Enhanced UWB Radio Channel Model for Short-Range Communication Scenarios Including User Dynamics

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***Abstract*— In this paper we propose a SISO UWB radio channel model for short-range radio link scenarios between a fixed device and a dynamic user hand-held device. The channel model is derived based on novel experimental UWB radio propagation investigations carried out in typical indoor PAN scenarios including realistic device and user terminal antenna configurations. The radio channel measurements have been performed in the lower UWB frequency band of 3GHz to 5GHz with a 2x4 MIMO antenna configuration. Several environments, user scenarios and two types of user terminals have been used. The developed channel model represents an enhancement of the existing IEEE 802.15.3a/4a PAN channel model, where antenna and user-proximity effects are not included. Our investigations showed that significant variations of the received wideband power and time-delay signal clustering are possible due the human body proximity effects and hand-held antenna configurations.**

I. Introduction

Ultra wide band (UWB) is emerging as a future communication technology for short-range, personal area network (PAN). Independent of the actual type of UWB system implementation, either single-band or multi-band, the performance of a UWB receiver significantly depends on the characteristics of the radio propagation channel. Due to the large frequency span used by the system ($>$ 500MHz), the combined effect of the radio channel and antennas used have to be analysed and modelled for typical propagation scenarios.

Channel models derived from several UWB propagation investigations are available in the literature, the majority listed in [1], [2], [3]. All these UWB propagation investigations focused on describing the typical LOS and NLOS propagation channels only with antennas having frequency independent radiation patterns and without considering user proximity effects.

The user proximity effects for handheld devices have been extensively investigated only for the GSM/UMTS frequency bands e.g. [4], [5]. For UWB PAN scenarios, some of these aspects have been addressed earlier in *static* UWB propagation investigations [6], [7], [8].

This paper presents a channel model proposal based on novel UWB short range radio propagation investigations carried out in the 3GHz to 5GHz frequency band [9]. Extensive radio channel meeasurements were performed in typical indoor, *dynamic* PAN scenarios including realistic device and user terminal (hand-held) antenna configurations. Several indoor environments, user scenarios and two types of user terminals have been investigated in order to increase the statistical significance of the derived results.

The developed SISO channel model represents an enhancement of the existing IEEE 802.15.3a/4a PAN channel model, where antenna user-proximity effects are not included [1], [2], [3]. The existing IEEE UWB PAN channel models have been used as starting point and several enhancements are proposed based on the new experimental data sets [9], [10].

The main goal of this work was to introduce the effects of user proximity and dynamics in the a channel model which can be successfully used in physical (PHY) layer simulations for low- to high- data rate UWB systems in typical PAN scenarios [10].

The paper is organized as follows. Section II describes the experimental work, the scenarios and the data processing. In Section III is presented the proposed channel model enhancements and parameters. Section IV contains the main conclusions of this work.

II. Radio propagation investigations

A. Experimental set-up

The radio channel measurements were conducted with a *UWB sliding correlator* channel sounder. The measurement bandwidth was 2.5GHz centred at 4.5GHz. The effective delay resolution was 0.4ns [9]. The radio channel sampling rate (time domain) was 39Hz, which accommodates the expected channel change rate at the normal walking speed of 1m/s (at the upper frequency of 5GHz). The dedicated measurement set-up allowed the full separation of the 2x4=8 simultaneously measured radio links. A more detailed description of the measurement equipment can be found in [9].

An array of four UWB planar monopole elements (Figure 1 top) with an impedance bandwidth of 2GHz to 10GHz, was used at the fixed device (FD) (Figure 1 bottom).

Two user devices (UD) were employed, equipped with two different types of antennas: commercial SkyCross antennas (HH1, Figure 2 top right) and custom made UWB cylindrical monopole (HH2, Figure 2 top left) with an impedance bandwidth of 2GHz to 10GHz. For each UD, two antenna elements have been used simultaneously (Figure 2 bottom).

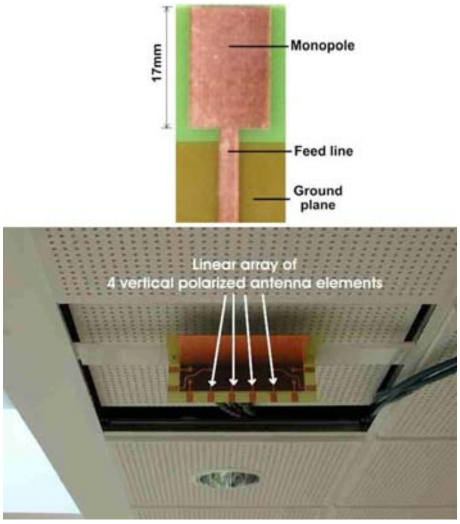

Fig. 1. Linear antenna array with vertical polarised elements used for the fixed device (FD)

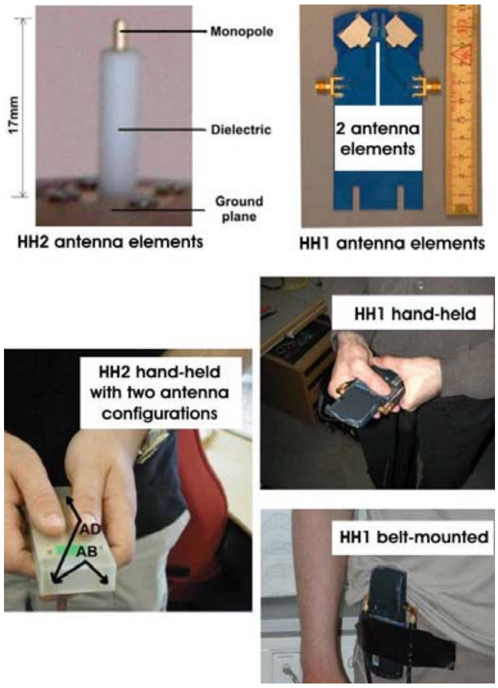

Fig. 2. Antenna configurations used for the user hand-held device (UD)

With this antenna set-up all channel measurements have been performed in a 2x4 MIMO (2 transmit antennas, 4 receive antennas) configuration.

Table I summarises the main characteristics of the measurement environments, user routes and the FD heights. In all scenarios the UD was at approximately 1m height from the room's floor.

Three typical environments, laboratory (LAB), conference (CAN) and hallway (HAA), and several UD scenarios have been investigated along user routes, covering the most likely user movement patterns relative to the location of the FD.

The main difference between the LAB/CAN and HAA environments are the FD heights, which lead to a different signal clustering in the channel impulse response. Furthermore, in the LAB environment the density of the scattering objects (furniture, equipment, etc.) was much higher compared to the CAN and HAA environments.

On each user route, two HH1 scenarios have been investigated emulating the hand-held and belt-mounted use cases (Figure 2 right). For the HH2 two different antenna configurations have been used in the hand-held use case (Figure 2 left). Additionally, free-space, i.e. without the user-proximity, measurements have been performed at the start and end points of each user route. The environments were quasi-static and uncontrolled throughout the measurements.

TABLE I
MAIN CHARACTERISTICS OF THE MEASUREMENT ENVIRONMENTS AND USER ROUTES

Acronym	Description Area WxLxH [m]	FD height [m]	No. UD routes	FD-UD range [m]
LAB	Laboratory 8 x 14 x 2.3	2.3	6x5	2 - 7
CAN	Conference 15 x 17 x 2.3	2.3	4x3	2 - 7
HAA	Hallway 12 x 17 x 11	6.0	5x2	6 - 17

B. Data analysis

With the measurement setup described in Section II-A, a set of 61440, 24576 and 20480 complex impulse responses have been recorded on each of the 2x4=8 radio links in the LAB, CAN and HAA environments respectively. The obtained channel data was compensated for all system components.

For the channel model derivation, the modified Saleh-Valenzuela model, proposed in IEEE 802.15.3a [1] for UWB PAN, was used as starting point. The corresponding time/space and time-delay parameters have been extracted from the obtained measurement data. For the time-delay parameters, an adapted subtractive clustering algorithm together with a simple sensor-CLEAN processing for signal ray extraction, have been used [7], [9]. Figure 3 shows as an example an average (over 20 consecutive measured IR) and an instantaneous power delay profile (PDP) used for channel parameter estimation and IR feature extraction.

All IRs extracted for further analysis have been time-delay aligned,i.e. the mean propagation delay has been compensated. The first time-delay signal ray in the measured IR was determined to be the first signal sample with power 10dB above the average noise level in the IR. The signal-to-noise ratio (SNR) range in the measurement data was 15dB to 40dB.

The first step was to model the SISO radio channel in the investigated scenarios. In this analysis, each radio link data has been used as an independent channel measurement data set.

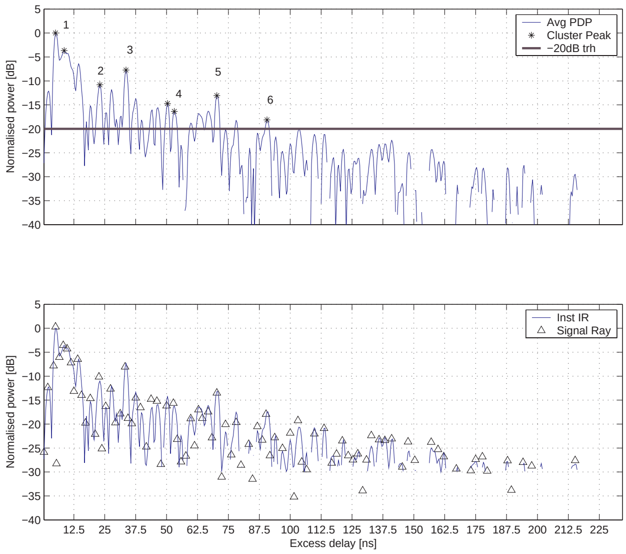

Fig. 3. Example of average PDP (top) and instantaneous IR (bottom) used for parameter estimation and feature extraction: signal cluster peaks (top); signal rays (bottom).

III. Enhanced SISO channel model

A. Channel model parameters

The general description of the parameters for the modified Saleh-Valenzuela channel model can be found in Reference [1]. Here we use the same notations and highlight only the differences introduced. The main parameters and notations used are listed here for convenience:

τ_{rms}	:	RMS delay spread [ns]
$W90$	:	90% IR energy delay-window length [ns]
α	:	signal cluster peak amplitude [V]
β	:	signal ray amplitude within a cluster [V]
Λ	:	cluster arrival rate [1/ns]
λ	:	ray arrival rate [1/ns]
Γ_1, Γ_2	:	average cluster peak power decay factors [dB/ns]
γ	:	ray power decay factor [dB/ns]
γ_t	:	ray power decay factor in the *tail cluster* [dB/ns]
σ_r, η_r	:	Weibull distribution scale and shape factor
σ_2	:	std deviation of ray log-normal fading [dB]
σ_c	:	std deviation of cluster log-normal fading [dB]
σ_x	:	std deviation of WB power log-normal fading [dB]

The first main characteristic of the proposed model is the *dual power decay* in time-delay domain for the average cluster peak power $E[|\alpha|^2]$, with different decay factors below and above the *50ns* excess delay threshold:

$$\begin{aligned} E[|\alpha|^2] \quad &\sim exp(-\tfrac{T}{\Gamma_1}) \quad \text{for T} \leq \text{50ns} \\ &\sim exp(-\tfrac{T}{\Gamma_2}) \quad \text{for T} > \text{50ns} \end{aligned} \tag{1}$$

The second characteristic of our proposed model is given by the modelling of the signal ray power, $|\beta|^2$, distribution over the average power decay *within each delay cluster*, $E[|\beta|^2]$. For this, a Weibull distribution was used, see eq. 2, similar to an earlier proposal presented in [3] for the modelling the ray power within the entire channel IR.

$$pdf(|\beta|^2 - E[|\beta|^2]) = \frac{\eta_r}{\sigma_r}\left(\frac{|\beta|^2}{\sigma_r}\right)^{\eta_r-1} exp\left[-\left(\frac{|\beta|^2}{\sigma_r}\right)^{\eta_r}\right] \tag{2}$$

As a third characteristic in our proposed IR modelling, the last signal cluster (e.g. #6 in Figure 3) is denoted the *tail cluster* and is treated separately from the other signal clusters.

The channel parameter values estimated from the performed channel measurements (free-space and user-proximity scenarios) and the differences from the IEEE UWB PAN models [1] are listed in Table II.

B. Comparison with the IEEE 802.15.3a/4a model

The main characteristics of our channel model proposal and the differences from the IEEE 802.15.3a/4a PAN models [1], [2] are:

1) The log-normal shadowing (σ_x) is simulated at a different time-scale then the generation of each individual IR, i.e. several consecutive IR realisations can have the same large-scale fading factor,
2) The signal clusters fade independently following a log-normal distribution (σ_c) and with higher standard deviation in the user-proximity scenarios,
3) The local average PDP has two main decay regions, below and above *50ns excess delay*, with two different power decay factors (Γ_1 & Γ_2), depending on the environment and the FD height relative to the UD,
4) Signal cluster peaks are generated only down to -20dB relative to the first signal cluster average peak power and the signal rays within the *tail cluster* are modelled with a different average power decay (γ_t),
5) The Weibull distribution (σ_r, η_r) is used in time-delay domain to describe the ray power distribution within each signal cluster,
6) Signal rays are generated only within a given cluster, i.e. there is no overlapping between the successively generated clusters,
7) The average signal spread values (τ_{rms}) in our PAN scenarios CAN and HAA were generally higher than the values specified for the IEEE CM3 and CM4 scenarios while in the LAB scenario the values were similar as for the IEEE CM2.

The characteristics 1) and 2) reflect the user-proximity and user-dynamics vs. free-space propagation conditions in the channel realisation (see Table II). In our investigations we determined a large-scale channel coherence time of approximately 0.5s, i.e. 20 consecutive IRs.

In the user proximity scenarios, the human body (hand, torso, etc.) introduces additional signal attenuation for individual signal rays (reflections) while the average structure of

TABLE II

RADIO CHANNEL PARAMETER VALUES ESTIMATED FROM THE MEASUREMENTS FOR FREE-SPACE (FS) AND USER-PROXIMITY (US) SCENARIOS. THE PARAMETER VALUES FOR THE IEEE802.15.3A UWB PAN MODELS CM2, CM3 AND CM4 ARE LISTED FOR COMPARISON (NU = NOT USED).

Parameter FS / US	LAB	CAN	HAA	CM2 (NLOS,0-4m)	CM3 (NLOS,4-10m)	CM4 (NLOS)
τ_{rms} [ns]	13 / 13	27 / 25	37 / 35	8 / -	14 / -	25 / -
Λ [1/ns]	0.060 / 0.068	0.056 / 0.056	0.056 / 0.060	0.4 / -	0.067 / -	0.067 / -
λ [1/ns]	0.6 / 0.6	0.6 / 0.6	0.6 / 0.6	0.5	2.1	2.1
Γ_1 & Γ_2 [dB/ns]	0.31 & 0.27 / 0.35 & 0.27	0.18 & 0.13 / 0.21 & 0.13	0.12 & 0.10 / 0.13 & 0.10	0.8 / -	0.31 / -	0.18 / - -
γ [dB/ns]	0.83 / 1.0	0.85 / 0.95	0.80 / 0.98	0.64 / -	0.54 / -	0.36 / -
γ_t [dB/ns]	0.3 / 0.3	0.2 / 0.2	0.2 / 0.2	NU	NU	NU
(σ_r, η_r)	(1.8, 1.0) / (1.8, 0.9)	(2.0, 0.8) / (2.0, 0.8)	(2.0, 0.8) / (2.0, 0.8)	NU	NU	NU
σ_2 [dB]	NU	NU	NU	3.4	3.4	3.4
σ_c [dB]	3.8 / 5.6	3.8 / 4.0	4.0 / 4.5	3.4 / -	3.4 / -	3.4 / -
σ_x [dB]	0.2 / 4.5	0.1 / 1.7	0.2 / 2.3	3.3 / -	3.4 / -	3.2 / -

the IR remains the same as in corresponding free-space cases. Thus, the cluster and ray arrival rates are the same as in the free-space scenarios, while all average signal power decay factors tend to be higher than in the free-space scenarios. Additionally, the user proximity and dynamics have an effect of higher shadowing/ fading of the signal clusters (independently) and of the received wide-band power, relative to the free-space scenarios.

The characteristic 3) was found to be environment dependent, similar to the proposal in IEEE 802.15.4a [2], and a simplified description using only two decay factors have found to be sufficient (eq. (1)). The decay factors are slightly different for user-proximity and free-space propagation conditions, respectively.

Modification 4) was introduced in order to simulate IR with with significant signal clusters statistics closer to the measured IR in all the PAN scenarios.

Modification 5) represents a modelling simplification which in combination with 6), provides simulated IR statistics sufficiently close to the measured ones, in terms of RMS delay spread and 90% IR energy delay window length (see Section III-C) [7], [8], [9].

The characteristic 7) is an indication of dense scattering CAN/HAA environments with relatively high power signal clusters at longer excess delays. The extracted time-delay IR parameters reflect this aspect. Compared to IEEE CM3/CM4 models, the cluster arrival rates were similar while the average cluster peak power decay rates were lower in our data/model. At the same time, the ray arrival rate was lower while the average ray power decay factor was higher in our data/model.

C. Channel impulse response simulation

The main steps for generating an IR realisation with the proposed model follow the procedure given for the IEEE 802.15.3a/4a PAN models [1], [2] with the modifications described in Section III-B. The output is in the form of real-valued discrete-time IR realisations.

The first note we have make here is that, although the channel realisation is generated initially as a continuous-time IR and then discretised, at this stage, the proposed model is upper limited in bandwidth to 2.5GHz (in the 3-6GHz band) as in our channel measurements. An oversampled version of the simulated IR is, however, possible to generate without increasing the effective time-delay resolution.

Secondly, the average path-loss is not included in this simulation process as we assume that the FD-UD distance does not change significantly during the simulated time interval. Shadowing of the radio signal is, however, included by means of the wide-band power log-normal distribution.

A third important note is that the *total signal delay*, which is variable in a dynamic user scenario, is not included in the IR simulations. As described in Section II-B in the measured IR used to derive the channel model the mean propagation delay has been compensated. Variations around the mean excess delay tend to be exponentially distributed. This phenomenon, however, still needs to be further studied, in the view of more realistic (IR-)UWB PHY layer simulations [10].

Figure 4 shows as an example the average channel PDPs (over 20 consecutive IR realisations) generated with our proposed model for free-space (static) and user-proximity (dynamic) scenarios in CAN-type environments.

Figure 5 shows the wide-band power fluctuations in 2000 consecutive simulated IRs in CAN-type environments for free-space and user-proximity scenarios.

In Table III are listed the statistics, from measurements and simulations, for the τ_{rms} and $W90$ parameters, in terms of mean value (μ) and standard deviation (σ) obtained from 2000 IR realisations (per environment) with SNR set to 30dB.

The comparison in Table III shows a good match between measurements and simulations, in the range of $\pm$3ns and $\pm$6ns for the τ_{rms} and $W90$, respectively. For both parameters, in the simulations lower standard deviation values have been obtained compared to the measurements.

A more detailed analysis of simulated vs. measured channel characteristics will be included in a follow-up publication.

IV. CONCLUSIONS

The PAN channel model proposals in IEEE 802.15.3a/4a [1], [2] are derived from extensive investigations and are speci-

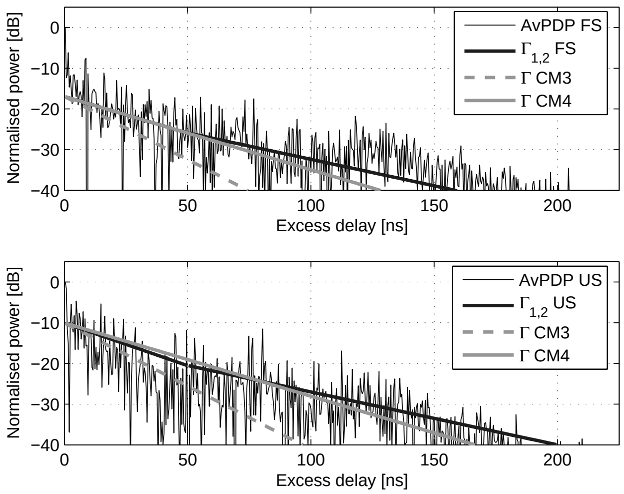

Fig. 4. Average PDP (over 20 consecutive IR realisations) corresponding to the CAN-type environments (see Table II) for free-space (FS) and user-proximity (US) scenarios.

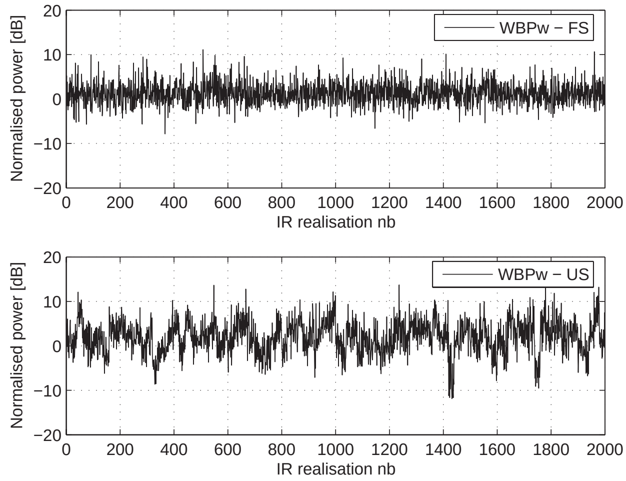

Fig. 5. Wide-band power fluctuations with simulated IRs corresponding to the HAA-type environments (see Table II) for free-space (FS) and user-proximity (US) scenarios.

TABLE III

COMPARISON OF MEASURED (MS) AND SIMULATED (SM) CHANNEL IMPULSE RESPONSE PARAMETERS: τ_{rms} AND $W90$. THE MEAN (μ) AND STANDARD DEVIATION (σ) VALUES ARE LISTED.

Parameter FS / US		LAB μ (σ) [ns]	CAN μ (σ) [ns]	HAA μ (σ) [ns]
τ_{rms}	Ms	13 (4) / 13 (5)	27 (6) / 25 (5)	37 (6) / 35 (6)
	Sm	14 (2) / 13 (3)	29 (3) / 26 (4)	39 (3) / 38 (5)
$W90$	Ms	29 (12) / 25 (13)	58 (19) / 51 (17)	90 (20) / 88 (22)
	Sm	30 (5) / 28 (9)	59 (10) / 51 (11)	86 (11) / 82 (15)

fied for several indoor environments. However, the underlying channel measurements and proposed modell do not capture the effects of the *user-proximity* and *user dynamics* for PAN terminals in typical scenarios. For this purpose, novel MIMO (2x4) UWB channel measurements have been performed in typical PAN scenarios with a fixed device and a dynamic user, hand-held terminal [9].

Our investigations show that significant variations of the received wideband power and time-delay signal clustering are possible due the *user-proximity*, *user dynamics* and *hand-held* antenna configurations.

The main result of this work was to introduce the effects of user proximity and dynamics in the a proposed channel model for typical PAN scenarios. Additional work is required in order to model all channel parameters which are relevant for the PHY level simulations.

The development of the UWB MIMO (2x4) radio channel model is currently ongoing. Investigation of additional PAN scenarios are planned for communication links between two or more dynamic user terminals.

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