Chip error probability of IEEE 802.15.4 wireless tranmission

Uroš Pešović[1] **Peter Planinšič**[2] **Dušan Gleich**[2]

[1]*Faculty of Technical Sciences Čačak, University of Kragujevac, Serbia*
[2]*Faculty of Electrical Engineering and Computer Science, University of Maribor, Slovenia*
E-mail: uros.pesovic@ftn.kg.ac.rs

Wireless transmissions can be significantly affected by influences from its surroundings, which are most commonly expressed in a form of error probability statistics. IEEE 802.15.4 wireless personal area networks (WPANs) use Direct Sequence Signal Spreading (DSSS) technique in order to be able to operate together with other types of wireless networks in 2.4GHz band. By use of DSSS, IEEE 802.15.4 transceivers are able in some level to cancel out interference from other types of networks. Such interferences have same influence as background noise and are most commonly modeled as Additive White Gaussian Noise (AWGN). This work presents mathematically based chip error probability model of IEEE 802.15.4 wireless communication in presence of AWGN. Presented results for theoretical chip error rate model are confirmed by simulation of IEEE 802.15.4 transmission through AWGN channel according to Monte Carlo method.

1 Introduction

IEEE 802.15.4 standard specifies physical and Medium Access Control layers for Low Power Wireless Personal Area Networks [1]. It is designed for low power, low cost battery operated devices, which are targeted for a wide range of applications. Its physical layer defines channels in several frequency bands, where a 2.4 GHz band is most widely used. Direct-Sequence Spread Spectrum (DSSS) signal spreading is used to provide coexistence of IEEE 802.15.4 WPANs in a crowded 2.4 GHz band, which is also used by other types of networks (IEEE 802.11 WLAN and IEEE 802.15.1 Bluetooth). Knowledge of error probability in such a harsh environment is crucial for efficient deployment of these networks.

Information bearing signal, sent through a wireless channel is received together with some unwanted signals, which are referred as noise. Noise can change the received signal in such a manner that is decoded with some data errors. Noise comes from various sources and can be classified into two groups: background noise and interference noise. Background noise signals have a small structure and arise from both human and natural sources, such as thermal noise and deep-space noise. Interference represents man-made signals, which come from other radio sources that occupy the same frequency band as the desired communication signal. If it is not compliant with information bearing signal (partially overlapping frequency spectrums or different modulation techniques), most likely will have the same effect as background noise.

State of the art in this field, as far as it is known, analyzes error probability of IEEE 802.15.4 transmission in a presence of background noise [2, 3] and regular interference from other types of networks (IEEE 802.11 WLAN and IEEE 802.15.1 Bluetooth) [4, 5, 6]. This paper presents on how AWGN noise affects chip error probability statistics in IEEE 802.15.4 wireless transmissions. Independent experimental simulations show that a chip error probability model for IEEE 802.15.4 wireless simulation is in close match with experimental data, obtained by simulations.

2 Structure of IEEE 802.15.4 transceiver

Radio devices compliant to IEEE 802.15.4 standard are designed as transceivers and they employ transmitter and receiver on the same chip. Typical functional structure of such transceiver is separated into transmission and reception part (Fig. 1).

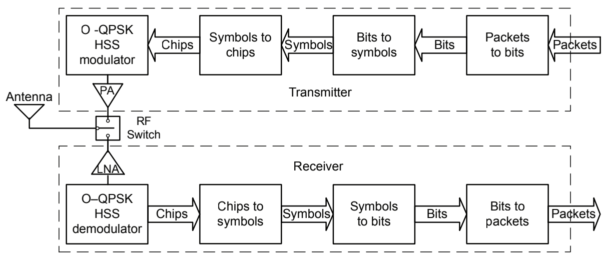

Figure 1: Structure of IEEE 802.15.4 transceiver

In IEEE 802.15.4 transmitter, packet ready for transmission is firstly partitioned into groups of four bits, which are referred as symbol words. Symbol words are spread into one of 16 IEEE 802.15.4 predefined orthogonal sequences containing 32 binary chips. Chip sequences are modulated with the use of Offset QPSK with a Half Sine pulse Shaping (O-QPSK HSS) modulation, which is similar to the Minimum Shift Keying (MSK), as explained in papers [7, 8]. This modulation uses two orthogonal phases, where even indexed chips are modulated onto inphase *I*, while the odd-indexed chips are modulated onto quadrature-phase Q. Chips for both I and Q phases are shaped by half sine pulses, Q phase is delayed by one chip period and added to I phase. O-QPSK HSS modulation is continuous phase modulation which can be used with energy-efficient nonlinear amplifiers; such as those used in IEEE 802.15.4 transceivers. Resulting baseband signal is modulated onto 2.4 GHz carrier, amplified and transmitted via antenna. O-QPSK HSS modulation can be mathematically described with equations (1) to (4) [3]:

$$I_i(t) = \sum_{n=0}^{15} c_{2n}^{i} h(t - 2nT_c) \quad (1)$$

$$Q_i(t) = \sum_{n=0}^{15} c_{2n+1}^{i} h(t - 2(n+1)T_c) \quad (2)$$

$$h(t) = \begin{cases} sin(\frac{\pi t}{2T_c}) & 0 \leq t \leq 2T_c \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

$$s_i(t) = \frac{1}{\sqrt{2}}[I_i(t)cos(\omega_c t) + Q_i(t)sin(\omega_c t)] \quad (4)$$

On receiver's side, wireless signals received by an antenna, are amplified and filtered by an analog front-end. After processing, they are brought to O-QPSK HSS demodulator, where information is extracted in a form of digital chips. In process of decoding, depending on the quality of the received wireless signal, some of the chips could be decoded incorrectly. Using signal despreading, received chip sequences are correlated with predefined chip sequences in order to choose most likely sequence. Beginning of the IEEE 802.15.4 packet is reserved for preamble field which consists of eight repeating symbols. Each time the preamble symbol word is received, it is correlated with expected symbol sequence. During the reception of preamble, receiver phase is shifted in order to achieve synchronization with incoming signal. After successful synchronization, beginning of packet is pointed by start frame delimiter, which is followed by information about packet length. Received symbol words are translated to bits, which are when reception is complete, are grouped into packets which are forwarded to the upper protocol layer. Since IEEE 802.15.4 does not use any kind of error correction technique on a bit level, even a single bit error will corrupt the packet and the packet needs to be retransmitted.

3 Chip error probability

Unlike constellations of QPSK and O-QPSK modulations, which have distinct symbols according to the phase value, phase of the O-QPSK HSS modulation continuously shifts through constellation quadrants, around a circle of radius $\sqrt{E_s}$ (Fig. 2). For simplification, we can assume that during one symbol period, the phase is stationary and located half way on the phase transition through constellation quadrant (Fig. 3). Consider that the alphabet used by O-QPSK HSS modulation is a set of four symbols (S_0,S_1,S_2,S_3) located in quadrants of a complex plane.

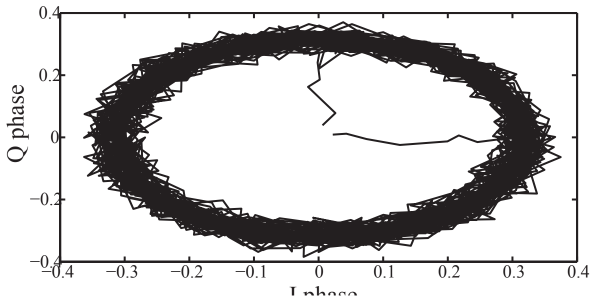

Figure 2: Constellation diagram of O-QPSK HSS with AWGN

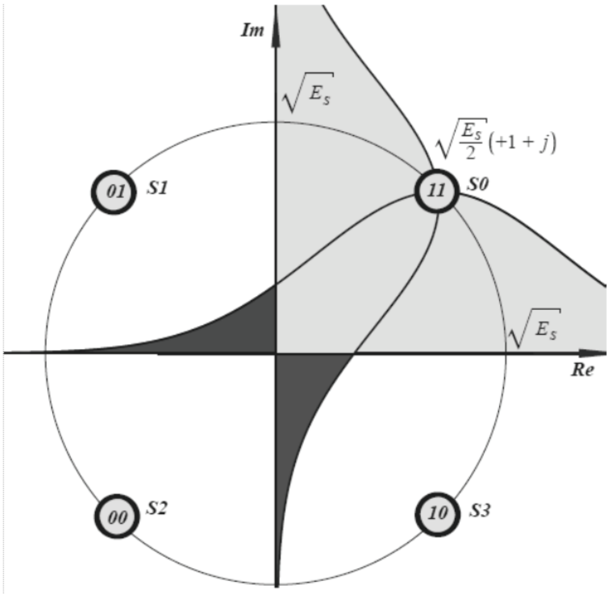

Figure 3: O-QPSK HSS constellation in presence of background noise

In a presence of the background noise, phase of the O-QPSK HSS modulated signal can change and position of the received symbol can move in any direction. Background noise is usually modeled as AWGN, which amplitudes the following Gaussian Probability Density Function (PDF)[9] presented in equation (5), where μ represents mean value and σ^2 represents distribution variance ($\sigma^2 = \frac{N_0}{2}$).

$$n(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (5)$$

Relative strength of background noise signal is usually given in terms Energy of Symbol to Spectral Noise Density ($\frac{E_s}{N_0}$) which represents ratio between symbol energy and noise spectral density. Since O-QPSK HSS codes two bytes per symbol, energy of each symbol is equal twice the energy of individual bit ($E_s = 2E_b$). When background noise is added to the received symbol, the resulting amplitude follows Gaussian probability distribution. For example, under influence of noise, symbol S_0 will be successfully decoded only if it stays inside its quadrant (light gray hashed regions of Fig. 2) as presented by equation (6).

$$P_c(S_0) = P(\Re > 0 \mid S_0) \cdot P(\Im > 0 \mid S_0) \quad (6)$$

If an influence of the noise is that big, it could cause symbol S_0 to shift to another quadrant and to be decoded incorrectly (dark gray hashed regions of Fig. 2). The influence of a background noise on the modulated signal can be represented by the probability of a received symbol error as in equation (7).

$$P_e(S_0) = 1 - P_c(S_0) \quad (7)$$

The probability of a successful symbol reception S_0 represents a product of probabilities that, on both axis, symbol is successfully decoded. This probability represents a surface of gray hashed regions in Fig. 2 and is calculated through integration of Gaussian PDF on the interval $[0, \infty]$ [9] and presented by equation (8). This integral is known as Gaussian tail integral or complementary error function.

$$P_e(S_0) = erfc\left(\sqrt{\frac{E_s}{2N_0}}\right) - \frac{1}{4}erfc^2\left(\sqrt{\frac{E_s}{2N_0}}\right) \quad (8)$$

The obtained formula shows that error probability is a function of ratio between symbol energy and noise spectral density. O-QPSK HSS modulation alphabet is Gray coded, so neighboring symbols differ only in one chip position while the opposite symbols differ in two chip positions. If symbol error flips symbol to its neighboring quadrant, a single-chip error will occur; if a symbol flips to opposite quadrant double chip the error will occur. The probability of received chip errors, known as Chip Error rate (CER) can be expressed by equations (9) to (15).

$$CER = \frac{P_e(S_0 \to S_1) + P_e(S_0 \to S_3) + 2P_e(S_0 \to S_2)}{2} \quad (9)$$

$$P_e(S_0 \to S_1) = P(\Re < 0 \mid S_0) \cdot P(\Im > 0 \mid S_0)$$
$$= \tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right) \cdot \left(1 - \tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right)\right) \quad (10)$$

$$P_e(S_0 \to S_2) = P(\Re < 0 \mid S_0) \cdot P(\Im < 0 \mid S_0)$$
$$= \left(\tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right)\right) \cdot \left(\tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right)\right) \quad (11)$$

$$P_e(S_0 \to S_3) = P(\Re > 0 \mid S_0) \cdot P(\Im < 0 \mid S_0)$$
$$= \left(1 - \tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right)\right) \cdot \tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right) \quad (12)$$

$$CER = \tfrac{1}{2} \cdot 2\left(1 - \tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right)\right) \cdot \tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right)$$
$$+\tfrac{1}{2} \cdot 2\left(\tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right)\right) \cdot \left(\tfrac{1}{2}erfc\left(\sqrt{\tfrac{E_s}{2N_0}}\right)\right) \quad (13)$$

$$CER = \frac{1}{2}erfc\left(\sqrt{\frac{E_s}{2N_0}}\right) = \frac{1}{2}erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (14)$$

4 Simulation results

In order to evaluate the mathematical model for chip error probability of IEEE 802.15.4 transmission, the independent simulation model has been developed in MATLAB. This simulation model consists of implemented IEEE 802. 15.4 transmitter and receiver, which communicate through AWGN channel. Transmitter employed signal spreading and O-QPSK HSS modulation, while the receiver is based on a coherent O-QPSK HSS demodulator with signal despreading and hard decision decoding. Simulations are carried out according to Monte Carlo method, with large number of packets with random content, in order to accurately simulate probability of chip error. Packets used in simulation have random content and constant length of 133 Bytes or 8512 chips. Accuracy of such simulations mainly depends of sample size, in this case, number of transmitted packets. Number of samples *n*, required to test probability *p* of some event with margin of error σ is [10] as in equation (16), where *q* represents complementary probability of *p* ($q = 1 - p$), z_α is ordinate value of normal distribution function of corresponding error of precision estimate α .

$$n = z_\alpha^2 \left(\frac{p \cdot q}{\sigma^2}\right) \quad (15)$$

Margin of error σ, can be replaced with relative error ε, which represent ratio of margin of error σ and expected probability *p*, as in equation (17).

$$n = z_\alpha^2 \frac{q}{p}\left(\frac{1}{\varepsilon}\right)^2 \quad (16)$$

Number of transmitted packets, required to test expected probability of smallest calculated chip error probability with relative error ε of 5 %, at 95 % confidence ($z_{(0.05)} = 1.96$), is just under 1000 packets. Table 1 presents results of chip error rate simulation as well as relative error between calculated and measured chip error probability.

Results of the mathematically derived chip error probability model, presented by line, are in a close match with results obtained by independent MATLAB simulation, presented by dots, for IEEE 802.15.4. wireless transmission in presence of AWGN (Fig. 4). This confirms that mathematically chip error probability model is correctly derived.

Table 1: Calculated and simulated chip error rate

$\frac{E_b}{N_0}$	Calculated CER	Number of packets	Simulated CER	Rel.error (%)
-8	0.2867	1000	0.2869	0.06
-6	0.2392	1000	0.2392	0.01
-4	0.1861	1000	0.1863	0.14
-2	0.1306	1000	0.1307	0.02
0	0.0786	1000	0.0786	0.12
2	0.0375	1000	0.0376	0.23
4	0.0125	1000	0.0125	0.32
6	0.0024	1000	0.0024	0.99
8	0.0002	1000	0.0002	1.72

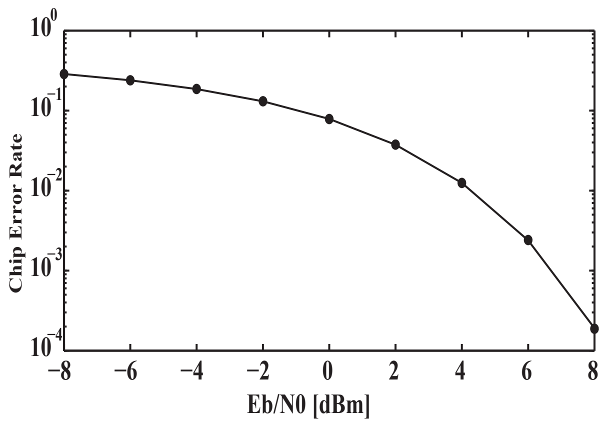

Figure 4: Chip error probability of IEEE 802.15.4 wireless transmission

5 Conclusion

Wireless transmission can be affected by influences of various disturbing sources from its surrounding. Those influences can be expressed in error probability of the received binary data. This paper presents new mathematical model which can be used to express chip error probability for IEEE 802.15.4 wireless transmission in the presence of AWGN. Correctness the proposed model was confirmed by MATLAB simulation of a IEEE 802.15.4 wireless transmission through AWGN channel, where results show a great similarity. Future work will be focused on development of an error probability models for bit and packet error probability of IEEE 802.15.4 wireless transmission.

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