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Propagation channel models for mobile communication

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Abstract

Propagation channel properties influence the development of wireless communication systems. During system design, channel properties are required to choose the suitable air interface (modulation, coding and access scheme). Comparisons and assessment of different solutions are performed using wideband propagation channel models. During network planning, prediction channel models provide valuable inputs to optimize network parameters. This article aims to present a short overview of these different propagation channel models. ***To cite this article: P. Pajusco, C. R. Physique 7 (2006).***

Résumé

Modèles des canaux de propagation des systèmes de communication mobile. Les caractéristiques du canal de propagation impactent le développement des systèmes de communication radio mobile. Lors de la conception, la connaissance des caractéristiques du canal permet de déterminer l'interface radio la mieux adaptée (modulations, codage, type d'accès…). Les modèles de canaux large bande permettent alors d'évaluer et de comparer différentes interfaces radio candidates. En phase de déploiement réel, les modèles de prévision fournissent de précieuses données pour l'optimisation de l'architecture et du paramétrage du réseau radio. Cet article a pour but de rappeler brièvement les principales techniques de caractérisation et les méthodes utilisées pour modéliser le canal de propagation. ***Pour citer cet article : P. Pajusco, C. R. Physique 7 (2006).***

Keywords: Propagation; Wideband; Channel model; Measurement; MIMO

Mots-clés : Propagation ; Large bande ; Modèle ; Mesure ; MIMO

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1. Introduction

The number of ADSL broadband consumers significantly increases all over the world. ADSL provides high data rates and permanent connection to the Internet network. At home, consumers use more and more Internet services such as online shopping, information, personal blog and emails, Video On Demand, Voice Over IP, … Consumers are expecting the same services wherever they are, especially in mobile configuration. This challenge requires more and more throughput and quality on wireless devices. Existing systems improve their performances by introducing new radio access schemes (EDGE, HSDPA, 802.11n, …). New technologies, such as Ultra Wide Band (UWB), are very promising to improve throughput.

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Propagation channel characteristics are highly dependent on the environment and the configuration. They influence the performance of wireless systems such as capacity, coverage or throughput. For instance, the path loss decay roughly defines the coverage area. Wideband characteristics are also important. A frequency selective channel will provide diversity gain. Space–time characteristics can change significantly the achievable Multiple Input Multiple Output (MIMO) capacity. These simple examples highlight that the development of efficient wireless systems require accurate knowledge of the propagation channel.

This article aims to present a general overview of propagation models. Section one introduces wideband channel sounding techniques and space–time characterisation required for MIMO studies. Section 2 presents the main principles of wideband propagation channel models. These models are used in link and system level simulation by standardization groups. They are dedicated to evaluate and compare different candidate interfaces. Section 3 deals with prediction models used in network planning (semi empirical) and advanced channel modelling (deterministic).

2. Channel sounding techniques

2.1. Wideband measurement principles

Measurements are very important to validate and tune propagation models. At the beginning of wireless communication, propagation experiments only dealt with field strength measurements. Due to the increase of systems bandwidth and the beginning of digital communication systems, channel sounders were used to characterise the channel impulse response. Three main sounding techniques can be highlighted:

- *Time domain measurements*: The basic idea is to transmit periodically a short pulse. The received signal is directly the impulse response of the propagation channel. It can be sampled with a Digital Sampling Oscilloscope (DSO). The bandwidth of such equipment can reach up to 15 GHz. The time domain technique seems very simple, but has to overcome severe problems. Short pulse generation is difficult when bandwidth is important especially with significant transmitted power. Moreover, the dynamic range and the link budget are very poor and the sounding bandwidth is limited.
- *Frequency domain measurements*: It consists in measuring successively the complex gain of the propagation channel at different frequencies. This technique, used by Vector Network Analysers (VNA), provides a good dynamic range and very large frequency bandwidth. The main limitations are the time duration and the synchronization between transmitter and receiver. The method is widely used to characterise static Ultra Wide Band (UWB) propagation channel.
- *Pulse compression measurements*: The basic idea is to transmit a periodic pseudo noise sequence which occupies the sounding bandwidth. Sequences can be generated in hardware using a simple shift register and a loop. The second way is to digitally optimize the sequence waveform and send it with an Arbitrary Waveform Generator (AWG). On the receiver side, the channel impulse response is obtained by correlation which enables hardware implementation on a very large bandwidth. Usually, the received signal is sampled and the channel impulse response is computed by numerical inversion. This approach, used in most of channel sounders, provides fast measurement time and a good dynamic range. The bandwidth ranges from 20 to 250 MHz. However, it can reach several GHz to investigate UWB modelling.

2.2. Multiple Input Multiple Output channel sounding technique

In late 1998, the beginning of Multiple Input Multiple Output (MIMO) studies required an upgrade of existing channel sounders. The basic solution consists in duplicating the receiver (RX) and the transmitter (TX) parts of a channel sounder. It corresponds to the structure of a real MIMO communication device. Using orthogonal sequences at each transmitter, receivers can estimate the different propagation channels. The main difficulty of this structure is the calibration process. Indeed, each TX and RX contains active components such as amplifier and mixer. Their characteristics change independently with temperature and time and require online calibration.

The second solution needs only one transmitter and one receiver. The channel sounder uses periodic sequences. So, the different channels are measured successively by switching the RX antenna. This principle is also used at the transmitter. Usually, one sequence is used to estimate a channel and one sequence is dropped to switch the antennas.

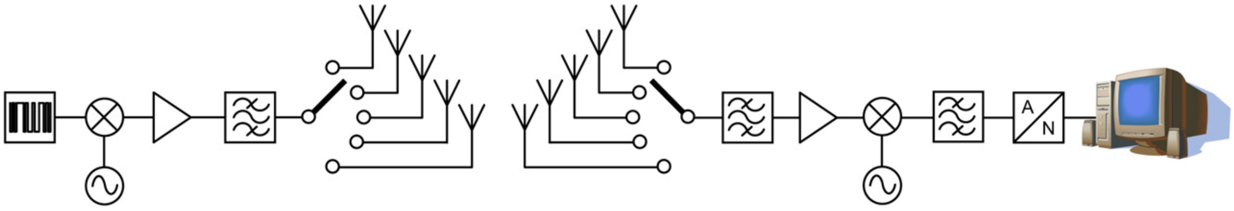


Fig. 1. Block diagram of a MIMO channel sounder.

Fig. 1. Synoptique d'un sondeur de canal MIMO.

This hardware structure reduces significantly the cost and simplifies calibration process. This principle, used in most of existing MIMO channel sounders, is depicted in Fig. 1. The duration of a MIMO channel measurement is $2 \times N_{\mathrm{TX}} \times M_{\mathrm{RX}} \times T_{\mathrm{Seq}}$ where N_{TX} is the number of TX, M_{RX} the number of RX and T_{Seq} the duration of a sequence. The duration is short enough to perform moving measurements.

2.3. Space–time characterisation

To optimize MIMO systems, accurate knowledge of the spatial properties of the propagation channel are required. Double directional measurements are performed using an antenna array at TX and RX. Then, azimuth and elevation power density at TX and RX can be computed at each excess delay.

The use of a virtual array is a skillful way to perform such analysis. A simple Single Input Multiple Output (SIMO) channel sounder is needed. The principle consists in using a real antenna array at the base station (BS) and a virtual linear array composed by the successive measurement points of the Mobile Station (MS). Fig. 2 presents results of such measurements carried out in urban environment [1]. It clearly highlights the difference of behaviour at the BS (low spreading) and at the MS (high spreading).

During the last decade, space time characterisation has been widely investigated. Many improvements were performed: more inputs and outputs on channel sounders, development of planar or spherical arrays in dual polarizations, high resolution algorithms to estimate directions of arrival and departure, ... Northern countries of Europe are leading this field of research. We can mention RUSK and the PROPsound$^{\mathrm{TM}}$ channel sounders respectively developed by the Medav and Elektrobit companies. These channel sounders support more than 1000 channels and the measurement bandwidth is greater than 100 MHz. For instance, such equipments enable to characterise a 16 × 64 MIMO link. These equipments are coupled with powerful antenna arrays. Fig. 3 presents some major achievements. Fig. 3(a) is a

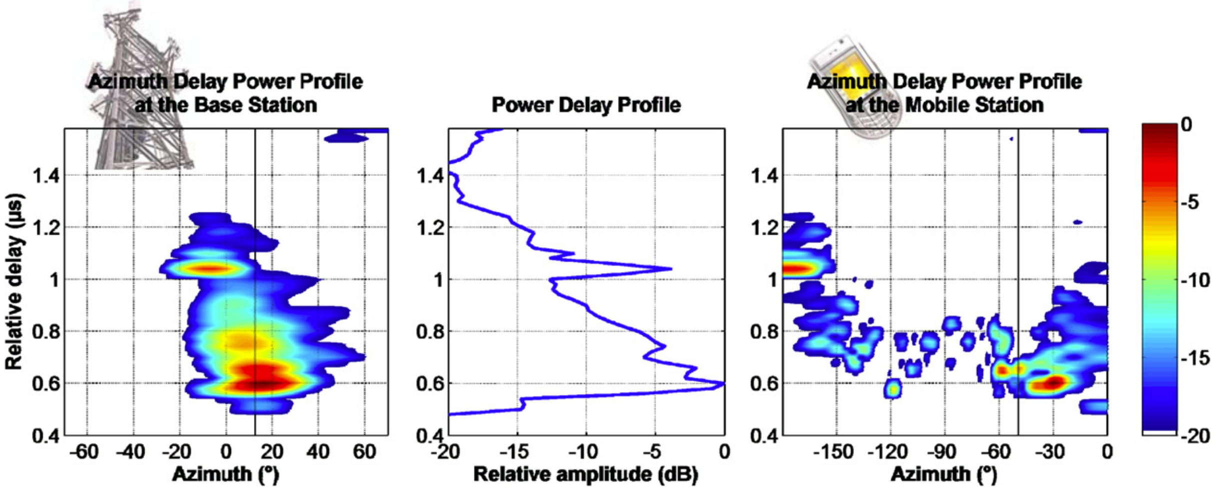
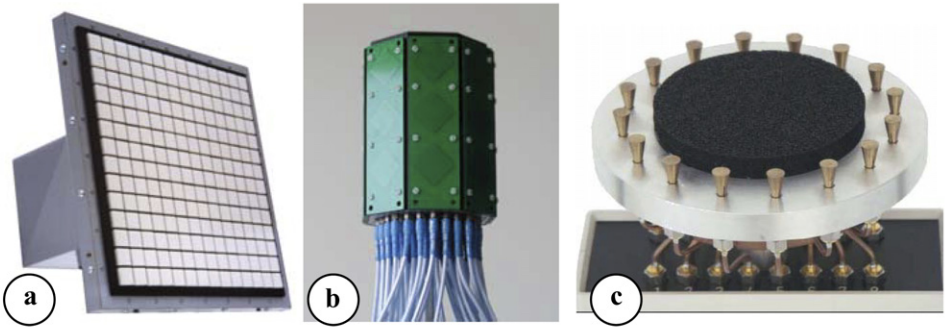


Fig. 2. Analysis of double directional measurement in urban area.

Fig. 2. Analyse doublement directionnelle en environnement urbain.



Sources

(a): IRK-Dresden
(b): Elektrobit
(c): Technical University of Ilmeneau

Fig. 3. Examples of antenna arrays.

Fig. 3. Exemple de réseaux d'antennes multi-capteurs.

5 GHz 8 × 8 elements with 3 lines of dummy elements. Fig. 3(b) shows a wideband array containing 25 patches in dual polarizations. Fig. 3(c) is a small circular antenna of 16 elements.

Such equipment (MIMO channel sounder + antenna array) makes it possible to accurately know all the characteristics of the propagation channel: excess delay, amplitude, polarization, directions of arrival and departure. The experiment and the offline processing are much more complex than a simple field strength measurement. However, collected data provide valuable knowledge to design advanced MIMO channel models.

3. Wideband channel models

3.1. Introduction

Wideband channel models are required in link and system level simulations. Usually, these models simulate the wide sense stationary behaviour of the propagation channel for each typical environment. The first model to represent the channel was introduced by Saleh and Valenzuela [2] in the late 1980s. In the same time, tap delay line models were proposed by COST 207. Later, geometrical models were introduced to include spatial properties and deal with MIMO.

3.2. Saleh and Valenzuela model

The Saleh and Valenzuela model [2] is a good starting point because it includes important basic ideas which are always used in recent models: cluster, rays and stochastic modelling. The channel impulse response is modelled by a set of rays. Several hundred of rays are needed, which leads to a realistic representation and suit for large bandwidth. The channel impulse response is made of different clusters. This concept represents a set of rays with similar properties

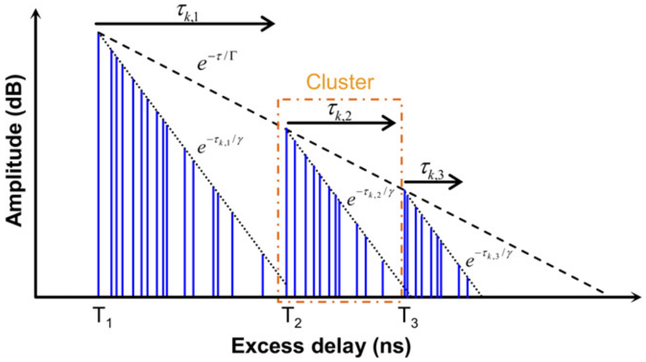


Fig. 4. Principle of Saleh and Valenzuela model.

Fig. 4. Principe du modèle de Saleh et Valenzuela.

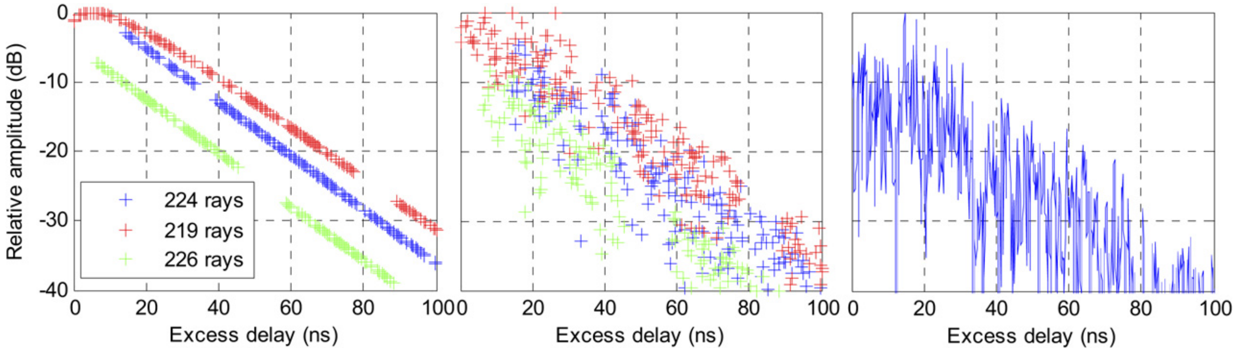


Fig. 5. IEEE 802.15.4a example (Office NLOS).

Fig. 5. Exemple de simulations du modèle IEEE 802.15.4a (Office NLOS).

such as excess delay, direction of arrival… Clusters are modelled by an exponential decay of the power (linear decay in dB) in time domain. The arrival time of clusters and rays are defined by a Poisson random process. The principle of the model is depicted in Fig. 4. The mathematical representation is recapped in following expressions:

$$h(\tau)=\sum_{l=1}^{l}\sum_{k=1}^{K_l}\beta_{k,l}\mathrm{e}^{j\theta_{k,l}}\delta(\tau-T_l-\tau_{k,l}) \tag{1}$$

$$\overline{\beta^2_{k,l}}=\overline{\beta^2(0,0)}\mathrm{e}^{-T_l/\Gamma}\mathrm{e}^{-\tau_{k,l/\gamma}} \tag{2}$$

$$p(T_l-T_{l-1})=\Lambda\mathrm{e}^{-\Lambda(T_l-T_{l-1})} \tag{3}$$

$$p(\tau_l-\tau_{l-1})=\lambda\mathrm{e}^{-\lambda(\tau_l-\tau_{l-1})} \tag{4}$$

where

- $\overline{\beta^2(0,0)}$ power of the first ray of the first cluster,
- L the number of clusters,
- K_l the number of rays of the cluster l,
- T_l the time of arrival of the lth cluster,
- τ_{kl} the time of arrival of kth ray in the lth cluster,
- Λ clusters rate, Γ the inter-cluster slope,
- λ ray arrival rate, γ the intra-cluster slope.

Different working groups on UWB used this principle to model the propagation channel. Some improvements have been added to the original paper: new shape of cluster, new statistical laws of times of arrivals of the clusters and the rays, taking into account the frequency response and statistical attenuation on the amplitude of the rays.

An example of simulation of the 'Office-NLOS' model of the IEEE 802.15.4a working group is presented in Fig. 5. The figure on the left-hand side presents the set of 650 rays split in three clusters. Parameters are obtained by a stochastic process. The power decay of the first cluster is not exactly a line contrarily to the initial Saleh and Valenzuela model. The middle figure includes statistical attenuation on the amplitude of each ray. The figure of right-hand side is the band limited representation of the impulse response including the effect of the frequency. The generation of the impulse response was obtained by using the open code source available in IEEE 802.15.4a working document [3].

3.3. Tap delay line model

Within the framework of GSM development, the co-operation COST 207 [4] introduced tap delay line models to represent the propagation channel. From a large amount of measurement data, a typical average Power Delay Profile

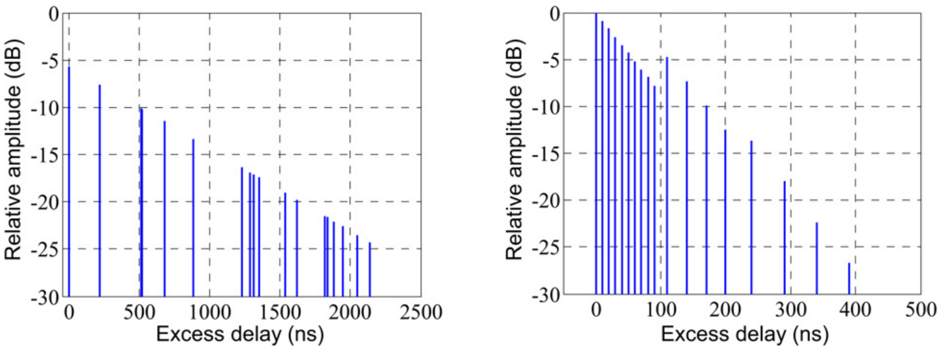


Fig. 6. 3GPP-TU (left-hand side) and ETSI BRAN A (right-hand side) models.

Fig. 6. Modèles 3GPP-TU (gauche) et ETSI BRAN A (droite).

(PDP) was defined for each kind of environment. According to the imited bandwidth of the system, the PDP were samples with a small number of paths. Then, the instantaneous channel impulse response was simply expressed by:

$$h(\tau) = \sum_{i=1}^{N} a_i.\delta(\tau - \tau_i)$$

N represents the number of paths. Each path is characterised by an excess delay τ_i and a fast fading a_i. These short term variations (temporal or spatial) are modelled by a statistical distribution and a Doppler spectrum.

This model was compliant with 1990s hardware simulators (only 6 or 12 paths). The simplicity to describe the model probably explained its success. This approach has been adopted in standardization by many other systems for fifteen years: GSM [5], IMT2000 [6], UMTS [7], WIFI [8], WIMAX [9],... The path number ranges from 3 to 20 according to the system bandwidth and the channel selectivity. For mobile configuration, the typical shapes of the Doppler spectrum to model spatial variation are 'flat', 'bowl' or 'Gaussian'. For the fixed systems, the typical shape to model the temporal fluctuations is 'round'. The principal limitations of the tap delay line model are its discrete form and the small number of paths. It implies a limited bandwidth and a periodic frequency correlation. As an example, Fig. 6 provides two models used in standardization. These examples highlight the concept of cluster introduced in the previous section. It can be noticed that the paths of the cluster are spread differently in the two examples.

3.4. Directional channel model

The use of multiple antennas at the transmitter and the receiver (MIMO) improves throughput and/or coverage. To study such systems, it is important to compute the channel model whatever the array (geometry and antenna pattern). The simplest way is to include a Power Angular Profile (PAP) on each tap. For instance, one tap in time domain can be split in different taps in azimuth domain according to the PAP. The Laplacian distribution is commonly used to describe the PAP. MIMO channel models adopted in standardization are generally based on existing SISO channel models. It enables backward compatibility. As an example, Fig. 7 shows one of the MIMO channel models recommended by the 802.11n standardization group [10]. It relies on the ETSI BRAN A SISO model. Three clusters were identified so that the sum corresponds to the initial PDP. For each cluster, an average direction and an angular dispersion were defined at the transmitter and the receiver. Due to the overlap of the clusters, some taps have an angular distribution made up of a sum of Laplacian distribution.

3.5. Geometrical Stochastic Channel Model

The Geometrical Stochastic Channel Model (GSCM) was introduced by the COST Action 259. It is a general concept based on a simplified representation of the environment. Clusters and isolator reflectors are spread over the simulation area. Each cluster is made of a collection of scatterers. Multipath characteristics are obtained by a basic ray tracing between transmitter, one (single bound) or several scatterers and the receiver. This geometrical approach

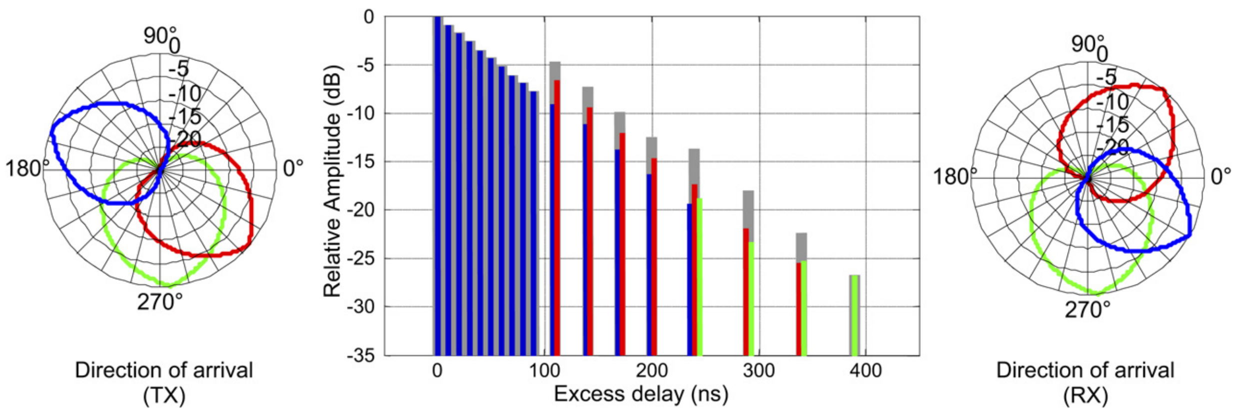


Fig. 7. IEEE 802.11n channel model (Model D).

Fig. 7. Modèle de propagation du groupe IEEE 802.11n (Model D).

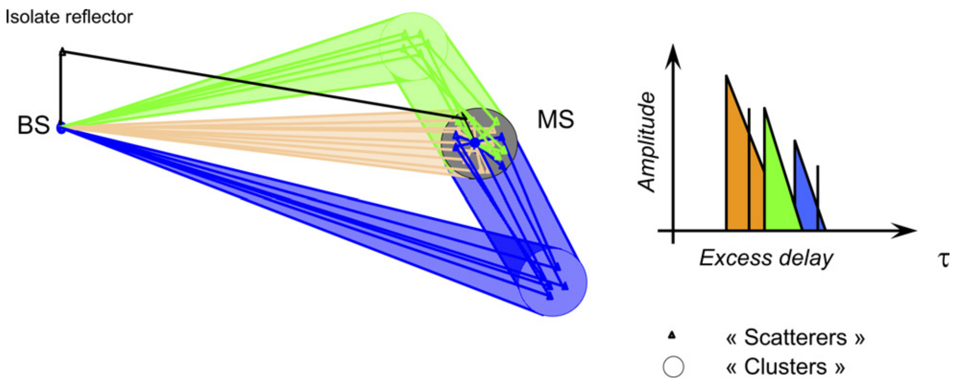


Fig. 8. Geometrical stochastic channel model principle.

Fig. 8. Principe du modèle géométrique stochastique.

naturally introduces the correlation between angular dispersion, temporal dispersion, effects of the distance… Fig. 8 presents the principle with 3 clusters and a far reflector.

The number and the location of reflectors, clusters and scatterers are obtained statistically. Each simulation provides a different propagation channel. The main advantage of this stochastic process is to simulate the wide variety of propagation channel encountered by a terminal in a specific environment. The main difficulty is to find the correct set of parameters to fit the measurement data.

3.6. Stochastic directional channel models

Directional channel models are defined by a single power delay profile for each kind of environment. These propagation models are not suited for system level simulation. To overcome this problem, stochastic directional channel models use a random process to generated tap delay line parameters. The model remains simple (limited number of taps) but simulates a wide set of propagation channels. This principle was adopted by the 3GPP [11] for UMTS system level simulation. The IEEE 802.20 standardization group also adopted this concept. 3GPP model parameters were tuned to Mobile Broadband Wireless Access (MBWA) system purpose [12]. In these two examples, the random process determines the parameters of the 6 tap delay line model: excess delay, power, directions of arrival and departure. Angular spread is set at 2° and 5° at the base station (depending on configuration) and 35° at the mobile station.

3.7. Conclusion

This section recapped the main principles of wideband propagation channel models. Tap delay line models are still widely used. They are simple, easy to use but suffer from limitations. Recent channel models are more complicated to support system level simulation of advanced radio access schemes. These channel models include random process, much more rays, spatial properties... Some of them include polarization modelling, effect of moving people, effect of fluorescent lamp... To promote the use of such realistic but complex models, free open source code is usually provided with the description of the model. Current researches on wideband channel modelling are focused on MIMO, UWB and antennas.

4. Path loss prediction models

4.1. Statistical models

Empirical also called statistical channel models predict the path loss with basic equations whose parameters are optimised with a large amount of measurement data. Such models are usually dedicated to a specific environment and configuration. Empirical models are very simple and accurate enough for dimensioning process. The three main principles are:

- *Okumura–Hata model*: Based on extensive measurements performed in Japan, Okumura proposed a path loss model for macrocell configuration [13]. Path loss is expressed as a sum of free space loss, antenna gain and correction factor available in look up curves derived from measurements. Hata improved the Okumura model by replacing table by formulas [14].
- *COST–Walfisch–Ikegami model*: Walfisch and Bertoni proposed a theoretical modelling of pathloss in a simplified configuration with same buildings height and streets width [15]. A simplified model was introduced by [16]. The path loss modelling is expressed as a sum of three terms: free space loss, path loss over building (multi-screen diffraction loss) and path loss of the last diffraction (roof-signal-to-street diffraction loss).
- *Two-slope model*: In line of sight and microcellular environment, ground reflection and direct path interfere. Depending on distance between BS and MS, it induces two different path loss behaviours. The two slope model is usually used to approximate path loss.

4.2. Geographical data bases

During radio network planning, more accurate propagation prediction models are used to optimize network parameters (base station placement, power, azimuth, code...). Accurate predictions require a precise description of the environment. Low Earth Orbit (LEO) satellite can provide high resolution pictures (∼1 m) of the Earth's surface. Such data provide the height of the ground, the type of cluster all over the world. Better resolution can be obtained locally with aerial data acquisition. Nowadays, many digital databases are available to describe the outdoor environment. They are suitable for propagation studies. Fig. 9 shows an example of 3D representation (right-hand side) in urban area. The corresponding picture is presented on the left-hand side. This example highlights some lacks in the 3D vector representation: shape of the roof, vegetation, urban furniture...

The indoor environment is more complicated because databases are usually not available. Manual operations are required. In practice, the main types of wall (stone, concrete, plasterboard...) are digitalized using the available ground map. The extrusion of walls on each floor leads to a simplified 3D representation of a building.

Indoor and outdoor databases remain a rough representation of the real environment. Objects are represented by a simple and homogeneous material, surfaces are plane, many objects are missing, ... The result is the lack of propagation phenomena such as scattering. These inaccuracies can lead to significant errors on the estimate of the coverage or MIMO capacity [20]. A rigorous representation of real environment is not possible for many reasons. Thus, it is important to estimate the error introduced by data base inaccuracy. This field of research is not yet widely investigated.

Fig. 9. Aerial data acquisition (left-hand side) and 3D representation (right-hand side).

Fig. 9. Photo aérienne (gauche) et la représentation vectorielle associée (droite).

4.3. Semi-empirical models

Statistical channel models are not suitable to design and optimize a real network. Prediction models, which utilize geographical databases, are required to provide enough accuracy. Semi-empirical models are a good trade-off between accuracy, complexity and computation time. Different models are available in the literature.

In an outdoor environment, when the base station antenna is mounted above roof top level (small cell configuration), path loss is mainly due to obstacles located in the vertical plane between TX and RX. Fig. 10 presents an example of an urban profile used by prediction models. Diffraction loss on buildings or terrain can be estimated using models such as Walfisch–Ikegami or Deygout models. In urban area, when the antenna is mounted below mean roof top level (microcell configuration), waves propagate mainly in the horizontal plane guided by streets (canyon effect). Attenuation at each crossroad can be estimated by semi-empirical formula using main street characteristics (angles and widths) [17]. This principle is much more time efficient than a 2D ray tracing to predict only field strength.

In indoor environment, the Motley–Keenan model [18] is widely used for coverage prediction. Propagation is supposed to be in straight line between TX and RX. The path loss depends on the number and kind of wall between TX and RX. More recently, Ref. [19] introduced an original multi-resolution algorithm based on the ParFlow approach. This fast model, which is currently 2D limited, takes into account all the propagation phenomena.

Path loss prediction has been widely investigated for many years. The result is a set of efficient models dedicated for each kind of configuration. Within the framework of the European project MOMENTUM [20], an algorithm and criteria were proposed to select automatically the best channel model depending on the link configuration. However, some discontinuities can appear locally on coverage when models are switched. Today, the real challenge is to have an adaptive and robust model whatever the configuration (environment, database, type of link, ...). Such a model should take advantages of all available models (accurate prediction), without discontinuity and ensure simple tuning process with measurements.

5. Deterministic modelling

5.1. Ray tracing models

Ray tracing models simulate propagation mechanisms and enable to predict the channel impulse response. This technique is very attractive, especially for MIMO modelling, because the space–time properties of the channel are directly obtained during the simulation. Ray tracing techniques are based on Geometrical Optics and the Uniform Theory of Diffraction. Direct, reflected, refracted and diffracted rays are considered. The environment is described by a set of plane surfaces (Fig. 11) with electromagnetic properties. Two main methods are used to obtain geometrical rays:

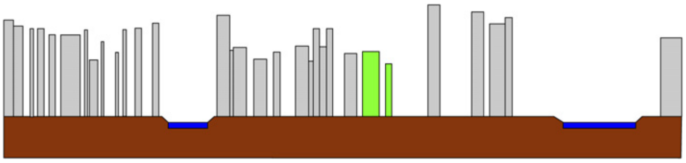


Fig. 10. Profile example in urban area.

Fig. 10. Exemple de profil en milieu urbain.

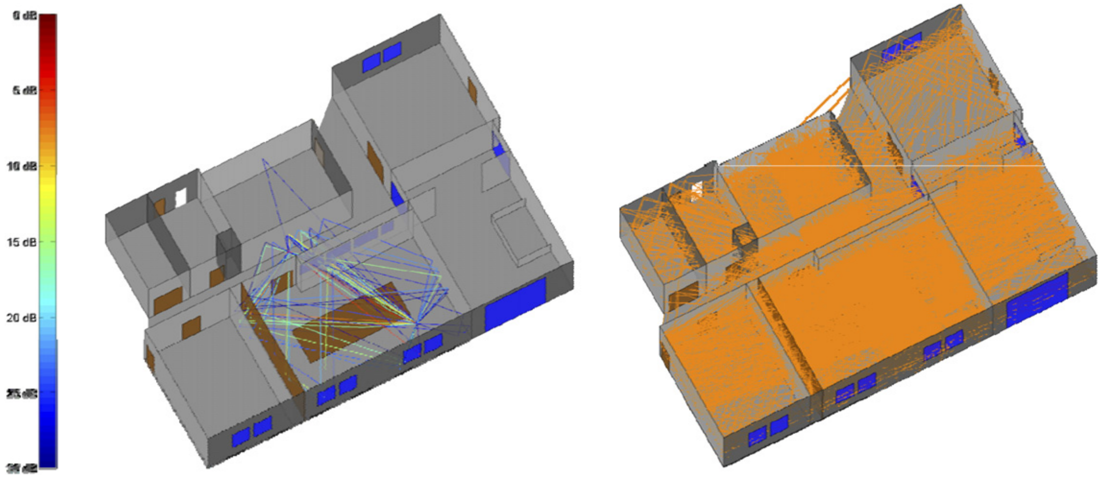


Fig. 11. Example of 3D ray tracing in indoor configuration (4 reflections, no diffraction).

Fig. 11. Exemple de simulation intérieure (4 réflexions et pas de diffraction).

- *Ray launching method*: This technique launches rays from the transmitter in all the 3D directions. Basically, when a ray impacts a surface, the ray trajectory is modified (reflection) and a refracted ray is created (transmission). When the impact is located near an edge, a new launch of rays is performed (diffraction point). Therefore, diffraction is very time consuming. Different criteria are possible to stop the building of a ray: number of interactions, boundaries of environment, path loss, … One of the difficulties of ray launching is to find the right rays close to the receiver. Ray building represents most of the simulation time. However, it is carried out only once whatever the location of the receivers.
- *Image method*: This technique builds the precise path between TX and RX. When the number of faces is large, a brute-force construction is inapplicable due to excessive computation time. Fig. 11 presents an example of ray tracing in indoor configuration. Only 4 reflections and no diffraction are taken into account. 1042 rays are found during geometrical building (right-hand side) but only 32 rays are significant (left-hand side).

Brute-force ray tracing methods are very time consuming. Acceleration techniques are required to perform realistic simulation. It is an active research topic. Some of the well-known techniques are:

- *2D simulation*: Ray generation is performed in two dimensions to speed up the computation. This approximation is only applicable when the propagation is mainly guided in horizontal planes [21]. Urban micro-cellular environment is a typical application.
- *2.5D simulation*: In outdoor configuration with some limitation on data description, a simple 2D simulation including the transmissions enables to compute exactly the rays in 3D [22]. The transmissions enable for instance to obtain diffraction points on the horizontal edges. This method provides the 3D accuracy with the 2D time efficiency.
- *Graph of visibility*: The method consists of computing the visibility between faces. This knowledge considerably speeds up the image method. The visibility criterion is generally an approximation. It is carried out by considering

the visibility between a limited numbers of points of each face. Last year, Ref. [23] proposed an analytic solution to rigorously compute visibility between faces.

Ray tracing method provides an asymptotic solution of Maxwell's equation. It can not be used with small objects or complex structures. To overcome this limitation, hybridization with other techniques such as Finite Difference Time Domain are investigated [24].

5.2. Finite Difference Time Domain

The Finite Difference Time Domain (FDTD) method was introduced by Yee in 1966 [25]. Space is represented by cells and the time is discretized. Maxwell's equations are solved using a set of finite difference equation. FDTD is an attractive method because impulse response can be simply computed all over the simulation area. Accurate results require about ∼20 cells per wavelength.

Many improvements have been introduced since the original paper. For instance, Perfectly Matched Layer was proposed in [26] to solve unbounded problem and enables free space simulations. Liu proposed to use Fast Fourier Transform to represent the spatial derivative [27]. Only two cells per wavelength are required to obtain a good accuracy. The result is a significant reduction of complexity and memory consumption. This is a promising technique to investigate deeply realistic indoor propagation environment.

6. Conclusion

This article has presented a very short overview of propagation channel characterisation and modelling. Propagation experiments are more and more complicated including antenna array at both sides of the link. This enables us to know accurately all the characteristics of the propagation channel: delay, amplitude, polarization, directions of arrival and departure, ... This knowledge is required to study new radio access schemes exploiting more and more propagation channel dimensions (space, time, frequency, polarization). As a result, the complexity of wideband channel models increases, especially in standardization groups. Space-time characteristics of new channel models are described statistically and enable to simulate a set of realistic channel models. Simple tap delay line models are still used but only to validate the air interface.

Field strength prediction models are important for network planning. Efficient models are available for each kind of environment. The tendency is to combine these models and provides adaptive prediction models. Considering computer progress and new acceleration techniques, deterministic channel models are very promising to profoundly investigate the wideband channel.

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