed wavefronts was developed to remedy this problem. Instead of counting hit-or-miss rays, the method in [67] takes the contribution of all nearby rays into account. The total field received by an antenna is the "weighted" sum of several wavefronts. Rays near the Rx contribute more power than those far away from the Rx. The distributed wavefronts method improves the accuracy of the calculated fields, but is relatively complex to realize (counts and keeps record of a large number of rays) and is also inherently inaccurate.

Yun *et al.* [68] proposed a simple method to avoid the ray double-counting problem. It is based on the fact that a ray from Tx to Rx is uniquely defined by a sequence of objects involved. Thus, when a ray is received, this sequence is stored. When another ray is received, the corresponding sequence will be checked with the existing sequences. If there is an identical sequence, the new received ray is a double-counted ray and should not be taken into account. This method adds little extra effort for the existing SBR code, but avoids ray double counting and, hence, improves the accuracy.

For the ray-tube launching model, the power is assigned to each tube according to its cross-sectional area. There is no need to make uniform ray distribution in theory in this case. It does not have the problem of double counting. Usually, the information of the cross section needs to be kept on track, and the reception scheme is different from the reception sphere model.

3) Other Issues: Rizk *et al.* [95] investigated the influence of database accuracy for ray-tracing techniques based on 2-D environments. The building layouts built with different maps, the materials assumed for the walls, the dimensions and locations of buildings, and the positions of Txs are examined.

In [96], the relationship between the received power and different ray combinations and interactions, wall material characteristics, antenna position offsets, and database inaccuracies were investigated.

In [97] and [98], comparisons between experiment and ray-tracing results were performed and it was found that the ray-tracing method was suitable for predicting signal and interference levels.

Rizk *et al.* [79] studied the repeatability of propagation measurements. It is pointed out that the divergence between the repeated measurements will be as large as 5 dB over a distance less than 50 m. The standard deviation between repeated measurements is about 3 dB. It is thus concluded that the comparison between measurements and predictions should emphasize the global tendency, instead of details.

Rizk *et al.* [99] examined the effects of lamppost and panel scattering in urban propagation simulation. The metal lamppost is approximated by a cylinder and the panel is represented by a finite plate. It is found that the scattering by metallic cylinders is as important as the reflections and diffractions. The panel can have a nonnegligible effect on the simulation results.

Tree effects of tree and vegetation on the propagation characteristics are investigated in [100]–[102]. The tree canopy is simulated as an elliptical cylinder horizontally placed to nearby buildings [101]. It is found that ten rows of wide trees may cause 4–5-dB extra path loss.

IV. Statistical Models

Small-scale channel modeling is concerned with multipath fading and is usually investigated using statistical methods. An impulse response model is often employed and, for time-invariant cases, its transfer function has the form

$$h(\tau) = \sum_{i=0}^{N-1} a_i \exp(-j\theta_i)\delta(\tau - \tau_i)$$

where a_i, θ_I, and τ_i are the amplitude, angle of arrival, and time delay of the ith multipath, respectively [26]. Usually, parameters such as the time delay spread, the coherence bandwidth, Doppler spread, and coherence time are of interest.

Turin *et al.* [103] studied the statistical model for urban multipath propagation based on experiments. It was found that the excess delay forms a Poisson sequence. The multipath spread was found to be almost totally dependent on the local environment of the Rx, independent of the distance between the Tx and Rx. Suzuki [104] further investigated Turin's experimental data and proposed a modified Poisson process to model the path arrival time. Turin's mathematical model was employed by Hashemi for the development of a simulation program for urban multipath propagation [105].

Saleh *et al.* proposed a statistical model for indoor multipath propagation [106]. The model is based on experimental results taken for a medium-sized two-story office building. The new model introduced the cluster-ray concept, i.e., the rays arrive in clusters. The cluster arrival times are modeled by a Poisson process. Within each cluster, rays are also arriving according to a Poisson process.

Rappaport *et al.* [44], [47] developed a measurement-based statistical model for factory buildings. The effect of Tx–Rx separation distance, small-scale Rx movement, and correlation of multipath amplitudes on local areas were examined.

V. New Trends in Propagation Predictions

As the fast development of wireless communications continues to progress, new techniques are employed to increase the capacity and the QoS of the deployed systems. The application of smart antennas and MIMO systems requires a spatio-temporal characterization of wireless channel. In addition to the path loss and time delay spread, angle-of-arrival and joint spatio-temporal models become necessary for the development of modern wireless communication systems [107], [108].

The currently developed spatio-temporal models usually assume certain distribution of scatterers around mobile stations and/or BSs and then derive the joint time-of-arrival and angle-of-arrival density functions. The scatterer distribution can lie in a circular area [22], an elliptical area [108], [109], or in clusters [110]. It is also found that, based on indoor measurements, rays can also arrive in clusters and a joint spatio-temporal model is developed for indoor environments [111].

As the more accurate modeling of outdoor-to-indoor propagation is needed, characterization of wall structures is receiving more attention. Walls are usually represented by half-space materials [8] or slab and layered models [76]. Measurement results are widely used for calculation of reflection and transmission through these walls [112]–[116].

Analytical and numerical characterization of walls is also available. Honcharenko and Bertoni [117] investigated the reflection and transmission properties of concrete walls with periodic structures. Chu *et al.* [118], [119] studied some composite wall structures using periodic surface-integral formulation. Both TE and TM incidences were treated. Chiu *et al.* [120], using the filament-current and thin-current assumptions, analyzed structures with laminated (N-ply) structures. The finite-element method is used in [121] for the analysis of propagation into reinforced concrete walls. Dalke *et al.* [122], using the FDTD method, analyzed the propagation properties of reinforced concrete structures. It is found that the transmitted field has resonance and nulls. These resonance and nulls are dependent on the structure and the thickness of the wall. These resonance-type effects are very important and may have critical impact on wide-band and ultra-wide-band communication systems.

Holloway *et al.* [123] proposed a different method to characterize complex walls with periodic structures. Holloway used the homogenized method to replace the complex wall with three layers of materials. The electrical parameters of the center layer are dependent on the angle of incidence. The resonant property is predicted and accurately characterized using this method. Fig. 8 shows a comparison between reflection/transmission coefficients calculated using Holloway's method and the FDTD method [124]. The resonant effects can be clearly seen in this figure. The possible use of FDTD in these calculations now opens the door for calculating a wide variety of these walls and the implementation of the obtained results in urban propagation modeling codes.

Another structure of interest is the metal-framed glass (windows) with periodic geometry. Since the size of the periodic cell is usually larger than the wavelength, caution has to be taken for its characterization. An equivalent-ray method was proposed by the authors to accurately characterize transmission through windows [125]. The proposed method represents each periodic cell (window) with an equivalent ray representation with amplitudes precalculated using UTD or a numerical method such as FDTD. When a ray hits the structure, it is replaced by precalculated rays entering the building (90 rays for 180° diffraction pattern). This is certainly different from accounting for transmission through windows by using a single complex transmission coefficient parameter. Preliminary results show that the method gives very

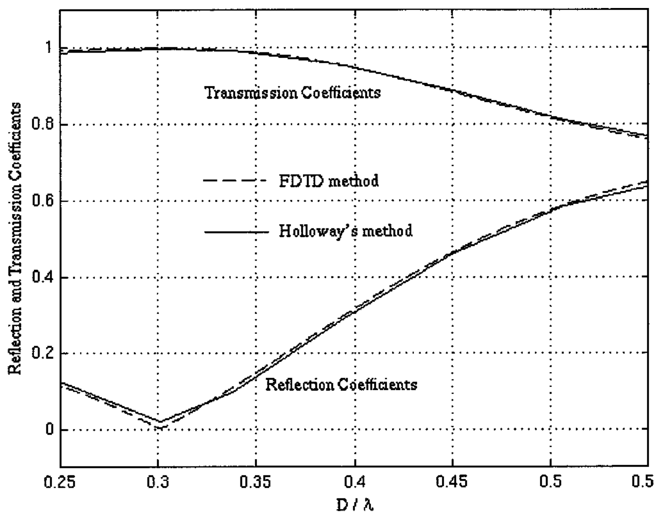

Fig. 8. Reflection and transmission coefficients for a composite wall: FDTD versus Holloway's method. D is the period and λ is the wavelength.

good accuracy compared with a full FDTD simulation of the entire window system [125]. This new equivalent ray-tracing representation of windows and metal-framed structures, therefore, provides a significant step toward integration of indoor and outdoor propagation prediction models.

VI. Conclusions

The tremendous development in wireless communications leads to the emergence of new ideas and techniques to increase capacity and improve the QoS. Smaller cell sizes, higher frequencies, and more complex environments need to be more accurately modeled and site-specific propagation prediction models need to be developed to achieve optimum design of next-generation communication systems. New techniques such as smart antennas and multiinput and multioutput systems need new propagation prediction models to characterize the joint spatio-temporal channel. This paper presented a review of the state-of-the-art propagation prediction models that range from early simple empirical formulas to modern site-specific ray-tracing-based models. It is shown that the ray-tracing method can provide path loss, time of arrival, angle of arrival, and even some statistic parameters for propagations in complex environments. New challenges were briefly discussed and new methods to meet these challenges were described. Specifically, new efforts to characterize walls of complex structures and develop equivalent ray-tracing models for windows and metal-framed structures were highlighted. These new developments, together with computationally efficient ray-tracing methods, are expected to lead the way toward the development of an integrated indoor/outdoor urban propagation model that takes into account the complex indoor/outdoor interface issues.

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