EXTRACTING INFORMATION FROM THE SPATIO-TEMPORAL ULTRAWIDEBAND CHANNEL

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Invited Paper

***Abstract*—**An overview of the propagation characteristics of ultrawideband (UWB) indoor radio channels is presented with an emphasis on the spatio-temporal channel properties. Extensive measurement results are provided and practical considerations are highlighted. The insight into robust UWB communications and sensor networks, provided by channel modeling, is discussed.
***Index Terms*—**Propagation, spatial channel, ultrawideband (UWB).

I. Introduction

The ever-growing requirement for high performance wireless communications in the last several decades has precipitated the development of innovative technologies. Among other advancements, recent times have witnessed a switch to wideband signaling techniques in order to improve the spectral efficiency and quality of service. Ultrawideband (UWB) communications technology, in particular, promises unprecedented data rates along with greater reliability [1]. Initially developed for military radars, UWB is now considered a leading contender for short-range high-rate communications and low-rate wireless sensor networks [2].

The defining characteristic of UWB systems is their large signal bandwidth. A system may be classified as narrowband, wideband or UWB depending on its fractional bandwidth, B_f, or absolute bandwidth, B. Thus, according to current FCC regulations in USA, a system is considered to be UWB if $B_f \geq 20\%$ or $B \geq 500$ MHz [3]. The behavior of a radio system over such a large bandwidth departs significantly from that of a narrowband system, as the propagation channel, antennas, and other components attain highly frequency-selective characteristics [4-6]. For this reason, the recent developments in UWB technology have been heralded as the harbinger of a major paradigm shift in future wireless communications.

Optimal UWB communications system design is a complex and multi-disciplinary process [7]. Its fundamentals take root in the characterization of the propagation channel [8] and system components [9]. The appropriate transceiver design and signal processing strategies are devised considering the channel information [10, 11]. This paper considers some of the key aspects of UWB channels that set them apart from narrowband channels.

II. Channel Models and Measurement

The large bandwidth of UWB systems renders the UWB channel highly frequency-selective. An appropriate channel representation must therefore be employed, such as the tapped delay line model in the time domain. Thus if α_l represents the complex amplitude of the l^{th} multipath component and τ_l its delay, then the impulse response of a channel with L multipaths can be expressed as

$$h(\tau) = \sum_{l=1}^{L} \alpha_l \delta(\tau - \tau_l), \qquad (1)$$

where $0 \leq \tau \leq \tau_s$ represents the time delay with respect to the first arrival, and τ_s is the maximum excess delay. The UWB channel model adopted by the IEEE 802.15.3a task group [8] is a modified form of the Saleh-Valenzuela model for indoor channels, and is formally similar to (1). Alternatively, a set of frequency-domain flat-fading channel coefficients can be employed such that each specifies the complex transfer characteristics of an arbitrarily small portion of the signal spectrum, so that the channel transfer function is

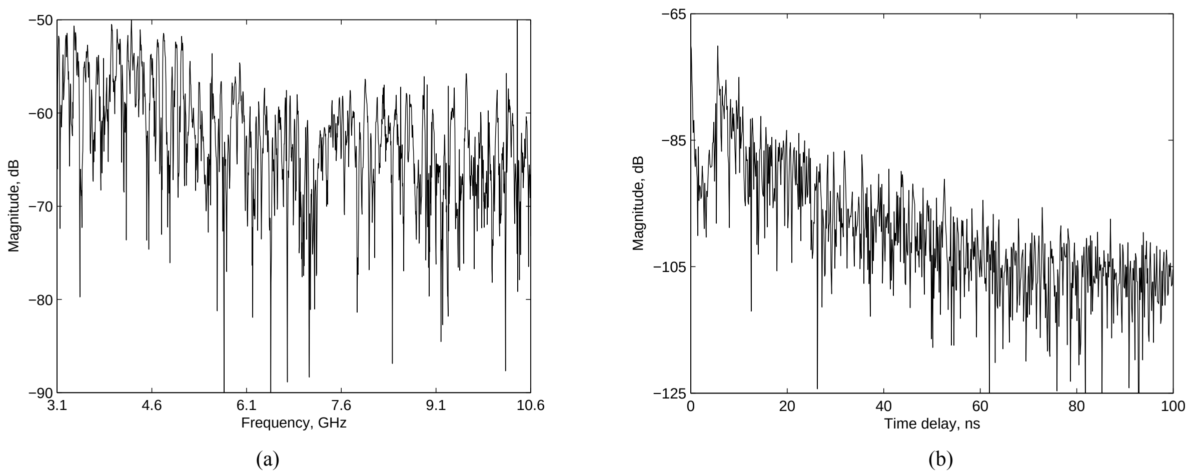

Fig. 1. A UWB channel measured in an indoor line-of-sight office environment: (a) channel transfer function, and (b) channel impulse response

$$H(f) = \sum_{k=1}^{n_f} A_k \delta(f - k\Delta f) \quad \text{s.t.} \quad \Delta f < B_c, \qquad (2)$$

where A_k is the complex amplitude at the k^{th} frequency bin, n_f is the number of frequency bins, B_c is the channel coherence bandwidth, and Δf is the frequency resolution. In (2), $f_l \leq f \leq f_h$, where f_l and f_h represent the frequencies at the lower and upper boundaries, respectively, of the UWB signal spectrum.

Radio channel models are based on empirical studies involving propagation measurements in the time or frequency domain. The wide bandwidth and propagation environments for indoor UWB systems imply that the channel time variance is minimal. A chirped frequency-domain measurement spanning a large bandwidth can therefore be undertaken with the help of a vector network analyzer (VNA) [12]. A VNA-based measurement is preferable as it allows channel measurement over a very large bandwidth – tens of gigahertz – without the complexity of sophisticated pulse generators and detectors required by pulsed time-domain channel sounders. The results reported in this paper are, therefore, based on indoor UWB measurements conducted with a VNA in the FCC-allocated frequency band (3.1–10.6 GHz).

Fig. 1(a) shows the UWB signal spectrum, $H(f)$, measured using a VNA in an indoor office environment, at a transmitter-receiver separation of 4 m. The signal attenuation during transmission varies significantly as a function of frequency over the signal bandwidth. The coherence bandwidth, B_c, for this channel transfer function can be calculated from the frequency-domain channel correlation, $r(\delta f)$, as $r(B_c) \geq r_{th}$, where r_{th} is the correlation threshold. Thus, if $r_{th} = 0.6$, then for the channel transfer function in Fig. 1(a), $B_c \approx 30$ MHz [13]. Clearly, therefore, $B_c \ll B$.

Fig. 1(b) shows the corresponding channel impulse response, $h(\tau)$, obtained from $H(f)$ via the inverse fast Fourier transform, where the propagation delay has been removed. A large number of resolvable multipath components are observed. The number of multipaths resolvable by a UWB system varies linearly with the signal bandwidth [10].

Thus channel measurement across frequency provides information about the spectral and temporal signal evolution. The characterization of the spatial dimension, however, requires measurements over a set of spatial locations, which can be achieved with an antenna array. If, however, the channel is quasi-static in time, aperture synthesis can be employed instead. The measured channel impulse response, $h(x, y, \tau)$, is then a function of both space and time, where x and y define the two-dimensional Cartesian coordinate system. As signal propagation in radio channels with vertically polarized omni-directional antennas occurs predominantly in the horizontal plane, the two-dimensional Cartesian basis enables sufficiently accurate description of the spatio-temporal UWB channel.

III. Multipath Direction Estimation

The directions-of-arrival (DOAs) of the impinging multipath components can be extracted from a spatial channel measurement using standard antenna array theory [14]. The Fraunhofer assumption can be invoked when the signal sources, i.e. the transmitter and scattering objects, are in the far field of the receiving antenna array. In that case, the

Fourier method provides the simplest procedure for the conversion of $h(x, y, \tau)$ into $h(\varphi, \theta, \tau)$, where φ and θ denote the elevation and azimuth angles, respectively, as defined in the spherical coordinate system [15]. If the signals originate in the Fresnel region, however, full wave techniques must be used [16]. Several other algorithms for image formation and DOA estimation have also been studied in literature, such as MUSIC and SAGE [17].

Fig. 2 shows the DOA profile of a line-of-sight (LOS) UWB channel, estimated using the Fourier method, in which the transmitter is located at $(\varphi, \theta) = (0°, 90°)$. As the synthetic aperture data for this figure is two-dimensional, there is an up-down ambiguity. It can be observed that the multipaths arrive in a small number of high-intensity clusters. The strongest intensity is received from the LOS direction, while a strong reflection from the ceiling is also observed. Note that the observed DOA profile also contains the effect of the receive antenna radiation pattern. Furthermore, it has been demonstrated in [15] that the UWB DOA profile varies with frequency due to the frequency-selectivity of the channel. In other words, the multipath signals arriving from a given direction do not necessarily have identical frequency content.

The multipath direction-of-departure (DOD) information can be obtained similarly, with the help of an antenna array at the transmitter. The DOA and DOD are sometimes jointly estimated in double-directional channel studies in order to determine the ray-paths traversed by the signal components between the transmitter and the receiver.

IV. Multiple-Antenna Techniques

This section discusses techniques involving multiple-antenna arrays and the consequent performance achievable by a UWB system. Multiple-antenna systems provide an additional degree of freedom in terms of the spatial properties of the channel, which can be used for performance improvement with advanced signal processing techniques [18-20]. Antenna arrays can make use of spatial, polar, angular, or pattern diversity. We will, however, limit our discussion to spatial arrays and consider the following applications of multiple antennas for UWB systems.

A. Diversity

Antenna diversity techniques are used widely in narrowband communications to improve the diversity order and the bit error performance. For UWB channels, however, antenna diversity does not carry the same meaning, as the diversity order is already very high due to the large frequency bandwidth and the consequent frequency diversity. A more appropriate interpretation of antenna diversity can therefore be provided in terms of the array gain obtained by the optimum combining of the signals received or transmitted by multiple antennas, so that the diversity improvement is the gain in the average received SNR.

The higher SNR provided by antenna diversity can be critical for UWB operation. It can significantly increase the coverage range, which is currently a severe limiting factor of UWB communications. It can also help reduce outage, or enable performance in a blocking scenario, such as between rooms on a floor.

For classical diversity performance, where the intent is to improve the diversity order in a narrowband wireless channel, the antennas are ideally spaced $\lambda/2$ apart, where λ is the wavelength. This inter-element spacing ensures that the fading correlation and antenna coupling are both acceptably low. The array gain, however, is realized independently of the fading correlation, and therefore the antenna spacing requirements of UWB diversity systems are governed only by the antenna coupling characteristics. A distance of 0.4λ is generally sufficient for low antenna mutual coupling [21], which translates to approximately 4 cm if the largest wavelength in the FCC UWB band is considered. Thus a three-element linear array would occupy nearly 8 cm, and is thus feasible for applications such as wireless networks and handheld devices.

The optimum diversity combining technique in fading channels is maximal-ratio combining (MRC), which scales the SNR linearly with the number of antennas if the channel state information is available at the receiver (CSIR), or $\Gamma = \rho N$, where ρ denotes the average SNR at each of the antennas, and Γ is the output SNR of the diversity system. Thus a receive diversity system, with two receive antennas in a single-input multiple-output (SIMO) configuration, can double the SNR, while a three-antenna system can improve it by 4.8 dB. A transmit diversity, or multiple-input single-output (MISO), system can provide similar performance if the channel is known at the transmitter (CSIT). The deployment of multiple-antenna arrays at both ends of the link, in a multiple-input multiple-output (MIMO) configuration, can further improve the diversity gain. Thus a MIMO system at each side, and with both CSIT and CSIR, can improve the SNR using dominant eigenmode transmission [22].

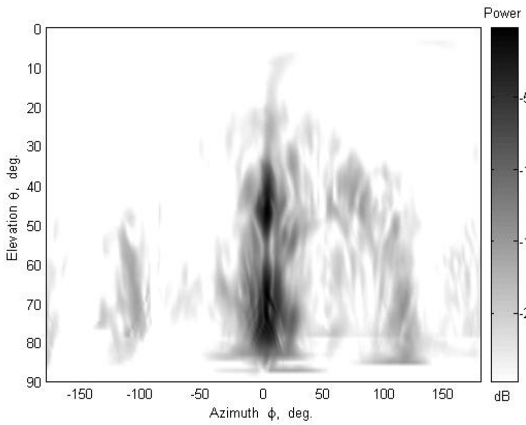

Fig. 2. The measured power at a synthetic aperture UWB receiver in an indoor line-of-sight UWB channel with the transmitter located at (φ, θ) = (0°, 90°)

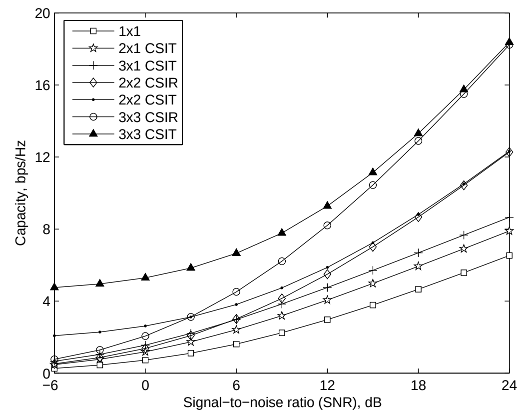

Fig. 3. The measured UWB multiple-antenna capacity at the 1% outage level in a variety of system configurations

UWB measurements have shown that a three-element array can provide an 8.3 dB gain [1, 18]. Such a large diversity gain can overcome many of the link budget, range limitation and outage problems faced by UWB communications and sensor networks. Table I lists the ergodic and 1% outage diversity gain, obtained from indoor UWB channel measurements using a variety of linear array configurations.

B. Spatial Multiplexing

MIMO arrays can provide spatial multiplexing in which multiple independent data streams are transmitted over the wireless channel in parallel [22]. MIMO systems thus yield significant performance gains by increasing the channel capacity and spectral efficiency by a large measure under the condition of sufficient signal decorrelation, introduced by rich scattering. Thus the information rate of a communications system can be increased *N*-fold by using an *N*-element array at the transmitter and a similar array at the receiver [23].

UWB MIMO evaluations can be undertaken by considering the channel to be composed of a large number of flat-fading channels [18, 24]. Under CSIR, the capacity of each of those flat-fading MIMO channels, denoted by $\mathbf{G}_k$, centered at the k^{th} frequency, can then be computed individually in terms of the eigenvalues, λ_i, of $\mathbf{G}_k\mathbf{G}_k^\dagger$ as [23]

$$C_k = \sum_{i=1}^{r_G} \log_2\left(1+\frac{\rho}{N}\lambda_i\right), \qquad (3)$$

where $r_G = \text{rank}\{\mathbf{G}_k\}$ and $(.)^\dagger$ denotes the conjugate transpose. If CSIT is available, the achievable capacity becomes

$$C_k = \sum_{i=1}^{r_G} \left\{\log_2\left(\frac{\rho}{N}\mu\lambda_i\right)\right\}^+, \text{ with } \mu = \frac{N}{r_G}\left(1+\frac{1}{\rho}\sum_{i=1}^{r_G}\frac{1}{\lambda_i}\right), (4)$$

where $\{.\}^+$ indicates the set of positive values. In either case, the capacity of the UWB channel, $\mathbf{H} = \{\mathbf{G}_k\}$, is given by $C = \underset{k}{\mathcal{E}}\{C_k\}$, where $\underset{k}{\mathcal{E}}$ denotes the expectation across the UWB band. With this formulation, the existing theory of MIMO channels can be easily extended to UWB systems. However, differences in the analysis and results for multiple-antenna UWB systems still exist because of the peculiar propagation characteristics of UWB channels.

From the UWB measurements reported in [1, 18], the system capacity of a single-antenna link at ρ = 10 dB is 2.5 bps/Hz. A three-element MIMO array with CSIR increases the capacity to 6.8 bps/Hz, while CSIT helps further increase the capacity to 8.2 bps/Hz. Furthermore, the analysis in [1] reveals that the increase in capacity due to CSIT, over a system without CSIT, is most significant at low SNR. Thus at ρ = 0 dB, CSIT provides an *N*-fold increase in capacity beyond that achievable without CSIT. This observation holds special significance for UWB systems typically operating at low SNR. Fig. 3 illustrates this point by plotting the measured UWB capacity as a function of the SNR. It is clear that channel knowledge at the transmitter, facilitated by a feedback link, can be a critical factor for the capacity of UWB multiple-antenna systems, underlining the requirement for the cognition of the propagation environment and the adaptation of the transmitter and receiver elements [25].

Table I. Antenna Diversity Gain of Measured UWB Channels

Array Configuration	Array Size	1% Outage SNR Gain, dB
SISO	1x1	0
SIMO with CSIR	1x2	3.1
SIMO with CSIR	1x3	4.9
MISO with CSIT	1x2	3.1
MISO with CSIT	1x3	4.8
MIMO with CSIT	2x2	5.7
MIMO with CSIT	3x3	8.3

V. Antenna Characteristics

Having discussed the applications of antenna array systems, we discuss the role of UWB antennas and their characteristics, which are of paramount importance in the context of system performance. The design of efficient wideband antennas is not trivial, and is complicated by practical constraints such as size and cost [26]. Several candidate UWB antenna designs have been proposed in literature, among which the biconical, bowtie, discone, D*dot, TEM horn, corrugated horn, and Vivaldi are some of the most popular [1].

UWB antenna design strategies typically concentrate on the optimization of various antenna radiation parameters such as the return loss, voltage standing wave ratio, and impedance matching [27]. The antenna phase center translation with frequency distorts its radiation pattern. In particular, discone antenna measurements have shown that the beamwidth and directivity of an omni-directional antenna vary considerably over the UWB band [5]. As a result of this angular-spectral distortion, the signal transmitted and received using a real UWB antenna suffers a reduced operating bandwidth. The consequent waveform distortion can be catastrophic for impulse radio UWB systems that rely on the correlation of the incoming multipath signals with the template [5].

VI. Localization

The large bandwidth of UWB systems leads to high temporal and spatial resolution. These attributes contribute towards the improvement in the localization and ranging capability of UWB sensor networks. Such systems are based on the time- or direction-of-arrival of the direct path, and estimate the location of the target device, or the transmitter, using this information. With a large bandwidth, the multipath resolution capability of the sensor increases, allowing for the distinction between adjacent multipaths, and consequently the rms ranging error falls.

Indoor UWB measurements in the 10–15 GHz band using omni-directional antennas show that the rms ranging error is inversely related to the bandwidth [28]. The experimental analysis further established that a signal bandwidth of approximately 4 GHz provides sufficient localization accuracy, and an increase in bandwidth does not yield a corresponding gain in ranging accuracy. Additionally, directional antennas provide a reduction in the ranging error [29], since a smaller antenna beamwidth reduces the number of received multipaths and angular spread, so that the likelihood of an overlap between the direct component and a subsequent component decreases.

Localization under non-line-of-sight propagation conditions remains an open research problem. UWB signaling can mitigate this problem in certain situations due to its propagation characteristics. The large bandwidth imparts nonuniform attenuation, penetration, diffraction, scattering, refraction, and reflection properties to the spectral components of the signal. Thus it is possible that even under LOS blockage, a certain portion of the signal spectrum leaks through, and provides a residual LOS signal to the receiver. In such a situation, the sensor localization performance would be improved significantly.

VII. Conclusion

This paper has presented a comprehensive overview of the elements of UWB antennas and propagation. The characteristics of the spatio-temporal UWB channel have been discussed in detail, with extensive results from indoor channel measurements. As an illustration of the information that can be extracted from the spatio-temporal channel characterization, we have discussed direction-of-arrival estimation techniques and results. The characteristics of

UWB antenna have been highlighted, and multiple-antenna techniques for diversity and spatial multiplexing have been analyzed. The localization capability of UWB sensor networks has also been considered. In summary, this paper has shown that spatio-temporal modeling is a valuable tool for system performance analysis and prediction.

Acknowledgements

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