Time and Distance Dependent DS-SS UWB Channel Modelling: BER and PER Evaluation

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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. Moreover, the performance evaluation of an ideal Minimum Mean Square Error (MMSE) receiver is exploited in terms of distance, noise and data rates dependence. Packet Error Rate (PER) analysis has been carried out by using a polynomial regression technique, through the Matlab tool, on simulation results. Simulation results are evaluated in terms of Bit Error Rate (BER) and PER vs. transmitter-receiver distance.**

Keywords-UWB; DS-SS; MMSE; IEEE 802.15.3a.

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. Due to this recent commercial interest , IEEE founded the task group 802.15.3a in order to standardize a physical layer for UWB communications systems.

In this paper we analyze the performance in terms of *Packet Error Rate* (PER) and *Bit Error Rate* (BER) of the *Direct Sequence - Spread Spectrum* (DS-SS) physical layer standard proposal, described in [1], in an indoor environment modelled by time and distance dependent impulse response, with fixed transmitters and receiver positions.

Considering references [2,3,5], our contribution is the modelling of a new channel model, in which the dependence on distance between transmitter and receiver is explicit, thus impulse response is also function of distance and not only of time. Therefore, the first path delay is, for the *Line of Sight* (LOS) scenario, the needed time to cover a fixed distance between transmitter and receiver, while, for the *Non-Line of Sight* (NLOS) scenario, we found that this 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].

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

In the following, a brief synthesis of the related works, channel model, performance evaluation of an ideal MMSE receiver 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

The task group 802.15.3a, in the last few years, have considered, for the physical layer of UWB *Wireless Personal Area Network* (WPAN), mainly three standards: DS-SS [1], *Orthogonal Frequency Division Multiplexing* (OFDM) [6] and *Time Hopping-Pulse Position Modulation* (TH-PPM) [7]. We focused on the DS-SS in this paper because it represents a possible candidate to be standardised in the next future.

General approaches for the channel modelling of UWB networks, taking into account multipath fading, shadowing and path loss have been considered in [2,3,5]. In particular, in [3], paths power attenuation was shown to follow a log-normal distribution, that is a function of the distance between the transmitter and receiver. In [2,5] 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 [5]. The path amplitudes follow a Rayleigh distribution law, with a double exponential decay model.

In [2], contrarily to [5], 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 [2], it is possible to account for the distance dependence modifying the first path time arrival and using, for the paths decay power, log-normal distribution laws obtained in [3].

In [4], 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 our treatment, instead, we have focused attention mainly on the performances of the MMSE receiver as a function of the rate and distance.

III. Channel Model

According with [2] and [5], we used a Saleh-Valenzuela (S-V) approach for the time-of-arrival statistics: paths arrive in clusters. 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.

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

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

where $d_{k,l}$ is the covered distance of the k-th path within the l-th cluster.

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

$$\begin{aligned}\overline{PL(d)} = &\left[PLo + 10\mu_\gamma \log d \right] \\ &+ \left[10 n_1 \sigma_\gamma \log d + n_2 \mu_\sigma + n_2 n_3 \sigma_\sigma \right]\end{aligned} \tag{2}$$

where the intercept point PLo is the path loss at $d_0 = 1$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.(2) represents the median path loss, while the second term is the random variation about the median value.

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 (1) into (2), we can obtain attenuated amplitude of each path, referenced to a unit amplitude, as

$$\beta_{k,l} = 10^{-\overline{PL(d_{k,l})}/20} \quad ; \quad \alpha_{k,l}(d_{k,l}) = p_{k,l}\beta_{k,l} ; \tag{3}$$

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:

$$h(t,d) = \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}(d_{k,l}) \delta(t - T_l - \tau_{k,l}) \tag{4}$$

IV. Performances evaluation of an ideal MMSE receiver and PER analysis

In DS-SS system, the k-th user's transmitted signal can be expressed as:

$$x_k^{\{v\}}(t) = \sum_{i=1}^{M} b(i) \cdot s_k^{\{v\}}(t) \tag{5}$$

where M is the packet length, the symbol $\{\}$ means that the signal $x_k(t)$ is also a function of the data rate v, while $b(i)$ is the bipolar representation of bits *Binary Phase Shift Keying* (BPSK) modulated by a signature waveform $s_k^{\{v\}}(t)$, so -1 or +1 can be assumed depending on the signalling bits. $s_k^{\{v\}}(t)$ consists of a train of pulses, known as *Gaussian UWB monocycles*, which are modulated by signature spreading sequence of user k, and depends on the data rate v (in fact, spreading sequence length is related to transmission rate and so to the pulses number, composing $s_k^{\{v\}}(t)$, and it changes on the basis of v).

If k-th user's signal is transmitted through a multipath channel, characterized by an impulse response $h(t,d)$ given by (4), the relative received signal can be expressed as:

$$y_k^{\{v,d\}}(t) = x_k^{\{v\}}(t) \otimes h(t,d) \tag{6}$$

where $\otimes$ is the convolution operator and $\{v,d\}$ denotes that $y_k(t)$ depends also on distance and rate.

A. Ideal MMSE Receiver

The signal received at the input of MMSE is:

$$r^{\{v,d\}}(t) = y_k^{\{v,d\}}(t) + n(t) \tag{7}$$

where $n(t)$ is zero-mean *Additive White Gaussian Noise* (AWGN).

The MMSE receiver is composed of a pass-band filter, for noise and out-of-band interferences suppressions, and an adaptive filter, which acts as a correlator [4].

The observation window of the adaptive filter represents the time in which it "examines" the received signal samples, in order to take a decision on the current bit value. Assuming that T is the duration of observation windows, then the i-th window for the i-th bit decision is:

$$\left(t_0+(i-1)T_b\ ;\ t_0+(i-1)T_b+T\right) \tag{8}$$

where T_b is the symbol period.

Without loss of generality, we assume that there is only one transmitting user, that we denote with k, and therefore that there is no interference due to a multiple channel access. In addition, we can suppose that $T=T_b$, because the i-th observation window contains the most of the energy of the i-th received bit (that is the time T_b is sufficient to estimate the i-th bit).

If user k, placed at some distance d from receiver, transmits with a data rate v a single positive bit through the channel, it is received as:

$$z_k^{\{v,d\}}(t)=s_k^{\{v\}}(t)\otimes h(t,d)\otimes h_b(t) \tag{9}$$

where $h_b(t)$ is the impulse response of the pass-band filter.

The number of signal samples in each observation window is:

$$N_b=T_b/T_s=(N\cdot L)/T_s \tag{10}$$

where T_s is the sampling time, N the number of samples with which each impulse is discretized and L is the length of used spreading sequence (that is to say the number of pulses for each symbol).

Referring to [4], we define:

$$j_0\triangleq\frac{t_0}{T_s},\quad \tilde{z}_k^{\{v,d\}}(j)\triangleq z_k^{\{v,d\}}(jT_s),\quad \tilde{r}^{\{v,d\}}(j)\triangleq r_b^{\{v,d\}}(jT_s),$$
$$\tilde{n}(j)\triangleq n_b(jT_s)\qquad j=1,2,\ldots \tag{11}$$

where t_0, and therefore j_0, is set so that i-th observation window contains most of the energy from the bit of user k, the symbols with a tilde denote the discrete-time version of the continuous-time signals while $r_b(\cdot)$ and $n_b(\cdot)$ are the bandpass filtered versions of $r(\cdot)$ and $n(\cdot)$.

Let us denote the taps vector of the adaptive filter and the received signal in the i-th observation window with:

$$\tilde{\mathbf{w}}\triangleq\left[w(1)\quad w(2)\quad\ldots\quad w(N_b)\right]^T \tag{12}$$

and

$$u^{\{v,d\}}(i)\triangleq\left[\tilde{r}^{\{v,d\}}\left(j_0+(i-1)N_b+1\right)\ \ldots\ \tilde{r}^{\{v,d\}}\left(j_0+(i-1)N_b+N_b\right)\right]^T \tag{13}$$

From (9) and (11) it can be written as follows:

$$u^{\{v,d\}}(i)=b_k(i)\cdot\bar{z}_k^{\{v,d\}}(i)+\bar{n}(i) \tag{14}$$

where

$$\bar{n}(i)\triangleq\left[\tilde{n}\left(j_0+(i-1)N_b+1\right)\ \ldots\ \tilde{n}\left(j_0+(i-1)N_b+N_b\right)\right]^T \tag{15}$$

$$\bar{z}_k^{\{v,d\}}(i)\triangleq\left[\tilde{z}_k^{\{v,d\}}\left(j_0+(i-1)N_b+1\right)\ \ldots\ \tilde{z}_k^{\{v,d\}}\left(j_0+(i-1)N_b+N_b\right)\right]^T \tag{16}$$

According to [4], the optimal tap vector to detect user k's i-th bit is:

$$\tilde{\mathbf{w}}=\left[\bar{z}_k^{\{v,d\}}(i)\cdot\bar{z}_k^{\{v,d\}^H}(i)+R\right]^{-1}\cdot\bar{z}_k^{\{v,d\}}(i) \tag{17}$$

where H denotes the conjugate transpose and $\boldsymbol{R}$ is the covariance matrix of $\bar{n}(i)$:

$$\mathbf{R}\equiv E\left\{\bar{n}(i)\cdot\bar{n}^H(i)\right\} \tag{18}$$

The i-th output of the MMSE filter can be written as:

$$\beta(i)=\tilde{\mathbf{w}}^H u(i)=\tilde{\mathbf{w}}^H\bar{z}_k^{\{v,d\}}(i)b_k(i)+e_g(i) \tag{19}$$

where $e_g(i)$ is the residual Gaussian noise after pass-band filtering.

Since the pass-band and MMSE filtering are linear operations and $n(t)$ is a zero-mean Gaussian variable, therefore $e_g(i)$ is a linear combination of $n(t)$ and it is also a approximately zero-mean Gaussian variable. So, the BER can be written as:

$$Pe(v,d,2\sigma^2)=Q\left(\sqrt{\frac{\tilde{\mathbf{w}}^H\bar{z}_k^{\{v,d\}}(i)}{\sigma_g^2}}\right) \tag{20}$$

where σ_g^2 is the variance of $e_g(i)$ and is given by:

$$\sigma_g^2=\sigma^2\sum_j\left|h_{bw}(j)\right|^2 \tag{21}$$

where $2\sigma^2$ is the PSD (Power Spectral Density) of the AWGN while $h_{bw}(j)$ is:

$$h_{bw}(j)\equiv h_b(j)\otimes\tilde{w}(j) \tag{22}$$

Eq.(20) expresses the BER for a DS-SS system utilizing an ideal MMSE receiver and subject to multipath fading for a given transmission rate, a given distance between transmitter and receiver and a given power level of the background noise. FEC techniques after the MMSE receiver have not been accounted such as in [4]. The expression (20) gives a lower bound for real MMSE performances (see examples shown in Figure 1).

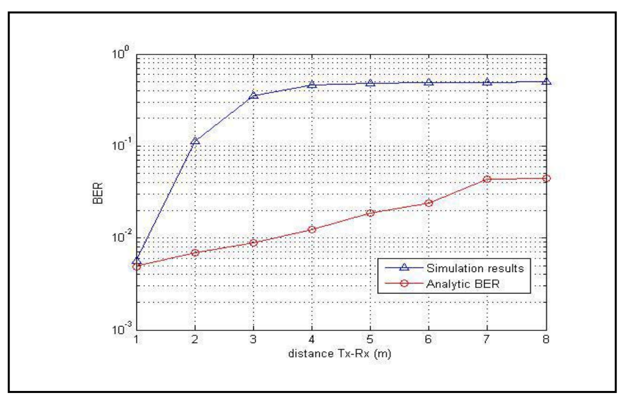

Figure 1. BER analytic and simulated vs. distance for NLOS scenario, rate 110 Mbps, noise variance 10^{-2}.

B. PER Regression Analysis

The PER analysis has been carried out by using a polynomial regression technique, by the Matlab tool, on simulation results. The general expression for the PER can be written by a $n^{\text{-th}}$ order polynomial regression:

$$PER(d)=\begin{cases}1 & d>d_{\max}\\ [a_0\quad a_1\quad \ldots\quad a_n]\cdot\begin{bmatrix}1\\ d\\ \vdots\\ d^n\end{bmatrix}=\langle a\rangle\cdot\langle d\rangle^T & d_{\min}<d\le d_{\max}\\ 0 & d\le d_{\min}\end{cases} \quad (23)$$

where the polynomial order, coefficients vector $\langle a\rangle$ and the distances d_{min} and d_{max} are related to the considered scenarios (LOS or NLOS), to the data rates and to the background noise level (d_{max} must be intended boundless where it is not specified). Specifically, from a regression analysis for the rate 110 Mbps in the *LOS* scenario with variance noise 10^{-2} the following values were obtained:

$$\langle a\rangle=[-0.2223\quad 0.5057\quad -0.2083\quad 0.06385\quad -0.008877\quad 0.000432] \quad (24)$$
$$d_{\min}=1m,\quad d_{\max}=8m,$$

which, substituted in (23),lead to:

$$\begin{cases}PER(d)=1 & d>8\\ PER(d)=0.000432\cdot d^5-0.008877\cdot d^4+0.06385\cdot d^3+ & \\ \qquad -0.2083\cdot d^2-0.5057\cdot d-0.2223 & 1<d\le 8\\ PER(d)=0 & d\le 1\end{cases} \quad (25)$$

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 (typically <0.5) indicates a better fit than a larger value: therefore the trend to zero of the norm means an almost perfect approximation [9].

In Figure 2 it can be seen how (25) approximates very well the PER above all for sufficiently large values (this is confirmed by norm which assumes quite a small value at 0.12765).

V. PERFORMANCE EVALUATION

Performance of the DS-SS physical layer has been evaluated through various simulation campaign. Scenario and results of simulations will be presented in the following.

A. Simulation Scenario

The transmitted bits are estimated using a MMSE receiver as described in [4]. This receiver uses an adaptive algorithm called *Normalised Least Minimum Square* (NLMS) to update weights vector *W*. The recursive formula to calculate the weights vector is specified in the following:

$$W(i)=W(i-1)+\mu_m\, e(i)\frac{u^*(i)}{\varepsilon+u^H(i)u(i)} \quad (26)$$

In (26), 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. For more details refer to [4].

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. Regarding the PER, in our simulations we used fixed packets size of 128 bytes. Further simulation parameters are listed in Table I.

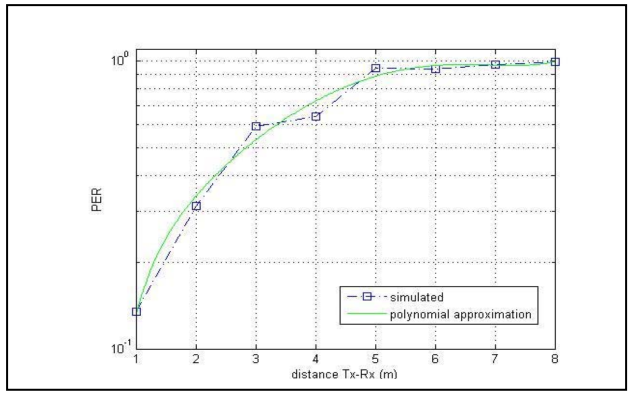

Figure 2. Simulation results and their polynomial approximation for 110Mbps-NLOS scenario, noise variance 10^{-2}.

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
transmission peak power (dB)	-10	-10

B. Simulation Results

In Figure 3, BER vs. distance curves for 110Mbps and 220Mbps in LOS and NLOS scenarios in the presence of low (variance 10^{-5}) and high (variance 10^{-2}) background white Gaussian noise are plotted.

If we observe the curves, we note that the 110Mbps data rate rejects *inter-symbol interference* (ISI) better than the higher rate because in longer ternary spread sequence there are more zero-valued windows, respect to a shorter sequence, in the autocorrelation function, so interference due to multipaths that are within these windows can be eliminated. In particular, ISI mitigation is greater in the LOS scenario where the presence of a stronger direct component makes bits estimation more simple. Besides, background noise 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).

Figure 4 show the PER trends for the rates 110Mbps and 220Mbps scenario LOS and NLOS for two distinct noise thresholds (variance 10^{-2} and variance 10^{-5}): increase of noise and distance make the estimation of the bits more complicated, therefore there is a general worsening of the PER with noise increase. If the BER and the PER are compared, it can be seen, instead, how the latter has a worse trend because of the distributed nature of the errors on the bits: in fact, the PER, as demonstrated in [8], is a function of the distribution of the BER and of the packet size, therefore if the packet size is made to go towards one (degenerate case) the PER converges towards the BER, vice versa at increase in the packet size the Packet Error Rate tends to one (Figure 5).

VI. CONCLUSION

In this paper a more realistic UWB channel model is considered. An explicit multi-path fading distance dependence is considered. The physical layer of the standard DS-SS 802.15.3a has been implemented. Simulation results show how the performance, in terms of BER and PER, of the UWB channel, for high data rate in the case of lower signal-to-noise ratio, degrades for increasing distance (1-10m). 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 (noise variance < 10^{-3}).

REFERENCES

[1] Reed Fisher, Ryuji Kohno, Michael Mc Laughlin, Matt Welborn, “DS-UWB Physical Layer Submission to 802.15 Task Group 3a”, *MERGED PROPOSAL* #2 802.15.3a Physical layer.

[2] Molisch, J. Foerster, and M. Pendergrass, “Channel Models for Ultrawideband Personal Area Networks”, *IEEE Wireless Communications Magazine*, Dec. 2003.

[3] S. Ghassemzadeh, R. Jana, C. Rice, W. Turin, and V. Tarokh, “Measurement and modeling of an ultra-wide bandwidth indoor channel,” *IEEETransaction on Commun.*, pp. 1786–1796, 2004.

[4] Qinghua Li, Member, IEEE, and Leslie A. Rusch, Senior Member, IEEE, "Multiuser Detection for DS-CDMA UWB in the Home Environment", *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS*, VOL. 20, NO. 9, DECEMBER 2002.

[5] Saleh and R. A. Valenzuela, “A statistical model for indoor multipath propagation,” *IEEE J. Selected Areas Comm.*, vol. 5, pp. 138–137, Feb. 1987.

[6] A. Batra et al., “Multi-band OFDM physical layer proposal,” Document IEEE P802.15-03/268r3, march 2004.

[7] A. F. Molisch, et al., “Mitsubishi Electric’s Time-Hopping Impulse Radio standards proposal”, *document IEEE P802.15-03112*, may 2003.

[8] Ramin Khalili, Kavé Salamatian, “Evaluation of Packet Error Rate in Wireless Networks”, MSWIM - Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems,Venice, Italy - October, 2004.

[9] M.A. Stevens, R.B. D'Agostino, “Goodness of Fit Techniques”, Marcel Dekker, New York 1986.

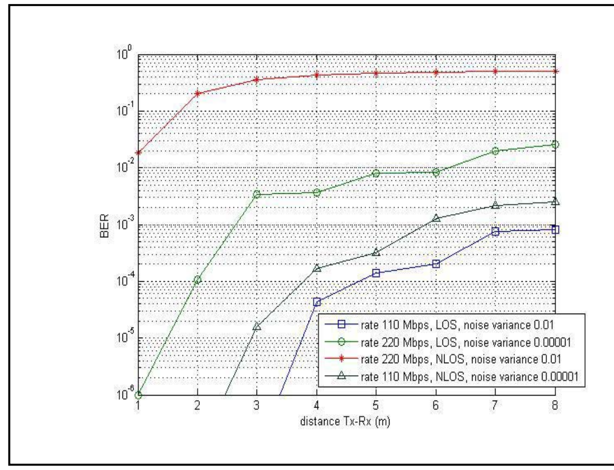

Figure 3. BER vs. distance for LOS-NLOS scenario, noise variance 10^{-5} and 10^{-2}.

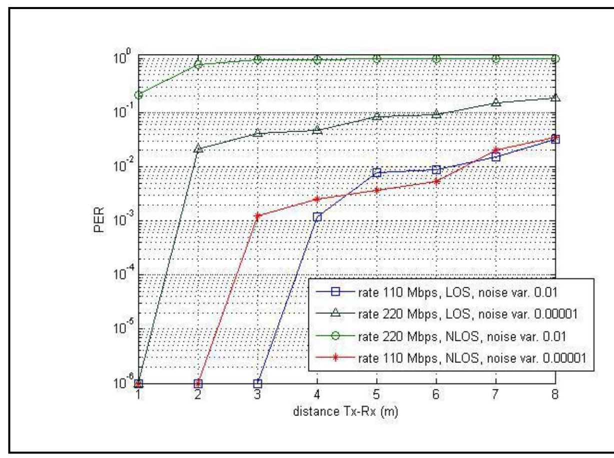

Figure 4. PER course for LOS-NLOS scenarios, noise variance of 10^{-5} and 10^{-2}.

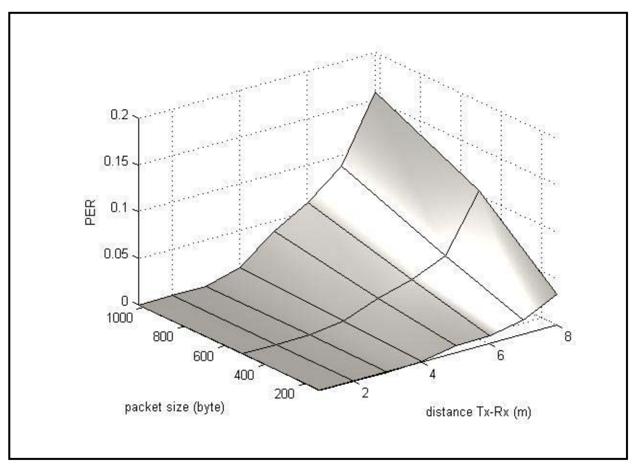

Figure 5. PER vs. packet length and distance for rate 110Mbps in LOS scenario with variance noise 10^{-2}.