BER Regression Analysis of DS-UWB based WPAN

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***Abstract*—Ultra-Wideband (UWB) radio is a viable candidate for short-range multiple access communications in dense multipath environments. This paper analyzes the efficiency of Direct Sequence - UWB physical layer standard proposal in a indoor environment with fixed transmitters and receiver positions. The performance evaluation is carried out using the UWB channel model provided by the IEEE 802.15 channel modelling subcommittee to model the dense multipath indoor environment typical of the UWB system. DS-UWB architecture has been implemented using a Matlab Simulink tool and simulation results are evaluated in terms of Bit Error Rate (BER) vs. transmitter-receiver distance and noise power spectral density. Moreover, a polynomial regression analysis is carried out on simulation results in order to obtain a closed formula to describe, for different scenarios, the BER as a function of data rates, noise Power Spectral Density (PSD) and distance between the transmitter and receiver.**

***Index Terms*—UWB, DS-UWB, MMSE, IEEE 802.15.3a.**

I. INTRODUCTION

Ultra-wideband radio communicates with baseband signal pulses of very short duration (typically the duration is a few nanoseconds) [1]. The "shape of the signal" has a frequency characteristic starting from near very low frequency (few Hz) to Gigahertz range; in particular an ultra-wideband system is defined by the *Federal Communication Commission* (FCC) as a communications system occupying a fractional bandwidth larger than 20% or an absolute bandwidth larger than 500MHz. Moreover, UWB signals have very low power spectral densities values (typically a few microW per MHz) and their energy is spread over a very large band, so they can coexist with incumbent systems in the same frequency range.

These characteristics and the possibility of achieving much higher data rates without the need to increase transmitter power make UWB technology a viable candidate for short (< 20 meters) range multiple access communications in dense multipath indoor, so IEEE founded the 802.15.3a task group [2] in order to standardize a physical layer for the UWB system.

The IEEE 802.15.3a has achieved the goal to merge the various UWB PHY specifications into two proposals: *Multi-Band Orthogonal Frequency Division Multiplexing* (MB-OFDM) UWB, supported by the *WiMedia Alliance*, and DS-UWB [3], supported by the *UWB Forum*. Actually, the two parts have not reached an accord, so the standardization process is in deadlock and both standards are going out on the market.

Starting from results on *Frame Error Rate* (FER) obtained in [4], we focus our attention on the BER trend of the DS-UWB standard proposal [3], in an indoor environment, modelled in accordance with ([4],[8]). With respect to [4], we also introduce the *Additive White Gaussian Noise* (AWGN) effects, so we carried out our analysis varying the channel scenario and the level of noise. Our main contribution is a three-variables regression analysis in order to obtain a closed formula to describe, for different scenarios, the BER as a function of data rates, noise PSD and distance between transmitter and receiver.

In the following related work are summarized in Section II, a brief description of the transmitter and receiver structure and of the channel model are given in Section III; performance evaluation and regression analysis are show in Section IV, while conclusions are summarised in Section V.

II. RELATED WORK

General approaches for the channel modelling of UWB networks, taking into account multipath fading, shadowing and path loss have been considered in [5],[6],[7] and [8]. In particular, in [5], power attenuation of the paths was shown to follow a log-normal distribution, which is a function of the distance between the transmitter and receiver. In [6],[7] and [8] the arrival of paths on each sampling time interval is not assumed, but they follow a cluster-based arrival rate. These characteristics are different from the classical IEEE 802.11 wireless networks channel models.

In the Saleh-Valenzuela (S-V) model, the paths arrival times are modelled through two Poisson distributions, where the first one is used to model the arrival time of the first path in each cluster, while the second one describes the arrival time of other paths in each cluster [6]. The path amplitudes follow a Rayleigh distribution law, with a double exponential decay model.

In [8], contrarily to [6], the authors propose a log-normal distribution to approximate the amplitudes of the power associated with the path components. However, in [2], the impulse response is not explicitly associated with the transmitter-receiver distance. Thus, following the model presented in [8], which is the formal model adopted by IEEE 802.15.3a, it is possible to account for the distance dependence modifying the first path time arrival and further attenuating other paths on the basis of the covered distance.

In [9], instead, an analytical treatment is carried out on the performances in terms of BER of an ideal MMSE for a fixed data rate. Specifically, the authors analyse the behaviour of the receiver in the presence of a multipath fading channel and as a function of the interferences due to OFDM devices, to the multi-access (that is, in the presence of other DS-UWB devices) and to the background noise. In [10], the authors described the MMSE equalization: *linear equalization* (LE) and *decision-feedback equalization* (DFE) are analysed. LE and DFE are both suitable choices for the DS-UWB system even if DFE has a better performance for high date rate, but equalization is also more complex in this case. In [4] and [10] the authors combine the RAKE receiver and the MMSE equalization to recover the transmitted signal, but in [9] is shown that the MMSE receiver alone can be sufficient to recover the data. In order to reduce the receiver complexity, in our model we use only the MMSE receiver with a linear equalization.

In [4] a treatment on the performance of DS-UWB and MB-OFDM systems is already carried out, but with respect to [4], we also introduce the *Average White Gaussian Noise* (AWGN) effects, so we carried out our analysis varying the channel scenario and the level of noise. Moreover, another important contribution is a three-variables regression analysis in order to obtain a closed formula to describe, for different scenarios, the BER as a function of data rates, noise PSD and distance between transmitter and receiver.

III. DS-UWB REFERENCE SYSTEM

In order to analyse the performance of the DS-UWB system we realized a simulator using the Simulink tool of Matlab.

We refer to [4], in which the DS-UWB standard has already been investigated in terms of FER. The analysis of the DS-UWB system performance under multipath fading, modelled using the channel model developed in the IEEE 802.15 channel modelling subcommittee [8], combined with AWGN, is carried out in terms of BER. Mainly, we try to find a closed formula for the average BER as a function of distance, data rate and noise PSD for the different channel configuration described in [8] (subsequently, in the paper we always refer to the average BER).

A. TRANSMITTER AND RECEIVER STRUCTURE

DS-UWB realizes a *Wireless Personal Area Network* (WPAN) with data payload communication capabilities of 28, 55, 110, 220, 500, 660,1000 and 1320 Mbps (in this work we analysed only 28, 55, 110, 220 and 500 Mbps data rates) [3]. This communication system divides the band into two independent bands of operations: the lower band occupies the spectrum from 3.1 GHz to 4.85 GHz while the upper band occupies the spectrum from 6.2 GHz to 9.7 GHz. In this work, we evaluated the performances of a DS-UWB system working in the piconet channel 1 of Lower Band with a chip rate of 1313 MHz. We used, as described in the proposal standard [3], BPSK modulation and ternary *Pseudo-Noise* (PN) of spreading. Moreover, we used the convolutional error correction technique with a variable rate (1, ½, ¾). The combination of the *Spreading Factor*, SF, (that is the length of the spreading code), the code rate and modulation used forms the current data rate (in Table I are shown the available data rates).

For every simulation campaign, we fixed the transmission power to -25 dB. The transmitted bits sequence is estimated using a *Minimum Mean Square Error* (MMSE) receiver because it is more effective than a four- or eight-fingered RAKE at multipath combining and its complexity is constant (receiver complexity does not go up linearly for each path whose energy is exploited), as described in [9].

At each bit epoch, a bit decision is made at the output of the correlator and it is then fed back to the adaptive filter. This receiver uses an adaptive algorithm called *Normalized Least Minimum Square* (NLMS) to upgrade weights vector ***w***. The equation to calculate the weights is specified below. For more details refer to [9].

$$w(i) = w(i-1) + \mu_m e(i) \frac{u^*(i)}{\varepsilon + u^H(i)u(i)} \tag{1}$$

In (1), μ_m is the step size, while ε is a small positive constant that has been added (to denominator) to overcome potential numerical instability in the update of the weights; *e(i)* is the error associated with the *i-th* estimated bit; *u(i)* represents the discrete input signal of the adaptive filter. We use a MMSE receiver with 16 taps per observation window and a step size of 0.5.

TABLE I
AVAILABLE DATA RATES FOR BPSK MODULATION IN THE LOWER BAND

Data Rate	Code Rate	SF
28 Mbps	1/2	24
55 Mbps	1/2	12
110 Mbps	1/2	6
220 Mbps	1/2	3
500 Mbps	3/4	2
660 Mbps	1	2
1000 Mbps	3/4	1
1320 Mbps	1	1

B CHANNEL MODEL

In our simulator, we utilize the UWB channel model provided by IEEE 802.15 channel modelling subcommittee [8]. This model is based on the *Saleh-Valenzuela* approach [6], which distinguishes between the cluster arrival time and ray arrival time modelled by two Poisson processes. The model proposed in [8] provides four different multipath fading scenarios: CM1 (which describes a *Line of Sight*, LOS, scenario with a distance between transmitter and receiver in the range 0-4 meters), CM2 (which describe a *Non-Line of Sight*, NLOS, scenario with a distance in the range 0-4 meters), CM3 (which depicts an NLOS scenario in the range 4-10 meters) and CM4 (which describes a very extreme NLOS scenario). The shadowing effect is also included in the model and it is assumed to be common to all environments (in particular, it is modelled as a lognormal distribution with a log-standard deviation of 3 dB). Further details on channel model can be found in [8].

In accordance with [4], a free path loss model is also employed. Specifically, the path loss for the distance between transmitter and receiver $d \geq 1\ m$ is given by:

$$PL(d) = 20\log_{10}\left(\frac{4 \cdot \pi \cdot d \cdot f_c}{c}\right), \quad f_c = \sqrt{f_{\min} \cdot f_{\max}} \tag{2}$$

where f_c is the geometric center frequency, with f_{min} and f_{max} being the lower and the upper -10 dB cutoff frequencies of the power spectrum, and c is the light speed. As in [4], we incorporate the eq.2 in each channel realization in order to account the distance dependent. In particular, using (2), each path is attenuated by a factor depending on distance really covered: this distance is computed on the basis of needed time to reach the receiver under the assumption that the path speed is the light speed. Furthermore, AWGN effects, modelled as the noise of parametric PSD, are added to the channel realizations.

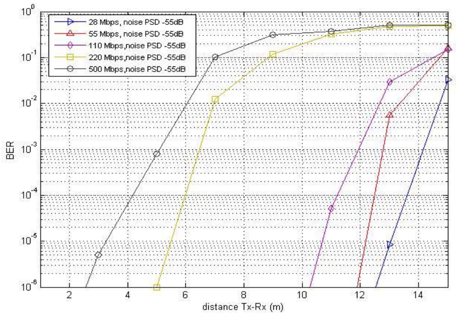


Fig.1 BER vs. distance Tx-Rx for CM1 scenario, noise PSD of -55dB.

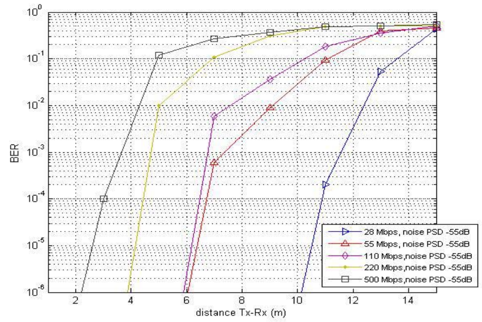


Fig.2 BER vs. distance Tx-Rx for CM2 scenario, noise PSD of -55dB.

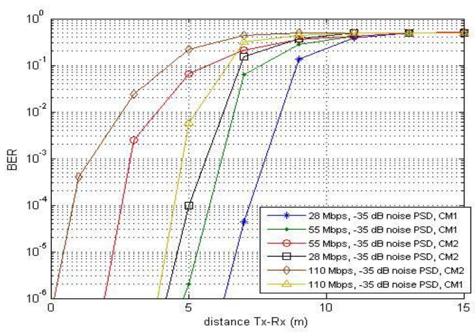


Fig.3 BER vs. distance for CM1, CM2 scenarios, noise PSD -35dB.

IV. PERFORMANCE EVALUATION

Many simulation campaigns were carried out in order to evaluate the performance of the DS-UWB physical layer for UWB technology. In the following simulation results and regression analysis will be presented.

A. *SIMULATION RESULTS*

Our simulation campaigns confirm the results obtained in [4] and show how the UWB systems are very sensitive to the transmitter-receiver distance and to noise PSD.

In particular, in Fig.1 the curves of average BER in a CM1 scenario are plotted with a noise PSD of -55 dB, for 28, 55, 110, 220, 500 Mbps data rates. In accordance with results obtained in [4], we can observe how, in the presence of a low noise level, only the lower data rates (28, 55, 110 Mbps) allow transmission over a sufficiently long distance (always >10 meters) while other data rates (220 Mbps and 500 Mbps) are more sensitive to the distance (220 Mbps data rate has an operative range of around 6 meters in the CM1 scenario while 500 Mbps data rate support transmission up to 6 meters in the same scenario). In fact, low rates reject *inter-symbol interference* (ISI) better than the higher rates because of longer spreading codes, which have more zero-valued windows than a shorter sequence in their autocorrelation function, so interference due to multipaths that are within these windows can be eliminated. In Fig.2, we show the average BER trend for the CM2 scenario for a noise PSD of -55dB. In this case, the performance degrades because CM2 describes an NLOS scenario, so the absence of a stronger direct component makes the impact of the ISI more damaging. We can see how only a 28 Mbps data rate allows communication for distances between transmitter and receiver higher than 10 meters, while operative ranges of 55 and 110 decrease considerably.

Finally, Fig.3 shows the curves of the average BER, in a CM2 and CM1 scenario, for 28,55 and 110 Mbps data rates in the presence of a noise PSD of -35dB. If we increase the noise up to -35dB, we can observe how the performances of 28 and 55 Mbps data rates worsen very quickly, because the presence of noise adds to the negative effects of the ISI: in fact the operative range of rate 28 Mbps is reduced to 7.5 meters, 55 Mbps operative range decreases to 6 meters, while the operative range for 110 Mbps falls to 5 meters. Also for the CM2 scenario, the presence of a higher noise level (PSD of -35 dB) reduces the performance of the system and so the supported operative range. (e.g. the operative range of 28 Mbps data rate is reduced to only 5 meters, while 110 Mbps falls to only 2 meters). In Table II, we summarize the operative range for all data rate in CM1,and CM2 scenario in presence of a low level of noise (-55 dB).

TABLE II

OPERATIVE RANGE FOR DS-UWB IN PRESENCE OF LOWER LEVEL OF NOISE (IN METERS)

Data Rate	CM1	CM2
28 Mbps	14.5	12
55 Mbps	13	8
110 Mbps	12	7
220 Mbps	7	5
500 Mbps	5	3.5

B. *BER REGRESSION ANALYSIS*

In order to obtain an expression for the average BER as a function of the distance *d* (in meters), the noise PSD *p* (in dB) and data rate *r* (in Mbps) a regression analysis was carried out, on the simulation results, by Mathworks' Matlab tool. Details on regression technique can be found in [11].

Since the BER assumes very low values for lower level of noise (in particular for CM1 scenario), we carried out the regression analysis on the BER logarithm reducing, in this way, the percentage of error.

The general equation of the logarithm of BER, for a fixed data rate and noise power level, can be expressed with a *n*-th order polynomial regression:

$$\log_{10}\left[BER(d)\right] = (a_n d^n + \ldots + a_3 d^3 + a_2 d^2 + a_1 d + a_0) \qquad (3)$$

where $a_i = f\left(p\right)$ with *i=0,1,…n*.

Therefore the average BER can be represented in the following way:

$$BER(d) = 10^{\left(\begin{bmatrix} a_0 & a_1 & \ldots & a_n \end{bmatrix} \begin{bmatrix} 1 \\ d \\ \vdots \\ d^n \end{bmatrix}\right)} = 10^{\langle a\rangle \cdot \langle d\rangle_n^T} \qquad 1m < d \le 15m \qquad (4)$$

where the notation $\langle\cdot\rangle$ is used to represent a row vector and $\langle\cdot\rangle^T$ is the transpose operator applied to the vector. In (4) $\langle d\rangle_n^T$ is a $(n+1)\times 1$ vector.

Considering another polynomial regression analysis on the a_i coefficients for different p values of noise, the polynomial expression of the a_i terms can be represented as follows:

$$a_i(p) = b_{m,i}p^m + \ldots + b_{2,i}p^2 + b_{1,i}p + b_{0,i} \tag{5}$$

with $i=0,\ldots,n$.

Therefore the coefficients of the PSD noise can be expressed in the following way:

$$\langle a(p)\rangle = \begin{bmatrix} b_{0,0} & b_{0,1} & \cdots & b_{0,m} \\ b_{1,0} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ b_{n,0} & \cdots & \cdots & b_{n,m} \end{bmatrix} \cdot \begin{bmatrix} 1 \\ p \\ \vdots \\ p^m \end{bmatrix} = B \cdot \langle p\rangle_m^T \tag{6}$$

Where $\langle p\rangle_m^T$ represent a $(m+1)\times 1$ vector.

A third regression is finally carried out on each coefficient of B, introducing in this way also the dependence on data rate r.

Therefore the coefficients of matrix B can be expressed as:

$$b_{i,j}(r) = c_{m',(i,j)}r^{m'} + \ldots + c_{2,(i,j)}r^2 + c_{1,(i,j)}r + c_{0,(i,j)} \tag{7}$$

Substituting (7) in (6) for each coefficient, we obtain the following formula:

$$\langle a(p,r)\rangle = \begin{bmatrix} b_{0,0}(r) & b_{0,1}(r) & \cdots & b_{0,m}(r) \\ b_{1,0}(r) & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ b_{n,0}(r) & \cdots & \cdots & b_{n,m}(r) \end{bmatrix} \cdot \begin{bmatrix} 1 \\ p \\ \vdots \\ p^m \end{bmatrix} = B(r) \cdot \langle p\rangle_m^T \tag{8}$$

In (7) and (8), the polynomials $b_{i,j}(r)$ and the degrees m, m' and n depend on considered scenario (CM1, CM2, CM3 or CM4). Substituting (8) within (4), the following equation can be obtained:

$$\begin{aligned} &BER(d,p,r) = 10^{\left(\left[B(r)\cdot\langle p\rangle_m^T\right]\langle d\rangle_n^T\right)}; \\ &1m \le d \le 15m;\ -55dB \le p \le -15dB; \\ &r \in [28Mbps,\ 55Mbps,\ 110Mbps,\ 220Mbps,\ 500Mbps]; \end{aligned} \tag{9}$$

where the $BER = f(d,p,r)$.

(9) is a general formula useful for all scenarios. In the following some examples of these functions for a fixed data rate and scenario are shown.

Specifically, for the CM1 scenario, the terms of matrix B are polynomials of degree 4:

$$\begin{aligned} &b_{0,0}(r) = 0; \\ &b_{0,1}(r) = 5.83\cdot 10^{-8}r^4 - 5.14\cdot 10^{-5}r^3 + 1.34\cdot 10^{-2}r^2 - 1.21\,r + 27.1; \\ &b_{0,2}(r) = 4.96\cdot 10^{-9}r^4 - 4.37\cdot 10^{-6}r^3 + 1.14\cdot 10^{-3}r^2 - 0.103\,r + 2.31; \\ &b_{0,3}(r) = 7.63\cdot 10^{-11}r^4 - 6.72\cdot 10^{-8}r^3 + 1.76\cdot 10^{-5}r^2 - 1.59\cdot 10^{-5}r + 3.67\cdot 10^{-2}; \\ &\vdots \end{aligned} \tag{10}$$

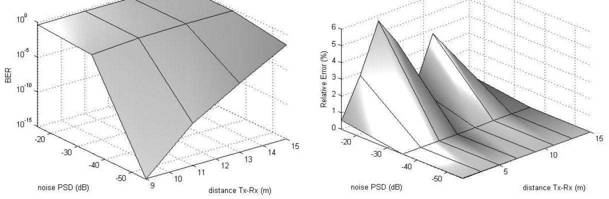
The goodness of this fit is confirmed by the observed value of the *determination coefficient* R^2 over the polynomial function [11]: in fact, the minimum observed value of R^2 is 0.9986 for r=500 Mbps. Another parameter that confirms the accuracy of regression is the relative error: in this case the maximum value observed on all rates is 6.12% still for r=500 Mbps.

If we fix the value of r to 28 Mbps in (10), we obtain the following elements for $\boldsymbol{B}$:

$$B(28) = B_1 = \begin{bmatrix} 0 & 2.7576 & 2.3623\cdot 10^{-1} & 4.4983\cdot 10^{-3} \\ 0 & -2.6200 & -2.2252\cdot 10^{-1} & -3.7242\cdot 10^{-3} \\ 0 & 7.2367\cdot 10^{-1} & 6.1369\cdot 10^{-2} & 9.9730\cdot 10^{-4} \\ 0 & -8.5716\cdot 10^{-2} & -7.2641\cdot 10^{-3} & -1.1693\cdot 10^{-4} \\ 0 & 4.6446\cdot 10^{-3} & 3.9324\cdot 10^{-4} & 6.3065\cdot 10^{-6} \\ 0 & -9.4918\cdot 10^{-5} & -8.0273\cdot 10^{-6} & -1.2853\cdot 10^{-7} \end{bmatrix} \tag{11}$$

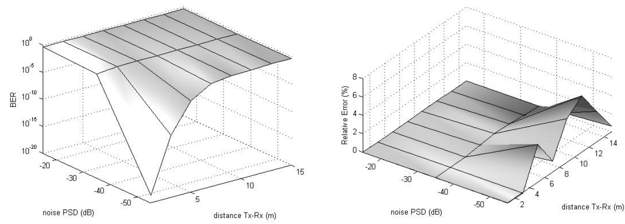
which, substituted in eq.9, leads to:

$$BER\,(d,p,28) = 10^{\left(\left[B_1\cdot\langle p\rangle_3^T\right]\langle d\rangle_5^T\right)}\ ,\ 1m < d \le 15m\ ,\ -55\,dB \le p \le -15\,dB \tag{12}$$



a) b)

Fig.4.a) BER vs. distance and noise PSD for rate 28 Mbps, CM1 scenario. b) Relative error committed by regression analysis.



a) b)

Fig.5.a) BER vs. distance and noise PSD for rate 500 Mbps, CM1 scenario. b) Relative error committed by regression analysis.

In Fig.4a the BER curve plotted using eq.12 is shown. The observed value of R^2 is in this case 0.9987. The relative error committed by regression analysis is plotted in Fig.4b (in this case the maximum relative error is 5.7%).

Instead for data rate 500 Mbps the coefficients of matrix $\boldsymbol{B}$ are:

$$B(500) = B_2 = \begin{bmatrix} 0 & 2.9904\cdot 10^{-1} & 2.6754\cdot 10^{-2} & 5.4362\cdot 10^{-4} \\ 0 & -7.3799\cdot 10^{-2} & -7.2802\cdot 10^{-3} & -1.5727\cdot 10^{-4} \\ 0 & 4.9434\cdot 10^{-3} & 5.2725\cdot 10^{-4} & 1.3152\cdot 10^{-5} \\ 0 & 3.1564\cdot 10^{-4} & 2.3988\cdot 10^{-5} & 1.9991\cdot 10^{-7} \\ 0 & -4.7717\cdot 10^{-5} & -4.2297\cdot 10^{-6} & -7.0111\cdot 10^{-8} \\ 0 & 1.4224\cdot 10^{-6} & 1.2916\cdot 10^{-7} & 2.2932\cdot 10^{-9} \end{bmatrix} \tag{13}$$

which, substituted in (9), leads to:

$$BER\,(d,p,500) = 10^{\left(\left[B_2\cdot\langle p\rangle_3^T\right]\langle d\rangle_5^T\right)}\ ,\ 1m < d \le 15m\ ,\ -55\,dB \le p \le -15\,dB \tag{14}$$

In Fig.5a we can see the BER trend, obtained by eq.14 for data rate 500 Mbps in a CM1 scenario. In this case, the *determination coefficient* R^2 over the polynomial function is 0.9986 as affirmed previously, while the relative error committed by regression approximation is plotted in Fig.4b, with a maximum relative error of 6.12%.

Instead, for the CM2 scenario, the terms of matrix B are even polynomials of degree 4:

$$\begin{aligned} &b_{0,0}(r) = 0; \\ &b_{0,1}(r) = -2.89\cdot 10^{-8}r^4 + 2.62\cdot 10^{-5}r^3 - 7.26\cdot 10^{-2}r^2 + 73.1\,r - 20.7; \\ &b_{0,2}(r) = -2.50\cdot 10^{-9}r^4 + 2.28\cdot 10^{-6}r^3 - 6.34\cdot 10^{-4}r^2 + 6.41\,r\cdot 10^{-2} - 1.81; \\ &b_{0,3}(r) = -3.83\cdot 10^{-11}r^4 + 3.51\cdot 10^{-8}r^3 - 9.90\cdot 10^{-6}r^2 + 1.01\cdot 10^{-3}r - 2.80\cdot 10^{-2}; \\ &\vdots \end{aligned} \tag{15}$$

In this case the minimum observed value of R^2 is 0.9966 for the data rate r=220 Mbps. The goodness of this regression is also confirmed by the relative error observed: in fact the maximum value observed on all rates is 6.8922% still for r=220 Mbps.

If we fix the value of r to 55 Mbps in (15), we obtain the following elements for $\boldsymbol{B}$:

$$B(55) = B_3 = \begin{bmatrix} 0 & 1.6372 & 1.5491\cdot10^{-1} & 3.2931\cdot10^{-3} \\ 0 & -8.1729\cdot10^{-1} & -7.6972\cdot10^{-2} & -1.6096\cdot10^{-3} \\ 0 & 1.6529\cdot10^{-1} & 1.5315\cdot10^{-2} & 3.1553\cdot10^{-4} \\ 0 & -1.6371\cdot10^{-2} & -1.4947\cdot10^{-3} & -3.0432\cdot10^{-5} \\ 0 & 7.9158\cdot10^{-4} & 7.1285\cdot10^{-5} & 1.4369\cdot10^{-6} \\ 0 & -1.4952\cdot10^{-5} & -1.3292\cdot10^{-6} & -2.6554\cdot10^{-8} \end{bmatrix} \quad (16)$$

which, substituted in eq.9, leads to:

$$BER(d,p,55) = 10^{\left(\left[B_3 \langle p \rangle_3^T\right] \langle d \rangle_5^T\right)}, \quad 1m < d \le 15m, \quad -55\,dB \le p \le -15\,dB \quad (17)$$

Fig.6a shows the BER course plotted using (12). We can see in Fig.6b how the polynomial approximation provided by (17) is very good (the maximum relative error committed is only 4.3591%). This trend is also confirmed by the observed value of R^2 that is 0.9993.

For data rate 220 Mbps, still in the CM2 scenario, the coefficients of matrix $\boldsymbol{B}$ take the following values:

$$B(220) = B_4 = \begin{bmatrix} 0 & 6.5071\cdot10^{-2} & 5.8497\cdot10^{-3} & 1.8940\cdot10^{-4} \\ 0 & 3.1655\cdot10^{-2} & 1.7761\cdot10^{-3} & -2.1415\cdot10^{-5} \\ 0 & -1.3985\cdot10^{-2} & -1.0170\cdot10^{-3} & -5.9758\cdot10^{-6} \\ 0 & 2.0065\cdot10^{-3} & 1.5368\cdot10^{-4} & 1.3760\cdot10^{-6} \\ 0 & -1.2314\cdot10^{-4} & -9.6223\cdot10^{-6} & -9.7543\cdot10^{-8} \\ 0 & 2.7661e\text{-}006 & 2.1830\cdot10^{-7} & 2.3434\cdot10^{-9} \end{bmatrix} \quad (18)$$

If we substitute the previous matrix in (9), we obtain the following expression:

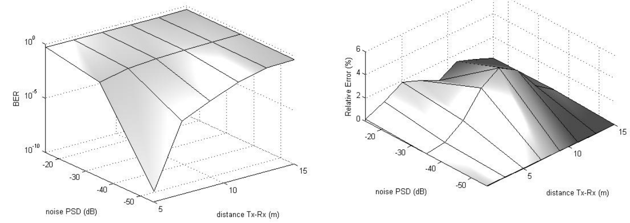
$$BER(d,p,220) = 10^{\left(\left[B_4 \langle p \rangle_3^T\right] \langle d \rangle_5^T\right)}, \quad 1m < d \le 15m, \quad -55\,dB \le p \le -15\,dB \quad (19)$$

In Fig.7a we can see BER trend, obtained by (19) for data rate 220 Mbps in a CM2 scenario.

In this case, the *determination coefficient* R^2 over the polynomial function is 0.9966, while the relative error committed by the regression approximation, plotted in Fig.7b, has a maximum value of 6.8922%.

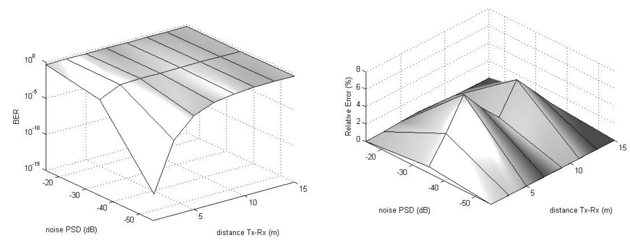
V. CONCLUSION

In this paper, we implemented the physical layer of the standard DS-UWB 802.15.3a [3]. Simulation results show how the performance, in terms of BER, of the UWB channel, for a high data rate in the case of lower signal-to-noise ratio (noise PSD ≥-15dB) degrades for increasing distance (1-15m). In particular, 28Mbps and 55Mbps rates are slightly influenced by transmitter-receiver distance, especially for the CM1 scenario with low noise power level. This is due to the low sensitivity to the inter-symbol interference. On the other hand, higher data rates (mostly rate ≥220 Mbps) are more sensitive to the transmitter-receiver distance and they can be supported for a shorter distance (in particular this distance decreases for the CM2, CM3 scenario and with very high noise power level). However, our main contribution is to provide BER analytic expressions for each scenario (in this paper we show only the formulas for the CM1 and CM2 scenarios), expressing it as a function of the data rate, noise PSD and distance between transmitter and receiver. In this way, we provide a good tool, usable for future applications, which allows the BER to be obtained directly, solving a three-variables polynomial. In order to achieve this purpose, on obtained simulation results, we have carried out a three-dimensional regression analysis utilizing the specific Mathworks' Matlab fitting tool.



a) b)

Fig.6.a) BER vs. distance and noise PSD for rate 28 Mbps, CM1 scenario. b) Relative error committed by regression analysis.



a) b)

Fig.7.a) BER vs. distance and noise PSD for rate 500 Mbps, CM1 scenario. b) Relative error committed by regression analysis.

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