An Overview of Ultra Wide Band Indoor Channel Measurements and Modeling

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***Abstract*—In this letter, an overview of reported measurements and modeling of the ultra wide band (UWB) indoor wireless channel is presented. An introduction to UWB technology and UWB channels is provided. Different UWB channel sounding techniques are discussed and approaches for the modeling of the UWB channel are reviewed. The available indoor UWB channel measurement results are consulted and accordingly, the major UWB channel parameters are presented and compared to those of narrowband systems. The novelty of this work is the gathering of different UWB channel parameters, analysis, and comparison. Added with the influence of UWB antenna in channel-modeling as well as the frequency-dependency of the channel parameters, leading to a conclusion on the UWB radio channel modeling.**

***Index Terms*—Conventional narrowband and wide-band systems (CNWS), inverse Fourier transform (IFT), time decay constant (TDC), ultra wide band (UWB) indoor wireless channel.**

I. INTRODUCTION

THE ULTRA wide-band (UWB) technology is already used in military applications and it may see increased use in the future for wireless communications and ranging. The technology offers many advantages over conventional narrowband and wide-band systems (CNWS). Due to the very wide bandwidth a fine time resolution can be achieved. The UWB signal penetrates many materials providing a functionality that would not be present in a system of comparable bandwidth at a significantly higher center frequency. High processing gains can be obtained that allow a large number of users to access the system.

The analysis and design of an UWB communication system requires an accurate channel model to determine the maximum achievable data rate, to design efficient modulation schemes, and to study associated signal-processing algorithms. Besides, because of the large frequency band occupied by the UWB signal, the antenna becomes an essential part of the UWB channel, as its frequency response changes over the entire bandwidth. The UWB signal can be seen as the integration of subnarrowband signals each having a center frequency which means that, the wavelength of the whole UWB signal will change significantly over the whole frequency band.

The structure of the letter is as follows. In Section II, an overview of UWB measurements is presented. In Section III, the time and frequency domain approach for the UWB channel modeling are discussed and followed by relevant UWB channel parameters which are reported in the literature. A comparison and analysis of those channel parameters of UWB and CNWS is given in Section IV. Concluding remarks appear in Section V.

II. UWB CHANNEL MEASUREMENTS

The main concept of UWB measurement techniques is to probe the channel with a suitable UWB signal. In this section, two measurement techniques are discussed.

A. Frequency Domain Sounding Technique

In this technique, a vector network analyzer is used to control a synthesized frequency sweeper, and an S-parameter test set to measure the sampled frequency response of the channel. The bandwidth centered around the frequency of interest is scanned by the synthesizer through discrete frequencies. For each frequency step a known sinusoidal signal is transmitted and detailed information about the magnitude and phase of the received signal are obtained. The channel impulse response is obtained using the inverse Fourier transform (IFT). Several UWB channel measurements have been performed based on this technique [1]–[4]. The measurements of [1] cover the frequency band recognized by FCC (i.e., 3.1–10.6 GHz), and results on the power decay profile as well as the frequency dependent decay of the channel gain are given. In [2], results on power delay profile and delay spread are presented and no results associated to the fading are investigated in this reference. UWB frequency domain and time domain measurements are reported in [4]. An overview of UWB channel measurements is given in Table I.

B. Time Domain (Pulse) Sounding Technique

This technique is based on employing a narrow pulse to probe the channel. The measurement resolution is equal to the width of transmitted pulse. The pulse repetition period should be carefully chosen to allow observation of the time varying response of individual propagation paths, and at the same time to ensure that all multipath components are received between successive pulses. Several UWB channel measurements have been performed using this technique [4]–[6] (see also Table I). Reported results on UWB channel modeling based on the measurements of [5] are found in the literature and accordingly, important channel parameters such as: path loss, shadowing, fading, power delay profile, arrival rate of multipath components and temporal correlation are investigated. The work of [6] focused mainly on UWB path loss, shadowing and rms delay spread. Based on the measurement results of [4], [5], a channel model was proposed for the IEEE 802.15.3a [7].

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TABLE I
OVERVIEW OF REPORTED UWB MEASUREMENTS IN FREQUENCY AND TIME DOMAINS

	UWB channel measurements	Frequency range [GHz]	Environment	Distance [m]
Frequency domain	Keignart (LETI) [2]	2-6	lab/office	up to 20
	Intel [4]	2-8	residential	1-20
	Ghassemzadeh (AT&T) [3]	4.375-5.625	residential	1-15
	Kunisch (IMST) [1]	1-11	office	3-10
Time domain	Yano (TDC) [6]	1.25-2.75	office	2-17
	Intel [4]	2-8	residential	1-20
	Win (TDC) [5]	0-1.3	lab/office	1-15

III. UWB CHANNEL MODELING AND MEASUREMENT RESULTS

A. UWB Channel Modeling

The UWB channel can be described by its time-variant impulse response $h(t,\tau)$, which can be expressed as

$$h(t,\tau)=\sum_{n=1}^{N(t)} a_n(t)\delta(t-\tau_n(t))e^{j\theta_n(t)} \tag{1}$$

where the parameters of the nth path a_n, τ_n, θ_n, and N are amplitude, delay, phase, and number of relevant multipath components, respectively. Another approach to characterize the UWB channel is to use the frequency domain autoregressive (AR) model. The basic idea of AR modeling is that the frequency response of the UWB channel at each point $H(f_n)$ can be modeled by an AR process. This model was first introduced in [8] for CNWS and was used later for UWB channel modeling [3]

$$H(f_n,x)-\sum_{i=1}^{p} b_i H(f_{\mathrm{n-i}},x)=V(f_n) \tag{2}$$

where $H(f_n,x)$ is the nth sample of the complex frequency response at location x, $V(f_n)$ is complex white noise, the complex constants b_i are the parameters of the model and p is the order of the model. $H(f_n,x)$ can be viewed as the output of a linear filter with transfer function

$$G(z)=\frac{1}{\prod_{\mathrm{i}=1}^{p}(1-p_i z^{-1})} \tag{3}$$

excited by $V(f_n)$. Based on the frequency domain measurements in the 4.3 to 5.6-GHz frequency band, a second order $(p=2)$ AR model is reported to be sufficient for characterization of the UWB indoor channel [3].

B. Measurement Results

1) Power Delay Profile (PDP): The UWB measurement results of [5] and [2] show that the PDP decreases exponentially with excess delay. The time decay constant (TDC) seems to follow a Lognormal distribution with mean of 39.8 ns and standard deviation of 1.2 dB for NLOS situations [5]. Moreover, the reported results in [2], show that the TDC is 29–35 ns and 41–56 ns for LOS and NLOS, respectively. In [9], another model referred to as double exponential decay model (i.e., two exponential decays one for the clusters and the other for the rays) is introduced to characterize the PDP of UWB channels. The reported results of [10] show that the double exponential decay model seems to match the UWB channel measurements for LOS as well as NLOS indoor propagation. The UWB measurements performed in a corridor also show path clustering [1].

2) Arrival Times: The arrival times of the multipath components for UWB seem to follow a negative exponential distribution and the arrival rate of the multipath components is found to be 1/(2.3 ns) [9]. In [4], the number of paths is investigated for different bin resolutions and the Rayleigh distribution is reported to give the best fit for the number of paths with standard deviation of seven and 30 paths for LOS and NLOS, respectively.

3) RMS Delay Spread (RDS): The RDS seems to follow a Normal distribution [2]–[4]. For LOS case, in [3] the $\mu_{\mathrm{rms}}=4.7$ ns and $\sigma_{\mathrm{rms}}=2.3$ ns, in [2] $\mu_{\mathrm{rms}}=8$–12 ns and $\sigma_{\mathrm{rms}}=3.3$ ns and in [4] $\mu_{\mathrm{rms}}=9$ ns are reported. For NLOS case, in [3] the $\mu_{\mathrm{rms}}=8.2$ ns and $\sigma_{\mathrm{rms}}=3.3$ ns, in [2] $\mu_{\mathrm{rms}}=14$–19 ns and $\sigma_{\mathrm{rms}}=1$–5 ns and in [4] $\mu_{\mathrm{rms}}=11.5$ ns, are reported.

4) Fading: The fading margin (i.e., overall received paths) of UWB is 5 dB [4], [11]. The effect of the bandwidth on the fading margin is investigated in [12]. The results show that when measurement bandwidths of 10 MHz and 1 GHz were used, the fading margins were about 30–40 dB and 3 dB, respectively. The measurement results reported in [1] show that the path fading can be modeled by a Rice distribution with Rice factor of -9 dB. The results of [9] show that deviation of arrival energy from the mean has a Rayleigh probability density function. In [5], the Gamma distribution is reported to give the best fit for the path amplitudes. In [10], the Lognormal distribution gives the best fit for the path amplitudes for both LOS and NLOS cases.

5) Correlation: Results of [5] show that temporal correlation between powers does not exceed 0.2 for UWB. In [13], the spatial correlation for fixed spacing of $s/\lambda=1/2$ (i.e., s is the spacing and λ is the wavelength) at frequencies 3, 5, and 7 GHz is found to be 0.5, 0.7, and 0.85, respectively, for the LOS case.

6) Path Loss (PL): According to [5], the PL exponent and the standard deviation of shadowing (SDS) are 2.4 and 5.9 dB, respectively, and the best model for the shadowing is the Lognormal distribution. The PL exponent is reported in [3] as 1.7 and 3.5 and for the SDS as 1.6 dB and 2.7 dB for LOS and NLOS, respectively. According to [4], the PL exponent and the SDS for LOS are 1.7 and 1.5 dB, respectively, and for NLOS are 4.1 and 3.6 dB, respectively. In [3] and [6], it was found that the RDS increases with PL.

IV. COMPARISON AND ANALYSIS

Radio signal propagation is usually affected by the characteristics of the antennas. For the CNWS, the frequency domain effect of the antenna can be well separated from the channel because the bandwidth is small and hence the antenna's frequency response can be assumed as flat over this frequency band. However, this is not the case for UWB. The frequency domain effect of the antenna can be compensated if its full frequency response is known. The radio designer may consider the antenna as a part of the channel. In this case, it is relevant to use different antennas for the UWB channel measurements in order to investigate the effect of its frequency dependency (e.g., a correction factor for the antenna effect can be proposed consequently). Usually the PDP in UWB decreases exponentially with the delay because later paths experience more attenuation. Due to strong reflectors situated in the channel, the PDP can follow a double exponential function. The same model is found for CNWS [14]. The arrival rate of multipath components is remarkably higher for UWB than for CNWS due to the high time resolution in UWB. The fading margin is much smaller in UWB than the fading margin of CNWS (i.e., about 25–40 dB) since more paths are resolved and consequently, the received power over all paths becomes higher. For UWB channel, the reported Rice factor is remarkably small which means that the Rice distribution converges to the Rayleigh distribution. However, since the number of multipath components arriving at a same delay (i.e., same bin) is remarkably small for UWB, the vector summation of the signals at that same delay gives less amplitude fluctuations, and the modeling of the path fading with the Rayleigh distribution seems inappropriate. Therefore, some distribution functions are introduced to characterize the small-scale rapid fading variations in UWB indoor environments such as POCA and NAZU [15] for NLOS and LOS, respectively. Different reported path loss exponents are perhaps due to different types of environments in which the measurements were performed. Additionally, the Lognormaly distributed standard deviations of shadowing are smaller for UWB when compared to those of CNWS, which are found 3–12 dB. The reported shadow fading is determined from the PL data by assuming that the variations of the received power around the theoretical PL curve have a Lognormal distribution. For UWB, this assumption may be inappropriate because UWB has a large bandwidth which means that the penetration through walls is different than for CNWS. The signals correlation found in [5] seems to be very small. We would expect a high correlation in amplitude as well as in time, since the probability of adjacent paths arriving within a small time interval, induced by the same scatterer, is relatively high. Further research is suggested. A comparison of the main UWB and CNWS channel parameters are summarized in [16]. Objects situated in the propagation medium between the transmitter and the receiver behave differently at different frequencies. The UWB propagation is heavily frequency dependent. Thus, the UWB wireless channel can be modeled by the impulse response method with frequency dependent parameters as

$$h(\tau, t, f_i) = \sum_{n=1}^{N(t,f_i)} a_n(t, f_i)\delta(t - \tau_n(t, f_i))e^{\theta(t,f_i)} \tag{4}$$

where f_i is the ith working frequency. In this direction, one possible way of modeling of the UWB channel can be considered by the following steps:

1) dividing the UWB signal into sub-wideband signals;
2) for each sub-band signal, a channel model is determined using the known wideband channel modeling methods;
3) integration of all outputs of channel to the sub-band input signals;
4) based on the input UWB signal and the obtained output signal after integration, a proper model of the UWB channel can be provided.

Using this approach, the effect of the antenna can be separated from each subband channel. After the integration of all outputs, an UWB channel model is obtained in which the frequency dependency effect of the antenna is compensated.

V. CONCLUSION

In this letter, an overview of the UWB indoor channel measurements and modeling based on recent literature is presented. The UWB channel can be described by the impulse response model as well as the frequency domain AR model. The UWB radio designer has to take into account the effect of the antenna characteristics in the UWB channel modeling. The reported results show that the received UWB signal power decreases exponentially with the excess delay. The double exponential model can also be used to describe the PDP. The time decay constant depends on the type of environment. The arrival rate of multipath components is higher for UWB than CNWS due to fine time resolution. The reported results indicate a limited temporal correlation between powers of multipath components. The UWB signal is more robust against fading than CNWS and the fading can be modeled by the Gamma distribution. The RDS follows a Normal distribution and its mean and variance are higher for the case of NLOS. The RDS values are smaller for UWB than for CNWS. The PL exponent as well as the SDS depend on the propagation medium and they are smaller for UWB than for CNWS.

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