An Ultra-Wideband Indoor NLOS Radio Channel Amplitude Probability Density Distribution

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***Abstract*— The initial results of the development of an Ultra-Wideband (UWB) radio channel model based on an UWB radio channel measurement campaign carried out at IMST premises are summarised. The derived amplitude statistical model applies for pass band UWB signals under NLOS conditions. From stepped frequency transfer function measurements in the range from 1 to 11 GHz, employing wideband biconical antennae and successive windowed Fourier transform, radio channel responses were obtained in delay windows of approximately 160 ns width. In different locations the radio channel transfer function was measured over a spatial grid of 1500 mm times 300 mm and 10 mm resolution in both horizontal axes. The obtained data were used to verify the statistical model described below.**

***Keywords*— Ultra Wideband, UWB radio channel, channel modelling**

I. Introduction

Extracting characteristic radio channel parameters from channel measurements and creating statistic channel models is a common method to assess the performance of air interface candidates in terms of error rates and outage probabilities. For the indoor radio channel the model of Saleh and Valenzuela [1] is widely accepted for conventional (narrow band) radio systems which usually have fractional bandwidths of less than a percent. Narrow band radio channels have been widely researched and a comprehensive overview is given in [2] in a tutorial survey. However, since all narrow band investigations are based on the Turin model, which implies frequency independent scattering [3], inaccuracies can be expected to result in the description of deterministic and statistical signal properties if simply extended to ultra wide bandwidth scenarios.

For the indoor domain only one paper is known to the authors, which deals with UWB propagation measurements [4] and two providing analysis to predict outdoor air radio channel characteristics [3], [5]. Other papers deal with UWB radio wave propagation in water or near the water-air interface [6], [7]. Also UWB reflection characteristics of certain bodies or structures have been reported [8] as well as some generic investigations on UWB beam propagation [9] and impulse reflection mechanisms [10].

UWB indoor radio channel measurements have been presented in [11], [12], [13], [14], [15], [16], [17], [18]. In [11] the frequency band under investigation ranged from VHF to 20 GHz. The influence of two 30 cm concrete walls with 3 internal layers of reinforcing steel bars on radio propagation and signal shape was determined using swept frequency measurements. It was shown that the transfer loss is approx. 20 dB/m at 2 GHz and approx. 110dB/m at 10 GHz for a flat dielectric constant, and that attenuation increases in a linear manner with frequency.

The measurements of [12], [13], [14], [15] and [16] seem to be based on the same measurement campaign. The measurements were taken in 14 different locations (rooms) at 7 x 7 equally spaced measurement points. It was observed that the fading range was only 5 dB, which is very low when compared to narrow-band systems, where 20 dB is not exceptional. It was shown, that many tens of resolvable paths exist and that a complex Rake receiver structure would be necessary to capture more than 50% of the incident energy. From the measurements a mean path loss exponent of 2.4 was determined and it was found that the power in delay bins is not Rayleigh distributed. In [18] the magnitude transfer function between (biconical wideband) antenna connectors was shown to be approximately inversely proportional to the frequency. 40 ns delay spread was reported using a frequency range from 2 to 12 GHz in a hall of 12 x 8 x 6 meters. In [17], [19] measurement data (1-11 GHz) were analysed in the time- and frequency domain. Measurements in office environments revealed delay spreads of about 15 ns at 5 m transmitter/receiver separation. The typical NLOS small scale fading variation was less than 1 dB.

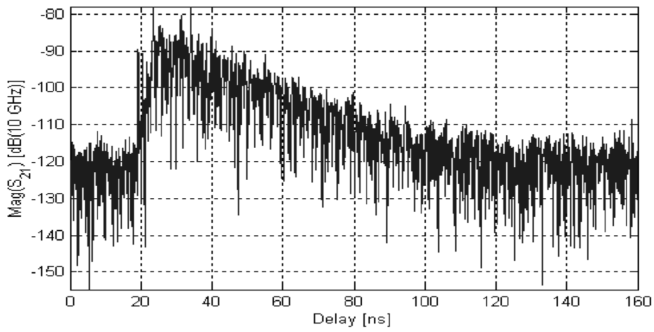


Fig. 1. Typical NLOS real valued radio channel response.

II. UWB statistical channel model

The pass band amplitude statistical model presented is based on the multiplicative combination of random potential and Gaussian processes. Basically it describes the statistical properties of the received UWB signal in the delay domain - it implies however certain statistical fading properties. The (on the average) exponential decay of energy in the delay domain, which represents the mean macro characteristics of a certain type of radio environment, has been widely observed. Single impulse responses, particularly in narrow band radio channels, can however considerably deviate from plain exponential decay and appear to be the sum of time-shifted, exponentially decaying 'clusters' of different magnitude and decay rate. These processes are well described by potential statistics. The micro-structure of the radio channel is assumed to follow a Gaussian distribution, for reasons discussed below. Both processes are considered statistically independent and the joint probability is written as

$$\hat{S} = \hat{P} \cdot \hat{G} \tag{1}$$

with $\hat{P}$ and $\hat{G}$ being statistical variables with potential and Gaussian probability density functions respectively. In the following the radio channel response is regarded without distinction being made between deterministic, specular, diffuse or otherwise specified multipath components, and in particular without introducing thresholds or manipulating amplitudes in any other way, e.g. by summation or averaging. The (spatial) correlation length δ of scattered signal, as observed in the receiver location, be the half-power width of the mainlobe of the received signal's temporal autocorrelation peak multiplied by the speed of light.

The signal delay axis is broken into bins of width equivalent to δ . Contrary to [16], where for increasing signal bandwidth a decreasing number of signals per delay bin is assumed, here the signal observed at the receiver is considered 'fractal' with respect to δ, that is, the number of propagation paths which in principle can be resolved is assumed to increase in a certain fashion with decreasing correlation length δ, i.e. with increasing bandwidth. This assumption is supported by UWB time domain characterisations [20] of canonical scatterers which reveal structural and temporal (multiple diffraction) object features which remain hidden in low bandwidth observations due to coherent superposition. In a sufficiently structured radio environment, the convolution process introduced by multiple scattering is expected to eventually lead to myriads of interfering signals, which cause a 'noisy' waveform to arrive at the receiver (see Fig.1). Analysis of the received waveform confirms a high degree of interference because the originally transmitted pulse shape is not observed.

The scattering elements of a NLOS environment are modelled as a composition of a huge number of multiple 'mirror' systems guiding energy to the observer with certain delays. Depending on 'mirror' size, shape and separation as well as on the curvature of the incident wave front, exchange of energy between 'mirrors' is assumed to be effected by various modes of wave propagation, e.g. spherical, cylindrical or even plane. However, in the context of this work the energy transfer between 'mirrors' is simply modelled as a random variable ν which defines the efficiency of a single 'hop' energy transfer. The efficiency of energy transfer through the m^{th} chain of 'mirrors' is hence given by the product $\nu_{m,1} \cdot \nu_{m,2} \cdot \nu_{m,n}$. The envelope of the sum of a huge number of signals coincidentally arriving at the receiver constitute an exponentially decaying series of numbers regardless of the distribution of $\nu_{m,n}$.

Stimulated by a Poisson impulse ($\delta \rightarrow 0$), the response of the scattering volume is a train of randomly spaced Poisson impulses with exponential amplitude decay tendency. It can be shown [21] that shot noise (low pass filtered series of randomly spaced Poisson impulses) is approximately Gaussian distributed if the time constant of the filter h(t) is large compared to the impulse arrival rate, i.e. if many Poisson impulses arrive during the time interval in which h(t) is significant. It is further shown [21] that under above condition the variance of the Gaussian-like process is a function of the filter response h(t) only. For the development of the UWB amplitude probability density function many Poisson pulses are supposed to arrive in the time interval corresponding approximately to the inverse receiver bandwidth, which in turn is assumed to be very small compared to the radio channel exponential decay constant, such that the exponential decay of the impulse response, while h(t) is significant, can be neglected. Let $\hat{P}$ and $\hat{G}$ respectively have probability density distributions

$$p(y) = \frac{1}{ay},\ with \int_{\frac{1}{c}}^{c} p\,dy = 1!\ and\ a = 2\ln c \quad (2)$$

and

$$g(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-x^2/2\sigma^2}. \quad (3)$$

Multiplication and integration of probabilities of (2) and (3), such that $\lambda = x{\cdot}y$ and further integration over the range of exponential decay ($1/c \rightarrow c$), leads to the amplitude probability density distribution of the UWB signal.

$$s(\lambda) = \frac{1}{\sigma\sqrt{2\pi}2\ln(c)} \int_{\frac{c}{\lambda}}^{c\lambda} \left| \int_{y}^{\infty} \frac{xe^{-x^2/2\sigma^2}}{\lambda} dx \right| dy \quad (4)$$

Solving (4) in the first quadrant yields for positive amplitudes ($\lambda \geq 0$)

$$s(\lambda) = \frac{erf(\frac{c\lambda}{\sigma\sqrt{2}}) - erf(\frac{\lambda}{c\sigma\sqrt{2}})}{\lambda \cdot 4\ln c};\ c > 1 \quad (5)$$

where erf is the Gaussian error function. Solving 4 in the 2nd quadrant yields a mirror-symmetric term for negative amplitudes. Hence 5 describes the probability density of positive and negative amplitudes, and reduces to a zero mean Gaussian distribution in case of $c \rightarrow 1$ (no exponential decay). It transits quasi-exponential characteristics for moderate decays to eventually converge towards purely potential behaviour in case of extended exponential decay $c \rightarrow \infty$.

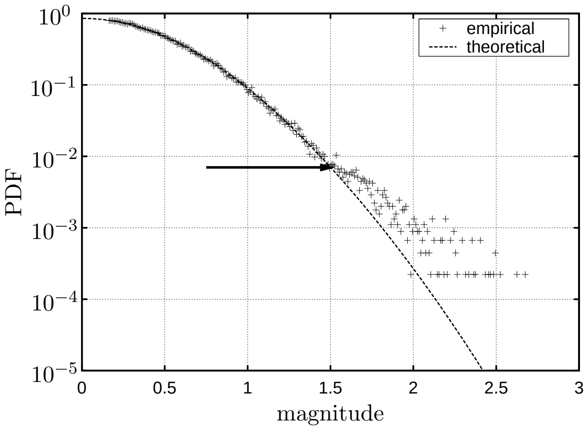
III. Discussion of results

Comparison of 5 with empirically obtained data, as depicted in Fig.2 and Fig.3, shows remarkable agreement. With increasing delay window width the signal amplitude probability density distribution increasingly differs from Gaussian. The various shapes of distributions can be interpreted to result from windowed impulse responses. For infinite delay window width and in the absence of a noise floor, the statistical UWB impulse response is potential distributed, whereas for narrow delay windows (no or hardly any exponential decay range within the window) the UWB signal is normal distributed (Rayleigh-distributed in base band terms).

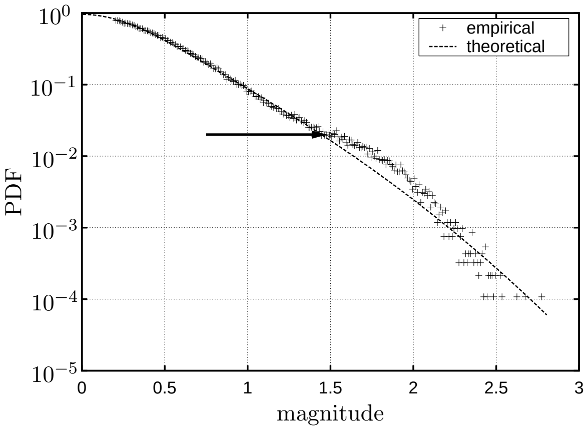
The sets of empirical data, taken in a furnished 5 x 5 x 2.7 meter office under NLOS conditions, comprise 900 (30x30) impulse responses measured in a regular grid with measurement points separated by 1 centimetre in both horizontal axes. In Fig.2 and Fig.3 the delay window width increases from 1 ns through 10 and 30 to 70 ns from top left to bottom right. Arrows indicate accumulated probabilities of approximately 98%-99%, at the point of divergence of empirical and analytical distributions. The remaining 1 to 2 percent which escape the proposed distribution may be attributed to exceptional propagation paths (initial peak amplitudes levels of the impulse response) where possibly the condition that many Poisson pulses arrive during the period where h(t) is significant is not met. The occurrence of such peak amplitude levels is predicted pessimistically in most cases by the proposed distribution. Minor disagreements between theoretical and empirical distributions in the area of small amplitudes in the 70 ns delay window are supposedly caused by the approaching noise floor (compare Fig.1).

Though no explicit assumptions have been made regarding the UWB signal fading distribution, the Gaussian distribution of the radio channel microcharacteristics in the delay domain, which was found to be invariant with respect to delay, necessarily translates into a delay-invariant Gaussian fading distribution. Hence the proposed distribution (5) can also be interpreted as the joint distribution of a Gaussian fading process and a potential process in the delay domain which is caused by the exponential decay of multiple clusters.

The markedly different result derived in [16], i.e. varying fading statistics versus delay, which is explained by delay-variant signal dispersion and consequently modelled as a Nakagami-m distribution, may be conditional on the method employed to derive the m-factor from multiple small sets (7x7) of measurement data. In any case, following the m-factor computation method of [16], the apparent phenomenon of a varying m-factor, i.e. the non-constant variance of the Gaussian fading process versus delay, was reproducible with our measurement data when the huge sets (900 measurement points each) were broken into

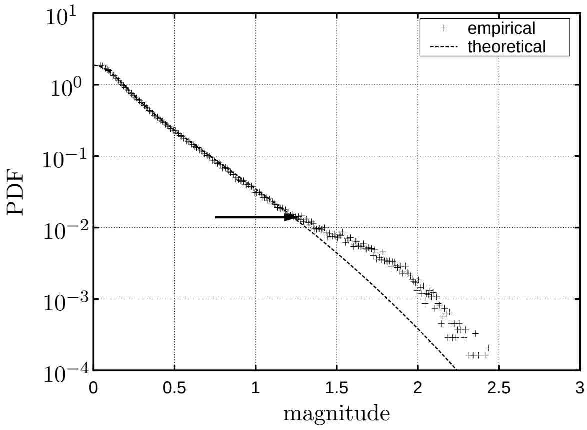


(a) Delay window: 1 ns.

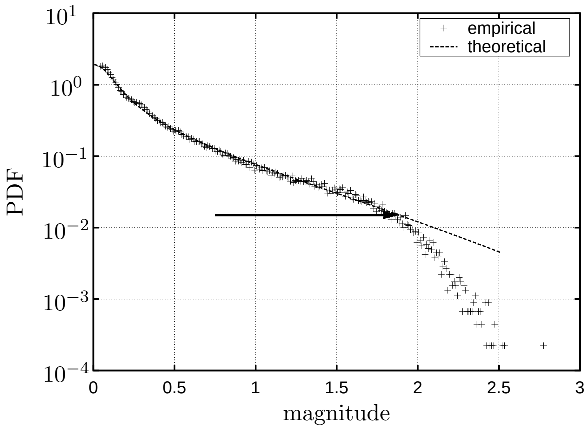


(b) Delay window: 10 ns.

Fig. 2. Amplitude pdf of UWB signals for various delay window widths. Negative amplitudes are not shown, σ is not normalized.



(a) Delay window: 30 ns.



(b) Delay window: 70 ns.

Fig. 3. Amplitude pdf of UWB signals for various delay window widths. Negative amplitudes are not shown, σ is not normalized.

multiple small sets, which suggests that the set size used in [16] may be insufficient to produce stable statistics.

IV. Conclusions

An amplitude probability density function for non-line-of-sight UWB signals covering the 1 to 11 GHz frequency range has been derived which builds on two independent statistical processes and provides good fit with empirically obtained data. Only a minor fraction (1-2%) of the observed (peak) amplitude levels appears to follow statistics different from the one proposed. The distribution is a single parameter distribution and provides the UWB signal amplitude probability density in the delay domain. It may be used in the design of UWB receivers which exploit continuous sections of the received UWB signal as well as in the design of Rake receivers. For narrow delay windows, as a major result, it predicts a Gaussian radio channel micro-structure in the delay domain, which implies delay-invariant Gaussian fading statistics. The Gaussian micro-structure was explained by the 'fractal' nature of the number of resolvable propagation paths with respect to signal bandwidth. Under the conditions set by our measurement campaign (e.g. bandwidth, environment) the number of multipath components coherently combining in a single delay bin must be assumed sufficiently high to result in the observed Gaussian UWB radio channel micro-structure.

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