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UWB Wireless Channels - Propagation Aspects and Interplay with System Design

Andreas F. Molisch

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Abstract

This paper will first present an overview of the current state of the art in the measurement and modeling of UWB propagation channels. We will point out the difference between the two main frequency band of interest (less-than 900MHz and 3.1-10.6 GHz), and describe the key channel parameters (attenuation, delay spread, arrival time statistics, amplitude statistics) in different environments. We will especially discuss the difference between "sparse" and "dense" models. We then analyze what channel parameters have the biggest influence on system performance. Various Rake receiver structures, OFDM cyclic prefix duration, and transmitted-reference structures exemplify the systems that show a clear dependence on channel parameters.

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UWB wireless channels - propagation aspects and interplay with system design

(invited paper)

Andreas F. Molisch[1,2] , *Senior Member, IEEE*

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[1] Mitsubishi Electric Research Labs, Cambridge, A, USA.
[2] Department of Electroscience, Lund University, Lund, Sweden.
email: Andreas.Molisch@ieee.org

***Abstract*— This paper will first present an overview of the current state of the art in the measurement and modeling of UWB propagation channels. We will point out the difference between the two main frequency bands of interest (<900MHz and 3.1-10.6 GHz), and describe the kay channel parameters (attenuation, delay spread, arrival time statistics, amplitude statistics) in different environments. We will especially discuss the difference between "sparse" and "dense" models. We then analyze what channel parameters have the biggest influence on system performance. Various Rake receiver structures, OFDM cyclic prefix duration, and transmitted-reference structures exemplify the systems that show a clear dependence on channel parameters.**

I. Introduction

Ultrawideband system (UWB) have many attractive properties, including low interference to and from other wireless sytems, low sensitivity to fading, easier wall-and floor penetration, and inherent security. UWB applications generally fall into two categories: radar and communications. UWB radar [1] was mostly investigated in a military context, but have recently also attracted commercial interest for vehicular safety. UWB communications, which are the topic of this paper, originally started with the spark-gap transmitter of Hertz and Marconi. However, it was not until the 1990s that the interest was renewed. The pioneering work of Win and Scholtz [2], [3], [4] developed the concept of time-hopping impulse radio (TH-IR) system. In 2002, the frequency regulator in the USA allowed unlicensed UWB transmission (subject to the fulfillment of a spectral masks), and other countries are expected to follow suit. Following these developments, commercial systems based on OFDM [5] and direct-sequence spread spectrum (DS-SS) [6] have been developed.

The ultimate performance limits of any communications system is determined by the channel it operates in. For a UWB system, this is the UWB propagation channel, which differs from conventional (narrowband) propagation in many respects. It is thus vital for a good system design to understand those differences and their impact on various systems. We will find that the channel does not only impose limits on the information-theoretic quantities like capacity and mutual information, but also determines the losses of practical implementations, like Rake receivers with a finite number of fingers. This paper discusses UWB propagation, channel models that have been established to describe its properties, and the impact they have on different types of systems.

In Sec. II, we discuss the propagation effects that cause the essential differences of UWB and narrowband systems. Next, Sec. III describes channel models for low-frequency ranges (below 1GHz), high-frequency (3-10GHz) short-range systems, and high-frequency long-range systems. Section IV then discusses the impact of the propagation on OFDM-based systems, Rake-receivers, and incoherent receivers. It also discusses the impact of the spatial characteristics of the channel on the design of UWB antennas. A summary and conclusions wrap up the paper.

II. Propagation effects

As mentioned in the introduction, UWB propagation differs basically from narrowband propagation. Under some standard assumptions [7], we find for narrowband propagation that each interaction of a transmitted (narrowband) wave with another object leads only to an attenuation, phase shift, and change in direction (and thus delay). For UWB, the transmitted signal contains many frequency components, each of which "sees" a different propagation environment. For example, the diffraction coefficient of a corner is quite different at 100 MHz compared to 1GHz; similarily, the reflection coefficients of walls and furniture can vary over the bandwidth of interest. The correct channel description is then given by

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

where $\chi_i(\tau)$ denotes the distortion of the $i-$th echo by the frequency selectivity of the interactions with the environment. Expressions for those distortions are given in [8].

Even more fundamentally, the pathloss depends on the frequency. Thus, we can define a *frequency-dependent pathloss*

$$PL(f) = E\{\int_{f-\Delta f/2}^{f+\Delta f/2} |H(\widetilde{f})|^2 d\widetilde{f}\} \qquad (2)$$

where Δf is chosen small enough so that diffraction coefficients, dielectric constants, etc., can be considered constant within that bandwidth; the $total$ pathloss is obtained by integrating over the whole bandwidth of interest. For a constant-gain antenna and free-space propagation, $\sqrt{PL(f)} \propto f^{-1}$; for indoor office environments, Ref. [9] found that $\sqrt{PL(f)} \propto f^{-m}$ with m varying between 0.8 and 1.4.

Another important difference to narrowband models arises from the fine delay resolution of UWB receivers (proportional to the inverse bandwidth). The number of echoes (multipath components) falling into each resolvable delay bin cannot be assumed to be very large, so that the small-scale statistics of the amplitude fading are not Rayleigh (or Rice) anymore. Especially in delay bins with small excess delays (compared to the arrival time of the LOS component), the number of arriving components per delay bin is small. Appropriate statistical distributions for the description of this effect will be mentioned in Sec. III.

Finally, we notice that in most narrowband channels, the impulse response is "dense" in the sense that each resolvable delay bin contains significant energy.[1] This is not necessarily the case for UWB systems. For 10 GHz bandwidth, each delay bin corresponds to a runtime difference of only 3cm.There are many propagation situations where no physical propagation path exists that corresponds to such a runtime difference.

The impact of these effect can depend on the relative bandwidth, the absolute bandwidth, and the carrier frequency:

- the variation of the pathloss over the bandwidth of interest is essentially determined by the relative bandwidth; the ratio of attenuations at the upper and lower edges of the considered frequency is $(f_\mathrm{u}/f_\mathrm{l})^{2m}$.
- the distortions of the underlying pulses depend on the relative bandwidth (which dictates how much the diffraction coefficient changes over the band of interest), the carrier frequency relative to the size of typical objects (if all components of the radiation have a wavelength that is much smaller than the size of typical objects, then diffraction might become irrelevant), and the absolute bandwidth in conjunction with the carrier frequency, as it determines whether material properties can change significantly over the considered bandwidth.
- the denseness or sparseness of the impulse response depends essentially on the absolute bandwidth, as well as the density of scattering objects.

III. Channel models

In this section, we describe the three most popular channel models. for different ranges of applications and frequencies. We find that there are considerable differences between high-frequency models (for the FCC band 3.1-10.6 GHz), and low-frequency models (below 1 GHz). Also, the environments in which the systems are operated (which in turn depend on the applications) have an impact. We note that the models described here are not the only available UWB channel models; however, they are the ones in most widespread use, and cover a range of effects that are important for the considerations of Sec. IV.

A. Low-frequency channel model

For frequencies below 1 GHz, the model of [10] is in widespread use. It is based on a measurement campaign performed in a typical office building. It characterizes the shape of the power-delay profile (PDP) of the UWB indoor channel in terms of path gains and delays of multipath components, i.e., by the pairs $\{G_k, \tau_k\}$, with $\tau_k = (k-1)\Delta\tau$, where $\Delta\tau = 2$ ns is the resolution of the considered system.[2] We distinguish between the *large* and *small* scale fading statistics. The *local path gains* G_k are derived by the superposition of these two effects. The average PDP is specified according to:

$$\overline{G}(\tau) = \frac{\overline{G}_\mathrm{tot}}{1+rF(\varepsilon)}\left\{\delta(\tau-\tau_1)+\sum_{k=2}^{L_\mathrm{r}}\left[re^{-\frac{(\tau_k-\tau_2)}{\varepsilon}}\right]\delta(\tau-\tau_k)\right\} \quad (3)$$

where, $\overline{G}_\mathrm{tot}$ is the total mean energy, given by the mean pathloss (which is described by a dual-slope model) and the shadowing (which is modeled as lognormal fading). The time decay constant ε is also modeled as a lognormally distributed random variable, as is the power ratio $r = \overline{G}_2/\overline{G}_1$, which indicates the amount of “extra” power (compared to the pure exponential decay law) carried in the first bin. Furthermore, $F(\varepsilon)$ is a normalization function. The probability density function of the G_k (describing the small-scale amplitude variations) can be approximated by a Gamma distribution (i.e., the amplitude distribution is Nakagami) with mean $\overline{G}_k$ and parameter m_k. The parameters m_k are Gaussian-distributed random variables, whose mean and variance is a function of the delay, so that the fading is more Ralyeigh-like for large delays. More details and an implementation recipe can be found in [10].

B. The IEEE 802.15.3a high-frequency channel model

The model was developed by the IEEE 802.15.3a standardization group for UWB communications systems in office and residential indoor environments with a range of less than 10 m. It distinguishes between four radio environments: LOS with a distance between TX and RX of $0-4$m (CM1), NLOS for a distance $0-4$m (CM2), NLOS for a distance $4-10$m (CM3), and a "heavy multipath" environment (CM4). The model is a modified Saleh-Valenzuela model [11]

$$h_i(t) = X_i\sum_{l=0}^{L}\sum_{k=0}^{K}a_{k,l}^{i}\delta(t-T_l^i-\tau_{k,l}^i) \quad (4)$$

where X_i represents the log-normal shadowing, and i refers to the i^{th} realization. The $a_{k,l}^i$are the tap weights of the k^{th} component in the l^{th} cluster, T_l is the delay of the $l-$th cluster, $\tau_{k,l}$ is the delay of the k-th MPC relative to the l-th cluster arrival time T_l. By definition, we have $\tau_{0,l} = 0$. The distributions of the cluster arrival times and the ray arrival times are given by a Poisson processes

$$\begin{aligned} p(T_l|T_{l-1}) &= \Lambda\exp\left[-\Lambda(T_l-T_{l-1})\right],\ l>0 \\ p(\tau_{k,l}|\tau_{(k-1),l} &= \lambda\exp\left[-\lambda(\tau_{k,l}-\tau_{(k-1),l})\right],\ k>0 \end{aligned} \quad (5)$$

where Λ is the cluster arrival rate, and λ is the ray arrival rate.

Both the small-scale fading (distribution of the amplitudes of the rays within a cluster) and the large-scale fading (energy of the clusters) are modeled as lognormally distributed, with the fading realizations being independent between rays and clusters. A bulk (total) shadowing is superimposed on the impulse response. A more detailed description can be found in [12], [13].

C. The IEEE 802.15.4a high-frequency channel model

As the 802.15.3a channel model is suitable only under some rather restrictive assumptions, the IEEE 802.15.4a channel modeling subgroup is currently developing a more general model. It encompasses a wider range of environments, including outdoor environments, factories and warehouses, as well as disaster scenarios. Furthermore, the generic structure of

[1] Situations with multiple scatterer clusters are a notable exception.

[2] By definition, the delay bin of the first quasi LOS path begins at $\tau_1 = 0$. The model prescribes the statistics of the path gains and its dependence on the delays τ_k.

the model is more general. While it is also based on a Saleh-Valenzuela approach, it includes delay dependence of the cluster and ray arrival rates and decay time constants. The small-scale fading is modeled as Nakagami or Rice (instead of lognormal), and the parameters also show a dependence on the distance between transmitter and receiver.

At the time of the writing of this paper, the model is still under development by the subgroup. A final version is expected to be approved by the IEEE 802.15.4a standardization group in Sept. 2004; the final report with details of the model can be found at www.802wirelessworld.com.

D. Comparison of the models

The crucial differences between the models are the following:

- *dense vs. sparse models:* the low-frequency model is a dense model, i.e., each resolvable delay bin carriers a significant amount of energy.[3] The HF models, on the other hand, model the arrival times of multipath components as random.
- *strength of the first component:* the LF model always models the first arriving component as the strongest of the power delay profile, irrespective of whether there is a line-of-sight or not.[4] This is not necessarily true for the HF models; the independent shadowing of the different clusters can cause the maximum of the PDP to be at a larger delay.
- *fading statistics:* different probability density functions are being used: while the LF model as well as the 4a-HF model use Nakagami distributions with delay-dependent m-parameters, the 3a-HF model uses a lognormal distribution with a variance that is independent of the delay. However, this is not necessarily related to physical differences in the propagation mechanisms, but rather an arbitrary modeling decision.
- *variations of the delay spread:* for the LF model, the PDP is given by a single-exponential decay, with a decay time constant that varies randomly; this necessarily leads to random variations of the delay spread as well. For the HF models, the decay time constants are fixed; however, the random variations of the cluster powers due to shadowing (and, in the case of the 4a model, the random nature of the number of clusters) lead to a randomization of the delay spread.
- *values of attenuation and delay spread:* the values for the delay spread, and the number of observed clusters, vary significantly between the models. While the HF-3a model shows delay spreads between 5 and 25ns, the LF model has about 40ns in a similar environment.
- *pulse distortions*: all of the above models use the model of the impulse response that is a sum of delayed and attenuated delta pulses; in other words, distortions of a pulse by a single reflection coefficient is not taken into account. This simplification can be partly justified by the measurements on which the models are based; however, more investigations might be needed in the future.

IV. Impact on system design

In this section, we analyze various UWB transmission schemes that have been proposed in the literature. Due to space restrictions, we do not discuss the schemes themselves, but only mention the impact that the propagation channel has on their performance.

A. OFDM

OFDM (possibly in conjunction with multiband transmission, see Sec. IV.B) has been suggested for high-data-rate UWB data transmission [5]. The most significant parameter for OFDM is the *maximum excess delay*, as it determines the length of the cyclic prefix (which in term determines many other system parameters, see, e.g., [14]). The dependence of UWB-OFDM systems on the delay dispersion thus does not differ significantly from that of narrowband systems - insofar as the delay spread does not depend strongly on the considered bandwidth. Density or sparseness of the impulse response do not have an impact.

Finally, systems with a large relative bandwidth offer better resilience with respect to shadowing, as different frequency components see different diffraction coefficients (see Sec. II). This implies that an OFDM system should code the information across different tones in such a way that the resulting frequency diversity can combat the shadowing (as well as the small-scale fading). Frequency diversity can be enhanced by multicarrier-CDMA [15] or pulsed OFDM [16].

B. Multiband principles

In recent years, several schemes have been proposed that divide the available frequency band into subbands, and transmit in different subbands at different times. This approach simplifies implementation, as the sampling and A/D conversion now has to be done only with a rate corresponding to the width of the subband instead of the full bandwidth. The UWB channel is thus converted into a number of narrowband channels, as most propagation effects in a 500MHz channel are in line with conventional (narrowband) propagation. The most significant effect for such systems is the different attenuations that the subbands undergo. The transmit power spectral density has to be constant; so that increasing the power for higher frequencies is not an option; however, stronger coding and/or lower-order modulation can be used to compensate for this effect. Similar to OFDM systems, it is also essential that coding/interleaving across different frequency bands is performed.

C. Rake receivers

For time-hopping impulse radio systems and DS-SS systems, Rake receivers are used for the matched filtering of the received signal. It is common to distinguish between $selective$ Rake (S-Rake) receivers, which collect the energy from the *L strongest* multipath components, and $partial$ Rake (P-Rake) receivers, which collect the energy from the *L first* multipath components [17].[5] For correlative receivers, it is very important whether the underlying pulses undergo distortions; any such distortion can significantly decrease the correlation coefficient and thus the collected energy.[6]

The relative performance of PRake and SRake depends mostly on whether the impulse response is "dense" or "sparse"

[3] Also note that the low-frequency model shows only a single cluster, so that really a set of contiguous bins carries the energy.

[4] Note, however, that due to the small-scale fading, the first component of the $impulse\ response$ need not be the strongest.

[5] The All-Rake can be seen as the limiting case of either of those structures, collecting all available energy.

[6] This is true only if the number of fingers is small. In the case that the Rake fingers are spaced regularly at delays corresponding to Nyquist sampling, the Rake can implement a filter that is ideally matched to the instantaneous impulse response irrespective of the underlying propagation processes.

[17]. For dense channels and monotonuous power delay profiles, PRake receivers collect most of the energy, as the taps with the (on average) highest energy are the ones used by the PRake. Of course, sparse channels are more likely if the system bandwidth is large. More detailed investigations in the impact of the bandwidth can also be found in [18].

We also find a significant impact of the amplitude fading statistics. SRakes provide selection diversity, and thus show a steep slope of the BER-vs-SNR curve; PRake receivers do not provide this diversity. However, in channels with small fading depth (e.g., Nakagami-fading with large m-factors), the selection diversity is not needed, so that PRake receivers also show a reasonably steep slope of the BER [17].

The biggest impact on the number of required Rake fingers stems from the environment. While residential environments require on the order of 10 fingers to collect half of the available energy with 7.5GHz bandwidth, that number can increase to 400 fingers in some industrial environments [19].

D. Incoherent receivers

The large number of required Rake fingers has lead to an increased interest in incoherent and differentially coherent receiver structures. For AWGN channels, the penalty for the use of incoherent reception is only about 3dB. However, this number increases significantly as the delay spread is increased. The receiver detects the energy over a predetermined time period that is essentially determined by the delay spread of the channel (in order to collect all multipath energy). At the same time, more noise energy is collected. Thus, a large delay spread (which necessitates a large integration time) decreases the performance of incoherent receivers. Sparse impulse responses are especially detrimental, as in the "empty" delay bins, the receiver collects only noise, but no signal energy.

The situation is somewhat similar for transmitted-reference (TR) schemes [20], which transmit an unmodulated reference pulse followed by a modulated data pulse; the receiver multiplies the received signal with a delayed copy of itself, and integrates the resulting signal. The main problem here is noise-noise crossproducts - due to the spreading, the SNR at the multiplier is usually negative. Sparse channel models lead to an output of a multiplier that has a smaller number of samples with signal energy compared to noise samples; thus the decision variable (output of the integrator after the multiplier) is noisier.

A major advantage of the TR scheme is that distortions of the transmit signal (according to the mechanisms of Sec. II) do not significantly influence the performance. The signal that is correlated with the receive signal is the reference signal, which has undergone exactly the same distortions as the data pulse. In channels where the pulse distortion is the dominant mechanism (e.g., a channel with a single diffraction), a TR scheme can theoretically yield a better performance than a Rake receiver.

E. Antenna patterns and multi-antenna solutions

The directional (spatial) characteristics of UWB channels determine the effectiveness of smart antennas and UWB-based MIMO systems, in a way that is very similar to the to conventional multi-antenna systems. One major difference is that beamforming at the transmitter is (for FCC-compliant systems) undesirable, as the restrictions on the transmitted power have to be fulfilled in every direction; directivity thus requires a backoff of the total power. There are, to date, only a few investigations of the directional characteristics of UWB channels [21], [9], [19]. The sample values obtained from these measurements to not yet allow general conclusions about UWB-MIMO system design.

V. Summary and Conclusions

We have presented an overview of ultrawideband propagation channels, their modeling, and their impact on the design of UWB communications systems. UWB propagation channels exhibit several basic differences to narrowband channels, most natably different fading statistics, frequency-dependent pathloss, and sparseness of the impulse responses. These properties influence, to a varying degree, all common receiver structures, including Rake, OFDM, multiband, and incoherent receivers. A deep understanding of UWB propagation is thus an essential requirement for a good system design.

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