Modeling and Simulation of a Physical Layer for WSNs based on Binary Sequences

Stevan Berber, Yuan Yuan, and Bongsue Suh,

***Abstract*—**The theoretical model and results of simulation of a communication system representing the physical layer of wireless sensor networks are presented in this paper. The spreading sequences used are generated according to the standard specification for low rate wireless sensor networks. Due to the sever influence of fading on signal transmission in this kind of networks, the chip interleaving technique is investigated as the mean for fading mitigation in the channel. The theoretical derivations for bit error rate (BER) in closed form are derived for the case when noise, noise and fading and interleavers are present in the communication system. It is proved that the BER can be significantly improved in fading channel using the interleaver/deinterleaver technique. The theoretical analysis, derivations of the closed form BER expressions and simulations are based on discrete time domain representation of all signals in the system. These discrete time domain system representations of signals allow direct implementation of the developed system in digital technology which was one of the aims of this research. Following the theoretical model, simulators were developed and the results of simulation confirmed the derived theoretical expressions.

***Keywords*—**Wireless sensor networks, physical layer design, fading channel, probability of error, interleavers.

I. Introduction

The limited power of sensor nodes requires specific design of sensor nodes in wireless sensor networks. The reduction in the nodes' power can be achieved by eliminating influence of fading inside the communication channel, because the power of nodes needs to increase in the presence of fading in order to communicate at the same distance [1]. It has been already shown that the fading in direct sequence spread spectrum systems [1] can be reduced by applying interleaving techniques [2, 3, 4, 5, 7, 8]. Wireless networks based on IEEE 802.15.4 Standard [9] are novel wireless technology. In these networks the specific binary sequences are proposed for message bits and symbols spreading. Thus, the interleaving techniques can be considered as the mean for fading mitigation. The physical layer design is a problem of particular interests in wireless sensor networks development, which was the subject of the latest research efforts. The designs of modulator and demodulator blocks for this network is presented in [10]. This design included theoretical modeling, simulation and the system's design in FPGA technology and its implementation in CMOS technology. Also, the transceiver design and development are presented in [9].

This paper presents the theoretical model and the related simulator of the communication system representing physical layer of WSNs in discrete time domain. Using this representation, it is easy to directly implement the system's blocks in DSP or FPGA technology. This is the first contribution of this paper, because, in the existing theory, these signals and their processing are represented in continuous time domain. Furthermore, this paper presents the theoretical analysis of the whole system and derivations of BER expressions for standard binary spreading sequence for both AWG noise and fading presence in the channel, which makes the second contribution of this paper. Based on the developed theoretical model of the system, a system simulator is developed which confirmed the theoretical findings. In particular, the theoretical BER curves were confirmed by simulation which makes the third contribution of this paper.

The paper is composed of 5 Sections. Section 2 presents the scheme of communication system that corresponds to the physical layer of WSNs. The system is analyzed assuming that the standard binary sequences are used for spreading. The procedure of generating spreading sequences is explained and their basic statistical properties presented. Also, the mathematical model, presenting signal processing procedures inside the system, is presented. In particular, the transmitter, the noise generator and the receiver are analyzed. In Section 3 the theoretical model of the system is presented and its mathematical model is developed in the case when AWGN and Rayleigh fading are present in the channel. The theoretical expressions for the probability of error and related theoretical BER curves are confirmed by simulation. Section 4 presents the results of system's analysis and the derivation of BER expressions when the interleaver and deinterleaver blocks are used to mitigate fading influence in the channel. These expressions are also confirmed by the system simulation. The system is simulated in MATLAB and the simulated BER curves are obtained and compared with theoretically expected curves. The simulation confirmed the theoretical findings. Section 5 contains conclusions.

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II. Theoretical Model Of the system

A. *Standard binary sequences*

Spreading binary sequences, used in this paper, are presented in Table 1. For each data symbol, which consists of four possible message bits, a unique sequence of chips is assigned.

Table 1 Standard spreading sequences

Data symbol, decimal	Data symbol, Binary. b_0,b_1,b_2,b_3	Chip values $(c_0, c_1, \ldots, c_{32})$
0	0000	11011001110000110101001000101110
1	1000	11101101100111000011010100100010
2	0100	00101110110110011100001101010010
3	1100	00100010111011011001110000110101
4	0010	01010010001011101101100111000011
5	1010	00110101001000101110110110011100
6	0110	11000011010100100010111011011001
7	1110	10011100001101010010001011101101
8	0001	10001100100101100000011101111011
9	1001	10111000110010010110000001110111
10	0101	01111011100011001001011000000111
11	1101	01110111101110001100100101100000
12	0011	00000111011110111000110010010110
13	1011	01100000011101111011100011001001
14	0111	10010110000001110111101110001100
15	1111	11001001011000000111011110111000

The spreading sequences are orthogonal to each other. Their autocorrelation function $R(\tau)$ has a pronounced peak for the zero chip delay, and small values for any other delay. For example, this function, for the 5^{th} and the 15^{th} sequence is presented in Fig. 1. The correlation was performed for several repetitions of the sequence. That is the reason the autocorrelation is represented by a periodic function. The peaks are, as it is expected, 32 chips apart.

The cross-correlation functions $C(\tau)$ of these two sequences have small values for any delay between them, as can be seen in Fig. 2. The values are roughly, between +0.2 and -0.2.

Therefore, due to their correlation properties, these sequences can be used in physical layer to spread message bits. However, the synchronization of the demodulated sequences and the locally generated sequence inside the receiver, need to be achieved [12, 13], which is separate problem that will not be mentioned in this paper.

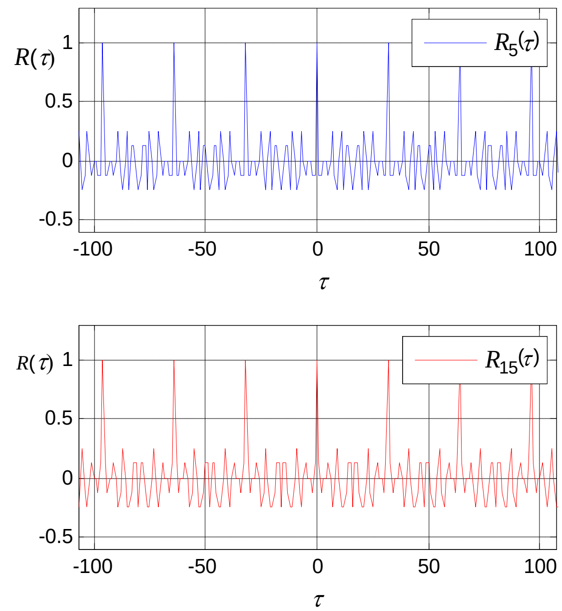

Fig. 1 Autocorrelation functions

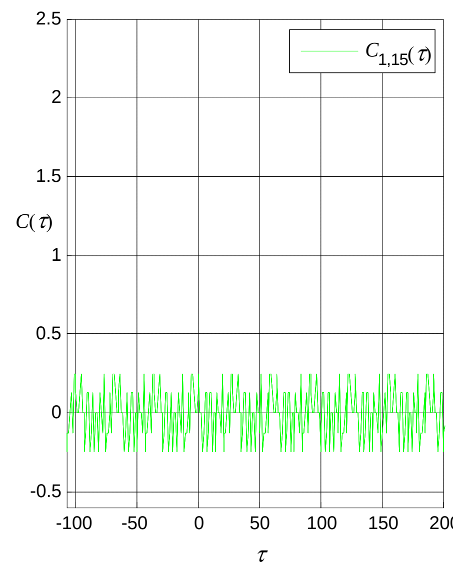

Fig. 2 Cross-correlation function $C_{5,15}(\tau)$

B. *Structure of the communication system*

One of the proposed modulation schemes in wireless sensor networks is quadrature phase shit keying (QPSK) modulation. In this paper, this modulation scheme will be analyzed. Fig. 3 presents a simplified structure of a system that uses offset QPSK (OQPSK) modulation and binary spreading sequences [9]. The system will be analyzed for two cases: first case is when the Additive White Gaussian Noise (AWGN) and fading are present in the channel, and second case is when the AWGN and fading are present in the channel of the system which have interleaver (IL) and deinterleaver (DI) blocks included into the structure of system, as can be seen in Fig. 3.

C. Transmitter operation

The source of information generates message bits $b_{j1}(k)$, which are spread by the binary spreading sequence $c_{in}(k)$. The resultant sequence is a chip sequence $m(k) = b_{j1}(k)c_{i1}(k)$. This sequence is split into in-phase and quadrature sequences according to the following procedure: The even-indexed chip sequence $m_I(k)$ goes to the in-phase branch an modulates the in-phase carrier . The odd-indexed chip sequence $m_Q(k)$ are delayed for a half of the chip duration, to achieve offset QPSK modulation, and goes into quadrature branch and modulates the quadrature carrier . The modulation procedure follows the specification as required by the Standard for wireless sensor networks [9].

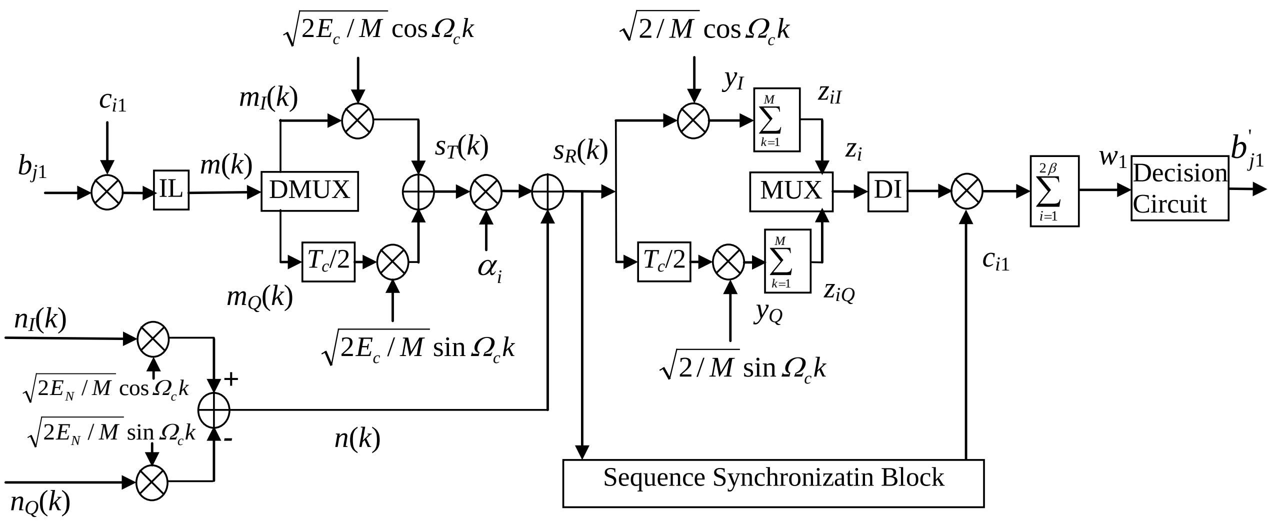

Fig. 3 Structure of communication System

The splitting of the spreading sequences is performed in the demultiplexer block (DMUX). The output of the modulator is the OQPSK signal expressed as

$$s(k) = m_I(k)\sqrt{2E_c/M}\cdot\cos\Omega_c k + m_Q(k)\sqrt{2E_c/M}\cdot\sin\Omega_c k \quad (1)$$

where E_c the energy per chip, M is the number of interpolated samples contained in one chip interval, $m_I(k)$ and $m_Q(k)$ are in-phase and quadrature chip sequences respectively, and Ω_c is the normalized frequency of the carrier.

For the energy of a chip equal E_c the energy of a bit is $E_b = 2\beta E_c$. It is important to note that the whole system, including the transmitter, receiver and the channel, is analyzed for discrete time domain signal representation. Thus, during system simulation, each chip and related noise sample are generated once for each chip interval. Then these samples are repeated (interpolated) M times inside the chip interval to allow the discrete time modulation of the carrier.

D. Discrete-time channel characterization

In the theoretical analysis, it is assumed that a discrete time noise sample is generated in each chip interval and the repeated M times to be added to M identical spreading sequences samples representing that chip. Each noise sample is one realization of a Gaussian random variable with zero mean and variance σ^2. Thus, the average noise energy in a chip is $E_N = M\sigma^2$. The noise variance can be expressed as $\sigma^2=BN_0$, where the noise bandwidth is $B=1/2T_c=1/2M$. Based on these relations, the energy of a noise in one chip interval can be simplified and expressed as the noise power spectral density, i.e., $E_N = N_0/2$.

The generator of the pass-band noise samples is presented in Fig. 3. It is constructed following this analytical expression

$$n(k) = n_I(k)\sqrt{2E_N/M}\cdot\cos\Omega_c k - n_Q(k)\sqrt{2E_N/M}\cdot\sin\Omega_c k\,. \quad (2)$$

In the noise generator scheme, the noise components $n_I(k)$ and $n_Q(k)$ are in-phase and quadrature noise samples of zero mean and unit variance. Due to the discrete time representation of the noise, the energy of noise inside a chip interval is E_N for M interpolated noise samples inside the chip interval. Thus, the noise generated according to expression (2) and Fig. 3 is the band-pass noise which is in the frequency bandwidth that corresponds to the bandwidth of the generated OQPSK signal.

It is assumed also that the fading is present in the channel. This fading is represented by a multiplier in Fig. 3. Therefore, in theoretical analysis and simulation, the generated transmitted signal needs to be multiplied by the fading coefficient α. This fading coefficient is a realization of a random variable that has Rayleigh distribution. The density function this random variable α is expressed as

$$f_\alpha(\alpha) = \frac{2\alpha}{b}e^{-\alpha^2/b}, \quad (3)$$

having the mean value $\eta_\alpha = (\pi b/4)^{1/2}$ and the variance value $\sigma_\alpha^2 = b(4-\pi)/4$.

E. Receiver operation

Having in mind that the channel is characterized by the AWGN and Rayleigh fading, the received signal $s_R(k)$ can be expressed in the following form [15]

$$s_R(k) = \alpha e^{-j\varphi} s(k) + n(k) , \qquad (4)$$

where α is the fading coefficient and φ is the phase shift represented by a uniformly distributed random variable inside the interval $-\pi$ to $+\pi$. It is assumed that the fading is slow, thus, the fading coefficient keeps its value to be constant in a bit interval. Furthermore, it is assumed that the phase shift φ is eliminated by the receiver's phase locked loop.

The receiver uses a coherent demodulator to demodulate the received signal $s_R(k)$. The demodulator consists of a multiplier and an adder. Only signal processing in the in-phase branch I will be presented because the processing in quadrature branch Q is identical to I branch. The output signal of the multiplier in I branch is

$$y_I(k) = [\alpha s(k) + n(k)]\sqrt{2E_c / M} \cdot \cos \Omega_c k \qquad (5)$$

Then, the M samples belonging to one chip are added to each other, which corresponds to integration in continuous time systems.

Suppose the first bit generated by the source is +1. For this case the output of the transmitter spreader is non-inverted spreading sequence $c_{i1}(k)$, i.e., $m(k)=c_{i1}(k)$. For this case, the output of the adder in I branch, the random sample z_i (one realization of a discrete time stochastic process Z_i) is obtained, expressed as

$$z_{iI} = \sum_{k=1}^{M} y_I(k) = \alpha\sqrt{E_c} \cdot c_{i1} + \sqrt{E_N} \cdot n_{iI} \qquad (6)$$

for even indices $i = 2, 4,\ldots, \beta$, and in Q branch as

$$z_{iQ} = \sum_{k=1}^{M} y_Q(k) = \alpha\sqrt{E_c} \cdot c_{i1} + \sqrt{E_N} \cdot n_{iQ} \qquad (7)$$

for odd indices $i = 1, 3,\ldots,\beta -1$. The multiplexer (MUX) is used to combine in-phase and quadrature sequences back into a 2β-chip sequence z_i that represents the soft values of all received chips for the first message bit and can be expressed as

$$z_i = \alpha\sqrt{E_c} \cdot c_{i1} + \sqrt{E_N} \cdot n_i \qquad (8)$$

where $i = 1, 2, 3, 4,\ldots, 2\beta$ and n_i are samples of the in-phase and quadrature baseband noise having zero mean and unit variance. The addition was performed in each chip interval and the obtained values z_i represent chip samples, i.e., their soft values. Each sample is composed of two terms: The first term belongs to the signal sent affected by the fading coefficient and the second term belongs to the noise that is added to the signal in the channel.

In the sequence correlator block, the locally generated reference binary chip sequence (c_{i1}, $i = 1, 2, 3, 4, \ldots, 2\beta$), which is obtained from the sequences synchronization block, is multiplied chip-by-chip with the incoming z_i sequence. The obtained products are accumulated and the resulting sum representing soft value of the first bit sent can be expressed as

$$w_1 = \sum_{i=1}^{2\beta} z_i c_{i1} = \alpha\sqrt{E_c}\sum_{i=1}^{2\beta} c_{i1}^2 + \sqrt{E_N}\sum_{i=1}^{2\beta} n_i \cdot c_{i1} = A + B \qquad (9)$$

The first term in this sample represents the signal part affected by fading and the second one is the noise part. This value is a random sample of a random variable W_1 defined for the first bit received.

III. Communication systems with Noise and fading

A. Closed form BER derivation for binary spreading

Due to the central limit theorem (CLT), the random variable W_1 in (6) can be approximated by the Gaussian random variable. In addition, if powers of all chips are equal, the mean of W_1 is

$$\eta_{w_1} = E\{w_1\} = E\{\sum_{i=1}^{2\beta} z_i c_{i1}\} = \sqrt{E_c} E\{\alpha\}\sum_{i=1}^{2\beta} E\{c_{i1}^2\} \qquad (10)$$

The variance of W_1 can be expressed in general form as

$$\sigma_{w1}^2 = E\{w_1^2\} - \eta_{w1}^2 = E\{(A+B)^2\} - \eta_{w1}^2 \qquad (11)$$

where, for equal chip powers, we may calculate the following expectations

$$E\{A^2\} = \left\{\left[\alpha\sqrt{E_c}\sum_{i=1}^{2\beta} c_{i1}^2\right]^2\right\} = 2\beta E\{\alpha^2\} E_c [E\{c_{i1}^4\} + (2\beta-1)E\{c_{i1}^2\}E\{c_{j1}^2\}] \qquad (12)$$

and

$$E\{B^2\} = E\left\{\left[\sqrt{E_N}\sum_{i=1}^{2\beta} n_i \cdot c_{i1}\right]^2\right\} = 2\beta E_N E\{c_{i1}^2\} \qquad (13)$$

For equal average powers of all chips, i.e., for

$$E\{c_{i1}^2\} = E\{c_{j1}^2\} = P_c \tag{14}$$

Using (11), (12), (13) and (14), the variance of W_1 can be expressed in the following form

$$\sigma_{w1}^2 = 2\beta E_c[E\{\alpha^2\}E\{c_{i1}^4\} - E^2\{\alpha\}P_c] + 2\beta(2\beta-1)E_c P_c^2[E\{\alpha^2\} - E^2\{\alpha\}] + 2\beta E_N P_c \tag{15}$$

Equation (15) can be further simplified taking into account binary chip spreading sequences (having the unit powers, P_c = 1) to the following form

$$\sigma_{w1}^2 = (2\beta)^2 E_c \sigma_\alpha^2 + 2\beta E_N \tag{16}$$

From equations (10) and (11) the probability of bit error can be derived as

$$p_{be} = \frac{1}{2} erfc\left[\frac{2\sigma_{w1}^2}{\eta_{w1}^2}\right]^{-1/2} = \frac{1}{2} erfc\left[\frac{2\sigma_\alpha^2}{\eta_\alpha^2} + \frac{2E_N}{2\beta\eta_\alpha^2 E_c}\right]^{-1/2} \tag{17}$$

Here, the energy of a bit is the sum of energies of all chips in a bit interval, i.e., $E_b = 2\beta E_c$. It is assumed that $E\{\alpha^2\}=b=1$. Having this assumption in mind the probability of error can be further simplified and expressed in the closed form as

$$p_{be} = \frac{1}{2} erfc\left[\frac{2(4-\pi)}{\pi} + \frac{4}{\pi}\left(\frac{E_b}{N_0}\right)^{-1}\right]^{-1/2} \tag{18}$$

where the energy of a bit is represented as $E_b = 2\beta E_c$.

B. System simulation and comparison

In the system simulation the power of the noise is controlled by defining the value of the noise energy E_N. The whole system is simulated in MATLAB. The theoretical BER (blue) in presence of fading for binary chip spreading and transmission expressed by (12) is compared with the BER obtained by simulation (magenta curve). Alongside with these curves the curve representing the probability of the system error in the presence of AWGN only is plotted in black colour. It is important to estimate BER accurately for each value of signal to noise ratio. To achieve the desired accuracy in BER estimation, the method of measurements with advanced specified accuracy is used, which is published in reference [14].

Due to the influence of fading the BER values in fading channel are significantly greater (blue curve) than in the case when AWGN only is present in the channel (black curve). For example, when the signal to noise ratio is SNR = 10 dB, the theoretical difference in BER is from $2.5\text{x}10^{-2}$ to $4\text{x}10^{-6}$, i.e., nearly for 4 order of magnitude. This degradation in BER due to fading substantially increases when signal to noise ratio increases.

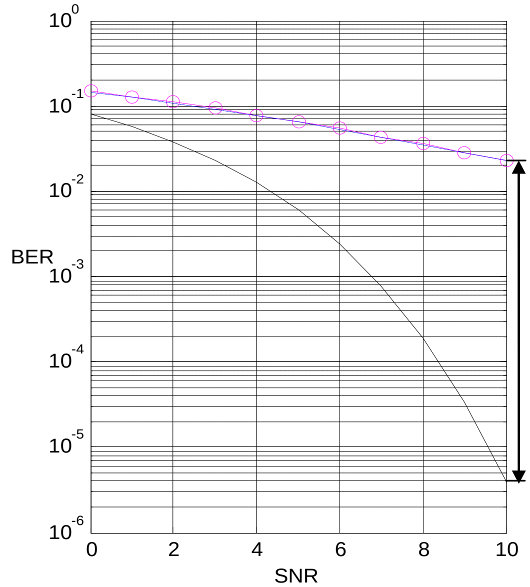

Fig. 4 BER curves for binary spreading sequences in the presence of AWGN and fading: theoretical (blue) and simulation for fading (magenta) and theoretical curve for AWGN only (black).

For the sake of comparison, the BER for standard binary sequences [9] are compared by the BER for chaotic sequences of the same average powers [16], as presented in Fig. 5.

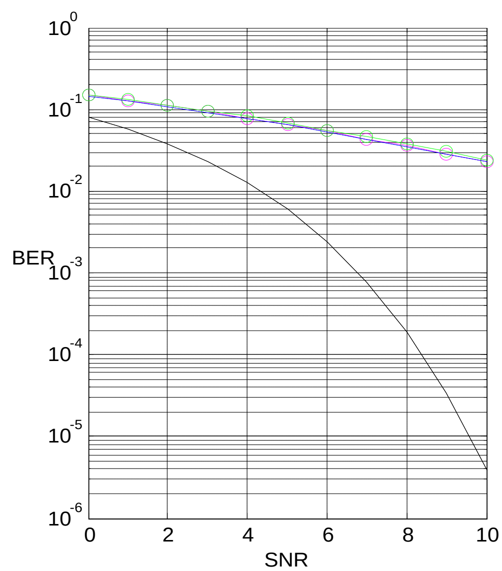

Fig. 5 BER curves for binary and chaotic spreading sequences in the presence of AWGN and fading: theoretical (blue) and simulation for binary sequence (magenta), chaotic sequence (green) and theoretical curve for AWGN only (black).

The BER in the case when a chaotic sequence is used is slightly worse than in the case when a binary orthogonal chip sequence defined by the Standard for wireless sensor networks is used. For both binary and chaotic sequences the BER in presence of fading is significantly worse than in the case when only AWGN is present in the channel (black curve in Fig. 5). This degradation in BER due to fading can be eliminated by using one of the diversity methods. In this paper, in order to eliminate this degradation of BER in fading, a method of fading mitigation using interleavers is investigated and presented in the next section.

IV. COMMUNICATION SYSTEM WITH INTERLEAVERS

Various diversity techniques can be applied to mitigate the fading in wireless communication systems, like space, phase, frequency and time diversity [4, 6, 7]. Extensive research was conducted related to the interleaver technique application to mitigate fading influence on signal transmission [2-5,7, 8]. The block interleaving technique was applied to mitigate Rayleigh fading in direct sequences spread spectrum systems [4]. In this section, this technique will be theoretically analyzed and then the system will be simulated to confirm theoretical findings.

It will be assumed that the interleaver (IL) and deinterleaver (DI) blocks are implemented into the system structure, as presented in Figure 3. The interleaver can have various size. In this analysis this block size will be defined by the spreading factor. Precisely speaking it will have 2βx2β block size, where 2β is the spreading factor and specifies the number of chips in a bit interval. Therefore, the interleaver will operate as follows. The first 2β chips of the first bit will be memorized in the first raw of a 2βx2β matrix, the second bit in the second raw until the last bit is memorized in the last raw corresponding to the spreading factor 2β. Then the chips are taken out column-wise to modulate the carrier. Thus, in the channel, the chips belonging to the same bit are separated in time domain for 2β chips.

The deinterleaver processing, which takes place at the receiver side, will be performed in inverse order. Namely, the samples of chips will be memorized column-wise and taken out raw-wise. In that case the chips belonging to a particular bit will be in the order as they were at the transmitter side. However, due to the chip interleaving each chip inside a particular bit will be affected with different, statistically independent, Rayleigh coefficient. A chip sample at the receiver, obtained after demodulation, can be expressed in the following form

$$z_i = \alpha_i \sqrt{E_c} \cdot c_{i1} + \sqrt{E_N} \cdot n_i \tag{19}$$

This value can be treated as a realization of a random variable Z_i at the time instant i, which belongs to the discrete time stochastic process. One stream of chips can be understood as one realization of this process. Realizations of this random variable are the soft values of the chips received.

If assumed that the first transmitted bit values is equal to +1, the output of the sequence correlator is a sum of 2β terms obtained by multiplying soft chip values by the locally generated synchronous sequence. The obtained sum is represented as one realization of a new random variable W_1, calculated at the end of a bit interval and expressed as

$$w_1 = \sum_{i=1}^{2\beta} z_i c_{i1} = \sqrt{E_c} \sum_{i=1}^{2\beta} \alpha_i c_{i1}^2 + \sqrt{E_N} \sum_{i=1}^{2\beta} n_i \cdot c_{i1} = A + B \tag{20}$$

The random variable W_1 has the mean and variance expressed as

$$\eta_{w_1} = E\{w_1\} = \sqrt{E_c} \sum_{i=1}^{2\beta} E\{\alpha_i\} E\{c_{i1}^2\} \tag{21}$$

and

$$\sigma_{w1}^2 = E_c [\sum_{i=1}^{2\beta} E\{\alpha_i^2\} E\{c_{i1}^4\} - \sum_{i=1}^{2\beta} E^2\{\alpha_i\} E\{c_{i1}^2\}] + 2\beta E_N E\{c_{i1}^2\} \tag{22}$$

In the case when the spreading sequence is in binary form, the average powers are one, and these values can be calculated as

$$\eta_{w_1} = E\{w_1\} = 2\beta \sqrt{E_c} \eta_{\alpha_i} \tag{23}$$

and

$$\sigma_{w1}^2 = E_c [\sum_{i=1}^{2\beta} E\{\alpha_i^2\} - \sum_{i=1}^{2\beta} E^2\{\alpha_i\}] + 2\beta E_N = E_c \sum_{i=1}^{2\beta} \sigma_\alpha^2 + 2\beta E_N = 2\beta E_c \sigma_\alpha^2 + 2\beta E_N \tag{24}$$

If the mean $\eta_\alpha = (\pi b/4)^{1/2}$ and variance $\sigma^2_\alpha = b(4-\pi)/4$, for Rayleigh variable, are inserted into (23) and (24), the mean and the variance of a bit soft value can be simplified to

$$\eta_{w_1} = 2\beta \sqrt{\pi/4} \sqrt{E_c} \tag{25}$$

and

$$\sigma_{w1}^2 = 2\beta E_c [\frac{4-\pi}{4} + \frac{N_0}{2E_c}] \cdot \tag{26}$$

Random variable W_1, presented by (20), can be understood as a function of 4β random variables, where β is a relatively large number. Due to the central limit (CL) theorem, this random variable has Gaussian distribution defined by the mean value (25) and variance (26). Therefore, for the binary message bits consisting of chaotic spreading sequences with unit average power, the probability of error can be expressed as

$$p_{be} = \frac{1}{2} erfc\left[\frac{2\sigma_{w1}^2}{\eta_{w1}^2}\right]^{-1/2} = \frac{1}{2} erfc\left[\frac{(4-\pi)}{\beta\pi} + \frac{4}{\pi}\left(\frac{E_b}{N_0}\right)^{-1}\right]^{-1/2} . \quad (27)$$

Eq. (27) is presented in Fig. 6 (magenta) alongside with the theoretical and simulated fading curves (green and blue), and the curve representing AWGN channel (black). The theoretically expected gain, due to the use of interleaver/ deinterleaver structure, is significant and increases when SNR increases. For example, if SNR = 10 dB, the theoretical gain in BER rate due to the application of the interleaver is decreased from $2.2x10^{-2}$ to $1x10^{-4}$. The improvement in BER value increases when SNR value increases. It can be seen also that, when BER is $2.2x10^{-2}$, the achievable saving in SNR is about 6 dB, as can be seen in Fig. 6. Therefore, by using interleavers, the system can save the energy, resulting in that the implementation of interleavers contributes to the reduction of power consumption of the devices. It is obvious that this saving increases when the required BER decreases.

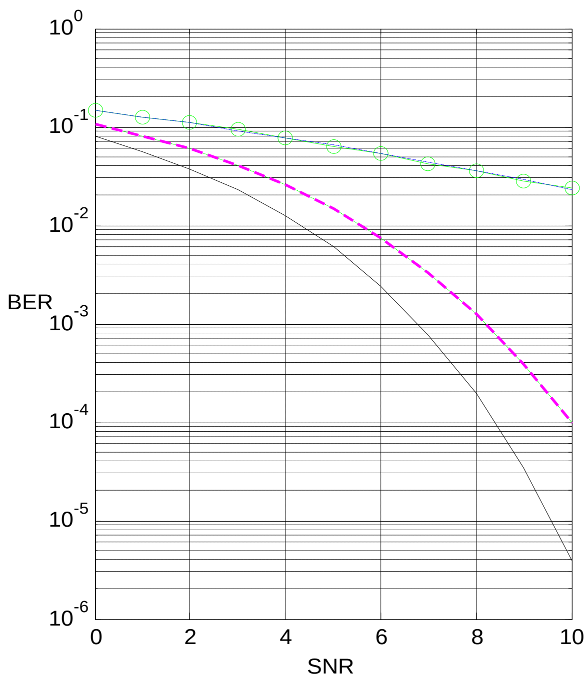

Fig. 6 BER curves in Rayleigh fading with inteleavers in presence of AWGN: theoretical (blue) for fading, theoretical (dashed magenta) for fading with interleavers, theoretical for noise only (black), simulated fading (green).

The system presented in Fig. 3, which incorporates the interleaver at the transmitter side and the deinterleaver at the receiver side, is simulated in MATLAB. The BER curves for interleaver/deinterleaver case and the case when the interleaver/deinteleaver blocks are not included are presented in Fig. 7. The theoretical BER curve for interleaver (green curve), obtained according to the theoretical expression of Eq. (27), is plotted just above the curve for BER in AWGN channel (black curve), but bellow the curve (blue) that is obtained in the system without interleaver/ deinterleaver structure.

The question how accurately the theoretical expression of Eq. (27) expresses the probability of error in the system. The comparison of the theoretical curve obtained from Eq. (27) (green) and the curve obtained by simulation (red stars) in Fig. 7, shows that there is overlapping of the graphs. Therefore, the theoretical expression of Eq. (27) is confirmed by the simulation of the system and the difference between the two curves is negligible.

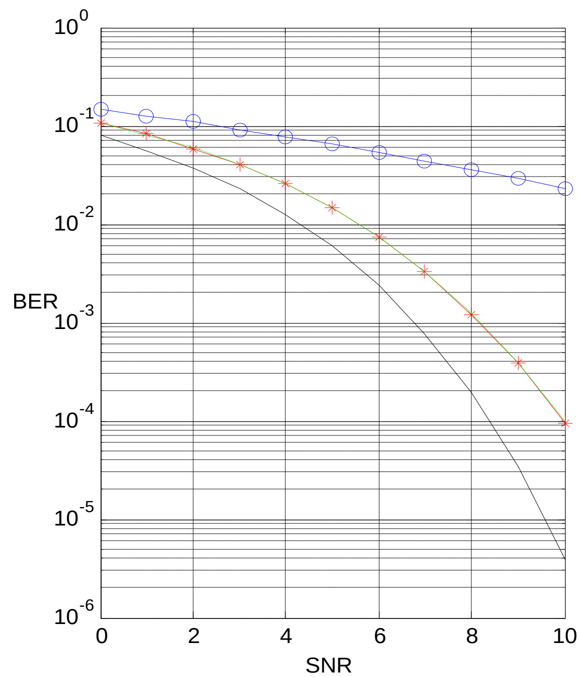

Fig. 7 BER curves for receiver with inteleaver/deinterleaver structure in presence of AWGN and fading: theoretical and simulated for fading (blue), theoretical with interleavers (green) followed by the simulation (red stars) for fading with interleavers and theoretical curve for noise only (black).

Therefore, by using interleavers, the system decorrelates the fading coefficients. In this way the influence of fading is randomized and it becomes similar to the influence of the AWGN. The shape of the curves under influence of fading follows in accordance with those obtained for AWGN channel. However the BER curves for fading are above BER curves for AWGN, which means, the fading additionally degrades signal transmission in respect to degradation due to AWGN. This is the reason the fading BER curve comes closer to the curve that is obtained for the case when only AWGN noise is present in the communication channel.

From theoretical expression of Eq. (27), it is obvious that the additional improvements in BER could be achieved if the spreading factor 2β increases. Therefore, it can be concluded that the block interleaving technique is an efficient procedure to mitigate fading in wireless sensor networks.

V. CONCLUSION

This paper presents the procedure of deriving probability of error expressions in closed form for the communication system representing the physical layer of wireless sensor networks in which standard binary sequences are used for spreading. The theoretical expressions are derived for two channel conditions of, channel with AWGN only and channels with both AWGN and fading. For both cases, the system is investigated with and without interleavers. All cases of the system are simulated in MATLAB and the theoretical probability of error expressions are confirmed to be in accordance with those from simulation results. In addition, theoretical analysis and simulations confirmed that a significant improvement in BER can be achieved by using interleaver and deinterleaver blocks in the system. Theoretical analysis and simulations conducted in this paper used signals represented in discrete time domain, which allows direct implementation of the system in digital technology.

REFERENCES

[1] Lee, S. J. and Miller, L. E., CDMA Systems Engineering Handbook, 1st edition, Artech House Publishers, Boston and London, 1998.

[2] X. Gui, Chip-Interleaving DS SS System over Rician Multipath Fading Channel, Wireless Communication and Mobile Computing, John Wiley & Sons, on-line, DOI/wcm.1230, 2011.

[3] R. H. Mahadevappa and J. G. Proakis, Mitigating multiple access interference and intersymbol interference in uncoded CDMA systems with chip-level interleaving, IEEE Trans. on Wireless Communications, vol. 1, 2002, pp. 781-792.

[4] S. M. Berber, R. Vali, Fading Mitigation in Interleaved Chaos-Based DS-CDMA Systems for Secure Communications, 15th WSEAS Int. Conf. on Communications, Corfu, Greece, July 15-17, 2011, pp. 1-6.

[5] H. Torii, M. Satoh, T. Matsumoto, and M. Nakamura, Quasi-Optimal and Optimal Generalized Mutually Orthogonal ZCZ Sequence Sets Based on an Interleaving Technique, International Journal of Communications, Issue 1, vol. 7, pp. 18–25, 2013.

[6] M. Bank, Y. Barish, S. Tapuchi, M. Bank, B. Hill, M. Haridim, Phase Diversity Method in Mobile Communication Systems, International Journal of Communications, Issue 2, vol. 6, pp. 64–71, 2012.

[7] L. Yu-Nan and D. W. Lin, Novel analytical results on performance of bit-interleaved and chip-interleaved DS-CDMA with convolutional coding, IEEE Transactions on Vehicular Technology, Vol. 54, 2005, pp. 996-1012.

[8] B. K. Upadhyaya, and S. K. Sanyal, Novel design of WiMAX multimode interleaver for efficient FPGA implementation using finite state machine based address generator, International Journal of Communications, Issue 2, vol. 6, pp. 27–36, 2012.

[9] "IEEE Std 802.15.4-2006 (Revision of IEEE Std 802.15.4-2003), Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), pp. 0_1-305, 2006.

[10] C. C. Wang, C. C. Huang, J. M. Huang, C. Y. Chang, C. P. Li, Zig-Bee 868/915-MHz Modulator/Demodulator for Wireless Personal Area Network, IEEE Transactions on Very-Large Scale Integration (VLSI) Systems, Vol. 16, No. 7, July 2008, 936-938.

[11] O. Nam-Jin, L. Sang-Gug, Building a 2.4-GHZ radio transceiver using IEEE 802.15.4, Circuits and Devices Magazine, IEEE, Vol. 21, 2006, pp. 43-51.

[12] G. Kaddoum, D. Roviras, P. Charge, and D. Fournier-Prunaret, Robust synchronization for asynchronous multi-user chaos-based DS-CDMA, Signal Processing, vol. 89, no. 5, pp. 807–818, 2009.

[13] R. Vali, S. Berber, and S. K. Nguang, Effect of Rayleigh fading on non-coherent sequence synchronization for multi-user chaos based DS-CDMA, Signal Processing, vol. 90, no. 6, pp. 1924–1939, 2010.

[14] S. M. Berber, Bit error rate measurement with predetermined confidence, Electronics Letters, vol. 27, p. 1205, 20th June 1991.

[15] S. Berber, Y. Yuan, B. Suh, Derivation of BER Expressions and Simulation of a Chip Interleaved System for WSNs Application, 17th WSEAS Int. Conf. on Communications, Rhodos, Greece, pp. 128-133, July 16-19, 2013.

[16] S. Berber, S. Feng, Chaos-Based Physical Layer Design for WSN Applications, 17th WSEAS Int. Conf. on Communications, Rhodes, Greece, pp. 157-162, July 16-19, 2013.