Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **66**, *3*, pp. 191–194, Bucarest, 2021

PERFORMANCE EVALUATION OF IEEE 802.15.4 NETWORKS IN THE PRESENCE OF α-η-μ FADING, INTERFERENCE AND NOISE

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Key words: Sensor networks, Performance, Fading, Interference, Chip error probability, Packet error probability.

A novel, mathematically tractable expression for evaluation of the average chip error probability (CEP) in the networks based on IEEE802.15.4 standard, operating in the 2450 MHz band, in the presence of α-η-μ fading, interference and additive white Gaussian noise (AWGN) is presented. The expression is validated by Monte Carlo simulations and represents the foundation for performance evaluation of the mentioned type of networks operating over any type of non-line-of-sight (NLoS) channel. In addition, we have demonstrated practical usage of the derived average CEP expression by evaluating the average packet error probability (PEP) for the above-described network operating conditions.

1. INTRODUCTION

IEEE 802.15.4 is a technical standard, which provides physical (PHY) and media access (MAC) control for operation of the low-rate wireless personal area networks (LR-WPANs). It is the most widely used foundation for realization of the wireless sensor networks (WSNs) and Internet of Things (IoT) applications. The IEEE 802.15.4 PHY layer defines channels in several frequency bands, whereas the unlicensed 2450 MHz ISM (Industry, Science and Medicine) band is the most commonly used worldwide.

Transmitted IEEE 802.15.4 signals in a wireless channel are affected by noise, fading and interferences. These disturbances cause distortion of the transmitted signal to the extent that receiver fails to identify received symbol correctly. Signal propagation conditions and network performance evaluation determinates design and deployment plan of a wireless network. Additionally, from the energy efficiency point of view, an insufficiently precise performance evaluation is likely to cause energy waste due to retransmission in automatic repeat request (ARQ) schemes or additional processing, due to encoding and decoding, in forward error correction (FEC) schemes. Along with worsened energy efficiency, fading, interference and noise negatively affect other parameters critical for normal network operation, such as latency and throughput. Therefore, an accurate evaluation of the transmission link is valuable when deciding on many network specific parameters, such as distribution of the transmission power per nodes, the network node density, selection of error correction scheme etc.

Instead of analyzing corrupted packets or packet error rates only, the CEP and related error patterns provide more in-depth insights on how transmitted sequence is detected by the receiving node and translated back to the corresponding symbol. A number of papers have dealt with the CEP and performances of IEEE 802.15.4 based networks. The signal propagation scenarios and related analyses in the most of published papers, as a rule, are limited to the combined influence of AWGN and fading only. Moreover, the influence of fading is evaluated by use of the well-known, but simple, distributions, such as Rayleigh, Rician and Nakagami-m, *e.g.* [1–3]. A more comprehensive average chip error rate analysis over Rayleigh and Nakagami-m fading channels, which includes the influence of interference, has been presented in [4], where the impact of Nakagami-m fading has been just partially evaluated, *i.e.* for $m = 1$ and $m = 2$ only. This is due to very complicated evaluation of the derived analytical expressions for values of the shaping parameter $m > 2$.

On the other hand, some more generalized fading models, such as α-μ and η-μ and their extensions, are already finding use in practical scenarios even though they have been relatively recently proposed. In [5], it was found that α-μ distribution yields the best fit to wind-blown foliage and human-induced fading in ground-surface narrowband communications at 400 MHz. In [6], an analysis based on a narrowband channel measurement at 5.9 GHz was carried. The results have shown that Nakagami-m, Rice, Weibull and α-μ distributions can match satisfactorily the empirical distribution associated with the measurement. Nevertheless, the α-μ distribution exhibits a better fit compared to the other distributions, making its use interesting to model the small-scale fading in vehicle-to-vehicle channels, where the large channel variations due to the mobility of transceivers, together with the other interacting objects, make it difficult to separate both the small- and large-scale fading. However, in the real-world environment there are situations in which even more flexibility is required.

A more general, physically based, α-η-μ fading model has been proposed in [7]. Subsequently, an analytical expression for CEP evaluation, for IEEE 802.15.4 wireless link over α-η-μ fading channel in the presence of interference and AWGN, would be a valuable tool in the performance analysis of this type of networks, and a novelty to the best knowledge of authors.

To summarize, the contribution of this paper is as follows:

- Novel analytical expression for average CEP evaluation over α-η-μ fading channel, in the presence of interference and AWGN, valid for arbitrary values of the fading parameters α, η, and μ.
- The derived CEP expression is foundation for evaluation of the other network performance parameters, such as average symbol error probability (SEP) and average PEP.
- The derived expression is general in the sense that it can be applied in performance analysis of IEEE 802.15.4 wireless links over all channels to which α-η-μ channel can be reduced, such as Rayleigh, Nakagami-m, Hoyt, Weibull, α-η and η-μ.

The organization of this paper is as follows: In Section 2,

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an analytical expression for average CEP has been derived. A theoretical base of the average PEP evaluation is presented in Section 3. Numerical results for arbitrary values of α, η and μ parameters, and proof of derivation correctness in a form of average CEP simulation results, as well as an illustration of the average PEP evaluation are all presented and discussed in Section 4. The conclusion has been given in Section 5.

2. DERIVATION OF THE CEP EXPRESSION AND IMPACT OF INTERFERENCE

According to the IEEE 802.15.4 standard, in the transceiver, each byte of binary data ($b_0b_1b_2b_3b_4b_5b_6b_7$) is grouped into two groups of 4-binary symbols – ($b_0b_1b_2b_3$) and ($b_4b_5b_6b_7$). Then, each 4-bit group is mapped to a specified 32-bit long PN sequence $C_0C_1C_2\ldots C_{31}$, which is called “chip“ sequence. Within the next step each bit/chip within a PN sequence is modulated using the O-QPSK modulator.

In general, the average symbol error probability for M-ary PSK in an additive white Gaussian channel (AWGC) is given by [8, eq. 5-2-56], *i.e.*:

$$P_{eM} = 1 - \int_{-\pi/M}^{+\pi/M} p_{\Theta_r}(\Theta_r)\,\mathrm{d}\Theta_r\,, \tag{1}$$

where Θ_r is the received symbol phase.

Since IEEE 802.15.4 standard uses offset quadrature phase shift keying (O-QPSK) modulation, a variant of phase-shift keying modulation using 4 different values of the phase to transmit, the previous expression for SEP reduces to [8, eq. 5-2-59]:

$$P_{e4} = 2Q\left(\sqrt{\frac{2E_c}{N_0}}\right)\left[1-\frac{1}{2}Q\left(\sqrt{\frac{2E_c}{N_0}}\right)\right], \tag{2}$$

where E_c and N_0 represent the chip energy and noise power spectral density, respectively. Using the identity:

$$Q(x) = \frac{\mathrm{erfc}\left(\frac{x}{\sqrt{2}}\right)}{2}, \tag{3}$$

where erfc(·) is the complementary error function, the eq. (2) can be rewritten as follows:

$$P_{e4} = \mathrm{erfc}\left(\sqrt{\frac{E_c}{N_0}}\right) - \frac{1}{4}\mathrm{erfc}^2\left(\sqrt{\frac{E_c}{N_0}}\right). \tag{4}$$

On the other hand, bit error probability (BEP) for O-QPSK modulation is the same as for binary PSK. In this case, it actually represents average CEP and is given by:

$$P_{e2} = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\gamma}\right), \tag{5}$$

where $\gamma = E_c/N_0$ represents the instantaneous chip signal to noise ratio (SNR).

Since the power levels of the interferers are neither constant nor equal, when the number of interferers M–1 is large, it is reasonable to assume that the central limit theorem (CLT) holds good.

Therefore, the both of them, interference and noise, could be modeled as zero-mean Gaussian random variables [9]. Starting from this approximation and having in mind the equations: [9, eq. E.38], [9, eq. E.39], [9, eq. E.60] and the above eq. (5), the average chip error probability for an IEEE 802.15.4 link in the presence of interference and AWGN can be represented by the following mathematical expression:

$$P(\gamma) = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{1}{\frac{1}{3N}\sum_{i=1}^{M-1}\frac{P_i}{P_0} + \frac{N_0}{2T_cP_0}}}\right), \tag{6}$$

where P_i is the power level of the i-th interferer, P_0 is the power level of the desired signal, and T_c is the chip period duration. The eq. (6) can be further simplified to the following form:

$$P(\gamma) = \frac{1}{2}\mathrm{erfc}\left(\sqrt{G\gamma}\right), \tag{7}$$

where

$$\frac{1}{G} = \frac{1}{3N}\sum_{i=1}^{M-1}\frac{T_cP_0}{N_0} + \frac{1}{2}. \tag{8}$$

The average CEP in the presence of α-η-μ fading is obtained from:

$$P_{\alpha-\eta-\mu} = \int_0^\infty P(\gamma)p_\gamma(\gamma)\,\mathrm{d}\gamma, \tag{9}$$

where $p_\gamma(\gamma)$ is the probability density function (PDF) of the instantaneous SNR given by [10, eq.1], *i.e.*:

$$P_{\alpha-\eta-\mu} = \frac{1}{2}\sum_{p=0}^{\infty}\frac{\sqrt{\pi}\alpha h^{\mu}\mu^{2(\mu+p)}H^{2p}}{p\Gamma(\mu)\Gamma\left(p+\mu+\frac{1}{2}\right)\bar{\gamma}^{\alpha(\mu+p)}} \times$$

$$\times\int_0^\infty \gamma^{\alpha(\mu+p)-1}\exp\left(\frac{2\mu h\gamma^{\alpha/2}}{\bar{\gamma}^{\alpha/2}}\right)\mathrm{erfc}\left(\sqrt{G\gamma}\right)\mathrm{d}\gamma, \tag{10}$$

where $h = (1+\eta)^2/4\eta$, $H = (1-\eta^2)/4\eta$ and $0 < \eta < \infty$.

The above eq. (10) can be rewritten in the following form:

$$P_{\alpha-\eta-\mu} = \sum_{p=0}^{\infty}\frac{\sqrt{\pi}\alpha h^{\mu}\mu^{2(\mu+p)}H^{2p}}{p\Gamma(\mu)\Gamma\left(p+\mu+\frac{1}{2}\right)\bar{\gamma}^{\alpha(\mu+p)}}, \tag{11}$$

where integral I is given by

$$I = \frac{1}{2}\int_0^\infty \gamma^{\alpha(\mu+p)-1}\exp\left(-\frac{2\mu h}{\bar{\gamma}^{l/k}}\gamma^{l/k}\right)\mathrm{erfc}\left(\sqrt{G\gamma}\right)\mathrm{d}\gamma. \tag{12}$$

Representing the exponential and complementary error functions in eq. (12) in the form of Meijer G-function, denoted as $\mathrm{G}_{p,q}^{m,n}(\cdot)$ and defined in [11], integral I can be rewritten as follows in the eq.(13), where $\alpha/2 = l/k$ and l and k are mutually prime numbers.

$$I = \frac{1}{2\sqrt{\pi}} \int_0^\infty \gamma^{\alpha(\mu+p)-1} G_{1,2}^{2,0}\left(G\gamma \,\middle|\, \begin{matrix} 1 \\ 0, \frac{1}{2} \end{matrix} \right) G_{0,1}^{1,0}\left(\frac{2\mu h}{\bar{\gamma}^{l/k}} \gamma^{l/k} \,\middle|\, \begin{matrix} - \\ 0 \end{matrix} \right) \mathrm{d}\gamma, \quad (13)$$

$$I = \frac{\sqrt{k}\, l^{\alpha(\mu+p)-1} G^{-\alpha(\mu+p)}}{2\sqrt{\pi}(2\pi)^{\frac{(l+k)}{2}-1}} G_{2l,k+l}^{k,2l}\left(\left(\frac{2\mu h}{k}\right)^k \left(\frac{l}{\bar{\gamma}}\right)^l \,\middle|\, \begin{matrix} \Delta(l,1-\alpha(\mu+p)), \Delta\left(l,\frac{1}{2}-\alpha(\mu+p)\right) \\ \Delta(k,0), \Delta(l,-\alpha(\mu+p)) \end{matrix} \right), \quad (14)$$

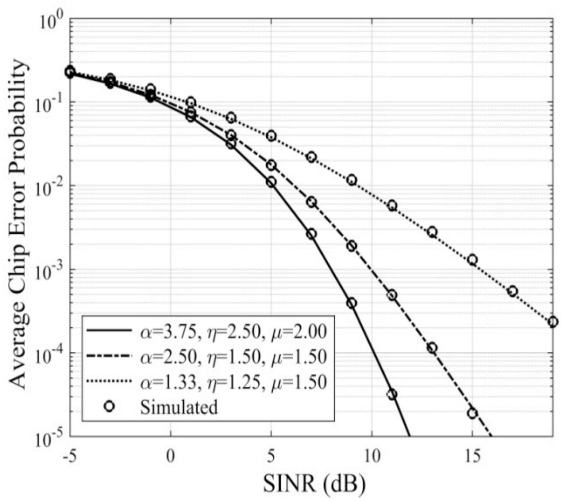

Fig. 1 – Average chip error probability for various values of α, η and μ.

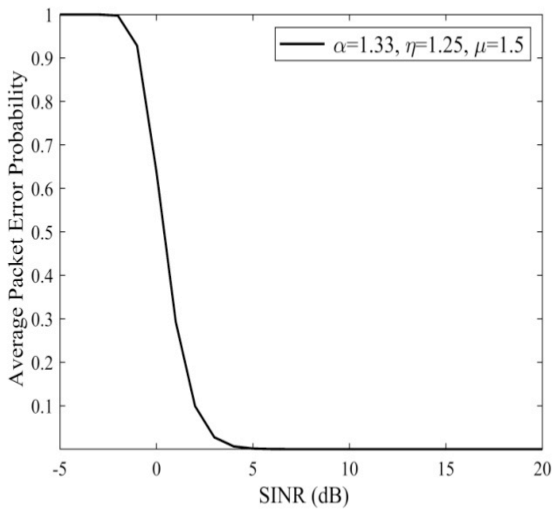

Fig. 2 – Average packet error probability in IEEE802.15.4 network at 2450 MHz in the presence of α-η-μ fading, interference and AWGN.

With help of [11, eq. 2.24.1-1], and after some straightforward mathematical manipulations, solution of the integral *I* could be written as in eq. (14).

3. PEP EVALUATION

As discussed in Section 2, the chip sequences for successive data symbols are concatenated and the resulting chip stream is modulated onto the carrier using the O-QPSK.

In this section, we combine chip error probability for an SINR (Signal-to-interference-plus-noise-ratio)[1] O-QPSK modulated chip stream for a given SINR with symbol error probability to obtain the PHY-level packet error rate for 2450 MHz IEEE 802.15.4 operation in the presence of α-η-μ fading, interference and AWGN. Therefore, if $P_{\alpha\text{-}\eta\text{-}\mu}$ is the probability of receiving a chip in error and $P_{symerr}(n)$ is the probability of symbol error when *n* chips are received in error [2, Table 3], the probability P_{SEP} of interpreting a symbol incorrectly is given by [2]:

$$P_{SEP} = \sum_{n=1}^{32} \binom{32}{n} P_{\alpha-\eta-\mu}^{n} \left(1 - P_{\alpha-\eta-\mu}\right)^{32-n} P_{symerr}(n). \quad (15)$$

A packet is received in error if any of its symbols is received in error. Thus, if a packet is *m* bytes (or 2*m* symbols) long, the probability P_{PEP} of receiving a packet in error (or the packet error rate) is given by [2, eq. 4]:

$$P_{PEP} = 1 - \left(1 - P_{SEP}\right)^{2m}. \quad (16)$$

4. DISCUSSION OF THE RESULTS

The CEP is plotted in Fig. 1 by using eq. (11) and eq. (14). It shows an excellent agreement between the theoretical calculation of CEP and respective simulation results, which proves correctness of our mathematical expressions.

Fig. 2 is a demonstration of the practical usage of the derived analytical expressions in terms of the average packet error probability defined by eq. (16) . It is calculated assuming the packet size to be 133 bytes (or 266 symbols), which is the maximum possible packet length under IEEE 802.15.4, Grey bit-to-symbol mapping and half sine impulse shaping. It shows that PEP on an IEEE 802.15.4 link shows a step-like increase from 0 to 1 as the SINR deteriorates beyond a threshold value, which for the values of the parameters used for depicting the above figures is around 5 dB. Thus, very small increase in CEP, particularly in the threshold proximity, might significantly impact the transmission reliability.

The practical impact of this analysis is briefly summarized in the following points:

- A generalized expression for an average chip error probability evaluation is derived. Namely, α-η-μ fading is a generalized fading channel model with clear physical interpretation reducible to other, simpler and widely used, fading models.
- Here derived expression could be applied in the case of non-homogeneous propagation environments due to the fact that such environments could be modeled by α-η-μ distribution. This could be of great importance for network designers.

The scenario analyzed in this paper includes presence of interference based on assumption that in practice there should not be any strongly interfering signal in a well-designed network. In such a low-interference regime, it is

[1] Editor's note

optimal, especially from the standpoint of capacity achieving, to treat the interference as additional noise.

The obtained results can be helpful to the designers of wireless communication systems using IEEE 802.15.4 standard in terms of creating rational systematic solutions for the desired system performances within the given system operating environment conditions.

5. **CONCLUSIONS**

In this paper, we derived a novel analytical expression for an precise evaluation of the average chip error probability in IEEE802.15.4 networks operating at 2450 MHz over α-η-μ fading channel in the presence of interference and AWGN. The interference is treated as an additional noise, which is rational in well-designed networks, especially from the capacity achieving point of view.

Monte-Carlo simulations validate derived expression, while its practical applicability is demonstrated on the average packet error probability evaluation.

The results presented in this paper can be the basis for future research on the impact of diversity techniques in order to reduce the fading of the IEEE 802.15.4 network, as well as the use of diversity systems with a combination of different numbers of combiners at the micro and macro level.

ACKNOWLEDGEMENTS

The work has been funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia within the project TR32023.

Received on September 3, 2019

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