Channel Models for Ultrawideband Personal Area Networks

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Abstract

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CHANNEL MODELS FOR ULTRAWIDEBAND PERSONAL AREA NETWORKS

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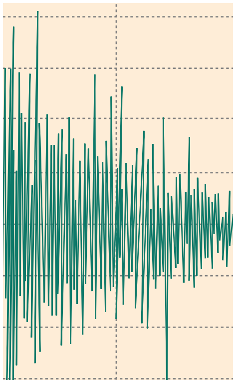

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ABSTRACT

This article describes the modeling of ultrawideband wireless propagation channels, especially for the simulation of personal area networks. The IEEE 802.15.3a standards task group has established a standard channel model to be used for the evaluation of PAN physical layer proposals. We discuss the standard model, the measurements that form its basis, and the possibilities for future improvements. The article points out the important differences between UWB channels and narrowband wireless channels, especially with respect to fading statistics and time of arrival of multipath components. The impacts of the different propagation conditions on system design, like Rake receiver performance, are elaborated.

INTRODUCTION

In recent years, ultrawideband (UWB) communications has received great interest from both the research community and industry. The potential strength of the UWB radio technique lies in its use of extremely wide transmission bandwidths, which results in desirable capabilities including accurate position location and ranging, lack of significant fading, high multiple access capability, covert communications, and possible easier material penetration. In February 2001, the American Federal Communications Commission (FCC) issued a report and order that allows the transmission of UWB signals if certain power restrictions are fulfilled. Other countries, especially Japan and Europe, are expected to issue similar rulings in the near future.

Because of the restrictions on the transmit power, UWB communications are best suited for short-range communications: sensor networks and personal area networks (PANs). The IEEE has established a standardization group, IEEE 802.15.3a, which is in the process of developing a standard for UWB PANs. The goals for this new standard are data rates of up to 110 Mb/s at 10 m distance, 200 Mb/s at 4 m distance, and higher data rates at smaller distances. Based on those requirements, different proposals are being submitted to 802.15.3a.

For the selection of the multiple access scheme, modulation, and other parts of the standard, a common channel model is required. Only a unique characterization of the channel guarantees a fair comparison of the different proposals. For this reason, IEEE 802.15.3a formed a subgroup for the development of such a channel model; its proposal was accepted by the full standardization group. In this article we describe this channel model, and discuss its strengths and weaknesses.

Wireless propagation channels have been investigated for more than 50 years, and a large number of channel models are available in the literature. The signal that has propagated through a wireless channel consists of multiple replicas (echoes) of the originally transmitted signal; this phenomenon is known as multipath propagation. The different multipath components (MPCs) are characterized by different delays and attenuations. The correct modeling of the parameters describing the MPCs is the art of channel modeling.

The first, and still most widely used, model is the flat Rayleigh-fading channel. The assumption of flat fading can be used when the considered system bandwidth is so small that the delays of the individual MPCs do not impact the system performance. Thus, at the receiver, *all* the MPCs can interfere (constructively or destructively). If there is a large number of MPCs, the *complex amplitude* has a complex Gaussian distribution, which results in a Rayleigh or Rician distribution of the amplitudes (envelope). This model has been sufficient for narrowband wireless systems.

Second- and third-generation cellular systems have larger bandwidths. Thus, the different delays of the multipath components influence the system performance, and have to be modeled. The power delay profile of the channel describes how much power arrives within a certain delay interval. For system analysis, the delay axis is typically divided into bins whose size is comparable to the inverse of the system bandwidth. If enough MPCs fall within such a delay

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bin, there is still interference between the MPCs, and the amplitude statistics *within each delay bin* is Rayleigh or Rice. Furthermore, we can anticipate that there are MPCs arriving within *each* delay bin. Several standardization organizations have developed models for system comparisons (GSM, W-CDMA, IEEE 802.11) that exhibit these basic properties.

However, all of those considerations were made for systems with a bandwidth of up to 20 MHz; such a system can resolve only paths whose run length difference is larger than 15 m. In UWB systems, the intended radiation can cover a bandwidth of almost 10 GHz, and the unintended radiation can cover an even larger frequency range. This large bandwidth can give rise to new effects. For example, only few multipath components overlap within each resolvable delay bin (resolvable run length is 3 cm), so the central limit theorem is no longer applicable, and the amplitude fading statistics are no longer Rayleigh. Also, there can be delay bins into which no MPCs fall, and thus are empty. It then becomes necessary to characterize the likelihood that this happens, and that an empty bin is followed by a full one. For a realistic performance assessment, a UWB channel model like the 802.15.3a standard model has to include all those effects.

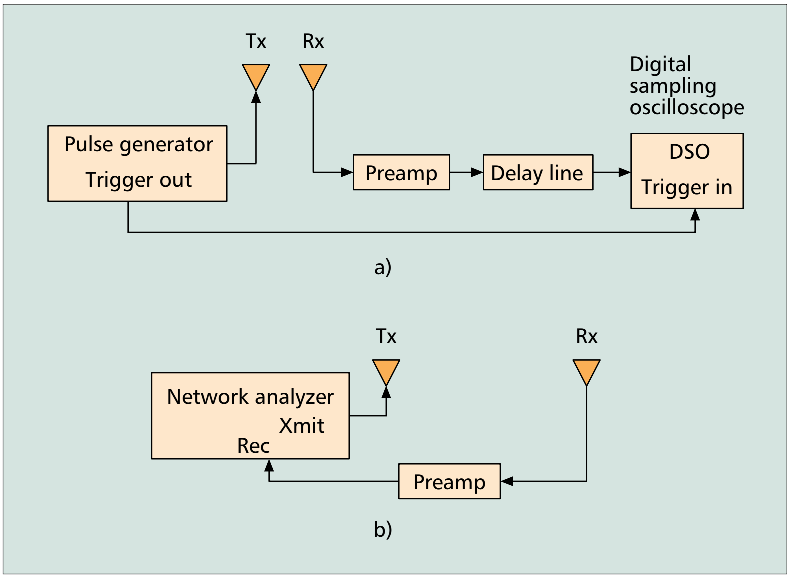
The remainder of the article is organized the following way: we discuss the measurements that form the basis of the model. We then describes the detailed specifications. A standard model is by necessity oversimplified, so we discuss those simplifications and what future research would be desirable to refine the model. A discussion on the implications of the model for system design and simulation conclude the article.

MEASUREMENTS

Only in the last few years have UWB measurement campaigns been performed (e.g., [1]). The 802.15 channel model is based on those, as well as on measurement campaigns performed explicitly for the standard. These measurement campaigns were carried out by various participants in the 802.15.3a Task Group, and resulted in several large data sets of UWB channel measurements. These data sets were then used to assess the goodness of fit of various proposed channel models, and to calibrate their parameters.

A variety of techniques were used in making the channel measurements. Direct UWB pulse soundings, in which the response of the channel to a UWB pulse is directly measured in the time domain, were made by several contributors. This technique has the advantage of directly measuring the response of the channel to the signals of interest. In addition, the impulse response (IR) of the channel can be recovered from these measurements by deconvolving the transmitted pulse from the channel output. However, the resolution of the deconvolved IR is limited by the bandwidth of the transmitted pulse.

Swept frequency measurements, in which a vector network analyzer is used to measure the complex response of the channel over a range of frequencies, were also performed. The impulse response of the channel can then be obtained via the inverse Fourier transform. As in the direct UWB sounding technique, the resolution of the IR is a function of the range of frequencies that are used to stimulate the channel. Typical setups for both the swept frequency measurements and the direct UWB pulse soundings are shown in Fig. 1. Many approaches to channel modeling are based on ray tracing, which tries to model these exact types of reflections for a given environment and clutter within the environment. Although this approach to channel modeling can be very accurate for a given environment, since the actual physics of the multipath phenomenon are taken into account, it is difficult to generalize. As a result, the channel modeling subcommittee adopted a more statistically based approach, described below.



■ Figure 1. *Measurement setups for a) direct UWB pulse sounding; b) swept frequency measurements..*

In addition to differences in measurement techniques, there were varying data collection priorities within the 802.15.3a Task Group. Some contributors were interested in the gross characteristics of channels that might arise in "typical" UWB applications, such as cable replacement in the home and office. In these cases, the measurements were set up so that the transmitter and receiver locations approximated what might be found in the given application. Other contributors were more interested in a complete statistical description of UWB propagation, on both the small and large scales. In these cases the measurements were typically laid out in a regular grid, with relatively small spacing between adjacent locations in the grid.

A wide variety of environment types are represented among the data collected by the 802.15.3a Task Group. In particular, residential environments (homes, apartments) and office environments are both represented in the data. The RF characteristics of these two environment types are quite distinct, due mostly to the higher proportion of metal construction materials found in office buildings as compared to residential

Source	Measurement bandwidth	Center frequency	Environment	Separation distance
IEEE P802.15-02/278-SG3a (S. Ghassemzadeh *et al.*)	1.25 GHz	5 GHz	Indoor, residential, LOS, NLOS	1–15 m
IEEE P802.15-02/240-SG3a (M. Pendergrass)	2 GHz	4 GHz	Indoor, residential, office, LOS, NLOS	< 10 m
IEEE P802.15-02/279-SG3a (J. Foerster *et al.*)	6 GHz	5 GHz	Indoor, residential, LOS, NLOS	< 10 m
IEEE P802.15-02/281-SG3a (J. Kunisch *et al.*)	10 GHz	6 GHz	Indoor, office, LOS, NLOS	3–10 m
IEEE P802.15-02/284-SG3a (A. F. Molisch *et al.*)	500 MHz	1 GHz	Indoor, office, LOS, NLOS	< 13.5 m
IEEE P802.15-02/280-SG3a (G. Shor *et al.*)	6 GHz	5 GHz	Indoor, office/campus, LOS, NLOS	< 10 m

Table 1. *Summary of channel measurements contributed to IEEE UWB channel modeling subcommittee.*

buildings. In addition to these environment types, most contributors distinguished between line-of-sight channels, in which there is an unobstructed path from transmitter to receiver, and non-line-of-sight channels.

Clearly, the availability of such a rich set of measurement data is desirable from a modeling perspective. However, the sheer size and variety of the database presents some serious challenges of its own, like finding good methods for comparing data taken from different sources, using different data collection and extraction techniques. After initial presentations in July 2002, the IEEE 802.15.3a channel modeling subgroup identified a set of criteria as an appropriate basis for comparing the channel model to the various sets of measurements, as discussed in the next section. These measurements encompass both residential and office sites, under both line-of-sight and non-line-of-sight conditions, with delay spreads ranging from 5 to more than 40 ns. Since the model was based on a wide range of measurement data, it makes it a useful tool for evaluating proposals for a UWB physical layer (PHY) for wireless PANs in a number of different operational environments. Table 1 summarizes the different sets of measurements that were contributed to the IEEE UWB Channel Modeling Subcommittee; a subset of measurements have been made publicly available at [2].

THE IEEE 802.15.3A STANDARD MODEL

A reliable channel model, which captures the important characteristics of the channel, is a vital prerequisite for system design. Toward this end, the IEEE 802.15.3a task group has evaluated a number of popular indoor channel models to determine which model best fits the important characteristics from realistic channel measurements using UWB waveforms. The goal of the channel model is to capture the multipath characteristics of typical environments where IEEE 802.15.3a devices are expected to operate. The model should be relatively simple to use in order to allow PHY proposers to use the model and, in a timely manner, evaluate the performance of their PHY in typical operational environments. In addition, it should be reflective of actual channel measurements. Since it may be difficult for a single model to reflect all of the possible channel environments and characteristics, the group chose to try matching the following primary characteristics of the multipath channel:

- RMS delay spread
- Power decay profile
- Number of multipath components (defined as the number of multipath arrivals that are within 10 dB of the peak multipath arrival)

Note that the actual channels resulting from the model may have several paths that are much weaker than 10 dB from the peak, while the above characteristic was simply used to compare to measurement results.

Three main indoor channel models were considered: the tap-delay line Rayleigh fading model [3], the Saleh-Valenzuela (S-V) model [4], and the Δ-K model described in [5], as well as several novel modifications to these approaches that better matched the measurement characteristics. Each channel model was parameterized in order to best fit the important channel characteristics described above. Although many good models were contributed to the group, the model finally adopted was based on a modified S-V model that seemed to best fit the channel measurements. In particular, the channel measurements showed multipath arrivals in clusters rather than in a continuum, as is customary for narrowband channels. This is a result of the very fine resolution UWB waveforms provide. For example, multipath results from reflections off walls, ceilings, furniture, people, and other objects that may be present within a room. Reflective paths that differ by 0.3 m in traveled distance will arrive at the receiver 1 ns apart. Since UWB waveforms can be up to 7.5 GHz wide, for example, paths separated by more than about 133 ps can be individually resolved at the receiver. As a simple example, this could result in a cluster of paths arriving at the receiver corresponding to reflections from a desk at one time, followed by a cluster of paths corresponding to reflections from the wall a few feet behind the desk, corresponding to a few nanoseconds greater delay.

Target Channel Characteristics[5]	**CM 1**[1]	**CM 2**[2]	**CM 3**[3]	**CM 4**[4]
τ_m [ns] (Mean excess delay)	5.05	10.38	14.18	
τ_{rms} [ns] (rms delay spread)	5.28	8.03	14.28	25
NP10dB (number of paths within 10 dB of the strongest path)			35	
NP (85%) (number of paths that capture 85% of channel energy)	24	36.1	61.54	
Model Parameters				
Λ [1/nsec] (cluster arrival rate)	0.0233	0.4	0.0667	0.0667
λ [1/nsec] (ray arrival rate)	2.5	0.5	2.1	2.1
Γ (cluster decay factor)	7.1	5.5	14.00	24.00
γ (ray decay factor)	4.3	6.7	7.9	12
σ_1 [dB] (stand. dev. of cluster lognormal fading term in dB)	3.4	3.4	3.4	3.4
σ_2 [dB] (stand. dev. of ray lognormal fading term in dB)	3.4	3.4	3.4	3.4
σ_x [dB] (stand. dev. of lognormal fading term for total multipath realizations in dB)	3	3	3	3
Model Characteristics[5]				
τ_m	5.0	9.9	15.9	30.1
τ_{rms}	5	8	15	25
NP10dB	12.5	15.3	24.9	41.2
NP (85 percent)	20.8	33.9	64.7	123.3
Channel energy mean (dB)	–0.4	–0.5	0.0	0.3
Channel energy standard deviation (dB)	2.9	3.1	3.1	2.7

[1] This model is based on LOS (0–4 m) channel measurements.

[2] This model is based on NLOS (0–4 m) channel measurements.

[3] This model is based on NLOS (4–10 m) channel measurements.

[4] This model was generated to fit a 25 ns RMS delay spread to represent an extreme NLOS multipath channel.

These characteristics are based on a 167 ps sampling time.

Table 2. *Multipath channel target characteristics and model parameters.*

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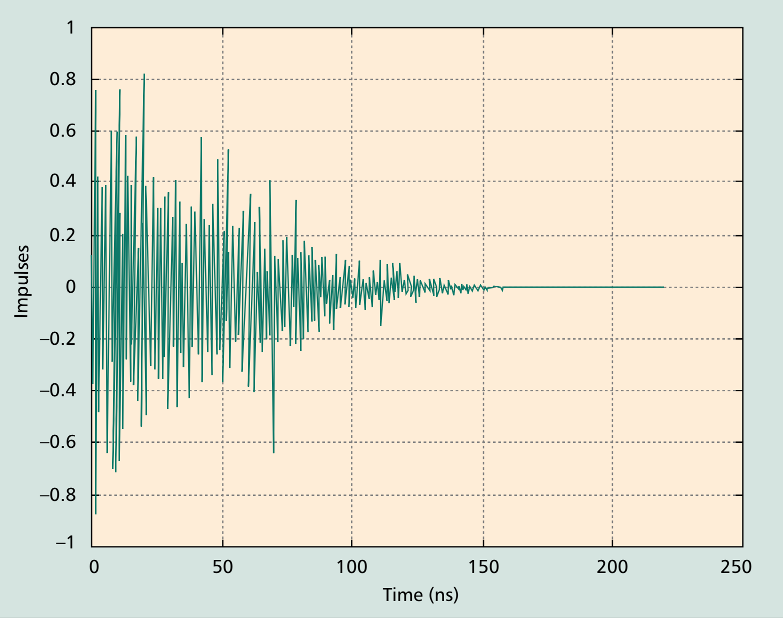
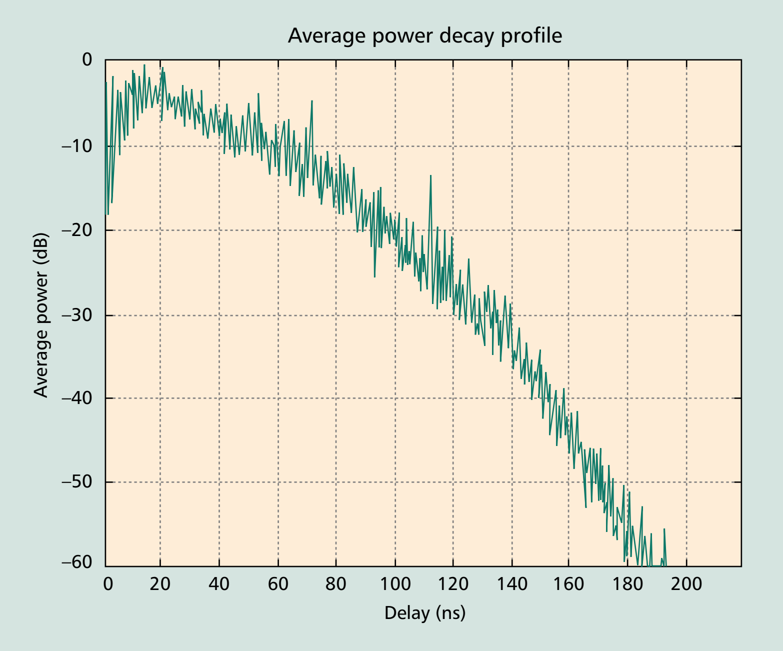
The S-V model was proposed in [4] to model the multipath of an indoor environment for wideband channels, on the order of 100 MHz. Even at this relatively narrow bandwidth (according to today's standards), a clustering phenomenon was observed in the channel. In order to capture this effect, the authors proposed an approach that modeled the multipath arrival times using a statistically random process based on the Poisson point process. In other words, the interarrival time of multipath components is exponentially distributed. In addition, the multipath arrivals were grouped into two different categories: a cluster arrival and a ray arrival within a cluster. This model requires four main parameters to describe an environment, which can be changed for different environments: the cluster arrival rate, the ray arrival rate within a cluster, the cluster decay factor, and the ray decay factor. The cluster and ray arrival rates are self-explanatory, and the decay factors are derived from the observed power decay profile. More important, these four parameters provide great flexibility to model very different environments.

The amplitude statistics in the original S-V model were found to best match the Rayleigh distribution, the power of which is controlled by the cluster and ray decay factors. However, the measurements in UWB channels indicated that the amplitudes do not follow a Rayleigh distribution. Rather, either a lognormal or Nakagami distribution can fit the data equally well, which has been validated using Kolmogorov-Smirnov testing with a 1 percent significance level. Based on these results, the S-V model was modified for the IEEE model by prescribing a lognormal amplitude distribution. The model also includes a shadowing term to account for total received multipath energy variation that results from blockage of the line-of-sight path. The final proposed model is described in more detail in Appendix A (see [6] for more details).

The proposed model parameters were designed to fit measurement results as described earlier, and Table 2 provides the results of this fit for a couple of different channel scenarios (LOS refers to line of sight, NLOS to non-LOS). Note that, when using the model, the total average received power of the multipath realizations is typically normalized to unity in order to provide a fair comparison with other wideband and narrowband systems. This can be done by either normalizing each realization or normalizing the total power, averaged over all realizations. The channel characteristics and corresponding parameter matching results in Table 2 correspond to a time resolution of 167 ps (corresponding to the 6 GHz bandwidth of the underlying measurements), although the output of the model described in the appendix yields continuous time samples (i.e., based on infinite bandwidth). How this model matches measurements with bandwidths greater than 6 GHz is unknown due to the lack of measurement data at this bandwidth.



■ Figure 2. *100 impulse responses based on the CM3 channel model (NLOS up to 10 m with average RMS delay spread of 15 ns).*



■ Figure 3. *Average power decay profile for the channel model CM3 (NLOS up to 10 m with average RMS delay spread of 15 ns).*

Figures 2 and 3, along with the channel measurement characteristics listed in Table 2, highlight characteristics of the multipath channel that are important to discuss. First, the multipath spans several nanoseconds in time, which results in intersymbol interference (ISI) if UWB pulses are closely spaced in time. However, this interference can be mitigated in a number of ways through proper waveform design as well as signal processing and equalization algorithms. Second, the very wide bandwidth of a transmitted pulse results in the ability to individually resolve several multipath components. The positive and negative implications of this fact are discussed later. For the actual comparison of proposals within IEEE 802.15.3a, 100 impulse responses were generated for each of the four model environments, and stored as publicly available Excel tables.

DISCUSSION OF THE MODEL AND TOPICS FOR FURTHER RESEARCH

As UWB is a rather recent topic, and the development time for the model was restricted by the necessity of having the model available for proposal evaluation, only a relatively small number of measurement results were available for the construction of the model. Also, the requirement of easy implementability enforced some oversimplifications. In this section we point out which aspects would be particularly amenable to improvement in the future.

PATH LOSS MODEL

The current model for path loss uses a simple free-space path loss formula $L = (4\pi d/\lambda)^2$, where the wavelength is computed at the center frequency (geometrical mean of upper and lower 10 dB cutoff frequency) of the system. Here and in the following, we assume implicitly that the antennas have a gain independent of frequency. Any antenna gain should be treated as part of the system, not as part of the channel.

For a more realistic assessment, the model for the received power should be derived from measurements. A recent measurement campaign [7] showed that the frequency dependence of the pathloss follows closely the simple f^2 law over the whole bandwidth of interest. It is thus sufficient to look at measurement campaigns with somewhat smaller bandwidth.

Reference [8] reports extensive measurements in residential dwellings, collecting a total of 300,000 frequency responses. It is important to note that many points were measured in each of the houses. This allows a new modeling of path loss: while there is still shadowing superimposed on a polynomial power decay law, now the decay exponent and shadowing variance also become random variables whose realizations change from house to house. Table 3 shows mean and standard deviation for LOS and NLOS situations for the path loss exponent γ, the path loss at 1 m distance PL_0, as well as the shadowing σ. The distributions of all variables is approximated reasonably well by Gaussian distributions.

While the above-mentioned measurements are important as a basis for modeling, they cover only selected indoor environments. For future work, it will be important to investigate whether office environments, industrial environments, airport halls, and even homes with different building structures (e.g., brick, which is much more common in Europe than the drywall used in the United States) lead to different parameterization.

In any case, the use of the more realistic path loss models allows us to anticipate typical UWB system performance. While the 802.15 channel model does not include the above model explicitly, it encourages comparisons of the link margin with the excess path loss (compared to free-space) obtained from it. We note that system proposals for the 110 Mb/s mode typically show a link margin of 3–6 dB at 10 m, while the excess path loss in NLOS situations is on the order of 30 dB. Thus, 10 m coverage distance is realistic only for LOS situations.

FADING STATISTICS

In the standard model, lognormal fading is assumed for both the cluster power and the ray amplitudes; this was based on the evaluation of the measurements described earlier. The total fading variance is composed of the variances for the clusters and rays; those are assumed to be equal.

The measurements mentioned earlier typically showed only 1–4 measurement points within an area of 10 × 10 wavelengths. Due to this, it is not easily possible to separate small-scale (ray) from large-scale (cluster) fading. Other measurement campaigns have found Nakagami amplitude statistics to be a good fit for small-scale fading [1]. The advantage of lognormal statistics for small-scale fading is that the summation of two lognormal processes (small-scale and large-scale, in our case) results again in lognormal fading. Furthermore, lognormal distributions are similar to Nakagami distributions for large values of the Nakagami-m parameter; however, note that it is not possible to approximate Rayleigh (i.e., Nakagami with $m = 1$) with lognormal distribution.

Another approximation of the current model is that the fading variance is independent of the delay. However, several measurement campaigns have demonstrated that the fading depth increases with delay. This also makes sense physically: for small delays, only a few multipath components arrive within one resolvable delay bin. For longer delays, the multipath components can take many different paths that all fall into the same delay bin, so the central limit theorem is valid, and the fading is Rayleigh distributed.

	LOS		NLOS	
	Mean	Std. dev.	Mean	Std. dev.
PL_0 (dB)	47	NA	50.5	NA
γ	1.7	0.3	3.5	0.97
σ (dB)	1.6	0.5	2.7	0.98

Table 3. *Statistical values of the path loss model parameters [6].*

This question is also strongly related to the question of the arrival rate of the multipath components. The SV model prescribes Poisson parameters that are independent of delays. This does not reflect reality; the interarrival times of multipath components tend to decrease with delay. One way of incorporating this into the model would be to use a delay-variant interarrival time. An alternative approach is the use of deterministic multipath components derived from a simple ray tracing, combined with Rayleigh distributed "background radiation."

TIME VARIANCE

The 802.15 standard model assumes that the channel stays either completely static, or changes completely from one data burst (about 100 μs) to the next. While this covers extreme cases, some important aspects, like adaptive channel estimation and interleaving, cannot be simulated realistically. Because of this, the standard recommends the use of a more detailed model when time variance is of importance.

A first step is to establish a model for the angular power spectrum (APS) of the radiation arriving at the receiver. The angular spread is modeled to increase with the delay of the arriving components. This assumption is intuitively appealing (components with the minimum excess delay need to arrive from the LOS direction, while later components can come from the directions of different scatterers), and was also confirmed by measurements [9]. As the receiver is moving over larger distances, it is also necessary to specify the autocorrelation function of the shadowing. Although this function is to be expected to be similar to "classical" narrowband shadowing autocorrelation functions, it is still something that should be investigated by further measurements.

The time variance due to moving transmitter or receiver can be treated by the well-known WSSUS model. The APS is related to the Doppler spectrum by a simple variable transformation, as shown in [10]. The generation of time-varying random channels with known Doppler spectra is well known and has been treated extensively in the wireless literature. The model for the angular spectrum is also useful for multiple-antenna systems.

However, for most PAN applications, the transmitter and receiver are stationary. The temporal variations stem primarily from the move-

We note that system proposals for the 110 Mb/s mode typically show a link margin of 3–6 dB at 10 m, while the excess path loss in NLOS situations is on the order of 30 dB. Thus, 10 m coverage distance is realistic only for LOS situations.

ment of scatterers. The most significant change in the impulse response occurs when a person moves through the connection line between TX and RX. In that case, the WSSUS model cannot be applied, because the assumption of stationarity is violated: the moving scatterer (the person) has a significant angular extent such that the channel may switch between LOS and NLOS characteristics. In that case a geometrical model (blocking off rays from a certain angular range) can be used for simulations.

Careful bandwidth selection of the UWB waveform can help balance the receiver complexity for capturing multipath energy while still benefiting from the reduced fading of the short duration of the pulses.

IMPACT ON SYSTEM DESIGN AND CONCLUSIONS

The structure of the channel model has a strong influence on the system performance assessment. For example, the long delay spread (several nanoseconds) can have both positive and negative implications. It is good in the sense that the multipath arrivals will undergo fewer amplitude fluctuations (fading) since there will be fewer reflections that cause destructive/constructive interference within the resolution time of the received impulse. On the other hand, the average total received energy is distributed between a number of multipath arrivals. In order to take advantage of that energy, unique systems and receivers need to be designed with multipath energy capture in mind. For a traditional impulse-based UWB waveform, this may consist of a rake receiver with multiple arms, one for each resolvable multipath component. However, as the bandwidth of the UWB waveform increases, the complexity of the RAKE receiver could become limiting in order to capture the same energy. As a result, careful bandwidth selection of the UWB waveform can help balance the receiver complexity for capturing multipath energy while still benefiting from the reduced fading of the short duration of the pulses.

Another aspect relevant to system design is that the channel model is *sparse*; in other words, not every resolvable delay tap carries significant energy. Any UWB system needs a Rake receiver to collect the energy of the multipath components arriving at different times; however, the number of available Rake fingers in the receiver is usually smaller than the number of multipath components. We thus have to select at which delays we can place the fingers of the multipath components. In a *dense* channel model, it is sufficient to always choose the first arriving multipath components, as those are usually the strongest; such a Rake is known as *partial Rake*. In a sparse model, a so-called *selective Rake* receiver must be chosen, which searches for the strongest multipath components and then places the Rake fingers at those delays. A low-cost partial Rake would thus be the method of choice in a dense channel, but not in a sparse one. Using a sparse channel model in the standardization thus has an influence on the decision process.

The 802.15 standard model presented earlier is mainly intended to allow a fair comparison between different system proposals submitted to the standardization bodies. It is not detailed enough to allow realistic performance assessments of systems in terms of absolute criteria like throughput and bit error rate. In order to achieve that, a more elaborate channel model will be needed in the future. Some suggestions for such improvements have been presented earlier. However, these suggestions only lined out a generic model structure; an actual parameterization will have to be based on future measurement campaigns. Also, campaigns will have to be performed in new environments, like office buildings, industrial environments, and airport halls (for the results of an extensive new campaign, see [11]). Finally, the influence of the immediate surroundings (e.g., the user for body-worn devices) on the transceiver characteristics will have to be identified.

Summarizing, the 802.15 standard model was an important step for the understanding of UWB channels, and was established in time to be useful for the selection process of the new standard for UWB high-data-rate communications. But it is not a universal stochastic model of the wireless propagation channel, and a lot of work will have to be spent by the channel modeling community before our understanding of UWB channels is complete.

ACKNOWLEDGMENTS

The authors are indebted to a number of significant contributions that were submitted to the IEEE 802.15.3a study group, which helped to form this channel model and provide a means of evaluating UWB physical layers for next generation, high-rate WPANs. The individual contributors are too many to name here, but are listed in [6], and the authors would like to acknowledge their contributions to art of UWB channel modeling.

REFERENCES

[1] D. Cassioli, M. Z. Win, and A. F. Molisch, “The Ultra-Wide Bandwidth Indoor Channel — From Statistical Model to Simulations,” *IEEE JSAC*, vol. 20, 2002, pp. 1247–57.

[2] http://ultra.usc.edu/New_Site/database.html

[3] IEEE 802.11-97/96, Naftali Chayat, Sept. 1997.

[4] A. Saleh and R. Valenzuela, “A Statistical Model for Indoor Multipath Propagation,” *IEEE JSAC*, vol. SAC-5, no. 2, Feb. 1987, pp. 128–37.

[5] H. Hashemi, “Impulse Response Modeling of Indoor Radio Propagation Channels,” *IEEE JSAC*, vol. 11, no. 7, Sept. 1993, pp. 967–78.

[6] J. Foerster, Ed., “Channel Modeling Sub-committee Report Final,” IEEE802.15-02/490; http://ieee802.org/15/

[7] J. Kunisch and J. Pamp, “Measurement Results and Modeling Aspects for the UWB Radio Channels,” *Proc. IEEE Conf. UWB Sys. and Tech.*, 2002, pp. 19–23.

[8] S. S. Ghassemzadeh *et al.*, “A Statistical Path Loss Model for In-Home UWB Channels,” *Proc. IEEE Conf. UWB Sys. and Tech.*, 2002, pp. 59–64; also S. S. Ghassemzadeh *et al.*, “UWB Indoor Path Loss Model For Residential and Commercial Environments,” accepted for publication *IEEE VTC 2003 Fall*, Orlando, FL.

[9] R. J. M. Cramer, R. A. Scholtz, and M. Z. Win, “Evaluation of an Ultra-Wide-Band Propagation Channel,” *IEEE Trans. Antennas and Prop. 50*, 2002, pp. 561–70.

[10] W. C. Jakes, *Microwave Mobile Communications*, IEEE Press, 1993.

[11] S. S. Ghassemzadeh *et al.*, “Measurement and Modeling of an Ultra-Wide Bandwidth Indoor Channel,” to appear, *IEEE Trans. Commun.*.

ADDITIONAL READING

[1] M. Z. Win and R. A. Scholtz, “Impulse Radio: How It Works,” *IEEE Commun. Lett.*, vol. 2, 1998, pp. 36–38.

[2] W. Hirt, “Ultra-Wideband Radio Technology: Overview and Future Research,” *Comp. Commun.*, vol. 26, 2003, pp. 46–52.

BIOGRAPHIES

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APPENDIX A

The multipath model adopted by the IEEE 802.15.3a committee for the evaluation of UWB physical layer proposals consists of the following discrete time impulse response:

$$h_i(t) = X_i \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}^i \delta\left(t - T_l^i - \tau_{k,l}^i\right),$$

where $\{\alpha_{k,l}^i\}$ are the multipath gain coefficients, $\{T_l^i\}$ is the delay of the lth cluster, $\{\tau_{k,l}^i\}$ is the delay of the kth multipath component relative to the lth cluster arrival time (T_l^i), $\{X_i\}$ represents the log-normal shadowing, and i refers to the ith realization.

Finally, the proposed model uses the following definitions:

T_l = the arrival time of the first path of the lth cluster
Λ = cluster arrival rate
λ = ray arrival rate; that is, the arrival rate of path within each cluster

By definition, we have $\tau_{0,l} = 0$. The distribution of cluster arrival time and the ray arrival time are given by

$$\boxed{\begin{aligned} &P(T_l \mid T_{l-1}) = \Lambda \exp[-\Lambda(T_l - T_{l-1})], \ l > 0 \\ &p(\tau_{k,l} \mid \tau_{(k-1),l}) = \lambda \exp[-\lambda(\tau_{k-1} - \tau_{(k-1),l})], \\ &\qquad\qquad k > 0. \end{aligned}}$$

The channel coefficients are defined as follows:

$$\alpha_{k,l} = p_{k,l}\xi_l\beta_{k,l},$$

$$20\log10(\xi_l\beta_{k,l}) \propto \text{Normal}(\mu_{k,l}, \sigma_1^2 + \sigma_2^2),$$

or

$$|\xi_l\beta_{k,l}| = 10^{(\mu_{k,l}+n_1+n_2)/20},$$

where $n_1 \propto \text{Normal}(0,\sigma_1^2)$ and $n_2 \propto \text{Normal}(0,\sigma_2^2)$ are independent and correspond to the fading on each cluster and ray, respectively,

$$E\left[\left|\xi_l\beta_{k,l}\right|^2\right] = \Omega_0 e^{-T_l/\Gamma} e^{-\tau_{k,l}/\gamma},$$

where T_l is the excess delay of bin l and Ω_0 is the mean energy of the first path of the first cluster, and $p_{k,l}$ is equiprobable ±1 to account for signal inversion due to reflections. Γ and γ are the cluster decay factor and ray decay factor, respectively. The $\mu_{k,l}$ are thus given by

$$u_{k,l} = \frac{10\ln(\Omega_0) - 10T_l/\Gamma - 10\tau_{k,l}/\gamma}{\ln(10)} - \frac{(\sigma_1^2 + \sigma_2^2)\ln(10)}{20}.$$

In the above equations, ξ_l reflects the fading associated with the lth cluster, and $\beta_{k,l}$ corresponds to the fading associated with the kth ray of the lth cluster. Note that a complex tap model was not adopted here. The complex baseband model is a natural fit for narrowband systems to capture channel behavior independent of carrier frequency, but this motivation breaks down for UWB systems where a real-valued simulation at RF may be more natural.

Finally, since the log-normal shadowing of the total multipath energy is captured by the term X_i, the total energy contained in the terms $\{\alpha_{k,l}^i\}$ is normalized to unity for each realization. This shadowing term is characterized by the following:

$$20\log10(X_i) \propto \text{Normal}(0,\sigma_x^2).$$