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Ultrawideband Propagation Channels and Their Impact on System Design

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Abstract

The performance of Ultrawideband (UWB) communications systems is determined by the propagation channels they operate in. This paper gives an overview of UWB channels and their impact on system design. The emphasis lies on (i) multiple antenna systems and (ii) body-area networks. We discuss the frequency depending on angular power spectra and show that spatial multiplexing can be used for achieving very high data rates in MIMO-UWB systems. For body-area networks, we find small delay spreads, so that high-rate communications can be supported with relatively simple receiver structures. Finally, we argue that the clustering structure and ”soft onset” property of UWB power delay profiles strongly influence the design of ranging systems.

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Ultrawideband propagation channels and their impact on system design[1]

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***Abstract*—The performance of Ultrawideband (UWB) communications systems is determined by the propagation channels they operate in. This paper gives an overview of UWB channels and their impact on system design. The emphasis lies on (i) multiple-antenna systems and (ii) body-area networks. We discuss the frequency dependence of angular power spectra and show that spatial multiplexing can be used for achieving very high data rates in MIMO-UWB systems. For body-area networks, we find small delay spreads, so that high-rate communications can be supported with relatively simple receiver structures. Finally, we argue that the clustering structure and "soft onset" property of UWB power delay profiles strongly influence the design of ranging systems.**

I. Introduction

Ultrawideband (UWB) communications systems are defined as having a relative bandwidth larger than 20% or an absolute bandwidth larger than 500 MHz. UWB systems can provide increased resistance to fading and interference, low interference to legacy systems operating in the same band, capability for precision ranging, and the possibility for low-cost, low-complexity transceivers [1], [2], [3]. They are thus considered a promising solution for a variety of applications, ranging from sensor networks to ultra-high-data-rate communications [4], [5], [6].

Interest into UWB communications started with the pioneering papers of Win and Scholtz in the 1990s [7], [8], [9]. It increased further with the report and order of the American frequency regulator in 2002 [10], which allowed the unlicensed use of UWB systems in the frequency range from 3.1 to 10.6 GHz, subject to certain constraints on the emitted power spectral density. In the following years, a number of UWB systems were developed, like the ECMA 268 standard (also known as "wireless USB") for high-rate, short-range data communications [11], the IEEE 802.15.4a standard for low-rate personal-area networks [12], as well as proprietory military and civilian communications systems.

In order to design, test, and improve UWB systems, a thorough understanding of UWB propagation channels and their impact on systems is indispensable. This topic has therefore been studied extensively in the past 10 years, and hundreds of papers have appeared. An extensive review was published by the author in 2005 [13]. The current paper is intended to update and extend this review,[1] and to treat two aspects that have become of interest only fairly recently: (i) propagation channels for multiple-antenna systems, and (ii) propagation in body-area networks.

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[1] the keynote speech will give a general introduction to UWB channels, not restricted to the time after 2005.

The remainder of the paper is organized the following way: Section II reviews the fundamentals of UWB propagation in Personal Area Networks (PAN) and summarizes some recent work in this area. Section III describes the angular dispersion of UWB propagation channels, which is vital for multiple-antenna systems. Section IV investigates the peculiarities of propagation in Body Area Networks (BANs). Section V analyzes the impact of propagation channels on certain system design aspects, in particular ranging and MIMO systems. A summary and conclusions wrap up this paper.

II. Propagation channels for Personal Area Networks

A. Delay dispersion

1) Fundamental form of the impulse response: The impulse response of a UWB propagation channel can be written as a sum of discrete multipath components (MPCs)

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

where N is the number of MPCs and the $a_i(t)$ are the (complex) amplitudes of the MPCs. The phases of the $a_i(t)$ vary quickly with time (or location of the MS), while $|a_i(t)|$ and τ_i, vary slowly. The function $\chi_i(t,\tau)$ denotes the (time-varying) distortion of the $i-$th MPC due to the frequency selectivity of the interactions with the environment. Note that the presence of $\chi_i(t,\tau)$ is the distinguishing property of UWB channels; for $\chi_i(t,\tau) = const$, the conventional narrowband model is recovered [14]. Extensive theoretical work on the distortion function has been done by Qiu (for a review, see [15]); recent experimental work includes [16], [17].

2) Clustering: It has been observed in many measurements that the MPCs are arriving in clusters. The most popular model reflecting this structure is the Saleh-Valenzuela model [18], which writes the impulse response as

$$h_{\rm SV}(t,\tau) = \sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}(t)\chi_{k,l}(t,\tau) \otimes \delta(\tau - T_l - \tau_{k,l}), \tag{2}$$

where $a_{k,l}$ is the tap weight of the k^{th} component in the lth cluster, T_l is the delay of the lth cluster, $\tau_{k,l}$ is the delay of the kth MPC relative to the l-th cluster arrival time T_l. K is the number of MPCs within a cluster. L is the number of clusters. A different approach, based on the $\Delta - K$ model, was analyzed in [19].

[1] Invited plenary talk for the IEEE 2007 International Symposium on Microwave, Antenna, Propagation, and EMC Technologies for Wireless Communications (MAPE 2007).

3) Interarrival times: The Saleh-Valenzuela model suggests that within each cluster, the interarrival times of the paths is a Poisson process; this model has been used extensively in the literature [13]. A generalized Poisson-mixture model was introduced by [20],[21] and also used in the standardized IEEE 802.15.4a model [22]. Parameterizations in different environments are summarized in [13]; in addition, the recent paper [23] discusses parameterizations for devices that are located close to the ground; [21] analyzes residential environments, [24], [25] investigate outdoor environments,

4) Cluster shapes: In the SV model, the average power delay profile of each cluster is assumed to be a single-sided exponential decay

$$E\{|a_{k,l}|^2\} \propto \Omega_l \exp(-\tau_{k,l}/\gamma_l) \quad \text{for } \tau_{k,l} \geq 0 \tag{3}$$

where Ω_l is the integrated energy of the $l-$th cluster, and γ_l is the intra-cluster decay time constant. The cluster powers, averaged over the large-scale fading, in general follow an exponential decay

$$10\log(\Omega_l) = 10\log(\exp(-T_l/\Gamma)) \tag{4}$$

However, in a number of NLOS environments, a soft onset of the power delay profile of a cluster has been observed. Such a soft onset can be well described by [22]:

$$E\{|a_{k,1}|^2\} \propto (1 - \xi \cdot \exp(-\tau_{k,l}/\gamma_{\text{rise}})) \cdot \exp(-\tau_{k,l}/\gamma_1) \tag{5}$$

Here, the parameter ξ describes the attenuation of the first component, the parameter γ_{rise} determines how fast the PDP increases to its local maximum, and γ_1 determines the decay at late times. Note that such a soft onset can be an inherent function of non-line-of-sight (NLOS) channels, but due to the "smearing" of the impulse response by the receiver filter is usually observable only with UWB systems.

5) Small-scale fading: The most frequently observed distributions for the small-scale fading is the *Nakagami distribution* (e.g., [26]),

$$pdf(x) = \frac{2}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m x^{2m-1} \exp\left(-\frac{m}{\Omega}x^2\right), \tag{6}$$

where $m \geq 1/2$ is the Nakagami m-factor, $\Gamma(m)$ is the gamma function, and Ω is the mean-square value of the amplitude. Furthermore, the *Rice distribution*: The Rice distribution [27] and the lognormal distribution [28] are also popular.

B. Frequency dependence of channel parameters

In a UWB scenario, the parameters characterizing the channel show a frequency dependence. The path gain dependence on the frequency is commonly modeled as being proportional to $f^{-2\kappa}$ [29] where $\kappa = 1$ corresponds to the standard "Friijs' law. Measured coefficients for κ range from negative values [22] to 1.3 [27], [30]. However, the pathloss exponent, which characterizes the distance dependence of the pathloss, does *not* show a frequency dependence according to the measurements in [31].

The number of resolvable multipath components tends to decrease with frequency; [30] measured approximately 30 resolvable MPCs in the $3.1 - 4.6$ band in an indoor environment, while the number decreased to 8 in the $9.1 - 10.6$ GHz band. Similarly, the rms delay spread decreases with frequency (approximately by a factor of 2, according to the measurements in [30]). Similarly, the angular spread (see Sec.III) decreases with increasing center frequency.

C. Standardized channel models

Two UWB channel models have been developed by international standardization bodies. The IEEE 802.15.3a channel model [32], [33] was developed in 2003 for the purpose of testing UWB communications systems over short ranges in residential and office indoor environments. The model is a very simple SV-based channel model with lognormal fading of each MPC.

The IEEE 802.15.4a channel model [22] is a model that is more general than the 15.3a model in several respects: (i) it is parameterized in more types of environments, and the parameters are valid for larger distances between TX and RX, (ii) it describes the "soft onset" of the power delay profile, which is important for ranging, (iii) it uses more general fading statistics, including mixed Poisson processes for the MPC interarrival time, and delay-dependent decay time constants, (iv) it has a more general frequency dependence of the pathloss.

It is noteworthy that both the 15.3a and the 15.4a channel models are suitable for simulations of UWB systems with arbitary data rates. [2]

III. Angular dispersion and polarization

A. Generic model

Since the middle of the decade, UWB systems with multiple antennas have gathered interest. There are a number of reasons for this development:

1) multiple antennas allow beamforming, and thus an increase in the effective signal-to-noise ratio at the receiver. This is important because the regulatory restrictions on the total transmitted power impose severe limits on the range of UWB systems.
2) calibrated multiple antenna structures allow the determination of the directions of incoming or outgoing multipath components, and thus improve the accuracy of geolocation.
3) when multiple antenna elements are present at both transmitter and receiver, spatial multiplexing can be used to increase the total feasible data rate. This method is of special interest for systems with target data rates beyond 1 Gbit/s. Note that spatial multiplexing can also exploit different polarizations in addition to (or instead of) spatially separated antenna elements.

Analysis of multiple-antenna UWB systems requires the description and measurement of the angular dispersion of UWB propagation channels. An appropriate generic channel model is a generalization of the double-directional channel model [34] to the UWB case. The double-directional channel model writes the total impulse response as a sum of double-directional contributions $\underline{h}_i$ of N MPCs

$$\underline{h}(\vec{r}, \tau, \Omega, \Psi) = \sum_{i=1}^{N(\vec{r})} \underline{h}_i(\vec{r}, \tau, \Omega, \Psi). \tag{7}$$

[2] it is a common misconception that the 15.3a model is particularly suited for the simulation of high-data-rate systems, while the 15.4a model is for low-rate systems. However, a channel model is *not* dependent on data rate, modulation format, etc., of the system tested in it.

where the spatial angle Ω characterizes the direction of arrival (DOA) of MPCs at the RX antenna, and the direction of departure (DOD) of waves from the TX antenna is denoted by Ψ. Within a region of stationarity A,[3] the contribution at a receiver location $\vec{r}$ can be written as a phase-shifted version of the contribution at a reference point $\vec{r}_0$ within A, with a phase shift

$$\Phi(\vec{r}, \vec{r}_0, f) = \frac{2\pi}{c_0} f \langle \vec{e}(\Omega_i), \vec{r} - \vec{r}_0 \rangle. \tag{8}$$

where $\vec{e}(\Omega_i)$ is the unit vector in the direction of the DOA. The equation for phase shifts at the transmitter is analogous.

The contributions of the MPCs are written as

$$\underline{h}_i(\vec{r}_0, \tau, \Omega, \Psi) = \underline{a}_i \chi_i(\tau - \tau_i) \delta(\Omega - \Omega_i) \delta(\Psi - \Psi_i), \tag{9}$$

when it can be assumed that the MPCs have discrete DOAs and DODs that do not depend on the frequency. A similar model, with a specific form for χ_i, was suggested in [35]. The complex amplitude $\underline{\alpha}_i$ is

$$\underline{\alpha}_i = \begin{pmatrix} \alpha_i^{\vartheta\vartheta} & \alpha_i^{\vartheta\phi} \\ \alpha_i^{\phi\vartheta} & \alpha_i^{\phi\phi} \end{pmatrix} \tag{10}$$

where ϑ and ϕ denote polarization along the ϑ and ϕ angles of a spherical coordinate system, respectively (due to the far-field assumption, two orthogonal polarizations are sufficient for the characterization). Note that the description assumes that the different polarization components of each MPC are distorted in the same way; a generalization to arbitrary distortions can be easily made but is omitted here.

Directionally resolved measurements can be done either by means of (rotating) directional antennas, or by antenna array measurements from which the parameters of the multipath parameters are extracted by means of high-resolution algorithms [36]. While the former method is more convenient, the latter method provides more information on the propagation mechanisms and the impact of different antennna characteristics and arrangements.Most measurements describe not the detailed characteristics of the MPCs, but rather the angular spread at the two link ends, which is defined as the second central moment of the angular power spectrum APS

$$S_\phi = \sqrt{\frac{\int APS(\phi)\phi^2 d\phi}{\int APS(\phi) d\phi} - \left(\frac{\int APS(\phi)\phi d\phi}{\int APS(\phi) d\phi} \right)^2}. \tag{11}$$

Note that other definitions of the angular spread exist [14].

B. Measurement results

The first measurements of an APS was provided in Ref. [37], [38], which used the CLEAN algorithm to extract the directions of the MPCs at the receiver from a 7×7 virtual array. The directional impulse response was modeled as a sum of cluster contributions. The mean DOA of the clusters was described as uniformly distributed, while the cluster angular distribution was described as Laplacian with a spread of $38°$. When distinguishing between LOS and NLOS situations, it turned out that cluster angular spreads for short-range scenarios are in the range of $30° - 70°$ and for long-range scenarios in the range of $20° - 30°$. Ref. [39] extracted the multipath parameters in an office environment finding that the significant MPCs (within 10 dB of the strongest component) typically come from a fairly small angular range ($<60° - 90°$). Similarly, residential environments show that most of the significant clusters have a mean DOA within a $60°$ sector [40].

The angular spread is directly related to spatial correlation, because a channel with small angular spread requires larger antenna separation for sufficient signal decorrelation. A number of measurements of UWB spatial correlation has been reported in the literature [41], [42], [43], [44]; [45]. For an overview of the results and their interpretation, we refer to [36]. In general, the papers indicate correlation coefficients below 0.5 for antenna spacings between 3 and 8 cm

Multiple-antenna systems can exploit not only antenna elements with different spatial positions, but also with different polarizations. The capacity gain that can be achieved with such systems strongly depends on the cross-polarization discrimination (XPD) of the channel. Only few measurements are available. [46] show that two orthogonal polarizations have a correlation coefficient < 0.1, but that the mean power of the co- and cross-polarized component differs by some 5 dB. The paper also concludes that a high mean capacity as well as a high outage capacity can be achieved with polarization-based MIMO systems.

IV. Propagation channels for Body Area Networks

During the past two years, a number of papers have described UWB propagation channels for body-area networks, i.e., networks where both transmitter and receiver antennas are located on the body of a person. Antennas can be implanted, directly attached to the skin, or be connected to the clothes of the person wearing them. Propagation of the waves can occur on and through the body, as well as via surrounding objects. Note that a number of simulations of such networks have been done by eliminating the effect of surrounding objects, thus leading to smaller delay spreads and higher pathloss than in realistic environments.

Ref. [47] performed measurements over the 3.1-10.6 GHz frequency range, with a spatial resolution of 2 cm, using a vector network analyzer. The measurements took place both in an anechoic chamber, and in an office (lounge) environment. The median of the rms delay spread was 6 ns, the maximum observed value was 12 ns. The number of Rake fingers required to collect 80% of the energy was 5 for a TX-RX separation of 15 cm, while it was 20 for a TX-RX separation of 85 cm. Ref. [48] measured on-body networks with different antenna types, namely horn antennas and planar inverted cone antennas (PICAs). They found a power-law pathloss, with pathloss exponents of 4.4 and 2.7 for horn antennas and PICAs, respectively. They also found a lognormal distribution of the delay spread, with a median of 3 ns. Measurements of propagation around the head from ear to ear [49] show delay spreads on the order of 1.5 ns.

Extensive measurement campaigns and parameter fittings were done by Fort et al. [50], [51], leading to the following important insights: (i) the lognormal distribution is most suitable to describe the small-scale fading (variations of the received power at different locations within a region of stationarity) on

[3] a "local region of stationarity" A, is defined as a region in which the parameters (delay, directions) of the MPCs stay constant [14].

a BAN, (ii) strong correlation between the fading of adjacent delay bins exists, (iii) either the lognormal distribution or the Nakagami-distribution is a suitable description for the small-scale fading due to the movement of the arms, (iv) MPCs propagating via ground reflections or wall reflections are important for the propagation between antennas on the front and back of the torso, and lead to a significant increase in the delay spread, (v) the Weibull distribution shows the best fit to measured inter-arrival times of the MPCs.

V. Impact on System Design

Every UWB communications system is influenced by the propagation channels. Reference [13] discusses the impact of channels on most modulation and receiver structures, in particular OFDM systems, multiband receivers, and Rake receivers. In the current paper, we confine our discussion to multi-antenna systems, BANs, and systems with precision ranging.

A. *Multi-antenna systems*

It is critical to understand the interaction between propagation channel, antenna elements, and systems for the design and analysis of systems with multiple antenna elements. The double-directional channel representation described in Sec. III is independent of the antennas. The antennas themselves show a dependence on frequency due to two effects:

- the phase shift between two antenna elements at locations $\vec{r}$ and $\vec{r}_0$, as given by Eq. (8), depends on the frequency.
- the antenna pattern of the antenna elements changes with frequency [52].

In conjunction, the two effects work together with the frequency dependence of the channels themselves.

Changes of the directional characteristics of channels and antennas increase the robustness of the system. If, e.g., the direction of the main antenna lobe is different in different frequency bands, it is implied that blocking MPCs from certain directions (e.g., by human bodies) need not lead to catastrophic outages. Of course, exploiting such increased diversity requires appropriate system design (coding across bands in a multband system, etc.). At the same time, the design of transceivers operating in the time domain is made more difficult by this increased dispersion.

The strong decorrelation of the signals even at closely spaced antenna elements (see Sec. III.B) implies that spatial multiplexing can be effectively used to increase the data rate of UWB systems. Exploiting polarization diversity can also greatly help in this respect, since orthogonally polarized signals are also highly decorrelated, as discussed in Sec.III.B. A number of modulation and coding schemes have been developed that exploit those capabilities.

B. *Body-area networks*

BANs show markedly smaller delay spreads compared to PANs. This eases the implementation of low-complexity transceivers even for high data rates. It is well established that both noncoherent receivers and transmitted-reference receivers [53], work best if the product of data rate and delay spread is much smaller than unity. The small delay spread of BANs (a few ns) thus offers the possibility of implementing such simple transceiver structures at data rates in the tens of Mbit/s. On the downside, the small delay spread and the correlation of the fading in adjacent delay bins also implies that little delay diversity is available.

C. *Ranging*

TOA-based ranging requires the determination of the time-of-arrival of the LOS component, i.e., the runtime from the transmitter to the receiver. Several effects make this task difficult in non-LOS situations:

- the LOS component can be completely blocked or suppressed so strongly that it is indistinguishable from noise. This situation can occur, e.g., when one of the two link ends is located behind a large metal object [54].
- the LOS component can propagate through a dielectric medium that has a speed of light that is significantly different from that in air. The resulting runtime of the signal then does not correspond to the geometrical distance between the two link ends.
- clock drift and other hardware nonidealities decrease the accuracy of the runtime estimation.
- the LOS component cannot be distinguished from other MPCs that follow it. Distinguishing the LOS is especially difficult when the power delay profile shows a "soft onset", i.e., the (quasi-) LOS component is weaker than the subsequent components. Furthermore, the cluster structure of the impulse response can increase the difficulty of extracting the quasi-LOS component [55].

The last effect is a major challenge in UWB systems, and often dominates the total error of a ranging estimate. Methods ranging from maximum-likelihood approaches to Baysean estimates have been proposed to combat this effect [56], [57].

The clustered structure of the impulse response has to be taken into account for channel estimation as well as the ranging process derived from it. Ref. [58] proposed an improved channel estimation algorithm that first estimates the cluster structure, and then the parameters within the clusters.

VI. Summary and Conclusions

We gave an overview of UWB propagation channels and their impact on system design. In particular, we discussed UWB channels for PANs and BANs, and the angular dispersion that is vital for multiple-antenna systems. While a number of important results have been obtained in the literature, many open questions remain. Especially in the area of angular dispersion and polarization diversity, more measurements and model parameterizations are required. Also, the interaction between channels and antennas will have to be considered in more detail.

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