ULTRAWIDEBAND ANTENNA ARRAYS AND DIRECTIONAL PROPAGATION CHANNELS

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ABSTRACT

The large spectral occupancy of ultrawideband (UWB) wireless signals significantly complicates the design of multi-antenna arrays and the characterization of propagation channels determining the performance of such arrays. This survey paper develops generic techniques for double-directional UWB channel characterization, and surveys methods for the extraction of the parameters of multipath components. The key channel attributes affecting multi-antenna performance, such as the angular spread and spatial correlation, are discussed in the light of measurement results. Guidelines for UWB array design are provided. Throughout the discussion, the differences from narrowband systems are highlighted.

1. INTRODUCTION

Ultrawideband (UWB) signals span very large instantaneous bandwidths as compared to conventional narrowband signals, ranging from 500 MHz up to 7.5 GHz [1, 2]. The current FCC regulations in USA permit UWB indoor devices to operate in the 3.1–10.6 GHz band. Besides providing data rates unprecedented in radio communications, UWB systems are inherently robust to fading and interference. UWB radars, positioning systems, and imaging devices also enjoy high resolution thanks to temporally short pulse signals.

The performance of a wireless system can be enhanced with a multi-antenna array. Narrowband phased-array radars, limited primarily to military applications due to their size and cost, can provide enhanced target detection and resolution. Electronic beam-steering systems with moderate array sizes are also sometimes deployed in commercial systems to improve the link budget, increase the data rate, or suppress interference. Like narrowband systems, UWB radar and communication systems can also obtain substantial performance gains by multi-antenna techniques.

Owing to the large bandwidth, UWB channels inherently enjoy multipath or frequency diversity. This is evident from Fig. 1, which shows the UWB channel impulse response measured in a typical indoor office environment. As a consequence of these attributes, UWB channels do not suffer from appreciable temporal or small-scale spatial fading [3]. While small-scale fading is negligible, antenna diversity and beamforming can boost the signal-to-noise ratio (SNR) significantly in some situations, and therefore extend the coverage radius, enable wall penetration, and mitigate shadowing.

An exciting application of multi-antenna UWB techniques is in very high data-rate communications. Based on the spatial-multiplexing variant of multiple-input multiple-output (MIMO) signaling and exploiting the large gain in capacity due to the wide bandwidth, UWB MIMO systems have the potential to increase the data-rate of UWB systems beyond the current state of the art (approximately 500 Mbps) to several Gbps. Such high rates will be useful in multimedia communications and related applications. These applications lead us to conclude that there is ample scope for multi-antenna UWB communications systems.

The efficient coupling of energy into the wireless medium over such a large bandwidth requires carefully designed antennas. The design and performance modeling of UWB antennas is considerably more complex than that of their narrowband counterparts [4]. In addition to the issues encountered in the design of individual UWB elements, antenna arrays give rise to complications of their own. The improvement in performance therefore comes at the cost of increased system complexity. In this paper, we highlight some of these design issues and identify some strategies to address them. Another focus point of this paper is the description of UWB propagation channels in a way that is suitable for MIMO systems. We derive the generalization of the double-directional channel description [5] to the UWB case, and also discuss the particular difficulties in performing and evaluating double-directional UWB channel measurements. This is followed by a detailed description of UWB array-based channel measurement results.

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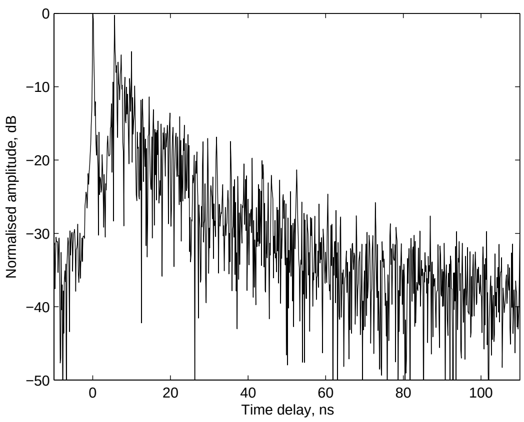

Fig. 1. The impulse response of an indoor UWB channel.

2. UWB ANTENNA ARRAYS

Apart from the antenna bandwidth, UWB arrays are in general similar to narrowband arrays except for structural differences that cater to the large bandwidth. In particular, the requirements for the phase relationship between the array elements often necessitate more stringent design considerations.

The simplest narrowband array configuration is the uniform linear array (ULA), which is shown in Fig. 2. Triangular, rectangular, hexagonal, and circular topologies have also been proposed as alternative spatial arrays designs [6, 7]. From aperture theory, a half-wavelength inter-element spacing is considered optimal for ULAs, as it minimizes the fading correlation and antenna coupling without causing the appearance of grating lobes. If the elements of a ULA are too closely spaced and the fading correlation is high, little gain in the capacity or diversity order is obtained. The net effect is then realized in the form of the array gain, and the effective degrees of freedom of the correlated spatial array reduce to unity.

Compact arrays are, however, highly desirable especially for consumer electronics applications. Arrays with a small number of antennas can be formed with collocated elements using polarization or pattern diversity. In dense scattering environments, physically compact dual- or tri-polar arrays can be an effective alternative to spatial arrays of the same dimensionality. Antenna pattern diversity has also been analyzed in literature, and found to yield performance close to that of spatial arrays. ULAs, however, continue to be a popular choice, as they are simple and economical to design, and analytically well understood. The optimal antenna spacing for a UWB ULA is not as clearly determined in general as that for a narrowband ULA. The reason is the wide range of wavelengths involved, each of which would imply a different optimal spacing.

For data transmission with diversity or spatial multiplexing, a simple rule of thumb then is to tailor the design to the lowest operating frequency. For beamforming and array-based measurements of the multipath angular spectrum, however, different rules apply [8], as discussed further in the next sections.

Further complications in array design arise from mutual coupling and imperfect matching of the antenna elements. Close spacing of the antenna elements leads to a coupling of the currents of the different antenna elements. This effect is well known from narrowband antenna theory [9], but raises additional problems in UWB by introducing a directional dependence of the impulse response [10].

Yet another problem in array design is the wideband matching of the antenna elements. The Fano theorem puts limits on the achievable antenna matching for wideband antennas [11]. However, for simplicity we will assume the absence of mutual coupling and imperfect matching in the remainder of this paper.

3. GENERIC CHANNEL DESCRIPTION

In order to analyze the performance of MIMO systems in realistic propagation channels, it is first required to set up appropriate channel models. As in the case of narrowband systems, there are two basic methods of describing MIMO channels: modeling of the transfer function matrix (i.e., the transfer function from each transmit antenna element to each receive antenna element), or a double-directional description of the propagation channel [12]. In the following, we will discuss both those description methods and the transformation between them, concentrating on the peculiarities of UWB MIMO systems.

We start by reviewing the double-directional channel description in narrowband channels [5, 13]. The total channel impulse response can be expressed as the sum of the contributions h_l of the L multipath components (MPCs), i.e.,

$$\begin{aligned} h(\mathbf{r},\tau,\Omega,\Psi) &= \sum_{l=1}^{L(\mathbf{r})} h_l(\mathbf{r},\tau,\Omega,\Psi) \\ &= \sum_{l=1}^{L(\mathbf{r})} h_l(\mathbf{r}_0,\tau,\Omega,\Psi) e^{j\frac{2\pi}{\lambda}\langle \mathbf{e}(\Omega_l),\mathbf{r}-\mathbf{r}_0\rangle} \end{aligned} \quad (1)$$

where τ is the delay variable, the spatial angle Ω characterizes the direction-of-arrival (DOA) of waves, and Ψ is the direction of departure (DOD) of waves from the transmitting antenna. The vector $\mathbf{r_0}$ is the position vector describing the location of the receiver within a "local region of stationarity," A, in which the parameters, i.e. the delays and directions, of the MPCs stay constant, and $\mathbf{e}$ is the unit vector pointing into the direction of Ω. It is assumed that the transmitter is located at the origin of the coordinate system.

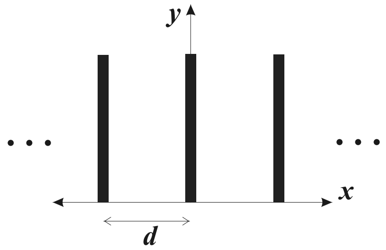

Fig. 2. A uniform linear array (ULA) with inter-element spacing 'd'.

In the narrowband case, the double-directional impulse response of a single MPC can be written as

$$h_l\left(\mathbf{r}_0,\tau,\Omega,\Psi\right)=\alpha_l\delta\left(\tau-\tau_l\right)\delta\left(\Omega-\Omega_l\right)\delta\left(\Psi-\Psi_l\right), \quad (2)$$

where the complex amplitude α_l is

$$\alpha_l=\begin{pmatrix}\alpha_l^{\vartheta\vartheta} & \alpha_l^{\vartheta\phi}\\ \alpha_l^{\phi\vartheta} & \alpha_l^{\phi\phi}\end{pmatrix} \quad (3)$$

with superscript ϕ and ϑ denoting the polarization in azimuth and elevation, respectively.

In the UWB case, each of the MPCs can suffer from delay dispersion, so that (2) must be replaced by

$$h_l\left(\mathbf{r}_0,\tau,\Omega,\Psi\right)=\alpha_l\chi_l\left(\tau-\tau_l\right)\delta\left(\Omega-\Omega_l\right)\delta\left(\Psi-\Psi_l\right), \quad (4)$$

where the pulse distortion χ depends on the interaction of the wave with the surrounding objects, and the electromagnetic properties and geometric shape of the objects. As a consequence of the MPC distortion, not only the instantaneous transfer function

$$H\left(\mathbf{r},f,\Omega,\Psi\right)=\mathcal{F}_{\tau\to f}\left\{h\left(\mathbf{r},\tau,\Omega,\Psi\right)\right\}, \quad (5)$$

but also the frequency correlation function

$$E\left\{H^{\dagger}\left(\mathbf{r},f,\Omega,\Psi\right)H\left(\mathbf{r},f+\Delta f,\Omega,\Psi\right)\right\} \quad (6)$$

depends on f, which implies that the WSSUS assumption [14] is not fulfilled in the frequency domain.

Another representation of directional channels gives the impulse response of the channel at the elements of an antenna array. Thus, the impulse response becomes a matrix if we have arrays at both link ends. We denote the transmit and receive element coordinates as $\mathbf{r}_T^{(1)},\mathbf{r}_T^{(2)},...,\mathbf{r}_T^{(N_T)}$, and $\mathbf{r}_R^{(1)},\mathbf{r}_R^{(2)},...,\mathbf{r}_R^{(N_R)}$ respectively, so that the transfer function from the i^{th} transmit to the j^{th} receive element becomes [12, 15]

$$\begin{aligned}H_{i,j}&=H\left(\mathbf{r}_T^{(i)},\mathbf{r}_R^{(j)}\right)\\&=\sum_l H_l\left(\mathbf{r}_T^{(0)},\mathbf{r}_R^{(0)},f,\Omega_l,\Psi_l\right)\mathbf{G}_T\left(f,\Omega_l\right)\\&\quad \text{x } \mathbf{G}_R\left(f,\Psi_l\right)e^{j\left\langle\mathbf{k}(\Omega_l),\mathbf{r}_T^{(i)}\right\rangle}e^{j\left\langle\mathbf{k}(\Psi_l),\mathbf{r}_R^{(j)}\right\rangle}\end{aligned} \quad (7)$$

where G_T and G_R are the patterns of the transmit and receive antenna elements, respectively, and **k** is the unit wave vector in the direction of the l^{th} DOD or DOA. The location vector $\boldsymbol{r}_T^{(i)}$ is measured from the position of the reference antenna of the transmit array, and similarly for the receive array.

In an environment with significant propagation in three-dimensional space, the elevation angle of the MPCs has a strong impact on the MIMO channel matrix, even if the MIMO arrays are horizontal ULAs. The attenuation of an MPC depends on the elevation angle via the antenna elevation pattern. In addition, the elevation pattern is strongly frequency-dependent [16]. For a dipole-like antenna, the azimuthal plane shows a maximum at a low frequency, but a null at higher frequencies. This can lead not only to a misestimation of the azimuthal angles (as in the case of narrowband signals), but also a misestimation of the channel frequency characteristics.

4. DIRECTIONAL CHANNEL MEASUREMENT AND MODELING METHODS

The double-directional channel representation and the channel transfer function matrix are generic channel description methods. We now address the measurement and modeling of the channels. The most widespread method of measuring double-directional channels is by means of antenna arrays [5, 17-20]. This is nothing but a direct measurement of the transfer function matrix in (7). An alternative is a direct measurement of the impulse response in a certain direction by connecting a (time-domain or frequency domain) channel sounder to directional antennas. However, this approach is not widely used in the UWB literature. It has only been applied to measure the impact of antenna directivity (with the directional antennas pointed towards each other) on impulse responses [21], but not general double-directional impulse responses.

From the array measurements, it is possible to extract a statistical description of the channel. The most important parameter for MIMO systems is the spatial correlation coefficient between antenna elements,

$$\rho_{\left|\mathbf{r}_T^{(i)}-\mathbf{r}_T^{(m)}\right|,\left|\mathbf{r}_R^{(j)}-\mathbf{r}_R^{(n)}\right|}=\mathcal{E}\left\{H^{\dagger}\left(\mathbf{r}_T^{(i)},\mathbf{r}_R^{(j)}\right)H\left(\mathbf{r}_T^{(m)},\mathbf{r}_R^{(n)}\right)\right\}, \quad (8)$$

where $\mathcal{E}\{.\}$ is the expectation over the statistical ensemble. Note that there are differences between the narrowband and the UWB case about what measurements can be used as part of the statistical ensemble. For narrowband measurements, it is common to consider transfer functions, $H(f_i)$, with a set of different values of f, namely f_i, as members of the statistical ensemble[1] in order to obtain a sufficiently-sized ensemble. Such an approach is based on the assumption of *frequency ergodicity* [22], which in turn

[1] Measurements with $H(f_1)$, $H(f_2)$ are assumed to be statistically independent if $|f_2-f_1|$ is larger than the coherence bandwidth of the channel.

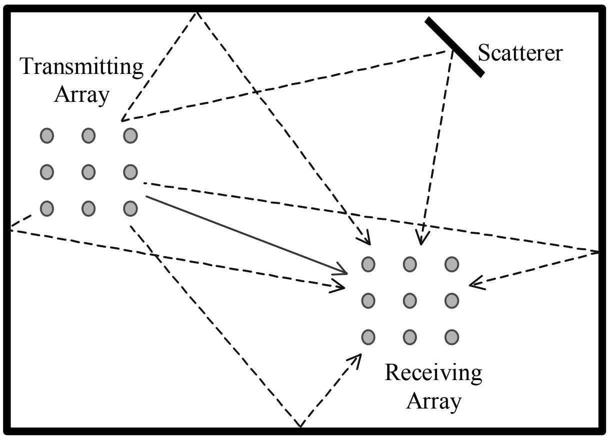

Fig. 3. Double-directional measurement of an indoor multipath channel using transmitter and receiver arrays.

implies stationarity in the frequency domain. In the UWB case, such an approach is only valid if the members of the ensemble have frequencies within a range B, i.e., $f_0 - B/2 < f_i < f_0 + B/2$. The range B has to be chosen in such a way that frequency ergodicity is fulfilled within that range; among other requirements, the fractional bandwidth, B/f_0 , should be less than approximately 10%, and the electromagnetic properties of the interacting objects, as well as the properties of the transmit and receive antenna elements, are required to be approximately constant within B.

Intuitively, the correlation coefficient varies as a function of the frequency band. Two antennas with a certain geometrical spacing $\left|r_T^{(i)} - r_T^{(m)}\right|$ have a different separation in units of wavelength in different frequency bands. We thus find that the correlation coefficient generally decreases with increasing frequency, as discussed later in this section in the light of measurement results.

5. MULTIPATH PARAMETER ESTIMATION

The extraction of the directions-of-arrival from the measurement results is an important step in the evaluation of array measurements – both for channel modeling purposes, and for geolocation purposes. In the narrowband literature, DOA estimation has drawn a great deal of attention over the years, and a number of different methods have been developed. In general, we can distinguish two groups of methods: spectral estimation methods, and parametric estimation methods [23]. The former group comprises Fourier (Bartlett) beamformers, Capon's beamformer, and MUSIC [24]. The challenge in UWB is the violation of the narrowband assumption, so that the beamforming matrices have a different structure at different frequencies. Frequency-dependent focusing matrices [25] and spatial resampling [26], or combinations thereof [27] are used as a preprocessing step before spectral estimation is applied. A method for improved computation of the correlation coefficient in the UWB case based on Hermite wavelets was suggested in [28]. Note, however, that these techniques usually do not aim for a joint estimation of arrival time and angular spectra. An alternative group of methods includes high-resolution parameter estimation methods like the ESPRIT [29] and SAGE algorithms [30]. They allow the extraction of the delay, DOA, DOD, and amplitude of the MPCs.

The most widely used high-resolution algorithm in the UWB literature is the CLEAN algorithm, first introduced in [31], and also applied in [32, 33]. It operates as follows. The delay and direction of the strongest echo is first determined by a delay-and-sum beamformer. The contribution of this MPC is then subtracted from the total signal, and the next largest component is determined. This process is continued until the residual energy falls below a threshold.

SAGE is a maximum-likelihood algorithm that tries to find the model parameters that optimize the likelihood function, i.e., minimize the deviation of transfer function as reconstructed from the parameterized model from the measured transfer function. As the direct optimization of the parameters is prohibitively complex, SAGE obtains the solution in an iterative way. The original SAGE algorithm [30] uses a data model based on the narrowband assumption. For UWB applications, [34] divided the measurement results into a number of subbands, and optimized the parameter so that the sum of the likelihood functions in all the subbands was maximized.

The main difficulty in applying parametric estimation techniques to UWB array measurements (besides the violation of the narrowband assumption) is the pulse distortion functions, χ_l,, which need to be considered in the parameter extraction process. Two approaches have so far emerged in the literature to deal with the pulse distortion functions: (i) ignore it, or (ii) assume a certain, parameterized form of the distortion function that is identical for all MPCs, and estimate its parameters. As an example for the latter approach, the pulse distortion function measured in free space (including the distortions by the antennas) can be assumed for all received pulses [35].

6. RESULTS OF MEASUREMENT CAMPAIGNS

A number of measurement campaigns have been undertaken in the last few years to characterize the spatial UWB channel. In most of those studies, propagation only in the azimuthal plane is considered.

This simplifying assumption may lead to inaccurate channel modeling in rich multipath environments, such as indoor office or industrial environments, especially if the antennas radiate significant energy in directions off the azimuth. In the rest of this section, we summarize some of the key results from recent empirical studies of UWB spatial channels, describing their angular spread and correlation characteristics.

In a pioneering work [31], a set of indoor time-domain UWB measurements were conducted using receiving antenna arrays, and the MPC directional information was extracted with the CLEAN algorithm. The azimuth-domain angular impulse response was modeled as

$$h(\varphi) = \sum_{p=0}^{\infty}\sum_{q=0}^{\infty} h_{qp}\delta\left(\varphi - \Phi_q - \omega_{qp}\right), \tag{9}$$

where h_{qp} is the amplitude of the q^{th} arrival in the p^{th} cluster, Φ_q is the mean DOA of the p^{th} cluster, and ω_{qp} is the DOA of the q^{th} arrival in the p^{th} cluster. A uniform distribution was assumed for Φ_q, while ω_{qp} was modeled with a zero-mean Laplacian distribution with $\sigma_\varphi = 38°$. In a more detailed analysis [17], σ_φ was found to lie between 31°–67° for short-range LOS scenarios, while for long-range NLOS scenarios, it was between 21°–30°. These angular spreads are wider than those reported for indoor channels with narrower bandwidth, such as in [36].

The dependence of the DOA on frequency was analyzed in [18], using indoor measurements in the 2–8 GHz band and the CLEAN algorithm. A small number of MPC clusters were observed: up to two and four in LOS and NLOS scenarios respectively. The angular spread was shown to decrease with an increase in frequency within this band. It is, however, not clear as to what extent the reduced angular spread can be attributed to the increased directivity of the CLEAN beamformer.

The DOAs in both azimuth and elevation were analyzed in the FCC-allocated UWB band in [19] using the Fourier method. Arrivals off the azimuth with significant energy levels were reported. Frequency-dependent angular scattering was also observed, owing in part to the frequency-variant antenna dispersion and in part to the differences in the propagation modes at different frequencies.

Double-directional characteristics of the UWB channel were evaluated in [37], in which the authors extracted the multipath parameters in an office environment and analyzed the underlying physical propagation mechanisms. From this study, the significant MPCs (within 10 dB of the strongest component) typically come from a fairly small angular range of less than 60°. Results for residential environments are given in [38]. Some 10 significant clusters, each of which had only a few degrees of angular spread, were identified; most of the clusters had a mean DOA within a 35° sector. Another important conclusion from this paper was that 25% of the energy could not be ascribed to specularly reflected components.

Angular clustering of MPCs is directly related to spatial correlation, as a channel with small angular spread requires larger antenna separation for sufficient signal decorrelation. The angular power spectrum and the spatial correlation function, in fact, form a Fourier transform pair. Given this close relationship, we discuss some measurement results on UWB spatial correlation.

Sounding the 1.4–3.4 GHz indoor channel, [39] analyzed the spatial correlation as a function of time delay and frequency. In the LOS scenario, the first three channel taps (corresponding to arrivals within the first 5 ns) were highly correlated, with coherence distances of over 1 m, while the latter taps showed swifter decorrelation (qualitatively similar results were also obtained in [20]). This difference was less pronounced in NLOS channels. The dependence of correlation with frequency was investigated using a narrowband signal approach, and an inverse relationship was demonstrated. This observation is significant, as it suggests that the multi-antenna performance of a multiband scheme, such as MB-OFDM, may vary with the subband's center frequency. In [40], the spatial correlation mainlobe width decreased as the center frequency was increased in NLOS channels, as expected, but the reverse trend was reported for LOS channels. The reliability of the latter observation and its implications were, however, questioned by the authors.

For MB-OFDM signals in the 3.1–10.6 GHz band, an antenna spacing of d = 3 cm was shown to achieve sufficient decorrelation in LOS and NLOS environments [41]. Similarly, low correlation was reported in [42] with d = 6 cm in the same frequency range, while in [43], transmit arrays decorrelated the 3.1–4.5 GHz UWB channel with d = 8.5 cm.

The effect of the transmitter-receiver separation on UWB signal correlation was considered in [44], based on 3–11 GHz measurements. It was found that both the transmit and receive correlation were significant at separations of less than 3 m in LOS scenarios, but NLOS channel correlation was virtually unaffected by the variation of this separation from 3 to 6 m. The measurements in [43] confirmed the decorrelation with increasing transmitter-receiver separation. Note that these results contradict the indoor measurements in [45], which reported that the transmit correlation of narrowband channels decreased with distance. This difference is, however, more likely to be due to the specific measurement conditions, including the local scattering, than to the channel bandwidth. An explicit relationship between correlation and bandwidth is not known, but a wider bandwidth is believed to lower the correlation in general.

In summary, these empirical results, obtained from array-based measurements, help us predict that multi-antenna UWB channels exhibit significant decorrelation and large angular spreads. These characteristics allow very high performance MIMO systems.

7. CONCLUSION

An overview of UWB antenna arrays has been provided, with an emphasis on the major differences from narrowband systems. Double-directional UWB channel characterization techniques, based on transmitter and receiver arrays, have been developed. Empirical multi-antenna analyses show that UWB channels experience larger angular spreads than narrowband channels, especially under NLOS scenarios. Also, UWB signal decorrelation is achieved with relatively small inter-element spacing. These results help us predict the performance of MIMO techniques in the UWB channel.

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