

1

Introduction

1.1 Book Objective

The characteristics of the propagation channel are of great importance for designing wireless communication systems, analyzing communication qualities, and simulating the performance of networks. However, in most books on wireless communications, propagation channels are usually presented in only one or two chapters, which describe the fundamental characteristics of channels – for example path loss, shadowing, and multipath fading – and present some standard models. Since the procedures for measuring the wireless channels, the methodologies adopted for parameter estimation, and the modeling approaches implemented are neglected in these books, it is impossible for readers to understand how the models are established for specific scenarios. This also results in suspicions about the applicability of models, and questions also arise about the appropriateness for implementation in channel simulations.

Furthermore, fast-growing wireless communication networks and services bring greater demands for high spectral efficiency. Numerous techniques have been used, all essentially exploiting the resources from propagation channels. For example, parallel spatial channels are resolved and utilized by multiple-input, multiple-output (MIMO) techniques for diversity or multiplexing. Similar MIMO techniques in other domains, such as in polarizations and in wavefronts, have been developed. It is of no doubt that future wireless system design will be more and more adaptive to the environments in which they are used. Network architecture design is also becoming increasingly complicated in order to make the most use of specific channels. For example, the techniques of distributed antennas, massive MIMO, relay, cooperative transmission, and joint processing all require detailed knowledge of channels in both a stochastic sense and in site-specific scenarios. Therefore, channel characterizations based both on theoretical approaches and real measurements are going to become critical in the future.

Considering the multiple aspects of a channel, it is actually a “mission impossible” to write a book that is sufficiently comprehensive that every topic of channel studies is included. This book is written with the aim of covering only some aspects of the propagation channel:

- the high-resolution approach of analyzing channels based on measurement data
- stochastic channel modeling either using empirical parameters or based on simulation of scattering.

The objectives of this book are threefold. First, the book provides the fundamentals of both empirical measurement-based and theoretical-scattering-based channel modeling. The topics covered are widely spread, touching on the fields of wideband channel measurements, model parameter extraction, stochastic model generation, and theoretical channel modeling. Second, the book provides some updated channel models, which can be used for practical simulations. Engineers in the wireless communication industry can therefore use them to evaluate their system performance. Thirdly, this book highlights ongoing trends, revealing some fresh research results that might be interesting for researchers when designing new systems.

1.2 The Historical Context

1.2.1 Importance of Channel Characterization

The statistical characteristics of channels can significantly influence the design of wireless communication systems. For example, the path-loss model, based on the measurements in specific regions, can be used to determine the appropriate value of the separation between cells, in order to keep the interference below a certain threshold. Shadowing models can be used to determine the maximum and the minimum transmission power in order to avoid blindspots in the coverage. Multipath fading models, which include the fading rate and fading-duration characteristics, can be used to determine the packet length and the transmission rate. Delay spread models can be used to evaluate the frequency selectivity of the environment, so as to determine the coherence frequency bandwidth or the separation of the orthogonal channels in the frequency domain. Doppler frequency spread models can be used to calculate the coherence time of the channel, and therefore determine the cycle duration to renew the estimate of channel coefficients. The models in the spatial domains, for example the cluster-based bidirectional models, can be applied to determine the antenna beamwidth in beamforming applications, or to calculate the degrees of freedom for channels with MIMO configurations. Stochastic models themselves are based on extensive measurements in many environments categorized into specific types, such as outdoor, indoor, urban/suburban, and so on; they are therefore valid in similar environments.

The model parameters can be used to determine the many thresholds used in communication systems. For example, for frequency hopping multiple access systems, the frequency offsets due to the Doppler effect of the channel, and the timing problems due to the multipath arrivals at different time instants, can cause a certain portion of the desired signal's energy to appear in spurious adjacent frequency bins; consequently the detection of the desired signal becomes difficult [Joo et al. 2003], and the detection matrix may have erroneous entries [Yegani and McGillem 1993]. With the knowledge of the delay-Doppler frequency dispersion behavior of channels in certain environments and scenarios, the threshold level of envelope detectors can be appropriately selected. Furthermore, if the instantaneous knowledge of the channel dispersion characteristics is available, the channel can be equalized accordingly.

1.2.2 Single-input, Single-output Channel Models

Channel investigation started at the end of the 1960s [Okumura et al. 1968]. At that time, wireless systems were built for voice communications using frequency division multiple

access technique. The channel characteristics of interest when the single-input, single-output (SISO) system was considered was therefore the fading distributions at particular frequencies.

For outdoor scenarios, it has been found that the fading distribution is Rayleigh in a local geographical area with diameter of less than a few hundred wavelengths, and lognormal over large geographical areas [Lee and Yeh 1972, Okumura et al. 1968, Schmid 1970, Turin et al. 1972]. Suzuki [1977] considered more distributions, including the Nakagami and lognormal distributions, to fit the empirical data. It was found that the Rayleigh distribution is not always a good fit for most data, and that the lognormal distribution is often better. A possible reason for this observation is that the distribution – actually a mixture of Rayleigh distributions with a lognormal mixing distribution – is an intermediate distribution between the Rayleigh and the lognormal distributions [Suzuki 1977].

For indoor propagation environments, the SISO channel models have been established for the line-of-sight (LoS) and obstructed LoS (OBS) scenarios, as in the factory and open-plan office cases [Kozlowski et al. 2008, Rappaport and Seidel 1989, Rappaport et al. 1991, Saleh and Valenzuela 1987, Seidel et al. 1989, Yegani and McGillem, 1989a,b, 1991]. The motivation for investigating indoor SISO channels is to provide models for indoor deployment of radio systems that accommodate data rates up to 1 Mb/s. Such systems include the Digital European Cordless Telephone (DECT) 802.41 and WLAN (IEEE 802.11) standards, as well as the communication systems for autonomous guided vehicles (AGVs) [Rappaport et al. 1991]. The interesting characteristics of the channels in indoor environments include the path loss and delay spread. It has been found that the delay spread can be several times greater in unpartitioned factory buildings than in partitioned office buildings [Hawbaker and Rappaport 1990b]. Besides the large-scale parameters, the detailed wideband characteristics of the channel, for example the dispersion of the channel in the delay domain, has been examined. For example, Hawbaker and Rappaport [1990a] found the so-called “pulse overlapping” phenomenon, which revealed that even in the LoS scenario the OBS path components can be added to the LoS path components within the resolution of transmitted pulse, resulting in so-called multipath fading.

Furthermore, resolvable rays in the time domain have been applied to modeling channels. This kind of model was called a discrete model. For outdoor environments, discrete channel models consist of discrete rays or discrete peaks of the power-delay profiles [Cox and Leck 1975, Turin et al. 1972]. The magnitude of each ray can be set to follow the lognormal distribution [Suzuki 1977]. The correlation bandwidth is also applied as a model parameter for channels [Cox and Leck 1975], and this is large when the channel-delay profile exhibits several dominating discrete peaks, but small when multipath is severe [Cox 1972]. Since the channel-impulse response in the delay domain is available, the distribution of the number of paths, and the mean and standard deviations of logarithmic path strength are considered for channel characterization [Cox 1972]. Furthermore, by using multiple observations of the channel, the Doppler frequency spectrum has also been computed and used for modeling the channel [Cox 1973]. In addition, the trend of describing the channel properties in two dimensions has appeared in the literature [Cox 1973]. The Doppler spectra versus delay and the distribution of path strength versus delay have been studied for outdoor channels in urban environments [Cox 1973]. The small-scale characteristics of the channel – the channel property at specific delays – have become important for modeling.

Some important observations have been obtained through measurement. For outdoor urban environments, the excess delay of a channel at 900 MHz can be up to 9–10 μs [Cox 1973];

the delay spread, defined as the square root of the second central moment of the power-delay profile, is 2–2.5 μs . The path with 0.1 μs resolution exhibits a Rayleigh distribution, inferring that the fading coefficients for the first arrival path can be modeled as a Gaussian random process. For paths with different delays, uncorrelated scattering is confirmed by the observation that their Doppler frequency power spectra are quite different. The conclusion that paths with different delays are uncorrelated seems more useful for urban environments. Some authors have proposed to use correlated paths to construct discrete models, but this contradicts the observations of Cox [1973].

For indoor manufacturing environments, Yegani and McGillem [1991] provided the statistics for channels in different sites in a factory under four scenarios with different settings of LoS/OBS, and sparsely or densely distributed scatterers. It was found that the interarrival times of the paths were well modeled by the Weibull distribution, the number of paths by the modified beta distribution, and the path-gain coefficients by the Rayleigh, Rician, and lognormal distributions. The values of the parameters of these distributions were reported by the authors. It is interesting to observe that the average number of paths for different sites at a fixed threshold of signal strength is about the same, an indication that the statistics of the number of paths arriving at the receiver is not very sensitive to the topography of the factory site. Furthermore, the geometry of the factory and the layout of the working area have a strong influence on the distribution of the path-gain coefficients. There are also some new findings, for example when the dynamic range is not selected the path-gain coefficients follow the lognormal distribution regardless of the LoS, OBS, or how densely distributed the scatterers are. As for the threshold, when this is greater than -10 dB the path-gain distribution follows the Rician PDF, but when lower than -10 dB, the Rayleigh distribution provides a better fit. Thus, the estimated PDF for gain coefficients depends on the level of the dynamic range set at the receiver.

The research into channels for SISO has evolved into multiple areas. For example, polarization characteristic have been investigated since the 1970s, when polarization diversity was used to combat multipath fading. Employing orthogonally polarized channels over the same microwave link for satellite communications can result in twice the system capacity as when using single-polarized antennas [Lee and Yeh 1972]. In 2001, Andrews et al. [2001] pointed out that six channels without any correlation can immensely improve the transmission rate and system capacity of a wireless communication system, by polarization in a scattering-rich environment. Channel models have been proposed that can be used to generate the channel responses with an arbitrary pair of vertical and horizontal polarizations at both transmitter and receiver sites [3GPP 2007, Jeon et al. 2012]. Besides the cross-polarization discriminations (XPDs) of individual propagation paths, these models also involve the responses of antennas in different polarizations.

Jiang et al. [2007] studied the correlation coefficients for both copolarized and crosspolarized channels. They found that:

- polarization decorrelation outperforms spatial decorrelation in the strong LOS scenario
- horizontally polarized channels are more correlated than vertically polarized channels
- the correlation of copolarized channels increases as the Rician K factor increases
- channels have much higher correlation in the elevation domain.

A strong conclusion was that the crosscorrelation of crosspolarized channels is not affected by the environment, while the performance of copolarized channels is scenario dependent.

1.2.3 Spatial Channel Models (SCMs)

Estimating the direction or bearings of incoming signals has been a research topic for years. The original objective was for signal detection and estimation, including radar target tracking and component separation. The methods used for estimating direction of arrival are similar to those used in time-series spectral analysis and they are applied specifically with the samples obtained from spatially distributed arrays of sensors, including antennas for receiving electromagnetic waves and microphones for acoustic signals.

The study of the arrival angles of signals as part of the design of communication systems can be traced back to the 1970s. For example, Lee and Brandt [1973] found from field measurements of mobile radio signals that the signal arrival is concentrated at elevation angles lower than 16° . Based on this finding, an omnidirectional antenna with vertical directivity is usually selected to increase the average received signal strength.

There are also many practical concerns that require a knowledge of the spatial characteristics of a channel. For example, when MIMO techniques are used in communication systems, the spatial diversity and/or multiplexing gains need to be evaluated based on realistic modeling of the covariance of the spatial channels. Furthermore, in the case where the beamforming technique is used in a base station, it is necessary to know the distribution of the energy in the direction of arrival; in other words how the energy is concentrated and what its spread is in the dominant path. Additionally, with directional parameters, the propagation of the waves can be easily visualized when the actual constellation of the scatterers is presented for specific environments. Geometry-based channel modeling (GBSM) has flourished in the last decade. One major reason is that channel dispersion in the directional domains can be obtained by spectral analysis of the measurement data.

Spatial-spectral analysis methods can be categorized into two classes: spectral-based methods and parametric-model-based methods. Theoretically, conventional methods such as the periodogram [Schuster 1898] and the correlogram [Chatfield 1989], which belong to the category of spectral-based methods, are not applicable in many cases due to the limited spatial aperture of the sensor array and the responses of the sensors. Eigenstructure-based methods have therefore been widely adopted. These include the MUltiple SIgnal Characterization (MUSIC) algorithm and its many variants [Asztély and Ottersten 1998, De Jong and Herben 1999, Friedlander 1990, Jäntti 1992, Kaveh and Barabell 1986, Krim and Proakis 1994, Krim et al. 1992, Rao and Hari 1993, Rao 1990, Salameh and Tayem 2006, Stoica and Nehorai 1989, Wang et al. 2001] and other subspace-based methods, such as the propagator method [Marcos et al. 1994; 1995, Tayem and Kwon 2005], and Estimation of Signal Parameters by Rotational Invariance Techniques (ESPRIT) (which does not result in a spectrum, but provides analytically the solutions for parameter estimates) [Asztély and Ottersten 1998, Jäntti 1992, Paulraj 1986].

In the 1990s, algorithms based on parametric models of channels were used to extract channel-model parameters from measurement data. The maximum-likelihood estimator and the approximation of it with an iterative estimate updating procedure can be used to estimate both the deterministic parameters and the statistical parameters of channels depending on the generic model applied. These algorithms are also called super-resolution methods, as they may achieve higher resolution than conventional spectral-based methods. Typical examples of these algorithms are the expectation-maximization (EM) algorithm [Frenkel and Feder 1999, Moon 1997, Nielsen 2000, Zhang et al. 2001], the space-alternating generalized expectation-maximization (SAGE) algorithm [Fessler and Hero 1994, Fleury et al. 1999,

Taparugssanagorn et al. 2007, Yin et al. 2007; 2006a], Richter's Maximum likelihood (RiMAX) algorithm [Richter, 2004; 2005, Richter et al. 2000; 2003], and the variants of the SAGE algorithm produced by adopting models different from the widely used resolvable specular path model [Bengtsson and Ottersten 2000, Yin et al. 2006b]. The papers cited here analyse and compare these algorithms, and also cover aspects such as the impact of the antenna arrays used for data collection and the influence of the model mismatch between the usually applied resolvable specular-path model and the true scattering effect.

These algorithms are applied to extract multidimensional parameters of channels from measurement data. The parameters include the direction of arrival, direction of departure, delay, Doppler frequency and polarization matrices of individual propagation paths. The estimates are used to construct the stochastic geometry-based or ray-based channel models, such as:

- the well known 3GPP TR 25.996 models [3GPP 2007]
- the Wireless World Initiative New Radio (WINNER) II spatial channel model-enhanced [IST 2007]
- the IMT-advanced channel models [ITU 2008].

In the spatial channel model, clustering of multiple paths is a necessary step for generating the small-scale parameters of the channel, such as the cluster delay spread, cluster angular spread, and the time-variant behavior of the clusters. How to appropriately cluster the multiple propagation paths has been discussed in literature [Czink et al. 2005a,b]. At first, visual-inspection-based clustering methods were proposed [Czink 2007a], but this is impractical for a large amount of measurement data. Moreover, the clustering results may not be unique when users have different opinions about the clusters. Automatic clustering methods, requiring minimum interactions of users, were designed as an alternative. These methods make use of the so-called multipath component distance measure (or environment characterization metric) to group the paths into a cluster [Czink et al. 2005b; 2006]. Readers are referred to Czink 2007b for the detailed description of various clustering methods and their performance.

The multipath clustering concept has also been extended to the modeling of time-variant channels [Czink et al. 2007a,b, Xiao and Burr 2008, Xiao et al. 2007]. The objective of introducing time-variant clusters is to reduce the computational complexity when generating spatial-correlated time-variant channel realizations or channel matrices. The parameters of the clusters, especially the centroid of clusters, are tracked through consecutive channel snapshots [Czink and Galdo 2005, Czink et al. 2007b]. It was found by Czink et al. [2007b] that for both outdoor and indoor scenarios clusters can be easily tracked. The histogram of the logarithmic cluster lifetime follows an exponential distribution of the cluster lifetime for outdoor scenarios.

1.2.4 Channel Models for 5G

Recently, the fifth generation (5G) of wireless communication has attracted tremendous research attention. The increasing demand for high-data-rate communications for 5G has motivated use of signals transmission at higher frequency bands (HFB) beyond 6 GHz [Andrews et al. 2014].

The European Seventh Framework project "Mobile and wireless communications enablers for the twenty-twenty information society" (METIS) proposed for 5G communications a

frequency band ranging from 450 MHz to 85 GHz [Jämsä et al. 2014]. Channel characterization for HFBs has been focused on 60 GHz millimeter (mm-) wave propagation [Collonge et al. 2004, Correia and Frances 1994, Daniels and Heath 2007, Moraitis and Panagopoulos 2015, Piersanti et al. 2012, Smulders 2009, Weiler et al. 2015, Yang et al. 2006]. The large-scale characteristics, such as path loss, shadow fading, frequency selectivity, and the influence of human bodies and different materials on channels, have been investigated for the 60 GHz frequency [Collonge et al. 2004, Correia and Frances 1994, Piersanti et al. 2012, Yang et al. 2006]. High-resolution parameter estimation (HRPE) algorithms, such as space-alternating generalized expectation-maximization (SAGE) [Fleury et al. 1999] and Richter’s maximum likelihood estimation (RiMAX) [Richter and Thomä 2005], have been used to extract multipath components (MPCs) from the outputs of virtual linear or planar arrays [Gustafson et al. 2014b; 2011, Martinez-Ingles et al. 2013]. Multipath clusters were identified and their statistics have been reported as stochastic channel models for various propagation scenarios [Gustafson et al. 2014a,b]. Besides the mm-wave frequency bands, more channel measurement studies for other HFB frequencies have been carried out recently, such as

- 10–11 GHz [Belbase et al. 2015, Kim et al. 2015, Weiler et al. 2015]
- 28–38 GHz [Azar et al. 2013, Rappaport et al. 2013, Wu et al. 2015]
- 70–73 GHz [Karttunen et al. 2015, Nie et al. 2013a, Semkin et al. 2015, Zhang et al. 2014]
- 81–86 GHz [Semkin et al. 2015].

A common setup in these studies is that antennas with narrow half-power beamwidth (HPBW), such as pyramidal horn antennas, are used [MacCartney et al. 2013, Samimi et al. 2013, Zhang et al. 2014]. One motivation for using narrow-HPBW antennas in such measurements is that the large antenna gain resulting can counteract the significant path-loss in HFB propagation. Furthermore, if the antenna’s HPBW is narrow enough, a direction-scan-sounding (DSS) method can be used by rotating the antenna’s axis towards different directions: the channel is “scanned” in multiple directions. Based on these measurement studies, power delay profiles (PDPs) and path-loss models for omnidirectional channels have been synthesized from directional observations, and channel models for HFB wave propagation have been proposed for outdoor cellular, backhaul, and indoor propagation scenarios [Hur et al. 2014, MacCartney and Rappaport 2014, Nie et al. 2013b].

1.2.5 *Other Kinds of Channel Model*

Future generations of wireless communication systems will employ new techniques that rely on channel modeling for more complex network constellations. For example, design of the distributed antenna, cooperative relay and joint processing systems, or algorithms require models of co-existing multilink channels. Some preliminary works have been done on multilink correlation channel models [Yin et al. 2011; 2012a,b,c,d].

Other channel models exist for the non-stationary scenarios and distributed scenarios. Some models focus on the specific behavior of the channels, such as their reciprocity behavior with respect to time and frequency, their polarization characteristics, interference, and the LoS and NLoS probabilities and so on.

1.3 Book Outline

This book contains ten chapters. It starts by introducing the phenomena of propagation considered in wireless communication channels and defines the terminologies and parameters used to characterize their properties. Then generic parametric models for channel multiple components are introduced. The approaches adopted in channel characterization and modeling from theoretical and experimental aspects are elaborated respectively. A focus of the book is on high-resolution channel parameter estimation methods for extracting deterministic specular-path components and statistical dispersive components from measurement data. Next, the general procedures and key techniques adopted for constructing stochastic models based on parameter estimates are described. Finally, some specific channel models are presented as examples of implementing the methods and techniques introduced in this book. Below is a detailed description of the content in individual chapters.

Chapter 2 “Characterization of Propagation Channels” begins by introducing three phenomena of fading in wireless channels: path loss, shadowing, and multipath fading. Then the stochastic characterizations of these phenomena are described. Following that, we emphasize the duality relationship between the selectivity and dispersion of multipath fading, and also explain the definition of the wide-sense stationary uncorrelated-scattering (WSSUS) assumption and its applicability in practice. In this chapter, a review of propagation channel modeling is provided, describing the different approaches that aim to accurately and/or efficiently generate channel impulse responses with desired channel characteristics. These channel models are categorized into two main classes: MIMO channel models and vehicle-to-vehicle (V2V) channel models.

Chapter 3 “Generic Channel Models” introduces the basic mechanisms of radio propagation, the representation of channels in terms of multidimensional spread functions, and the generic models usually applied for channel parameter estimation. These generic models include the specular-path model, dispersive-path model, time-evolution model for the path parameters, and power spectral density models for individual components. Furthermore, the influence of system configurations – for example the amplify-and-forward relay systems – on the format of the generic models is also described. Finally, the model of the received signal in, for example, the channel sounding context is given.

Chapter 4 “Geometry-based Stochastic Channel Modeling” describes the difference between the geometry-based deterministic modeling approach and the geometry-based stochastic modeling approach, the details of the latter for the regular-shaped and irregular-shaped scenarios. Furthermore, the simulation methods of the theoretical/mathematical reference model in reality are introduced.

Chapter 5 “Channel Measurements” introduces the methodologies, equipment, and procedures of measuring the impulse responses of propagation channels. Besides the general description of channel measurements, we go one step further to discuss the influence of imperfections that occur during the calibration of the equipment on the measurement results. For example, we analyze the impact of the existence of time-variant phase noise and the inconsistency between the measured and real radiation-pattern measurements. We also, for the first time, provide experimental analysis on how the directionality of the radiation of antennas influences parameter estimation results. All of these studies are based on experimental data. We focus on introducing the phenomena, and only briefly describe several solutions available at present. The readers are encouraged to discover more solutions for these important issues.

Chapter 6 “Deterministic Channel Parameter Estimation” focuses on the high-resolution parameter estimation algorithms based on the generic specular-path model. These are used for extracting the parameters of individual path components from measurement data. Besides the traditional SAGE and RiMAX algorithms, which have been used extensively for parameter estimation in MIMO measurement-based channel modeling, we also introduce some newly developed estimation methods, which are expected to be used in the very near future for accurate channel modeling. For time-varying scenarios, where the path parameters evolve with respect to time, a tracking scheme based on the particle filter concept is elaborated. For each method introduced, we include the results of performance evaluations that were carried out by processing real measurement data.

Chapter 7 “Statistical Channel Parameter Estimation” describes another category of parameter estimation methods, which use generic models for the power spectral density of the channel to estimate the statistical parameters, such as the second moments of the channel/channel components. Two methods are introduced: the generalized array manifold (GAM) model-based approach and the power spectral density-based approach. These methods, although not been widely adopted, can result in more accurate estimates of channel statistics. We also describe the practical limitation of the methods when used in practice.

Chapter 8 “Measurement-based Statistical Channel Modeling” systematically describes modeling procedures that are based on measurements in detail. Both the common issues in the modeling – clustering algorithms and data segmentation – are discussed, along with specific approaches and recent new topics in channel modeling, such as non-stationarity modeling, relay, and cooperative multipoint (CoMP) channel modeling.

Chapter 9 “In Practice: Channel Modeling for Modern Communication Systems”, as the last chapter of the book, provides the examples of models established using the methods introduced in earlier chapters. These examples cover many common scenarios that have been popular for channel modeling in recent years. The readers can use this chapter as a collection of models recently developed for the MIMO, vehicular, relay, CoMP, and multilink channels. Students can undertake trials for other scenarios based on the procedures presented in these examples.

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