Chapter 1
Measurement and Modeling of Wireless Channels

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1 Introduction

As wireless signals traverse the path from a transmitter to a receiver, they will be diffracted, scattered and absorbed by the terrain, trees, buildings, vehicles and people that comprise the propagation environment. In the process, the signal may be distorted or impaired in various ways. The presence of obstructions along the path may cause the signal to experience greater attenuation than it would under free space conditions. If the signal is scattered by obstacles located throughout the coverage area, replicas of the signal may take multiple paths from the transmitter to the receiver. Because the replicas will arrive at the receiver after different delays, the signal will experience *time dispersion*. Because the replicas will also arrive from different directions, the signal will experience *angular dispersion.* If either the scatterers or one of the terminals is in motion, rapid changes in the phase relationship between multipath components will cause the signal to fade randomly, perhaps deeply. Such variation in received signal strength over time is equivalent to *frequency dispersion*. The correlation between fading observed at the output of adjacent receiving antennas will depend upon the type and configuration of the antennas and the range of angles over which the incident signals arrive.

The objective of channel modeling is to capture our knowledge and understanding of the manner in which the propagation environment impairs and distorts wireless signals in a form useful in the design, test and simulation of wireless communications systems. Designers and developers use such channel models to predict and compare the performance of wireless communications systems under realistic conditions and to devise and evaluate methods for mitigating the impairments and

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distortions that degrade wireless signals. The importance of channel models in wireless system design has long been recognized. Indeed, some have proclaimed that:

> Of all the research activities related to mobile radio that have taken place over the years, those involving characterisation and modeling of the radio propagation channel are among the most important and fundamental [1].

Channel models are the basis for the software simulators, channel emulators and RF planning tools that are used during the design, implementation, testing and deployment of wireless communications systems, as summarized in Fig. 1. They can also be used to precisely define the degree of impairment that a wireless system must be able to tolerate in order to: (1) meet the requirements for certification by standards groups and/or (2) comply with contractual obligations.

Like any other mathematical model, a channel model is *an abstract, simplified, mathematical construct that describes a portion of reality.* In order to limit its complexity, a channel model must necessarily focus on those aspects of the channel that affect the performance of a system of interest and ignore the rest. As researchers develop more sophisticated signaling schemes in order to deliver faster, more reliable communications, it will be necessary to develop new channel models that capture the nature of the relevant impairments and their dependence on the environment. As systems are deployed in ever more demanding environments and, in some cases, in higher frequency bands, it will be necessary to extend existing models.

In this chapter, we review and summarize recent progress in measurement and modeling of wireless channels for mobile and personal communications systems and identify common issues. In Section 2, we present a brief history of the field. In Section 3, we review the approaches used to characterize wireless channels and propagation environments. In Section 4, we explore the process by which new channel models are developed. In Section 5, we consider the methods and approaches used to measure wireless channels. In Section 6, we review some of the key mile-

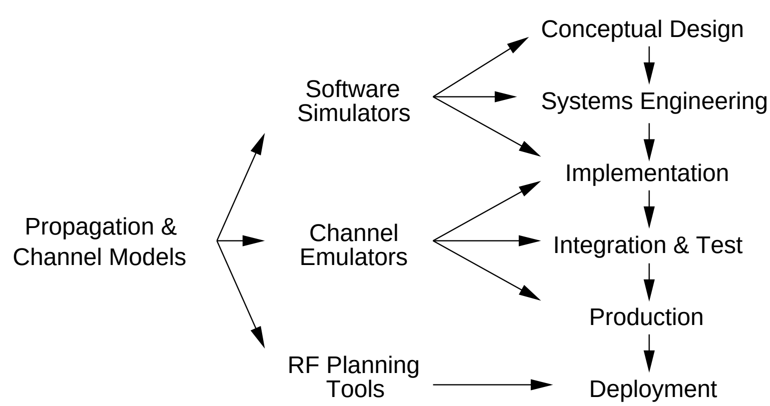

Fig. 1 The roles of channel models in the product development process.

stones achieved by the channel modeling community during the past decade. In Section 7, we conclude with some general remarks.

2 A Brief History

The need to understand and characterize wireless channels has been recognized since the earliest days of wireless communications. During the 1920's and 30's, researchers began intensive studies of the ionosphere and its effect on wireless propagation at high frequencies. Such studies introduced methods such as swept-frequency channel sounding and concepts such as wide-sense stationary uncorrelated scattering (WSSUS) channels that are still used in various forms today [2]. The development of radar at the MIT Radiation Lab during the Second World War led to pioneering work concerning the effect of the troposphere, hydrometeors and ground reflections on radiowave propagation at very high frequencies [3]. During the 1950's, the insights gained were used to plan and deploy the first long-distance point-to-point microwave systems. Many of these tools and techniques were later adapted for use in land mobile radio and cellular telephony deployments.

During the 1960's and early 1970's, several key discoveries ushered in the modern era of channel modeling for mobile and personal communications systems. Okumura *et al.* [4] revolutionized planning of mobile radio systems that operate over a broad range of frequencies between 100 MHz and 1 GHz by demonstrating that path loss in urban and suburban macrocell environments could be simply modeled in terms of the distance between the base station and remote terminal, the heights of their respective antennas above ground level, and the nature of the intervening terrain. Clarke [5] and others helped to transform mobile radio propagation from an empirical to an analytical science by showing that the U-shaped Doppler spectrum characteristic of signals received by mobile terminals could be modeled by a scenario in which incoming radio waves: (1) propagate in the horizontal plane, (2) arrive over a uniform distribution of azimuthal angles and (3) are received by an omnidirectional antenna.

Development of a rigorous treatment of linear time varying wideband channels by Bello [6] provided essential tools and insights for analyzing wideband wireless channels that vary over time, *e.g.,* due to changes in either the propagation environment or the location of the mobile terminal. The introduction of the spread spectrum cross-correlation technique for measuring the magnitude of the channel impulse response (CIR), *i.e.,* the *power delay profile* (PDP), by Cox [7], made it possibly to routinely characterize time dispersion by wideband mobile channels. The channel measurement results later obtained by various research groups using this technique provided a solid foundation for the analysis and simulation of the first generation of digital mobile radio systems. By the early 1970's, it was clear that thorough characterization of the wireless channel was an essential first step in devising methods for achieving good link- and system-level performance in the presence of channel impairments and distortions. Many of these pioneering results were captured in a widely cited volume prepared by researchers at Bell Labs [8].

During the 1980's, the pace of development in mobile and personal communications increased dramatically as: (1) business and private consumers expressed an unprecedented demand for wireless communications technology and (2) spectrum regulators opened up new spectrum, authorized new services and set new goals for both performance and spectral efficiency. This prompted more intensive efforts to characterize the propagation environment and to develop the technologies required to realize next generation systems. The European COST[1] 207 action concerning *Digital Land Mobile Communications* was conducted from 1984-1988 with a mandate to provide a firm technical foundation for development of GSM, the European standard for second generation cellular telephony. Prior to COST 207, mobile radio propagation researchers and research groups tended to operate fairly independently and communicate mostly through conferences and journals. COST 207 brought together industry, government and academic researchers from across Europe under a common umbrella and thereby encouraged more formal collaboration between channel modeling researchers. A key contributor to its success was the establishment of a mechanism by which those who would use the channel modeling results to evaluate alternative technology strategies and proposals could contribute to project goals and priorities.

The success of COST 207 set the stage for follow-on ventures, including COST 231 - *Digital Mobile Radio Towards Future Generation Systems* (1989-1996), COST 259 - *Wireless Flexible Personalised Communications* (1996-2000), COST 273 - *Towards Mobile Broadband Multimedia Networks* (2001-2005), and COST 2100 - *Pervasive Mobile and Ambient Wireless Communications* (2007-2009). The success of the COST actions encouraged similar collaborative channel modeling activities by standards groups. Such efforts yielded the fixed wireless channel models developed by the IEEE 802.16 Working Group on Broadband Wireless Access Standards, the MIMO (multi-input/multi-output) channel models developed for wireless LAN applications by IEEE 802.11's Task Group TGn, the ultrawideband (UWB) channel models developed by IEEE 802.15's TG3a and 4a, the 60 GHz channel models developed by IEEE 802.15's TG3c, the spatial channel models developed for wide area systems under the aegis of 3GPP (the Third Generation Partnership Project) and the enhanced wide area spatial channel models developed under the aegis of the Wireless World Research Forum's Wireless World Initiative New Radio (WINNER) project and the European Sixth Framework Programme.

[1] COST or *European Cooperation in the field of Scientific and Technical Research* is one of the longest-running European programs that support cooperation among scientists and researchers across Europe

3 Characterization of Wireless Channels

A channel model is a simplified representation of reality that captures those aspects of channel behavior that affect the performance of a particular class of wireless technologies. The fundamental principles of channel modeling for mobile and personal wireless communication systems that operate at frequencies of 800 MHz and above have been recounted in [8]-[11].

The ITU-R's IMT-2000 program has defined three basic propagation environments within which terrestrial mobile and personal communications systems are deployed. Picocells refer to indoor environments with transmitter-receiver separations of less than a few hundred metres. Microcells refer to outdoor environments in which both the base station and remote terminal antennas are placed below local rooftop level in the same street canyon (or adjoining side streets) with the remote terminal located at distances of up to 1 km away. In such cases, a *line-of-sight* (LOS) often exists between the base and remote. Macrocells refer to outdoor environments in which the base station antenna is placed well above local rooftop level while the remote terminal is placed well below local rooftop level at distances of up to several km from the base. In such cases, the link generally operates under *non-line-of-sight* (NLOS) conditions.

Path loss is the most fundamental measure of channel quality. In decibels, path loss, PL is defined as

$$PL = P_t + G_t + G_r - P_r, \tag{1}$$

where P_t and P_r are the time-averaged power levels (in dBm) at the output of the transmitter and the input of the receiver, respectively, and G_t and G_r are the gains (in dBi) of the transmitting and receiving antennas. The relationship between path loss and the distance, d, between the transmitter and receiver generally follows a power-law relation and can be described by

$$PL(d) = PL_0 + n \cdot 10\log_{10}\frac{d}{d_0} + X_\sigma, \tag{2}$$

where PL_0 is the value of path loss (in dB) at the reference distance d_0, n is the distance exponent and X_σ is a zero-mean Gaussian random variable with standard deviation σ. The random variable X accounts for the location variability or *shadow fading* that is generally attributed to differences in the degree to which the path is obstructed at different points throughout the coverage area.

For systems with fractional bandwidths $\Delta f/f_0$ that are less than 20% where Δf is the occupied bandwidth of the signal and f_0 is the carrier frequency, path loss can generally be assumed to be constant over the band. For systems with large fractional bandwidths and/or which operate near a frequency where specific attenuation due to gaseous absorption changes rapidly, it may be necessary to model the frequency dependence of path loss as well. In such cases, it is reasonable to assume that the frequency and distance dependence of path loss are separable, yielding

$$PL(f,d) = PL(f)PL(d). \tag{3}$$

The relationship between path loss and frequency is generally found to follow a power-law relation that can be modeled by

$$\sqrt{PL(f)} \propto f^{-\kappa}, \tag{4}$$

where κ is the frequency exponent and $\kappa = 1$ in free space.

Signal Fading. Scattering by objects in the propagation environment causes multiple replicas of the received signal or *multipath components* (MPCs) to arrive via different paths. Small changes in the position of either the scatterers or either end of the wireless link will usually have only a small effect on the amplitudes of the *physical* MPCs that comprise a *resolvable* MPC. [2] However, the phase shifts between the physical MPCs may change significantly causing large changes in the strength of the resolvable MPC. If, over time, the signal follows a complex Gaussian distribution, the magnitude of the signal envelope, x, will follow a Rayleigh distribution,

$$p(x) = \frac{2x}{\Omega} \exp\left(-\frac{x^2}{\Omega^2}\right), \tag{5}$$

Ω is the average power in the signal. If the signal also has a fixed component, its magnitude will follow a Ricean distribution,

$$p(x) = \frac{2(K+1)x}{\Omega} \exp\left(-K - \frac{(K+1)x^2}{\Omega}\right) \cdot I_0\left(2\sqrt{\frac{K(K+1)}{\Omega}}\,x\right), \tag{6}$$

where K is the Ricean K-factor, $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind and Ω is the average power in the signal. For $K = 0$, the distribution reverts to Rayleigh. Otherwise, if neither distribution applies, others have been found to fit measured data, including: (1) the Weibull distribution,

$$p(x) = \frac{\beta}{\Omega} x^{\beta-1} \exp\left(\frac{-x^\beta}{\Omega}\right), \tag{7}$$

where $\beta > 0$ is the Weibull fading parameter and Ω is the average power in the signal, and the distribution reverts to Rayleigh for $\beta = 2$, and (2) the Nakagami distribution,

$$p(x) = \frac{2}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m x^{2m-1} \exp\left(-\frac{m}{\Omega} x^2\right), \tag{8}$$

where $m \geq 1/2$ is the Nakagami m-factor and $\Gamma(m)$ is the Gamma function. Over a time interval during which the channel is stationary, knowledge of the form, scale and shape of the fading distribution completely specifies the first-order statistics of the signal envelope.

Time-varying Signals. The rate at which the amplitude and phase of a received signal varies over time is captured by the corresponding Doppler spectrum. The

[2] When the transmitted signal is a single carrier with constant frequency and amplitude, only one MPC can be resolved.

classic Doppler spectrum, expressed in baseband form by

$$R(f) = \frac{1}{\pi} \frac{1}{\sqrt{f_D^2 - f^2}}, \quad |f| \le f_D, \tag{9}$$

where f_D is the maximum Doppler frequency, is characteristic of signals received when the terminal at one end of the link is in motion [5]. In indoor or fixed wireless environments, the Doppler spectrum may take on other shapes, *e.g.,* the peaky spectrum proposed in [12],

$$R(f) = \frac{2}{\pi^2} \sqrt{4f_D^2 - f^2}\, K\left(\frac{\sqrt{4f_D^2 - f^2}}{2f_D}\right), \tag{10}$$

where $K(\cdot)$ is the complete elliptic integral. Computing the Doppler spectrum of a signal generally requires knowledge of both the amplitude and phase of the signal over time. The *average fade duration* (AFD) and the *level crossing rate* (LCR) offer an alternative method for capturing both the first and second-order statistics of the signal envelope based upon amplitude-only received signal data.

Delay Spread or Time Dispersion. The data rate of a digital communications system is determined by the number of symbols that are sent per second and the number of bits that are represented by each symbol. As the symbol rate increases, time dispersion due to multipath scattering may cause time delayed replicas of one symbol to be received within the time slot reserved for a subsequent symbol. The resulting *intersymbol interference* (ISI) may cause bit errors and will ultimately degrade the performance of the link. In spread-spectrum-based systems, however, use of multi-fingered rake receivers allows one to enhance the received signal using temporal diversity.

The time-varying impulse response of a wireless channel may be represented as the response of a tapped delay line filter with N taps and is given by

$$h(\tau,t) = \sum_{i=1}^{N} a_i(t)\delta(\tau - \tau_i), \tag{11}$$

where a_i and τ_i are the complex (and time varying) amplitude and the delay of the ith tap which corresponds to the ith resolvable MPC. The resolution of the taps (or the duration of the corresponding delay bins) is given by the inverse of the occupied bandwidth. A particular coefficient a_i may have both fixed and time-varying components and is completely described by the amplitude and phase distributions that define its first-order statistics and the Doppler spectrum that defines its second-order statistics. Past work has suggested that the arrival rate of the MPCs often follows a Poisson distribution.

For wideband systems that occupy bandwidths of several MHz or less, there are relatively few resolvable taps and the corresponding channel impulse response models are very simple. As the occupied bandwidth increases, the number of MPCs that can be resolved increases dramatically. As first observed by Saleh and Valenzuela [13], the resolvable MPCs may appear to form clusters leading to a channel impulse response of the form

$$h(t) = \sum_{\ell=1}^{L}\sum_{k=1}^{K} a_{k,\ell}\exp(j\phi_{k,\ell})\delta(t-T_\ell-\tau_{k,\ell}), \tag{12}$$

where L is number of clusters, K is the number of rays within each cluster, T_ℓ is the delay of the ℓth cluster, and $a_{k,\ell}$, $\phi_{k,\ell}$ and $\tau_{k,\ell}$ are the amplitude, phase and delay of the kth tap within the ℓth cluster. While such clustering is very apparent in some environments, it is not as apparent in others. Some have found that an exponential decay multiplied by a noise-like variation with lognormal statistics provides an equally valid representation over a wide range of deployment scenarios within typical residential and commercial environments [20].

Linear Time Varying Wideband Channels. The time-varying channel impulse response can be expressed in alternative forms. Because the wireless channel is linear and time-variant (LTV), the simple Fourier transform pair that relates the LTI impulse response $h(t)$ and LTI frequency response $H(j\omega)$ of linear time invariant systems must be replaced by a more complicated set as described in [6] and as given by

$$\begin{array}{ccc} h(\tau,t) & \underset{F}{\overset{F^{-1}}{\longleftrightarrow}} & S(\tau,\nu) \\ {}_{F^{-1}}\uparrow\downarrow\;{}_{F} & & {}_{F^{-1}}\uparrow\downarrow\;{}_{F} \\ T(f,t) & \underset{F}{\overset{F^{-1}}{\longleftrightarrow}} & H(f,\nu) \end{array} \tag{13}$$

where, $S(\nu,\tau)$ is the Doppler-delay-spread function, $H(f,\nu)$ is the frequency-dependent Doppler spread function, $T(f,t)$ is the time-varying frequency response, t and f denote time and frequency while τ and ν denote delay and Doppler frequency and $F$and F^{-1} denote the Fourier and inverse Fourier transforms, respectively. Thus, time dispersion is equivalent to frequency variation (or selectivity) and frequency dispersion is equivalent to time variation (or selectivity).

Angle of Arrival. If a system uses either a directional antenna or multiple antennas to achieve greater performance, one must account for the distribution of angles over which incoming MPCs arrive at the receiving antenna. In the case of directional antennas, the convolution of the *angle-of-arrival* (AoA) distribution with the free space antenna pattern gives the *effective* antenna pattern which determines the antenna's effectiveness in rejecting interfering signals from different directions. In the case of multiple antenna elements, the AoA distribution determines the mutual correlation between signal fading observed on adjacent elements.

The AoA distribution is characterized by its mean direction and angular extent. Three common distributions which have been found to fit the AoA distributions that are observed across the azimuth angle ϕ in macrocell and/or in indoor environments include the uniform distribution,

$$p(\phi) = \frac{1}{2\pi}, \tag{14}$$

the zero-mean Gaussian distribution,

$$p(\phi) = \frac{1}{\sqrt{2\pi}\sigma_\phi} \exp\left(-\frac{\phi^2}{2\sigma_\phi^2}\right), \tag{15}$$

where σ_ϕ is the standard deviation of the distribution, and the zero-mean Laplace distribution,

$$p(\phi) = \frac{1}{\sqrt{2}\sigma_\phi} \exp\left(-\frac{|\sqrt{2}\phi|}{\sigma_\phi}\right), \tag{16}$$

where σ_ϕ is once again the standard deviation of the distribution.

Spatial Channel Models. When both the angle of arrival and the time of arrival are known, one can identify the locations of individual scatterers. The result is referred to as a spatial channel model [14]. A method for extending the Saleh-Valenzuela (S-V) CIR model to the spatial domain is described in [15].

4 Development of New Channel Models

Development of a new channel model begins with discussion between the channel modeler and the wireless system designer/developer. First, they must agree upon which aspects of channel behavior are important and must be captured, and which can be ignored. If important aspects are neglected, the model will not be useful. If, however, too many aspects are considered, the resulting model could be overly complex and would likely require considerable additional effort to develop.

The channel modeler and the designer/developer must also agree upon the nature of the physical environment(s) to be considered and the manner in which the transmitting and receiving antennas will be deployed. This will be often be captured in the form of *usage scenarios* that will describe, in broad terms, how devices that employ the technology will be used. They must also decide whether the model is to be broadly representative of the scenarios in which wireless devices based upon the technology are likely to be used, *i.e., site-general*, and the extent to which it must capture the manner in which the channel parameters depend upon the design parameters that describe the configuration of the link.

The nature and degree of the propagation impairments observed on a wireless channel will be affected by the gains, beamwidths, polarizations and orientations of the transmitting and receiving antennas. If the width of the angle of arrival distribution of incident signals is narrower than or at least comparable to the beamwidth of the receiving antenna, then one can usually separate the distortions introduced by the wireless channel (which are captured by the channel model) from the distortions introduced by the antennas (which are captured by the antenna model). If the two sets of distortions cannot be easily separated, one often has little choice but to model them together. The combination of the wireless channel and the transmitting and receiving antennas is often referred to as the *radio channel.*

The nature and degree of the propagation impairments also depend upon many design parameters and environmental factors including the carrier frequency, the distance between the transmitting and receiving antennas, the relative heights of the antennas above ground level, the nature, height and density of the scatterers in the environment and the nature of any obstructions that lie between the antennas. The decision to fix a design parameter or environmental factor, treat it as an independent variable or simply ignore it will depend upon: (1) the extent to which the channel parameters are affected by that design parameter or environmental factor and (2) the likely range of values which the design parameter or environmental factor might take on in the usage scenario.

The channel modeler and the designer/developer must decide whether to develop the model by simulation, by measurement, or some combination. Although simulation-based methods such as ray tracing are potentially less expensive and time-consuming than measurement-based approaches, they are limited by the assumptions upon which they are based and the possibly tremendous amounts of detail regarding the type and location of the scatterers in a typical environment that one may need to supply to them. Measurement-based methods are widely used to characterize wireless channels because they can provide results that are: (1) of immediate use to designers and developers and (2) useful in the validation of results obtained from simulation-based methods. The limitations of measurement-based approaches are described in the next section. Measurement- and simulation-based approaches to channel modeling are increasingly seen as complementary; many channel modeling studies employ both approaches.

Once the decision to collect channel measurement data has been made, whether as the primary basis for the channel model or to validate simulation results, the channel modeler must configure a suitable channel sounder. Alternative approaches are described in the next section. Important considerations include: (1) whether the channel is static or time-varying, (2) the nature of the antennas, including the manner in which the antenna pattern varies with frequency and, if applicable, the degree of mutual coupling between co-located antennas, (3) non-linearities in the transfer functions of active devices used in the instrument, especially if multi-carrier or other complex signals are used as stimulus signals, (4) the amount of phase noise in signals generated by oscillators in the system, (5) the size, weight, and transportability of the equipment, (6) the sensitivity of the equipment to the environment, especially temperature and (7) cost.

The next step is to collect the required measurement data and reduce them, *i.e.,* extract the channel parameters of interest. Often, measurement campaigns are conducted in two stages, as depicted in Fig. 2. Development runs are used to assess the performance of the channel sounder, identify potential models against which the measurement data can be reduced, and to provide an opportunity to fine-tune the instrument and the data collection protocol as required. Upon completion of the development runs, production runs are conducted in order to collect the vast amount of measurement data required to yield statistically reliable results. In order to en-

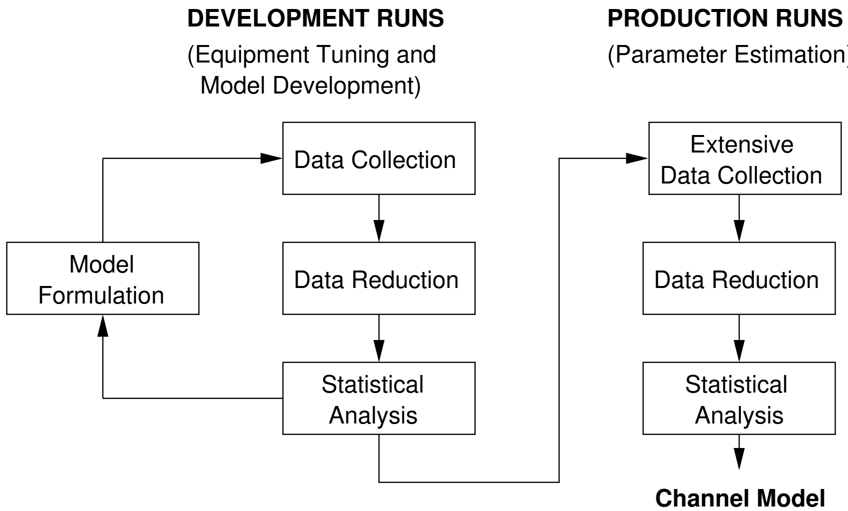

Fig. 2 Development of measurement-based channel models.

sure the consistency of the data set collected during production runs, changes to the equipment and/or the data collection protocol are strongly discouraged. The next step is to estimate the channel parameters and their marginal distributions, mutual correlation, relationship to environmental and design parameters and so forth. The final step is to cast the results in the form of a model useful in the analysis, design and simulation of wireless communications systems and verify that the model is consistent with the measurement data upon which it is based.

5 Measurement of Wireless Channels

An instrument used to measure the response of a wireless channel is a stimulus-response test set commonly referred to as a *channel sounder*. Depending upon the aspects of the channel that are of interest, a channel sounder may take many different forms. A useful approach to classifying channel sounders distinguishes between instruments used to collect narrowband channel response data, wideband channel response data and channel response data collected using multiple transmitting and/or receiving antennas.

Narrowband Channel Sounders. The simplest channel sounder consists of a source that transmits a single carrier and a narrowband receiver that measures the received signal strength at a remote location. Because single carrier measurements only capture the channel response at a single frequency, the temporal resolution is effectively infinite and one cannot distinguish between replicas of the signal that arrive with different delays. In order to obtain useful estimates of the broadband path loss from single carrier measurements, one must obtain the average values of the received signal strength based upon data collected by temporal and/or spatial sampling.

Wideband Channel Sounders. Transmitting a single carrier but sweeping it across numerous frequencies in quick succession and in synchronization with a tunable narrowband amplitude-only receiver allows one to measure the scalar frequency response of the channel. In cases where the position of the receiving antenna is fixed, such an approach allows one to suppress multipath fading by computing averages taken over frequency instead of location. Because this method does not permit one to measure the phase of the frequency response, one cannot estimate the channel impulse response by applying the inverse Fourier transform to the measured data.

A vector network analyzer (VNA) is a swept-frequency stimulus-response test set that measures the complex frequency response of a system by sweeping a single carrier across numerous frequencies in quick succession and comparing the amplitude and phase of the received signal at each frequency with those of the corresponding transmitted signal. Using a VNA to directly measure the complex frequency response of the channel allows one to recover the channel impulse response by applying the inverse Fourier transform to the measured response. While VNAs are frequently used to measure channel responses over short ranges, especially in indoor or enclosed spaces, their usefulness is limited by: (1) the relatively slow rate at which individual frequency sweeps are collected and the resulting need to ensure that the channel is either static or, at the very least, changes over time scales far longer than the frequency sweep time, (2) the size and weight of most VNAs which generally renders them too large to be considered portable, and (3) the special effort required to synchronize the transmitter and receiver and provide amplitude and phase references over ranges greater than a few hundred metres.

The first practical method for measuring the wideband channel response over wide areas was reported by Cox [7] in the early 1970's. The technique involves transmitting a wide-band pseudo-random noise (PRN) signal and correlating the signal observed at the receiver with an identical PRN signal. The signal that appears at the output of the correlator is the complex impulse response of the channel. In modern versions of such channel sounders, the receiver is often a vector signal analyzer (VSA). A VSA is an RF tuner followed by a pair of high-speed analog-to-digital converters and a deep sample capture memory that allows one to record a complex time series that includes the in-phase and quadrature components of the received signal. The cross-correlation between the received signal and the PRN signal is then performed in software. The resolution of the channel sounder and the maximum resolvable delay are set by the chip duration and the length of the PRN sequence.

An alternative approach to broadband channel sounding involves transmitting a signal composed of multiple carriers with prescribed amplitude and relative phase, using the VSA to estimate the complex frequency spectrum, then taking the inverse Fourier transform of the complex envelope to recover the channel impulse response. In this case, the resolution of the channel sounder and the maximum resolvable delay are set by the number of carriers and the frequency interval between them.

Whether one is transmitting pseudo-random noise or multiple carriers, one is effectively collecting frequency response data at all points simultaneously and thereby avoiding the blind time associated with the swept-frequency approach. VSA-based channel measurement schemes suffer from various limitations: (1) The maximum bandwidth that one can measure is determined by the maximum rate at which the analog-to-digital converters in the VSA's front-end can sample the received signal, (2) the maximum sample duration that one can measure is determined by the size of the deep memory used to store the received signal, and (3) the dynamic range and sensitivity of the receiver are determined by the resolution of the analog-to-digital converters in the VSA's front-end.

Multi-Antenna Measurements. Use of multiple transmitting and receiving antennas in conjunction with suitable signal processing or data reduction techniques allows one to characterize aspects of the channel that depend upon the distribution of angles at which signals leave the transmitter and/or arrive at the receiver, *e.g.,* the correlation between the fading signals observed at each antenna element in spatial diversity and MIMO transmission schemes. The simplest approach involves using fixed antennas at the transmitter and/or receiver. Mounting a single antenna on a mechanical positioner and moving it through a sequence of closely spaced points in space allows one to generate a virtual array and thereby characterize spatial correlation, temporal correlation, and angle-of-arrival distributions. Full characterization of MIMO channels involves estimating the angle-of-arrival distribution observed at the receiver for rays launched at each of the possible angles-of-departure from the transmitter. The result is referred to as a *double-directional channel model* [16].

Limitations of Measurement-Based Methods. Direct measurement of a wireless channel offers several advantages, as outlined in the previous section. However, the approach has several limitations: (1) It often takes considerable time and effort to collect and reduce a statistically significant amount of data. Moreover, redoing measurements if errors are found is equally time-consuming. (2) In many environments, the size, weight and power consumption of the measurement equipment can be problematic. (3) If the width of the angle-of-arrival distribution exceeds the beamwidth of the antenna, then it will be difficult to separate distortions introduced by the channel from distortions introduced by the antenna. (4) It is generally difficult to accurately measure the phase difference between the transmitted and received signals unless steps are taken to substantially reduce frequency drift and phase noise, *e.g.,* through a direct connection between the transmitter and receiver or use of precise frequency standards. (5) The expense and complexity of the measurement system increases rapidly as the measurement goals become more sophisticated. (6) Before applying the results, one must confirm that the measurement environment is sufficiently similar to the deployment environment. Nevertheless, the measurement-based approach has proven to be sufficiently useful and productive that it will likely remain the principal method for characterizing wireless channels for many years to come.

6 Recent Advances in Channel Modeling

In this last section, we review recent advances in channel modeling that have been motivated by the introduction of new signaling schemes (UWB and MIMO), new environments (body-centric communications and short-range vehicular environments) and/or new frequency bands (the 60 GHz and THz bands).

6.1 Channel Models for Ultrawideband Wireless Systems

In February 2002, the FCC released a report and order (R&O) that authorized the use of short-range wireless links that use at least 500 MHz of bandwidth between 3.1 and 10.6 GHz. The R&O limited the effective isotropic radiated power (EIRP) to -41.3 dBm/MHz or less in order to limit the interference that such ultrawideband (UWB) devices may cause to other services. Such a limit was deemed appropriate for UWB links of 10 metres or less. From 2002-2007, the ITU-R's Task Group 1/8 under Study Group 1 assessed the compatibility between UWB devices and other radiocommunication services and prepared recommendations for UWB regulations. Since then, most jurisdictions around the world have authorized UWB devices although many allocations are considerably more restrictive than that authorized by the FCC.

The lead up to and release of the FCC R&O played a crucial role in stimulating interest in the potential of UWB wireless technology amongst both developers and researchers. In late 2001, the IEEE 802.15 Working Group on Wireless Personal Area Networks formed Study Group 3a (SG 3a) to assess the potential for developing a UWB-based physical layer (PHY) that could support data rates of hundreds of Mb/s over ranges of up to 10 metres subject to the restrictions imposed by the FCC's emission mask. In late 2002, Study Group 4a (SG 4a) was formed with a mandate to assess the potential for developing a UWB-based PHY layer that would replace much of the functionality of ZigBee wireless technology but with lower power consumption and adding accurate real time location services (RTLS). SG 3a and 4a became full Task Groups in 2002 and 2004, respectively.

The FCC's decision to effectively restrict UWB data communication to the band from 3.1 to 10.6 GHz eliminated impulse radio from contention as the basis for a PHY layer for such systems and created a need for a fresh effort to characterize the UWB channel. One of the first tasks of the UWB SGs was to develop channel models suitable for fairly comparing alternative PHY and MAC layer proposals. Because IEEE 802.15.3a's main focus was on high speed peripheral interconnect in residential and office environments, they produced four channel models that correspond to: LOS 0-4 m, NLOS (0-4 m), NLOS (4-10 m), and a extreme NLOS multipath channel based upon a 25 ns RMS delay spread [17]. Because IEEE 802.15.4a's main focus was on sensor networks, they took a different approach and produced eight channel models that correspond to residential, office, outdoor and industrial environments [18]. They also produced a channel model for body area networks based upon UWB wireless technology, as will be described in more detail in a later section.

The results of the IEEE 802.15 channel modeling efforts reflect the notion that UWB channels differ from conventional wideband channels in several important respects: (1) UWB devices operate over a very wide frequency range so both the distance and frequency dependence of path loss must be accounted for. (2) The extremely wide bandwidth occupied by a UWB signal allows the system to resolve extremely fine detail in the channel impulse response. Because the resolvable delay bins are so narrow, sparse channels with significant delays between resolvable MPCs often occur. The small-scale fading statistics are different from the wideband case because each resolvable MPC consists of fewer physical MPCs. (3) The frequency dependence of path loss distorts individual MPCs such that the time varying impulse response given in (1.11) is now given by

$$h(t,\tau) = \sum_{i=1}^{N} a_i(t)\chi_i(t,\tau) * \delta(\tau - \tau_i), \tag{17}$$

where $\chi_i(t,\tau)$ denotes the time-varying distortion of the ith echo due to frequency selective interaction with the environment and $*$ denotes convolution. Because adjacent taps are influenced by a single physical MPC, the WSSUS assumption is no longer valid [19].

The density of scatterers varies greatly between environments. In most environments, the density of scatterers is low to moderate so clustering of MPCs can easily be observed. In other environments, the density of scatterers is so high that one cannot resolve individual clusters. IEEE 802.15.4a adopted two alternative models for the CIR. In the sparse, multi-cluster case, the modified Saleh-Valenzuela model applies and the shape of the corresponding power delay profile is given by the product of two exponential functions,

$$E\{|a_{k,\ell}|^2\} \propto \exp(-T_\ell/\Gamma) \cdot \exp(-\tau_{k,\ell}/\gamma), \tag{18}$$

where Γ and γ are the cluster and ray decay constants, respectively, T_ℓ is the delay of the ℓth cluster, and $\tau_{k,\ell}$ is the delay of the kth ray within the ℓth cluster. As noted earlier, the cluster-based S-V model is only one of several options for modeling UWB channels. Other simpler models, including a single exponentially decaying cluster with lognormal variation, have been found to provide a representation with equal statistically validity over a wide range of deployment scenarios within typical residential and commercial environments [20].

In the dense, single cluster case, the envelope of the PDP can be described as

$$E\{|a_{k,\ell}|^2\} \propto (1 - \chi \cdot \exp(-\tau_{k,\ell}/\gamma_{rise})) \cdot \exp(-\tau_{k,\ell}/\gamma_1), \tag{19}$$

where χ denotes the attenuation of the first component, γ_{rise} describes how quickly the PDP rises to its maximum value and γ_1 describes the decay after the maximum has been reached.

Although 802.15.4a found that the cluster arrival times are well-described by a Poisson process, the inter-cluster arrival times are exponentially distributed, i.e.,

$$p(T_\ell | T_{\ell-1}) = \Lambda_\ell \exp\left(-\Lambda_\ell (T_\ell - T_{\ell-1})\right), \ell > 0, \tag{20}$$

where Λ_ℓ is the cluster arrival rate (assumed to be independent of ℓ). 802.15.4a models ray or resolvable MPC arrival times as a mixture of two Poisson processes where

$$\begin{aligned} p(\tau_{k,\ell} | \tau_{(k-1),\ell}) = {} & \beta \lambda_1 \exp[-\lambda_1 (\tau_{k,\ell} - \tau_{(k-1),\ell})] \\ & + (1-\beta)\lambda_2 \exp[-\lambda_2 (\tau_{k,\ell} - \tau_{(k-1),\ell})], k > 0, \end{aligned} \tag{21}$$

β is the mixture probability and λ_1 and λ_2 are the ray arrival rates. In cases where the ray density is high and leads to a high MPC arrival rate, the CIR is represented by a tapped delay line model with regular tap spacings.

Details of the manner in which the propagation channel affects various UWB transmission schemes, including time-hopping impulse radio systems, direct sequence spread spectrum (DSSS) systems, orthogonal frequency multiplexing (OFDM) systems and multiband systems are described in [19]. For example, the number of resolvable MPCs determines the number of fingers that a rake receiver will require in order to capture enough of the energy in the received signal. The range and coverage of UWB systems tend to degrade as the carrier frequency increases and the free space path loss and diffraction losses both increase.

6.2 Channel Models for MIMO-based Wireless Systems

Consider a wireless communications system that uses only one transmission path to send data. Shannon's Law gives the maximum capacity C_1 of the link in bits/s/Hz as

$$C_1 = \log_2(1+\rho) \tag{22}$$

where ρ is the signal-to-noise ratio (SNR) at the receiver input. In practice, scattering by objects in the environment leads to multiple transmission paths between the transmitter and receiver. Such paths are often so closely spaced in angle that one cannot distinguish between them through simple beamforming. Instead, a more sophisticated approach is used which is based upon the use of *space-time* coding to distribute the data stream over the N_T transmitting antennas and recover the stream by suitably combining the signals received by the N_R receiving antennas [21]. Because the multiple transmission paths fade independently of each other, this approach also increases overall link reliability. Numerous methods for realizing MIMO-based systems in this manner have been proposed over the past decade [22].

The capacity C of a MIMO-based system with N_T transmitting antennas and N_R receiving antennas (in bits/s/Hz) is given by

$$C = \log_2\left[\det\left(\mathbf{I}_{N_R} + \frac{\rho}{N_T}\mathbf{H}\mathbf{H}^*\right)\right], \tag{23}$$

where $(*)$ denotes the transpose-conjugate, $\mathbf{H}$ is the $N_R \times N_T$ channel matrix and we have assumed that the N_T sources have equal power and are uncorrelated [21]. Further analysis suggests that the capacity of the system will reach its peak when the transmission paths experience uncorrelated Rayleigh fading. However, full appreciation of the strengths and limitations of these schemes requires that their performance be assessed in realistic propagation environments. A variety of analytical and model-based approaches have been proposed [23].

The most obvious way to characterize the MIMO wireless channel is to configure a channel sounder that directly characterizes $\mathbf{H}$. In a *true array* system, the channel sounder incorporates the coding and signal processing required to estimate all of the elements of $\mathbf{H}$ simultaneously. In a *switched array* system, the channel sounder is simplified by using high-speed switches to sequentially connect a single transmitter and a single receiver to all possible pairs of elements in the transmitting and receiving arrays in turn before the channel changes appreciably. Although such systems closely resemble practical MIMO-based systems and can accommodate time-varying channels, (1) the results are tied to specific antenna types and configurations, (2) it is difficult to separate the effects of mutual coupling between array elements from the correlation between transmission paths, and (3) the measurement system is relatively complex and expensive.

In a *virtual array* system, the channel sounder uses a single transmitter and receiver (*e.g.,* a VNA) connected to single transmitting and receiving elements, respectively. Precision mechanical positioners moves the transmitting and receiving elements to the points that define the virtual transmitting and receiving arrays. Such a system is much more versatile than the true or switched array systems because: (1) it eliminates the effect of mutual coupling and (2) it allows an arbitrarily large number of points in the virtual array to be evaluated. Its major shortcoming is that it may take several minutes to translate the antenna elements to all of the points in the virtual array. Accordingly, the technique is mostly used in static indoor environments.

If the virtual receiving array is sampled finely enough and at enough points with the transmitting antenna fixed, it is possible to resolve the angle-of-arrival distribution at the receiving antenna using an AoA estimation algorithm such as ESPRIT or similar. The width of the AoA distribution is a strong indicator of the correlation between fading experienced at the output of adjacent antenna elements. If the frequency response of the channel is measured at each point, then the channel impulse response can also be estimated. Correlating the time-of-arrival associated with a given MPC with the corresponding angle-of-arrival allows one to estimate the spatial channel model that describes the propagation environment and to determine the extent to which scatterers form spatial clusters [14].

A *directional channel sounder* uses virtual arrays at both ends of the link to more fully account for the characteristics of the antennas and local scatterers. As above, the finite time required to sample the virtual array limits the approach to characterizing static channels. In essence, a directional channel sounder allows one to resolve the effect that a ray leaving the transmitter in a particular direction has on the time-of-arrival and angle-of-arrival distributions observed at the receiver. Directional channel models capture all of the information required to analyze a MIMO link and estimate its capacity [16].

Once the MIMO channel has been characterized, perhaps by a combination of simulation and measurement-based methods, designers and developers can begin using the channel models that describe environments of interest to design, test and evaluate the performance of alternative antenna configurations, signaling schemes and space-time-codes. IEEE 802.11 TGn proposed a set of wideband MIMO channel models appropriate for comparing the performance of MIMO-based wireless LANs [24]. In the TGn channel models, each tap in the CIR is described by a channel matrix $\mathbf{H}$ which is resolved into a fixed LOS matrix $\mathbf{H}_F$ and a Rayleigh NLOS matrix $\mathbf{H}_v$,

$$\mathbf{H} = \sqrt{P}\left(\sqrt{\frac{K}{K+1}}\,\mathbf{H_F} + \sqrt{\frac{1}{K+1}}\,\mathbf{H_v}\right), \tag{24}$$

where K is the Ricean K-factor and P is the power contained in each tap. Because it is assumed that each tap contains a number of individual rays or physical MPCs, the complex Gaussian assumption can be justified. The correlation between antenna elements is determined by the *power angular spectrum* (PAS). Given the receive and transmit correlation matrices $\mathbf{R}_{tx}$ and $\mathbf{R}_{rx}$, respectively, $\mathbf{H}_v$ is given by

$$\mathbf{H}_v = \mathbf{R}_{rx}^{1/2}\,\mathbf{H}_{iid}\,\left(\mathbf{R}_{tx}^{1/2}\right)^T \tag{25}$$

where $\mathbf{H}_{iid}$ is a matrix of independent zero mean, unit variance, complex Gaussian random variables and the elements of $\mathbf{R}_{tx}$ and $\mathbf{R}_{rx}$ are the complex correlation coefficients between the ith and jth antennas in the transmitting or receiving array, respectively. An alternative approach uses the Kronecker product of the transmit and receive correlation matrices. TGn specified six models of this form that correspond to RMS delay spreads ranging from 0 to 150 ns.

3GPP and, later, the WINNER project, proposed a set of MIMO channel models appropriate for comparing the performance of MIMO-based systems used to provide wide area coverage in macrocell environments [25] [26]. For each of the scenarios considered, the WINNER project produced two types of channel models. The first is a generic model which captures the double-directional channel including the amplitude, phase, delay, angle-of-departure, angle-of-arrival and polarization of each ray in a manner which is independent of the details of the transmitting and receiving arrays. The second is a reduced-variability model which is suitable for calibration and comparison simulations. The results of the TGn, 3GPP and WINNER standards group activities and related COST actions concerning MIMO-based systems are summarized in [27].

6.3 Channel Models for Body Area Networks

Body area networks (BANs) are compromised of wireless links between ultra low power (ULP) wireless devices located in close proximity to the human body. Such devices may be implanted within the body (implanted nodes), attached to the skin, embedded within clothing, mounted on items attached to or carried by the body (body surface nodes), or located at distances up to 5 m away (external nodes). They may be used to: (1) monitor the physiological condition of an individual for health care, athletic training and workplace safety applications, (2) monitor environmental hazards in the vicinity of an individual in order to enhance workplace safety, (3) monitor and control the state of protective gear or safety equipment worn by individuals in hazardous environments, (4) communicate with other ULP devices in the immediate vicinity for personnel monitoring and authentication applications, (5) provide the individual with the means to command and control the ULP sensors and devices in his vicinity, *e.g.,* through a wrist-, arm- or chest-mounted control panel, and/or (6) relay signals from ULP wireless devices to distant networks, *e.g.,* wireless LAN or cellular networks [28] [29].

Implementation of the wireless sensor nodes intended for use in body area networking applications presents special challenges. Not only must they be physically small in order to be unobtrusive, they must operate from the same small battery for periods ranging from weeks to months at a time. Although simple transmitter-receiver pairs have been used to establish wireless connections in applications that involve just a pair of nodes, the effort required to provide them with full networking capabilities would be considerable. As a result, much interest has focused on devices based upon existing ULP wireless networking standards such as Bluetooth low energy (BLE), ZigBee and IEEE 802.15.4a. At the same time, it is widely recognized that the wireless propagation environment in the vicinity of the human body is considerably different from the personal area and sensor network environments for which existing standards were developed. As a result, other techniques, such as near-field techniques have been considered. In recognition of the growing interest in body area networking and the limitations of existing standards, IEEE 802.15 recently formed TG6 to develop a short-range wireless communication standard that has been optimized for this purpose.

Wireless signals may propagate from one sensor node to another via three types of paths: (1) through the body, (2) around the body and (3) reflection or scattering from objects in the surrounding environment. Both electromagnetic field simulation studies and direct measurement have shown that propagation through the body is negligible at UHF frequencies and above. It is important to distinguish between direct transmission around the body and scattering from objects in the environment. Otherwise, link performance in open areas that have relatively few scatterers could be overestimated. In body area networking applications, antennas are located in close proximity to the body and their radiation characteristics are greatly affected. Determination of the extent to which antenna effects can be separated from propagation effects is an ongoing issue in body area channel modeling studies [30].

The first standardized model for body area networking environments was produced by IEEE 802.15.4a [18]. Additional details were reported in [31] and [32]. It applies to UWB propagation between 3.1 and 10.6 GHz. The researchers characterized the body area channel using two alternative approaches: electromagnetic field simulation based upon the finite-difference time-domain (FDTD) approach and direct measurement using a VNA. Their major findings include: (1) the distance around the perimeter of the body is the correct measure of transmitter-receiver separation, (2) there are always two clusters of MPCs in the channel response - one due to direct transmission around the body and the second due to reflection from the ground, and (3) the small-scale fading statistics are best described by a lognormal distribution.

Their 802.15.4a BAN path loss model distinguishes between devices that are placed on the same side of the body and on opposite sides. The separation between clusters depends upon the position of the transmitting and receiving antennas with respect to each other and the ground. To incorporate this effect easily but without unduly complicating the model, they defined three scenarios corresponding to the transmitter placed on the front of the body and the receiver placed on the front, side or back of the body. The distance ranges for those environments are 0.04-0.17 m, 0.17-0.38 m, and 0.38-0.64 m, respectively. Within each cluster, the very short transmission distances result in ray arrival times that are shorter than the delay resolution of the systems that they considered. Accordingly, they used a tapped delay line model to represent each cluster.

While several earlier efforts by others produced anecdotal results, IEEE 802.15.4a was the first to collect and reduce sufficient data to produce a preliminary model suitable for use in simulation. Their basic model is conservative; it does not include the effects of scattering from the environment which may be important if the receiver is otherwise well shadowed. However, they have suggested methods by which such scattering could be incorporated if required. The main purpose of the TG4a BAN channel models is to allow fair comparison of the performance of alternative PHY and MAC layer proposals. They are not intended to predict absolute measures of performance, nor do they address some important issues relevant to network layer issues. Thus, while TG4a's work represents a significant milestone in the characterization of UWB BAN channels, much additional measurement data is required and much additional work remains.

In January 2007, IEEE 802.15.6 formed a channel modeling committee and directed it to produce a new set of BAN channel models that will allow alternative PHY and MAC proposals to be fairly compared under its own standardization efforts. The committee presented its final report in November 2008 [33]. Their scenarios covered transmission between implanted, body surface and external nodes. The scenarios involving implants were limited to the 402-405 MHz band. The scenarios involving nodes on the body surface include the 13.5 MHz, 5-50 MHz, 400 MHz, 600 MHz, 900 MHz, 2.4 GHz, and the 3.1-10.6 GHz bands. The scenarios involving external nodes were limited to the 900 MHz, 2.4 GHz, and the 3.1-10.6 GHz bands. The effect of body posture and body movement was included. Although the models formulated by TG6 represent a significant advance over those formulated by TG4a, they suffer from the same limitations: They are based on a limited amount of measurement data and are not suitable for predicting absolute performance. Once again, much additional work remains.

6.4 Channel Models for Short-Range Vehicular Networks

Intelligent transportation systems (ITS) are a suite of emerging technologies that will be used to make operation of land vehicles in urban centres or along transportation corridors safer and more efficient. A variety of wireless technologies have been proposed and/or evaluated for use in ITS applications including RFID technology, wide area cellular networks, and mobile satellite networks. Because much of the information that will be delivered and exchanged in ITS applications is time-sensitive and location-dependent, short-range vehicular networks have attracted particular interest in recent years.

Short-range vehicular networks comprise short-range wireless links between a vehicle (via an *onboard unit* (OBU)) and roadside units (also known as *roadside equipment* (RSE)) to form *vehicle-to-infrastructure* (V2I) networks, and between a vehicle and other vehicles in the immediate vicinity to form *vehicle-to-vehicle* (V2V) networks. Anticipated applications of such networks include: (1) enhancing traffic safety by providing warnings and alerts in real time, (2) easing traffic congestion by adaptively changing traffic rules, (3) providing location-dependent information to drivers, (4) aiding traffic regulation enforcement, (5) enabling electronic payments and toll collection, (6) assisting in direction and route optimization, (7) providing information concerning services for travelers and (8) enabling automated highways.

Although interest in the potential for short-range vehicular networks to enable ITS applications dates back almost two decades, a major impediment to progress was the lack of a common, interoperable hardware platform that could be used in each of the envisioned roles. In the early 1990's, the ITS community proposed: (1) that a standard for Dedicated Short Range Communications (DSRC) be developed in order to meet this need, (2) that such systems be deployed in or near the 5.8 GHz ISM band, and (3) that it support data rates of at least 1 Mb/s. Since the early 1990's, the European, Japanese and American standards for DSRC have taken different paths. European and Japanese DSRC systems are single-carrier systems and are in active use, although mostly for electronic toll collection. In the United States, the DSRC standard is based upon IEEE 802.11p, a variant of the IEEE 802.11a OFDM-based standard that can operate in various licensed and license-exempt bands between 4.9 and 5.9 GHz and which incorporates enhancements to its MAC layer that are required for successful operation in mobility environments [34].

Usage models for short-range vehicular environments must account for four main features of the environment: (1) the nature of the link (V2V or V2I), (2) the speeds of the vehicle(s) at each end of the link, (3) the nature of surrounding environment and (4) the density and speed of the vehicles that comprise the surrounding traffic.

The number of combinations is large so some discretion is required when selecting the subset to be characterized. Once the usage models have been identified, the characteristics of the link may be determined either by simulation using ray-tracing combined with realistic models of objects in the environment, *e.g.,* [35] or by direct measurement using a channel sounder that has been deployed in representative environments.

As with channel models for other environments, a short-range vehicular channel model must account for (1) variation of signal strength with distance, (2) variation of signal strength over time and (3) time dispersion of the signal or, equivalently, the frequency selectivity of the channel. However, the vehicular environment is considerably more dynamic than other environments. First, at least one end of the link is a vehicle in motion. Second, many of the other vehicles that can obstruct or shadow that link are also in motion. Third, if the antennas used by the OBUs are placed below rooftop level, the vehicle itself will obstruct or shadow the link in certain directions. As a result, short-range vehicular channels are both time and frequency selective.

Measurements of the vehicular channel have recently been reported by several researchers, including [36], [37] and [38]. Although differences between the scenarios considered make direct comparisons difficult, some general conclusions can be drawn. First, unlike macrocell channels, which experience their longest delay spreads in open areas such as expressways or bridges where distant scatterers can make significant contributions to the response, short-range vehicular channels are influenced almost exclusively by local scatterers and experience their longest delay spread in street canyons under NLOS conditions whether they are formed by buildings in urban areas or by large trucks in the vicinity of the vehicle in highway environments. Second, shadow fading occurs much more rapidly in vehicular environments than in macrocell environments because the dominant obstructors are both smaller and closer to the vehicular terminal and are often in motion relative to the vehicle. Third, the Doppler spectrum frequently deviates from the classic U-shaped spectrum. This is likely due to the AoA distribution being extremely non-uniform.

Comparisons of the channel impulse responses experienced on vehicular and macrocell channels also show significant differences. First, taps in the channel impulse response persist for a much shorter time than in macrocell environments due to rapid changes in the configuration of the scatterers that contribute to the response. Finally, the amplitude distributions experienced on individual taps is frequently best described by a Nakagami distribution with an m-factor of less than 1, *i.e.,* worse than Rayleigh. In any case, measurement-based modeling of vehicular channels is still at an early stage and standardized channel models have not yet been adopted by any of the major groups that are responsible for setting DSRC standards and certifying DSRC equipment.

6.5 Channel Models for 60 GHz and Terahertz Systems

In recent years, several groups have proposed that new wireless technologies capable of delivering data rates at 1 Gb/s and above be developed for deployment in the 60 GHz band. Such technologies would permit wireless replacement of very high speed short-range wired connections such as those based upon IEEE 802.3-2005 (Gigabit Ethernet) or IEEE 1394b-2002 (FireWire 800) [39]. Others with a longer view have proposed that new technologies capable of delivering data rates of 10 GB/s and above be developed for use in the unlicensed band between 300 GHz and 1 THz [40]. Proponents acknowledge that THz technology is still in its infancy and it will take at least a decade to deliver THz wireless devices to consumers.

Propagation at 60 GHz. At frequencies above 10 GHz, absorption due to atmospheric water vapor and oxygen play a significant role in determining the useful range of wireless links. In particular, wireless links that are deployed near the oxygen absorption line near 60 GHz experience losses of 10-15 dB/km beyond the usual free space and diffraction losses. While this precludes the use of 60 GHz systems for links longer than about 2 km, the losses are entirely manageable for: (1) LOS links used to provide last mile connectivity in outdoor environments or (2) NLOS links used within a room in a home or office. Moreover, the rapid reduction in signal strength with distance is advantageous because it drastically reduces the interference caused by nearby systems in the same band and permits much denser deployment and a higher rate of frequency re-use than would otherwise be possible.

In recent years, spectrum regulators around the world have allocated a large amount of spectrum near 60 GHz for use by short-range wireless systems. In the United States and Canada, the band from 59 to 64 GHz has been allocated to license-exempt applications with a maximum output power of 27 dBm and an average power density that does not exceed 9 μW/cm^2, as measured 3 metres from the radiating structure. In Japan, the band from 59 to 66 GHz has been allocated to license-exempt applications with a maximum output power of 10 dBm and a maximum effective isotropic radiated power of 57 dBm. Other jurisdictions, including Australia and Korea, have made similar allocations. It is widely expected that Europe and most remaining jurisdictions will soon follow. Compared to the regulatory hurdles which have plagued UWB outside the United States, the situation in the 60 GHz band is much more favorable [41].

Standards Activities at 60 GHz. Various standards groups are actively developing wireless technologies suitable for providing short-range multi Gb/s connectivity at 60 GHz. IEEE 802.15's Task Group 3c is developing a 60 GHz alternative physical layer for the high rate Wireless Personal Area Network (WPAN) developed by Task Group 3. In Europe, Ecma TC 48 is developing a similar standard. Various other groups are also developing technologies and/or proposing competing standards, including the WirelessHD consortium led by Broadcom, Intel, LG Electronics, Panasonic, NEC, Samsung, SiBEAM, Sony and Toshiba. Although most groups have defined specific usage models in which the proposed systems are expected to operate at specified levels of performance, IEEE 802.15c plans the most ambitious coverage and is apparently the only group to sponsor a channel modeling committee.

The IEEE 802.15.3c channel modeling committee proposed channel models corresponding to LOS and NLOS links in residential, office, library, desktop environments (CM 1-8) and in a kiosk environment (CM-9). In the channel modeling committee's final report, they emphasize that their usage models are only representative of the many scenarios in which 60 GHz equipment might be deployed. The models that the committee has proposed are based upon measurement results that have been reported in the published literature, *e.g.* [42] and submitted directly to the committee [43].

The IEEE 802.15.3c 60 GHz channel models bear many resemblances to the IEEE 802.15.3a/4a 3.1-10.6 GHz UWB channel models. First, as in the UWB case, path loss depends upon both frequency and distance so their path loss models have been designed to capture both. Second, as in the UWB case, the occupied bandwidth of the signal is sufficiently wide that the channel impulse response is revealed with very fine resolution and MPCs are observed to arrive in clusters. Accordingly, the 60 GHz CIR model is also based upon the Saleh-Valenzuela model with extensions that capture certain unique aspects of the LOS component. The distribution of the cluster arrival and ray arrival times are described by a pair of Poisson processes. Analysis of measurement data has shown that both the cluster and ray amplitudes can be modeled by lognormal distributions.

Because the carrier frequency is so high, even walking speeds (1.5 m/s) can lead to Doppler spreads of several hundred Hertz. Unlike IEEE 802.15.3a or 4a, the IEEE 802.15.3c channel model also captures the angular spread of the channel response in the form of a power azimuth profile distribution. The distribution of the cluster mean angle-of-arrival, conditioned on the AoA of the previous cluster, is uniform. The ray AoAs within each cluster are modeled either by zero-mean Gaussian or zero-mean Laplace distributions.

The committee's task was made more difficult by the relative lack of 60 GHz channel measurement data that has been reported in the literature, and, in particular, the lack of measurement data that addresses the specific usage models proposed by the committee. While the committee's standardized models provide a useful basis against which alternative PHY or MAC layer proposals for use in 60 GHz systems can be evaluated and compared, further measurement campaigns are required in order to fill in key gaps.

Propagation in the THz Band. At frequencies between 300 GHz and 1 THz, atmospheric attenuation can reach hundreds of dB/km. At 300, 350, 410, 670 and 850 GHz, the atmospheric attenuation is sufficiently low, *i.e.,* less than 50 dB/km, to permit deployment of short-range links and the available bandwidth is approximately 50 GHz or greater. Only a few detailed studies of THz transmission in indoor environments have been reported to date, *e.g.,* [44]. Direct transmission will likely perform best but is extremely susceptible to accidental and/or intermittent blockage. As in the case of infrared wireless LANs, indirect transmission in which signals reach the receiver via reflections from walls and ceilings may offer more consistent performance. However, much work remains in order to determine the performance that can be achieved in typical usage scenarios.

7 Conclusions

During the next decade, a new generation of wireless technologies will further improve the performance and reliability of wireless systems while increasing the range of applications in which they can be used. Many of these systems will use new signaling schemes while operating in higher frequency bands and/or being deployed in harsher environments than ever before. The degree to which these new technologies will meet end user expectations will ultimately depend upon the accuracy and fidelity with which channel modelers characterize the impairments and distortions that these systems will experience under realistic conditions. Measurement- and simulation-based approaches to channel modeling are increasingly seen as complementary; many studies employ both. Recent progress by the channel modeling community suggests that both the developers and end users of these new systems will be well served.

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