PER ANALYSIS AND PERFORMANCE EVALUATION OF DS-SS UWB NETWORKS

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ABSTRACT

The low cost of devices and the possibility of achieving higher data rates without increasing transmitter power make *Ultra-Wideband* (UWB) radio a viable candidate for short-range multiple access communications in dense multipath environments. This paper analyses the efficiency of the *Direct Sequence - Spread Spectrum* (DS-SS) physical layer standard proposal in an indoor environment with fixed transmitters and receiver positions. The modelling and the performance evaluation of a new channel model, where impulse response is also distance-dependent, are outlined. *Packet Error Rate* (PER) analysis has been carried out by using a polynomial regression technique, through the Matlab tool, on simulation results obtaining an expression for the PER as function of distance and packet length. Simulation results are evaluated in terms of PER vs transmitter-receiver distance.

I. INTRODUCTION

The low cost of devices and the possibility of achieving higher data rates without the need to increase transmitter power make UWB radio a viable candidate for short-range multiple access communications in dense multipath environments.

For the above reason, IEEE has been created the 802.15.3a task group, which is still working to a project providing a high speed physical layer for image and multimedia applications.

Among standard proposals submitted to the 802.15.3a work group, we have chosen to analyze the DS-SS physical layer proposal because it is a viable candidate to be standardized in the next future.

The DS-SS technique provides a *wireless Personal Area Network* (WPAN) with a very high data payload communication capabilities. DS-UWB supports two independent bands of operation: the lower band occupying the spectrum from 3.1 GHz to 4.85 GHz and the upper band occupying the spectrum from 6.2 GHz to 9.7 GHz. *Binary Phase Shift Keying* (BPSK) and *4-Bi-Orthogonal Keying* (4-BOK) are used to modulate the data symbols, with each transmitted symbol being composed of a sequence of UWB pulses. The various data rates are supported through the use of variable-length ternary spreading code sequences, with sequence lengths ranging from 1 to 24 pulses or "chips".

In this paper we realize a new UWB channel model in which the dependence by distance between transmitter and receiver is explicit. In opposition to [2,5], we modeled a impulse response that is function of time and distance. The distance dependence is obtained setting, for the *Line Of Sight* (LOS) scenario, the first path delay to the needed time to cover distance between transmitter and receiver. For the *Non-Line Of Sight* (NLOS) scenario, we experimentally found that the first path delay is uniformly distributed in an interval proportional to the length of the straight line, connecting transmitter and receiver, which is computed ignoring possible obstacles. Once the delay of rays, following the first path, has been obtained, according to the Saleh-Valenzuela model [5], we estimate the distances covered by each path, so we can compute the attenuation of impulse response gain coefficients using Ghassemzadeh's model [3].

The performance evaluation of UWB channel, in accordance with the standard model IEEE 802.15.3a, is exploited in a wide operative range.

Moreover, in order to obtain an expression for the PER as a function of the distance between transmitter and receiver and the packet length, a polynomial regression has been carried out, on the simulation results by Mathworks' tool Matlab.

In the following, a brief synthesis of the related works, channel model, PER analysis and simulation results are respectively given in section II, section III, section IV and section V. Conclusions are summarised in section VI.

II. RELATED WORK

At present, three standards are the most considered by the 802.15.3a task group: the DS-SS [1] technique, the *Orthogonal Frequency Division Multiplexing* (OFDM) proposal [8] and the *Time Hopping-Pulse Position Modulation* (TH-PPM) proposal [9].

DS-SS system has already been described in the previous section. The second standard proposal provides a wireless PAN with high data payload communication capabilities and it employs orthogonal frequency division multiplexing for a total of 122 sub-carriers that are modulated using *Quadrature Phase Shift Keying* (QPSK). The TH-PPM proposal instead provides a wireless PAN based on the scheme suggested by Win and Scholtz in [10], modified to avoid catastrophic collision due to multi access.

The performances analysis of the proposed standards needs a channel model describing well enough the phenomena involving wireless communications. Some UWB channel models, taking into account path loss, shadowing and multipath effects, have been proposed in [2,3,5,11,12]. In particular, in [5], the authors prove that the paths arrive in cluster and so they propose a double Poisson law to model paths and cluster arrival time while for the decay power of clusters it is adopted a Rayleigh distribution (*Saleh-Valenzuela*, S-V, model). The paths clustering distinguishes the previous model from the classical 802.11 model, in which the impulse response is modeled as the output of a linear filter. In [2] the authors use the S-V approach for the arrival time statistics, while they found that decay amplitude statistics best fit the log-normal distribution rather than the Rayleigh. that was used in the original S-V model. However in [2] the impulse response is not a explicit function of distance: in fact parameters distributions are set on the basis of considered scenario (LOS or NLOS) and distance range (e.g. the CM2 configuration modeled a NLOS scenario with a range of 4-10 meters). In [3], instead, the authors found a lognormal law in which paths attenuation are function of distance between transmitter and receiver, but small scale fading statistic are not given.

In our model we use S-V approach to describe arrival time of paths and clusters, while we apply law found in [3] to model decay power of path. Thus, our contribution is the modeling of a impulse response that is also direct function of distance and not only of time.

III. Channel Model

According to [2] and [5], we used a *Saleh-Valenzuela* (S-V) approach for the time-of-arrival statistics: paths arrive in a cluster, so we need to distinguish between the cluster arrival time and ray arrival time. In [2] and [5] it is assumed that the arrival time of first path is zero, while our model provides an explicit distance dependence. In fact, for LOS scenarios, we assume that the delay of the first path (direct component) is the necessary time to cover the distance between the transmitter and receiver. If d is this distance in meters, then the time of arrival is given by $T_1 = \frac{d}{c}$, where c is the light speed in m/s. For the NLOS scenario, instead, we experimentally found that the time of arrival of the first path is uniformly distributed in the interval $\left(\frac{d}{c} \; ; \; \frac{d+1}{c}\right]$.

For both scenarios, as described in [5], the delay of rays that follow the first path is a Poisson process with rate λ, while the clusters arrival is another Poisson process with rate Λ, which is smaller than the ray arrival rate. Therefore, defining:

- T_l, the arrival time of the first path of the *l-th* cluster;
- $\tau_{k,l}$, the delay of the *k*-th path within the *l-th* cluster relative to the first path arrival time,
- Λ, cluster arrival rate;
- λ, ray arrival rate, i.e., the arrival rate of path within each cluster;

the distributions of clusters and rays arrival times are given by:

$$P(T_l / T_{l-1}) = \Lambda \, e^{-\Lambda(T_l - T_{l-1})} \quad l > 0 \tag{1}$$

$$P(\tau_{k,l} / \tau_{k-1,l}) = \lambda \, e^{-\lambda(\tau_{k,l} - \tau_{k-1,l})} \quad k > 0 \tag{2}$$

Once the paths delay are obtained, we can compute the effective distances covered by each path:

$$d_{k,l} = \tau_{k,l} \cdot c \qquad k = 1 \ldots K; l = 1 \ldots L \tag{3}$$

where $d_{k,l}$ is the covered distance of the *k*-th path within the *l*-th cluster, K is the paths number of the *l*-th cluster and L is the number of total clusters.

As described in [3], the power attenuation in decibels, due to distance, is at some distance d:

$$\begin{aligned} \overline{PL(d)} = & \left[PLo + 10\mu_\gamma \log d \right] \\ & + \left[10 n_1 \sigma_\gamma \log d + n_2 \mu_\sigma + n_2 n_3 \sigma_\sigma \right] \end{aligned} \tag{4}$$

where the intercept point PLo is the path loss at $d_0 = 1\,\text{m}$, μ_γ and σ_γ are respectively the average value and the standard deviation of the normal distribution of the decaying path loss exponent γ. The shadowing effects, in accordance with [3], are modelled through a zero-mean Gaussian distribution with standard deviation σ, normally distributed and characterized by an average value μ_σ and standard deviation σ_σ.. n_1, n_2 and n_3 are zero-mean Gaussian variables of unit standard deviation N[0,1]. The first term of eq.(4) represents the median path loss, while the second term is the random variation about the median value. Gaussian distributions for n_1, n_2 and n_3 must be truncated so as to keep γ and σ from taking on impractical values. The solution is to confine them to the following ranges:

$$n_1 \in [-1.25, 1.25] \qquad n_2, n_3 \in [-2, 2] \tag{5}$$

If we denote with $\alpha_{k,l}(d_{k,l})$ the gain coefficient of the *k*-th path relative to the *l*-th cluster, then inserting distance computing in (3) into (4), we can obtain attenuated amplitude of each path, referenced to a unit amplitude, as:

$$\beta_{k,l} = 10^{-\overline{PL(d_{k,l})}/20} \tag{6}$$

$$\alpha_{k,l}(d_{k,l}) = p_{k,l} \beta_{k,l} \tag{7}$$

where $p_{k,l}$ is equiprobable +/-1 to account for signal inversion due to reflections.

Therefore, the time-distance dependent channel impulse response is described by:

$$h(t,d) = \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}(d_{k,l}) \delta(t - T_l - \tau_{k,l}) \tag{8}$$

where k=1…K and l=1…L.

In Fig.1 an impulse response realizations for the NLOS scenario and for a distance between transmitter and receiver respectively of 1m is plotted. We can see that distance increase also means a rise of first path delay and more power attenuation of the components.

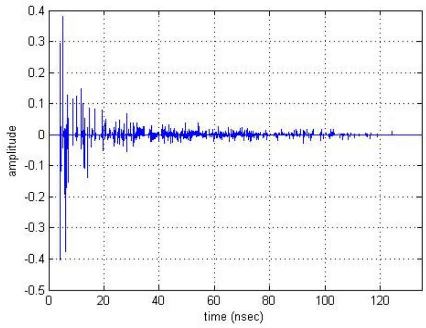

Figure 1: Impulse Response for NLOS scenario with Tx-Rx distance =1m.

IV. PER Regression Analysis

In order to obtain an expression for the PER as a function of the distance *d* and the packet length *s* (in byte), a polynomial regression has been carried out, on the simulation results by Mathworks' tool Matlab. The curve of the PER for the data rate 110 Mbps in the LOS scenario and for different packet length *s* is shown in Fig.2 and Fig.3 (noise variance 10^{-2}). Further details on polynomial regression technique can be found in [14].

A measure of the goodness of fit is the Euclidean norm of residuals, where the fit residuals are defined as the difference between the ordinate data point and the resulting fit for each abscissa data point. A smaller value of the norm of residuals indicates a better fit than a larger value: therefore the trend to zero of the norm means an almost perfect approximation. The maximum observed value of the Euclidean norm over all obtained polynomial functions is 0.0035711.

The general equation of the PER for a fixed data rate and packet length can be expressed with a *n*-th order polynomial regression.

$$PER(d) = a_n d^n + a_{n-1} d^{n-1} + \ldots + a_2 d^2 + a_1 d + a_0 \quad (9)$$

where $a_i = f(s)$ with i=0,1,…m.

PER can be represented in the following way:

$$PER(d) = \begin{cases} 0 & d < d_{\min} \\ \begin{bmatrix} a_0 & a_1 & \ldots & a_n \end{bmatrix} \cdot \begin{bmatrix} 1 \\ d \\ \vdots \\ d^n \end{bmatrix} = \langle a \rangle \cdot \langle d \rangle^T & d_{\min} \le d \le d_{\max} \end{cases} \quad (10)$$

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 eq.(10) $\langle d \rangle$ is a $1 \times (n+1)$ vector.

Considering another polynomial regression analysis on the a_i coefficients for different values of packet length *s*, the polynomial expression of the a_i terms can be represented as follows:

$$a_i(s) = b_{i,a_m} s^m + \ldots + b_{i,a_2} s^2 + b_{i,a_1} s + b_{i,a_0} \quad (11)$$

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

Therefore the coefficients of the packet length can be expressed in the following way:

$$\langle a(s) \rangle = \begin{bmatrix} b_{0,a_0} & b_{0,a_1} & \ldots & b_{0,a_m} \\ b_{1,a_0} & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ b_{n,a_0} & \ldots & \ldots & b_{n,a_m} \end{bmatrix} \cdot \begin{bmatrix} 1 \\ s \\ \vdots \\ s^m \end{bmatrix} = B \cdot \langle s \rangle^T \quad (12)$$

Substituting eq.(12) within eq.(10), the following equation can be obtained:

$$PER(d,s) = \begin{cases} 0 & d < d_{\min} \\ [B \langle s \rangle^T] \langle d \rangle^T & d_{\min} \le d \le d_{\max} \end{cases} \quad (13)$$

where the $PER = f(d,s)$. The polynomial order, distances d_{max} and $\boldsymbol{d_{min}}$ and coefficients matrix B are related to the considered scenarios (LOS or NLOS), to the noise variance and to the data rates.

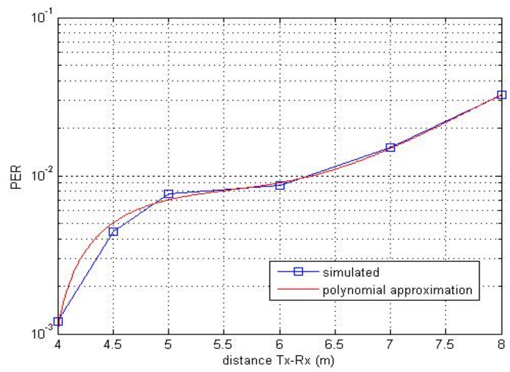

Figure 2: Simulation results and their polynomial approximation for 110Mbps-LOS scenario, noise variance 10^{-2}, packet length of 128 bytes.

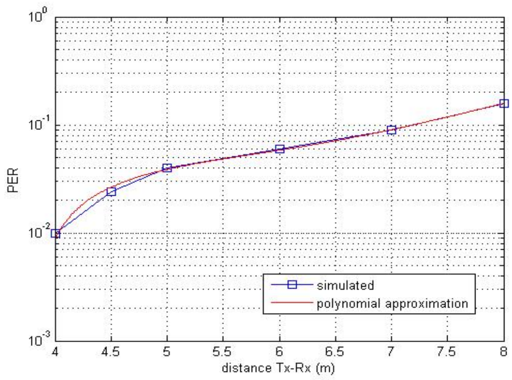

Figure 3: Simulation results and their polynomial approximation for 110Mbps-LOS scenario, noise variance 10^{-2}, packet length of 1024 bytes.

Specifically, from a regression analysis for the rate 110 Mbps in the LOS scenario with a noise variance of 10^{-2} the following values were obtained:

$$B=\begin{bmatrix} 0.083099 & -0.0027895 & 3.195\cdot 10^{-6} & -1.1646\cdot 10^{-9} \\ -0.069848 & 0.0017556 & -2.1629\cdot 10^{-6} & 8.3817\cdot 10^{-10} \\ 0.013741 & -0.0003256 & 4.0608\cdot 10^{-7} & -1.5715\cdot 10^{-10} \\ -0.00087312 & 2.0083\cdot 10^{-5} & -2.5181\cdot 10^{-8} & 9.8171\cdot 10^{-12} \end{bmatrix} \quad (14)$$

$$d_{max}=8m,\ d_{min}=4m,$$

which, substituted in eq.(13), leads to:

$$PER\,(d,s)=\begin{cases} 0 & d<4 \\ \left(\begin{bmatrix} 0.083099 & -0.0028 & 3.195\cdot 10^{-6} & -1.165\cdot 10^{-9} \\ -0.06985 & 0.00176 & -2.163\cdot 10^{-6} & 8.382\cdot 10^{-10} \\ 0.01374 & -0.00033 & 4.061\cdot 10^{-7} & -1.571\cdot 10^{-10} \\ -0.00087 & 2.008\cdot 10^{-5} & -2.518\cdot 10^{-8} & 9.817\cdot 10^{-12} \end{bmatrix}\cdot\begin{bmatrix} 1 \\ s \\ \vdots \\ s^3 \end{bmatrix}\right)\cdot\begin{bmatrix} 1 \\ d \\ \vdots \\ d^3 \end{bmatrix} & 4\le d\le 8 \end{cases} \quad (15)$$

$$128\le s\le 1024$$

In Fig.4 PER vs distance and packet length are plotted using eq.(15).

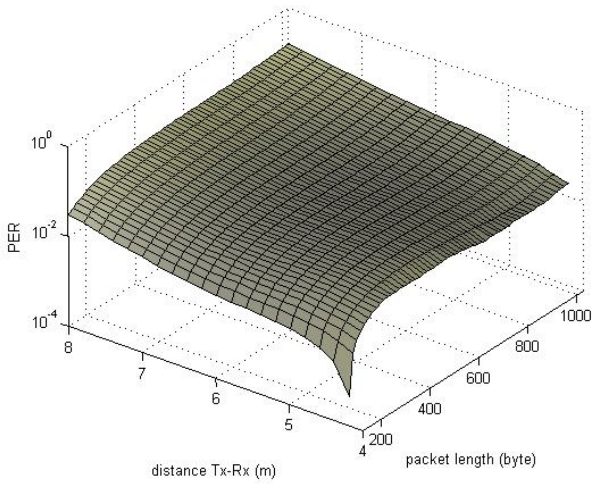

Figure 4: PER vs. packet length and distance for rate 110Mbps in LOS scenario with variance noise 10^{-2}.

V. SIMULATION SCENARIO

In order to recover the signal we employed an adaptive multi-user receiver, using the *Minimum Mean Square Error* (MMSE) algorithm. that is more effective than a four or eight fingered RAKE at multipath combining and its complexity is constant [4].

At each bit epoch, a bit decision is made at the output of correlator and it is then fed back to the adaptive filter. This receiver uses an adaptive algorithm called *Normalised Least Minimum Square* (NLMS) to upgrade weights vector *W*. The equation to calculate the weights is specified below. For more details refer to [4].

$$W(i)=W(i-1)+\mu_m\ e(i)\frac{u^*(i)}{\varepsilon+u^H(i)u(i)} \quad (14)$$

In (14), 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 64 taps per observation window size and a step size of 0.5.

We operate in low band piconet channel 1 with a chip rate of 1313 MHz. We also use PN ternary spreading codes of variable length and FEC of rate ½.

TABLE I
MODEL PARAMETERS

Symbol	LOS	NLOS
Λ [1/nsec] (cluster arrival rate)	0.004~0.0233	0.067~0.4
λ [1/nsec] (path arrival rate)	2.1~10.2	0.5~2.1
PL_0 [dB] (intercept point)	1.4754	1.7502
μ_γ (mean value of paths decay exponent)	1.7	3.5
σ_γ (std. dev. of paths decay exponent)	0.3	0.97
μ_σ [dB] (average value of shadowing standard deviation)	1.6	2.7
σ_σ [dB] (std. dev. of shadowing standard deviation)	0.5	0.98

VI. SIMULATION RESULT

In Fig.5, PER vs distance curves for 110Mbps and 220Mbps in LOS and NLOS scenarios in the presence of low background white Gaussian noise (variance 10^{-5}) and with a packet length of 128 bytes are plotted.

We can see how the 110Mbps data rate is poor influenced by *inter-symbol interference* (ISI) respect to the higher rate because of longer spreading codes that has more zero-valued windows than a shorter sequence in their autocorrelation function. In fact the interferences due to multipaths that are within these windows can be eliminated.

In particular, the performances are better in the LOS scenario where the presence of a stronger direct component makes the impact of the ISI less damaging.

The PER curve vs. transmitter-receiver distances for the LOS and NLOS scenarios with 10^{-2} variance and a packet length of 128 bytes is depicted in Fig.6. In this case the power level of the noise is almost the same as that of the signal, therefore it adds to the negative effects of the ISI further worsening the performance of the system (the impact of the noise is greater for longer distances and in the NLOS scenario because the power level of the signal received decreases with the increase in distance and in NLOS conditions).

The PER, as demonstrated in [13], is also a function of the size of the packet, therefore if the packet size is made to go towards one (degenerate case) the PER converges towards the

Bit Error Rate (BER), vice versa at increase in the packet size the Packet Error Rate tends to one (Fig.7).

VII. Conclusion

In this paper 802.15.3a DS-SS physical layer has been investigated in terms of PER. Performance evaluation has been carried out considering a new multi-path fading channel model in which impulse response is also function of distance and not only of time.

On the simulation results, a regression analysis, using Matlab tool, has been carried out: an analytic formula that expresses PER as function of distance and packet length was obtained.

Simulation results show how the performances, in terms of PER, for high data rate in the case of lower signal-to-noise degrades for increasing distance (1-8m). 28Mbps and 56Mbps rates are slightly influenced by transmitter-receiver distance, especially for LOS scenario with low noise power level. This is due to the low sensibility to the inter-symbol interference. On the other hand, higher data rates are more sensitive to the transmitter-receiver distance and they can be supported for a short distance (<4m) for the LOS scenario and with very low noise power level.

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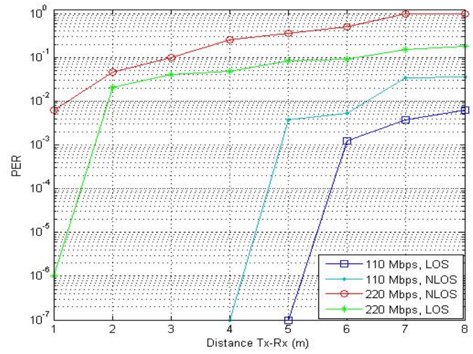

Figure 5: PER course for LOS-NLOS scenarios and noise variance of 10^{-5}.

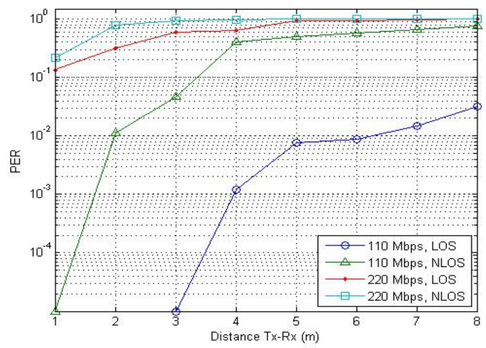

Figure 6: PER course for LOS-NLOS scenarios and noise variance of 10^{-2}.

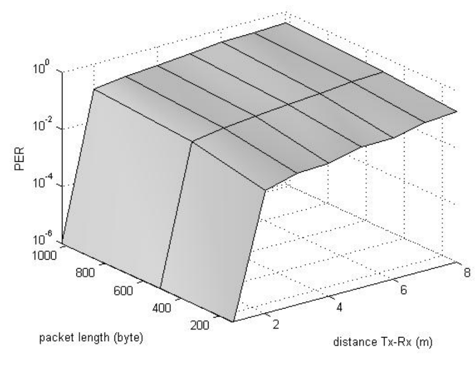

Figure 7: PER vs. packet length and distance for rate 220Mbps in LOS scenario with variance noise 10^{-2}.