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REVIEW PAPER

Wireless Channel Models for Indoor Environments

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ABSTRACT

Wireless networks have made significant advancement in recent times by adding a new dimension to the way people communicate. Development of wireless standards have constantly aimed at providing higher data rates even under complex environments using smart antennas, multiple-input, and multiple-output systems. This has necessitated an understanding of the indoor propagation channel. Channel models describe a communication channel and are essential in developing efficient wireless communication networks. This paper surveys different channel models used to characterise wireless indoor environment. This survey may be useful for the army, where the communication over wide areas during wargames that they hold periodically, is necessary. Moreover, it may also be useful for communication near the border areas for surveillance operations.

Keywords: Channel models, indoor propagation, smart antennas, wireless networks

1. INTRODUCTION

Wireless local area networks (WLANs) co-exist with fixed infrastructure networks to provide mobility and flexibility to users by freeing them from the constraints of physical wires. A number of wireless data communication systems have been developed to utilise the 2.4 GHz industrial, scientific, and medical (ISM) and 5 GHz unlicensed-national information infrastructure (U-NII) bands. IEEE 802.11 has been expanded considerably to include a family of WLAN standards. IEEE 802.11a standard operates in 5 GHz band and uses a 52-subcarrier orthogonal frequency division multiplexing (OFDM) with a maximum raw data rate of 54 Mbps. IEEE 802.11b has a maximum raw data rate of 11 Mbps and uses direct sequence spread spectrum (DSSS). IEEE 802.11g works in 2.4 GHz band but operates at a maximum raw data rate of 54 Mbps using OFDM. It offers backward compatibility with IEEE 802.11b. The models presented in this paper apply to WLANs that operate in the frequency range 2.4 GHz–5 GHz.

The IEEE 802.11e is a proposed enhancement to IEEE 802.11a and IEEE 802.11b to offer enhanced MAC layer quality of service (QoS) features that include prioritisation of data, voice, and video transmission. It enhances the distribution coordination function (DCF) and the point coordination function (PCF), through a new coordination function–the hybrid coordination function (HCF). The 802.11n is a standard proposed for throughput enhancements.

Under IEEE 802.11n, the raw data rate is estimated to reach a maximum of 540 Mbps using MIMO, signal processing and smart antenna techniques for transmitting multiple data streams through multiple antennas.

The WLANs face-hidden terminal problems and the possibility of being captured when operating in multi-path radio channels. The radio channel also introduces additional complexity to wireless system design and its performance analysis[1]. This has necessitated the knowledge of radiochannel in locating the access points (AP) to avoid interference and maximise WLAN performance.

2. NEED FOR CHANNEL MODELS

Communication channel dictates the performance of any communication system. Design of wireless networks requires an accurate characterisation of the radio channel. Wireless channels due to their unreliable behaviour, differ a lot from the wired channels. The received signal strength exhibits random fluctuations in wireless environment due to its time-varying nature[2]. Wireless channel is an inherently shared medium leading to multi-user interference. The random and shared nature makes communication over wireless channels a difficult task[3].

Received signal-to-noise ratio (SNR) is used to measure channel quality in time-varying wireless channels. These are distinguished by the propagation environment such as urban, suburban, indoor, underwater, and orbital. The WLAN primarily operates in an indoor environment having tremendous amount of impairment and variability. Indoor channels heavily depend on the placement of walls and partitions that dictate the signal path within the building[4]. The characteristics of an indoor radio channel vary between different environments and must be considered when modelling the radio channel.

When a WLAN radio frequency (RF) signal radiates through its environment, it bounces off obstructions like walls, floors, and other reflective surfaces. Figure 1 shows basic radiowave propagation mechanisms of reflection, diffraction, and scattering. These give rise to additional

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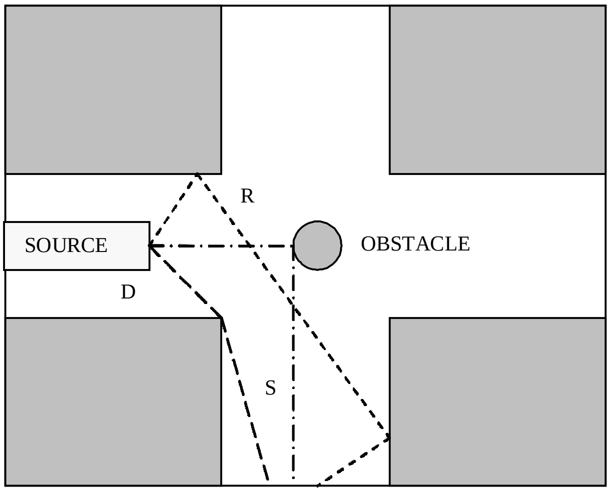

Figure1. Basic propagation mechanisms – reflection (R), diffraction (D), and scattering (S).

radio propagation paths beyond the direct optical line-of-sight (LoS) between the radio transmitter and receiver. As a result, multiple signal paths arrive at the receiver. The characteristics of these multiple paths are variable and fairly complex. To have a standard way to simulate these, RF channel models are used. The channel models attempt to generalise the complexities and establish an average behaviour for the channel in an indoor environment. The efficiency of a model is measured by the computational complexity and its accuracy is measured by the estimation error[5]. Complex propagation environments present the biggest obstacle to computational efficiency. Accuracy of a model depends on the accuracy of the locations, size of buildings, and other objects present in the environment. There are three approaches to modelling of indoor radio channels: (a) deterministic; (b) statistical; and (c) site-specific.

2.1 Deterministic Channel Models

Deterministic or theoretical approach is based on the principles of physics and provides an accurate knowledge of channel behaviour necessary for multimedia transmission[6]. These require exact data about the terrain, leading to a huge database of environmental characteristics. The consideration of huge amount of terrain data makes these models highly accurate even when applied to different environments. Though these models do not require any measurements to be made, measurements are used to check the accuracy. Algorithms for deterministic modelling are highly complex and lack computational efficiency. This resulted in restricting these to modelling smaller areas of micro cell or indoor environments. Uniform theory of diffraction (UTD) and frequency domain parflow (FDPF) constitute deterministic propagation models.

2.1.1 Uniform Theory of Diffraction Model

The UTD is a high-frequency method for solving electromagnetic scattering problems. According to UTD[7], a high frequency electromagnetic wave incident on an edge in a curved surface gives rise to a reflected wave, an edge-diffracted wave, and an edge-excited wave which propagates along a surface ray. The pertinent rays and boundaries are projected onto a plane perpendicular to the edge at the point of diffraction. Diffraction coefficients are determined for a perfectly conducting wedge illuminated by plane, cylindrical, conical, and spherical waves. The results are extended to the curved wedge.

Ray tube method[8] is based on UTD and it overcomes some of the limitations in ray-tracing methods. It is a point-to-point technique that guarantees high accuracy and is applicable to any complex environment. Three types of ray tubes, namely the transmitter, reflection, and diffraction ray tubes are defined on the plane view of quasi 3-D environment. The ray tubes are shown in Fig. 2. The transmitter ray tube represents bundle of rays from a transmitter and is described by the position of the transmitter and the tube angle of 2π radian. The reflection ray tube represents bundle of rays reflected by wall. It is described by the position of the image on the wall, the wall number, and the tube angle less than π radian. The diffraction ray tube consists of family of rays diffracted by corner and is described by the position of the corner, the corner number, and the tube angle. The tree structure comprising three types of ray tubes is constructed from site-specific information. Once the ray tube tree is completed, the ray-tracing is employed to find all the propagation paths. It is followed by the conversion of propagation paths on the plane view to 3-D. The final step involves deriving the expressions for fields contributed by each propagation path. Fields from all the paths are determined and their vector sum yields the total field at the receiver.

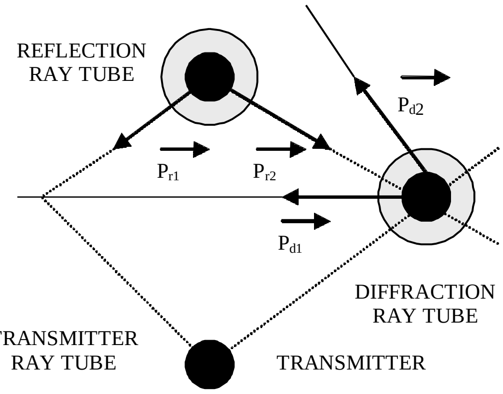

Figure 2. Types of ray tubes.

The parametric formulation of UTD[9] enables faster and accurate evaluation of diffracted field in propagation prediction models for indoor environments. It finds potential use in real-time propagation computations. Earlier models neglected diffracted rays for simplicity, leading to poor estimation of diffracted field in the shadow region, which is particularly prominent in indoor environments. Using inverse problem theory, a better approximation of the diffraction coefficient for a dielectric wedge is determined, leading to accurate estimation.

2.1.2 ParFlow Model

The ParFlow model is based on the Lattice-Boltzmann method (LBM), which was developed for gas-kinetic representation of fluid flow and can be used for modelling electromagnetic wave propagation. The ParFlow algorithm describes a system going from the excited state to the equilibrium state, using a regular structure of data to allow parallel computation of the diffusion process. It as based on the concept of partial flows used for the discretisation of the Maxwell's equations and applied either to the electrical field, magnetic field or both[10]. The indoor environment is described by a 2-D grid. It offers better accuracy when spatial resolution is high. Higher resolution increases the grid size and the computation time. It can be used in time domain and frequency domain.

Time Domain ParFlow (TDPF) is used as a discrete simulation method for propagation analysis in indoor and hybrid indoor-outdoor environments. The time average of the amplitude of the electric field is computed in each point and is based on the direct discretisation of the Huygens principle. It exploits a regular grid to propagate the free-space field along wires. The field at each pixel is divided into four components as shown in Fig. 3, representing directive flows along wires. Space and time are discretised in terms of finite, elementary units and are related with the speed of light and the space dimension[11]. Time domain technique is accurate when real-time and near-field measurements are not required.

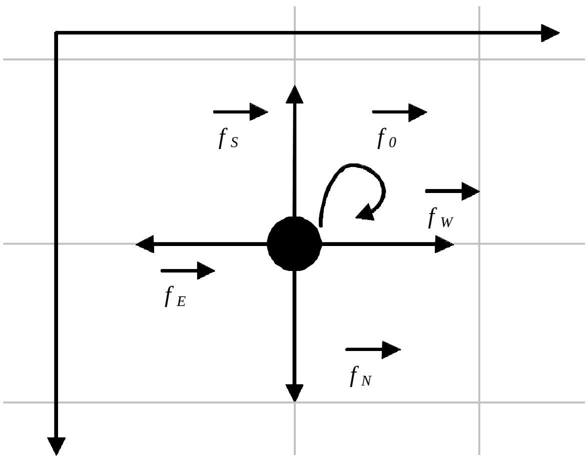

Figure 3. ParFlow node and its outward flow.

Frequency Domain ParFlow (FDPF) is a method used to solve discrete ParFlow equations. In a narrow-band system, a linear inverse problem in the frequency domain is used to compute the steady state. A multi-resolution formulation in frequency domain (MR-FDPF) is used to simulate indoor radio-wave propagation. It is based on the fact that all reflections and diffractions are taken into account with no impact on the computational load[12]. It involves two stages–a preprocessing stage where binary tree is built and scattering matrix is computed for each node, followed by a propagation stage where radio coverage map is computed for each source. This method is efficient in improving the computation time, when multiple coverage maps corresponding to different sources are considered.

2.2 Statistical Channel Models

In statistical or empirical models, the statistics of channel parameters are collected from actual measurements at various locations of the transmitter and receiver. As these models are independent of the layout and structural details of the coverage area, the requirement to survey layouts for individual applications is eliminated. They include selective parameters measured from representative categories of coverage areas[13]. Even when all the environmental factors can be separately recognised, these are implicitly taken into account during modelling. The accuracy of these models is dependent on the similarity between the environment considered for analysis and the environment from which the measurements are taken. Since these models average all the objects within the environment, these do not report variations in signal strength around any particular object. In addition, the relationship between site layout and channel response at a specific location cannot be provided using statistical models. On the positive side, these offer better computational efficiency and are easy to generalise. The Saleh-Valenzuela model and Log-distance path loss model with Log-normal shadowing are the empirical models used in modelling indoor radio environments.

2.2.1 Saleh-Valenzuela Model

Saleh-Valenzuela (SV) model is based on the physical realisation that the received signal rays arrive in clusters, with each cluster comprising several rays[14]. The clustering phenomenon is based on the observation of measured pulse responses. The arrival times of the first rays of the clusters and subsequent rays within each cluster were modelled as a Poisson process with different fixed rates. It was found that the arrivals come in one or two large groups with a 200ns observation window and the expected power of the rays in a cluster decayed faster than the expected power of the first ray of the next cluster. The main drawback of this model was that it did not have any information about the angles of arrival[15], but assumed that these were independent random variables uniformly distributed over the interval $[0, 2\pi)$.

2.2.2 Log-distance Path Loss Model with Log-normal Shadowing

This model is used to compute path loss exponent, a factor dependent on propagation environment[16]. Average large scale path loss for an arbitrary transmitter-receiver (T-R) separation is expressed as a function of distance using a path loss exponent. The presence of obstructions increases the value of path loss exponent which further increases the signal loss. For a given fixed distance, frequency, and transmission power, the received signal power varies due to the objects in and around the signal path. These stochastic, location-dependent variations are called shadowing. Random shadowing effects occurring over a large number of measurement locations having the same T-R separation, but different levels of clutter on the propagation path results in a phenomenon referred to as log-normal shadowing. This model includes close-in-reference distance (d_0), path loss exponent (n) and standard deviation (σ) of the zero mean Gaussian distributed random variable (X_σ), to statistically describe the path loss model for an arbitrary location with fixed T-R separation[17]. The average path loss PL (d) for a T-R separation d becomes

$$PL\ (d) = PL\ (d_0) + 10\ n \log\ (d\ /\ d_0) + X_\sigma$$

By accounting for variations in environmental clutter, this model leads to measured signal close to the average value.

2.2.3 Wide-Sense Stationary Uncorrelated Scattering Model

Time and frequency-selective fading occurring due to multi-path propagation is characterised usingWide-Sense Stationary Uncorrelated Scattering (WSSUS) propagation model. This model requires two sets of parameters, power delay profile (PDP) and doppler power spectra (DPS) to describe the propagation effects. A single function called scattering function characterises the WSSUS model. It is based on the assumption that channel is wide sense stationary so that the autocorrelation function in time is a function of only the time difference. Uncorrelated scattering implies that the autocorrelation function in frequency is a function of only the frequency difference. Using these assumptions, autocorrelation function in both time and frequency yields spaced-frequency, spaced-time autocorrelation function[18]. Performance of broadband mobile communication systems can be analysed using this model.

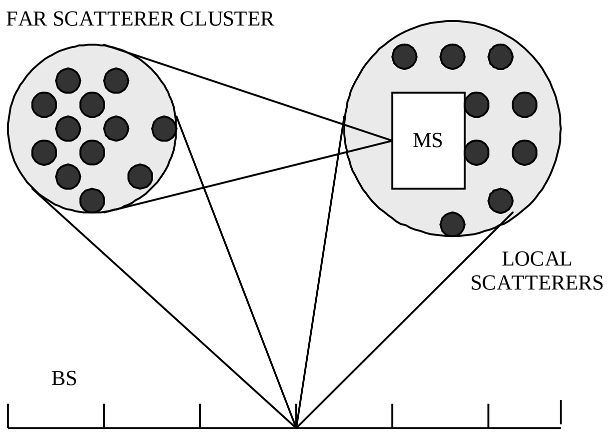

Figure 4. Geometry-based stochastic channel model.

2.2.4 Geometry-based Stochastic Channel Model

Geometry-based stochastic channel model (GSCM) is based on the directional channel. It provides a geometrical description of base station and mobile station in polar coordinates[19]. In real propagation environment, scatterers occur distributed in groups and are known as clusters. Figure 4 shows GSCM model based on the cluster representation of the scatterers. The model is based on a cluster of scatterers each representing single multi-path component. One cluster moves along with mobile station (MS) and is known as near cluster. The rest are called far clusters, distributed throughout the cell and each one having certain visibility regions. Each visibility region is the area visible from the corresponding cluster for the MS on its way through the cell. Circular regions are defined as visibility regions over the route of MS. When MS enters a visibility region, the far cluster becomes visible and scatterers start to create additional paths at the receiver. When the MS leaves this region, the cluster is made inactive. Visibility region covers specific part of MS route depending on the cell type. GSCM distinguishes macro cells (outdoor urban), micro cells (outdoor city) and Pico cells (indoor). Each of these uses different parameters for the placement of clusters and scatterers. While macro cells require small number of clusters (1-2), Pico cells require a mean number of 16 clusters for accurate channel modeling[20].

2.3 Site-specific Models

Site-specific models are based on numerical methods and can have detailed and accurate input parameters[21]. The advantage of these models is that it can accurately simulate simple indoor environments. The large computational overhead may prohibit these models from being used for complex environments. Ray tracing and Finite-Difference Time-Domain (FDTD) models fall under this category.

2.3.1 Ray-Tracing Models

The ray-tracing (RT) algorithm has been used for accurately predicting the site-specific radio propagation characteristics. It is gaining importance for propagation simulation of micro cells and Pico cells. Ray tracing is a technique of modeling the light path by following light rays as they interact with optical surfaces. Radiowaves are similar to lightwaves in that the phenomena of reflection, refraction and scattering apply to both[22]. This has facilitated ray-tracing approach in predicting the signal strength of radiowaves propagating in an indoor environment. Ray-tracing approaches lead to accurate path loss models. In this approach, the region around the transmitting antenna is divided into a cluster of rays and each ray is traced from source-to-receiver. The attenuation suffered in each path is computed. Reflections and diffractions are taken into account while tracing each distinct ray path. Finally, all the signal components that arrive at the receiver are added together. Ray-tracing method may produce only approximate results for realistic propagation environments when there is an inaccuracy in the environmental database.

There are several types of ray-tracing methods. Brute force method[23] involves the transmission of large number of rays with fixed angular separation. Intersection tests are performed on each ray to determine the scattering points followed by reception test. The advantage of this method is its applicability to complex environments. But it is computationally complex and accuracy is heavily dependent on separation angle.

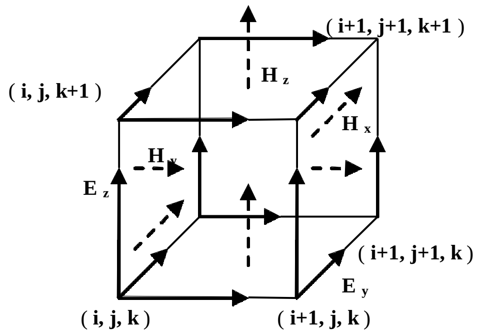

Figure 5. Yee Lattice.

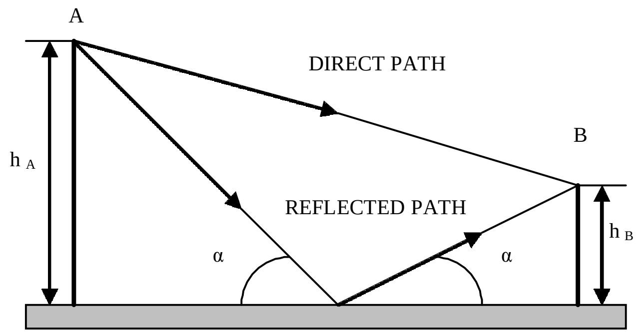

Figure 6. Geometrical two-ray model.

Image ray tracing method[24, 25] is a point-to-point tracing technique that produces accurate results without the necessity for reception tests. The accuracy of the results is dependent on the input data accuracy. Computational time is dependent on the number of the input obstacles and it is improved because the rays that do not reach the receiver are not considered. Due to the difficulty in selecting scattered rays, it is not applied to complex environments.

Two-ray ground reflection model[26] considers both the direct path and reflected propagation path between transmitter and receiver. Two-ray model, shown in Fig. 6, is used when a LoS path exists between the transmitting and receiving antenna. Though this model is best suited for predicting large-scale signal strength over long distance radio systems using tall towers, it provides reasonably accurate results for line-of-sight micro cell channels in urban environments.

Visibility tree approach is used to carry out an exhaustive search of propagation sequences between the transmitter and the receiver[27]. Visibility tree has a layered structure comprising nodes and branches. Each node represents an object and each branch represents LoS connection between two objects. The root node represents the transmitting antenna and the tree is constructed in a recursive manner, starting from root node. After building the visibility tree, path of each ray is back-tracked from the leaf to the root and the rules of geometrical optics are applied at each traversed node. It can be used for any propagation environment as path selection process does not depend on geometry. The creation of visibility tree becomes increasingly complex as we move from 2-D to 3-D environments.

2.3.2 Finite-Difference Time-Domain Model

Finite-difference time-domain (FDTD) method provides a simple and effective technique for modelling the field distribution in an indoor environment. WLAN planning requires numerous simulations for different access point locations, and thus needs fast computation of AP's coverage area[28]. In practical situations, FDTD is employed to reduce the complexity and to ease the simulation of reflection and diffraction.

Radio propagation characteristics can be derived by solving Maxwell's equations of electromagnetic wave propagation. FDTD results in a numerical solution of Maxwell's equations. Maxwell's time-dependent equations are approximated by a set of finite-difference equations wrt specific field positions on an elementary lattice[29]. The scheme was proposed by Kane Yee and the lattice structure is known as Yee Lattice. In the Yee lattice shown in Fig. 5, the electric field components correspond to the edges of the cube, and the magnetic field components to the faces. A grid is defined over the area of interest and initial conditions are specified. By employing central differences to approximate spatial and temporal derivatives, Maxwell's equations are solved directly. Solutions are determined iteratively at the nodes of the grid.

FDTD uses a leapfrog scheme for marching in time wherein the E-field and H-field updates are staggered. Spatial staggering leads to locating each E-field vector component midway between a pair of H-field vector components. Conversely, H-field components can also be located between pair of E-field components. The advantage of using this explicit time-stepping scheme is that it avoids the need to solve simultaneous equations and yields dissipation-free numerical wave propagation. On the negative side, an upper bound on the time-step is necessary to ensure numerical stability. Number of nodes and the simulation runtime increase proportionately with the size of the analysed environment.

This study has provided an understanding about the different modelling techniques. Deterministic models have proven to be computationally complex, statistical models lacked accuracy, and site-specific models offered limited applicability making these unsuitable for complex environments. Models were developed in the recent past to overcome these limitations. Deterministic plus statistical models combine the two approaches to solve some of the inherent problems[30]. Hybrid methods that use two or more approaches divide the original problem into a number of sub-problems and treat each one using the most suitable approach[31]. The theory of neural networks also yielded models like Artificial Neural Network (ANN) model, which use multilayer perceptron to compromise the limitations offered by deterministic and statistical models[32]. Further advancements in environmental database and computational resources may pave the way towards development of new models with improved accuracy.

3. CONCLUSIONS

A proper system design requires accurate and reliable radio channel models for efficient performance under complex environments. In addition, the next generation wireless systems also place stringent demands on the design of a radio system. This paper has presented a review of the indoor radio propagation based on deterministic, statistical, and site-specific models. The applicability of the models to various propagation environments has also been discussed. A key observation is that, the accuracy of the models depends on the accuracy of the database and the details of the objects present within the environment. Despite enormous efforts and progress till date, much work remains in the understanding and characterisation of wireless communication channels.

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