Throughput of IEEE 802.11 DCF in κ - μ Fading Channels

Rafael A. Pedriali, Heber R. da Silva, and Elvio J. Leonardo

Abstract—This letter investigates the throughput performance of the IEEE 802.11 Distributed Coordination Function over κ - μ fading environment. The approach considered includes signal capture model with incoherent addition of interfering signals and uniform attenuation for all terminals. The fading model selected allows flexibility and can offer better statistical fitting than traditional ones. Numeric results are presented.

Index Terms—Wireless communication, IEEE 802.11, Capture Effect, Throughput, κ - μ fading model.

I. INTRODUCTION

N Local Area Network (LAN) systems, efficiency is a fundamental issue and, as a result, protocols and system definitions have evolved continually, adding complexity and delivering higher data rates and channel usage. Some examples of this trend include Aloha, Fiber Distributed Data Interface (FDDI), Carrier Sense Multiple Access (CSMA), CSMA with Collision Detection (CSMA-CD) and with Collision Avoidance (CSMA-CA), IEEE 802.3, and IEEE 802.11 [1]. In general, wireline systems offer higher data rate, transmission quality and reliability when compared to wireless counterparts. The latter, however, offers the convenience of a connection without wires, which has been a very appealing attribute. As a result, particularly in recent years, with the development and proliferation of portable devices, wireless LAN (WLAN) systems have been deployed everywhere, especially those using the IEEE 802.11 protocol. Currently this protocol dominates its market segment and will be used in the cellular phone system fifth generation (5G) [2], [3].

The IEEE 802.11 protocol defines at the Medium Access Control (MAC) sublayer two access schemes: Point Coordination Function (PCF) and Distributed Coordination Function (DCF). The former is implemented in an infrastructured network, with a central controlling node termed Access Point (AP) [4]. In the latter, the AP is absent and an ad-hoc network is set up. This letter is focused on this second access mechanism.

The most relevant papers to this work are present in [5]–[8]. In [5], a two dimensional Markov model is used to evaluate the throughput of the IEEE 802.11 DCF, with the assumptions of fixed number of stations, ideal channel, and saturated traffic conditions. In [6], the model is refined to include capture effect under Rayleigh fading and non-ideal channel conditions. Also, an idle state is added to the Markov model to allow the analysis

R. A. Pedriali is with Wireless Technology Laboratory, School of Electrical and Computer Engineering, University of Campinas, Brazil, e-mail: rafaug.p@gmail.com. H. R. da Silva and E. J. Leonardo are with the Department of Informatics, State University of Maringa, Brazil, e-mail: hebermga@gmail.com and ejleonardo@uem.br

Digital Object Identifier: 10.14209/jcis.2019.27

of the unsaturated traffic situation. In [7], the authors propose a perfect power control by considering the signal capture model with coherent and incoherent addition of interfering signals in Nakagami-m, Rice, and Hoyt fading environments. In [8], the analysis of the throughput considers the two-way handshaking, and assumes a more generalized fading model, the η - μ model, which was introduced by Yacoub in [9] and that better represents the channel in a non-line-of-sight (NLOS) scenario. Moreover, the considered signal is composed by clusters of multipath waves in a non-homogeneous environment. Several others works have dealt with the channel throughput in specific protocols (e.g., [10]-[15]). Therefore, in order to expand a scenario not yet explored, this letter investigates the throughput performance of the IEEE 802.11 DCF in a typical small or pico-cell wireless communication scenario, i.e., using the κ - μ fading environment [9]. This is another generic fading model, but able to better represent a line of sight (LOS) channel condition, i.e., a scenario in which there is a direct non-obstructed path between the transmitter and receiver. This conditions are usually found in satellite transmissions [16], infrared communications systems, Li-Fi [17], and also in vehicular communications [18]. The considered approach includes signal capture model with incoherent addition of the interfering signals and uniform attenuation for all terminals.

This letter is organized as follows. Section II offers a brief explanation about the channel model and the MAC sublayer. Section III describes the signal capture effect, the channel throughput and the probabilities involved. Section IV presents channel throughput results. Finally, a conclusion is given in Section V.

II. PRELIMINARIES

A. κ-μ Fading Model

The κ - μ fading model was introduced in [9], and it is a model better suited to represent the small-scale fading variation in the presence of dominant, *line-of-sight* (LOS), components. The PDF of the squared random variable (RV), i.e., the signal power Ω , is given by

$$f_{\Omega}(\omega) = \frac{\mu(1+\kappa)^{\frac{\mu+1}{2}}\omega^{\frac{\mu-1}{2}}}{\kappa^{\frac{\mu-1}{2}}e^{\mu\kappa}e^{\mu(1+\kappa)\omega}} I_{\mu-1}[2\mu\sqrt{\kappa(1+\kappa)\omega}], \quad (1)$$

in which $\omega > 0$ represents the signal power, $\Omega = \omega/\hat{\omega}$ is the normalized power, $\hat{\omega} = E(\Omega)$ is the average power, $I_{\nu}(.)$ is the modified Bessel function of the first kind and order ν [19, Eq. 10.32.4], $\kappa > 0$ is the ratio between the powers of the dominant components and the scattered waves, and μ represents the real extension of the number of multipath clusters, and is given by $\mu = \frac{E^2(\Omega)}{V(\Omega)} \frac{1+2\kappa}{(1+\kappa)^2}$. The operators E(.)and V(.) denote expectation and variance, respectively. As a generic fading model, it can be used to represent more traditional ones, such as Rayleigh, Rice, Nakagami-*m*, and One-Sided Gaussian models by setting its parameters as follows. For Rayleigh, set $\mu = 1$ and $\kappa \rightarrow 0$; for Rice, set $\mu = 1$; for Nakagami-*m*, set $\kappa \rightarrow 0$; and for One-Sided Gaussian, set $\mu = 0.5$ and $\kappa \rightarrow 0$.

The PDF and CDF of the ratio of (envelope) RVs $\kappa - \mu/\kappa - \mu$ can be obtained from [20, Tables 2 and 3]. However, here the interest rests on the squared distribution that represents the signal power. Therefore, the PDF and CDF of the ratio $Z = \Omega_s/\Omega_n$, in which Ω_s and Ω_n follow (1), are expressed as, respectively,

$$f_{Z}(z) = \frac{z^{\mu_{s}-1}u^{\mu_{s}}}{e^{\mu_{s}\kappa_{s}+\mu_{n}\kappa_{n}}(uz+1)^{\mu_{s}+\mu_{n}}} \sum_{i=0}^{\infty} \frac{1}{i! B(\mu_{n}+i,\mu_{s})} \\ \times \left(\frac{\mu_{n}\kappa_{n}}{uz+1}\right)^{i} {}_{1}F_{1}\left(\mu_{s}+\mu_{n}+i,\mu_{s},\frac{\kappa_{s}\mu_{s}uz}{uz+1}\right), \quad (2)$$

$$F_{Z}(z) = \frac{(u z)^{\mu_{s}}}{e^{\mu_{n}\kappa_{n}}(uz+1)^{\mu_{s}+\mu_{n}}} \sum_{j=0}^{\infty} \frac{(u z)^{j} Q(j+1,\mu_{s}\kappa_{s})}{(j+\mu_{s})B(j+\mu_{s},\mu_{n})} \times (uz+1)^{-j} {}_{1}F_{1}\left(j+\mu_{s}+\mu_{n},\mu_{n},\frac{\mu_{n}\kappa_{n}}{1+u z}\right).$$
(3)

in which $u = \frac{\mu_s(\kappa_s+1)\hat{\omega}_n^2}{\mu_n(\kappa_n+1)\hat{\omega}_s^2}$, B(.,.) is the Beta function [19, Eq. 5.12.1], ${}_1F_1(.,.,.)$ is the Kummer confluent hypergeometric function [19, Eq. 13.2.2], and Q(.,.) is the regularized incomplete gamma function [19, Eqs. 8.2.4]. For this letter, the subscripts *n* and *s* are used to represent the incoherent addition of the interference signals (the denominator of *Z*), and the test (desired) signal (the numerator of *Z*), respectively.

B. Medium Access Control Sublayer

In the IEEE 802.11 protocol, the MAC sublayer (which belongs to the Data Link layer) was designed to support random access to a shared wireless medium. A mechanism based on the CSMA/CA is used with the aim of preventing the occurrence of collisions, i.e., when two or more stations transmit at the same time, commonly causing signal reception failure. When a station is ready to transmit a data frame, it first senses the channel activity. If the channel is sensed idle for at least a period of time defined as Distributed InterFrame Space (DIFS), the transmission happens. If the channel is sensed busy, the transmission is delayed according to the binary exponential backoff rules [5] explained below. A confirmation (ACK) frame is relayed back from the destination to the sender to confirm the correct reception of the data frame. If the ACK frame is not received, the sender assumes that the data frame has been lost and reschedule a retransmission according to the binary exponential backoff rules.

As already mentioned, this letter assumes that DCF mode is used, and therefore no AP is present. Also, two data dialogues are considered: two-way and four-way handshaking [4], which are explained in the following. The simpler twoway handshaking includes only the data frame transmitted by the sender and a positive ACK frame transmitted by the destination. The time interval between these two frames is defined as the Short InterFrame Space (SIFS). If the sender does not receive an ACK within the ACK timeout period, then a retransmission is scheduled in accordance with the binary exponential backoff rules. The four-way handshaking, also known as *Request To Send/Clear To Send* (RTS/CTS) mechanism, operates similarly to the two-way handshaking. However, before sending a data frame, the transmitting station sends a short RTS control frame. After the receiver station receives the RTS, it waits for a SIFS, and sends a CTS control frame to confirm it is ready to receive the data. Then the data and ACK frames follow as in the two-way handshaking. Note that the RTS and CTS frames are used to inform all stations of an incoming data dialogue and, therefore, all stations are expected not to interfere with the imminent transmission.

C. Binary Exponential Backoff Rules

The binary exponential backoff mechanism [5] is used to spread out in time transmission reattempts, i.e., repeated transmissions due to earlier failures. Whenever a station wants to transmit, it waits for the channel to become idle, transmits its data frame, receives the ACK confirmation frame and moves on. However, if no confirmation is received, a new retransmission is schedule to happen after a randomly chosen backoff time. This transmission procedure can be modeled by a Markov Chain, as depicted in Fig. 1.



Fig. 1. The Markov Chain for IEEE 802.11 DCF.

A backoff time k (expressed as an integer number of time slots) is uniformly selected from 0 and $W_i - 1$, in which $W_i = 2^i W_0$ is the contention window size for backoff stage $i, i \in [0,m]$, with i = 0 for the first retransmission, and W_0 is the initial contention window size.

Before the station can attempt a retransmission, the sending station has to wait the backoff counter to expire. While the channel remains idle, the backoff counter is decremented every slot. However, if the channel is busy, the backoff counter stops decrementing and remains unchanged. When k reaches zero

in any state (i, 0) and the medium is idle, the station is allowed to transmit. If successful, then the contention window is set to its initial value W_0 for a new transmission. Also, it is easy to see that the station moves to idle state (I) with probability $(1-q)(1-P_{eq})$, in which q is the probability that the station buffer has at least one data packet ready to be transmitted, and P_{eq} is the probability of a failed transmission. Otherwise, the backoff stage *i* is incremented by one and the contention window size doubles until it reaches its maximum size $W_m = 2^m W_0$. In that case the contention window no longer changes until the data packets is successfully transmitted, or the station reaches its maximum number of retransmissions attempts. In this last case, the transmission is abandoned.

D. Numerical Realization Example

Consider a station that is in idle state (I). Then two packets arrive for transmission, but the channel is busy. The transmission is delayed in accordance to the binary exponential backoff roles. Assume that k = 1 is drawn. The station's Markov chain moves from state (I) to (0, 1). After one timeslot, the state moves (with probability 1) to state (0,0), in which the station tries to transmit a packet. Assume that the transmission is unsuccessful. Then, a new k is drawn (say k = 3), which moves the state from (0,0) to (1,3). Again, the state is moved at each timeslot from (1,3) to the direction of (1,0). Then a new retransmission is attempted. Assume that a successful transmission is achieved, and the second packet starts in the Markov chain, i.e., another k is selected (say, k = 2), which moves the state from (1,0) to (0,2). The state then moves from (0,2) in the direction of (0,0), when the station tries to transmit. Assume that a successful transmission is confirmed, which makes the state to go back to idle (I). This realization example is summarized by $(I) \rightarrow (0,1) \rightarrow (0,0) \rightarrow (1,3) \rightarrow$ $(1,2) \rightarrow (1,1) \rightarrow (1,0) \rightarrow (0,2) \rightarrow (0,1) \rightarrow (0,0) \rightarrow (I).$

III. THE CAPTURE EFFECT AND CHANNEL THROUGHPUT

For wireless systems, the radio receiver can capture the desired packet even in the presence of n interfering signals if the power ratio between the desired signal and the joint interference signal at the receiver's antenna is greater than a particular threshold. In this case, the capture threshold can be expressed as $Z \triangleq \frac{\Omega_s}{\Omega_n} \ge 0$, in which Ω_s and Ω_n represent the random powers of the desired signal and the interference, respectively, also assuming that both are statistically independent. Then, the conditional capture probability for capture threshold z_0 , given the existence of n interfering signals, is given by $P_{capt}(z_0|n) = 1 - F_Z(z_0)$, in which $F_Z(.)$ is defined in (3).

Let *N* represent the number of contending stations, and n + 1 the number of interfering data packets. The unconditional capture probability in a generic timeslot can be expressed as

$$P_{cap} = \sum_{n=1}^{N-1} \binom{N}{n+1} \gamma^{n+1} (1-\gamma)^{N-n-1} P_{cp}(z_0|n), \quad (4)$$

in which γ is the probability that a station starts a transmission in a randomly chosen timeslot [7].

The probability that at least one among N existing stations is transmitting in a given timeslot is given as $P_t = 1 - (1 - \gamma)^N$.

A successful data packet transmission corresponds to one of these events: just one of N station is transmitting, or multiple stations are transmitting but there is a successful signal capture effect. Therefore the probability of a successful data packet transmission is given as [7]

$$P_s = \frac{N\gamma(1-\gamma)^{N-1} + P_{cap}}{P_t}.$$
(5)

A failed transmission due to a collision occurs if at least one other station among the remaining N - 1 is transmitting data packets at the same time, i.e.,

$$P_{col} = 1 - (1 - \gamma)^{N-1} - P_{cap}.$$
 (6)

A failed transmission occurs because of a collision or a channel error. Therefore its probability is given as

$$P_{eq} = 1 - (1 - P_e)(1 - P_{col}) = P_e + P_{col} - P_e P_{col},$$
 (7)

in which P_e the probability of a channel error.

As already defined, q corresponds to the probability that the station buffer has at least one data packet ready to be transmitted. Therefore

$$q = 1 - e^{-\lambda E\left\{S_{ts}\right\}},\tag{8}$$

in which λ represents the average data packet generation rate, and γ is the probability that a station starts a transmission in a random time slot, and is given as

$$\gamma = 2\left((W_0 + 1) + W_0 P_{eq} \frac{1 - (2P_{eq})^m}{1 - 2P_{eq}} + 2(1 - P_{eq}) \frac{1 - q}{q} \right)^{-1}.$$
(9)

Finally, $E{S_{ts}}$ is the average data packet length

$$E\{S_{ts}\} = (1 - P_t)\sigma + P_t(1 - P_s)T_c + P_tP_s(1 - P_e)T_s + P_tP_sP_eT_e,$$
(10)

in which σ represents a duration of an empty timeslot, T_c , T_s and T_e correspond to the average time a channel is sensed busy due to collision, the average time of a successful transmission, and the average time of a unsuccessful data transmission, respectively. These time values depend on the handshaking mechanism used. For the two-way handshaking, they can be calculated as

$$T_{c} = H + M + PL + ACK_{timeout},$$

$$T_{s} = H + M + PL + SIFS + 2\tau + ACK + DIFS,$$

$$T_{e} = H + M + PL + ACK_{timeout},$$
 (11)

in which *H*, *M* and *PL* are the time durations of the PHY header, MAC header and packet payload, respectively, *SIFS*, *DIFS*, *ACK* and *ACK*_{timeout} are the times specified in the standard [4], and τ is the propagation delay time.

For the four-way handshaking, those times are defined as

$$T_{c} = H + RTS + ACK_{timeout},$$

$$T_{s} = H + RTS + SIFS + H + CTS + SIFS + H + M$$

$$+PL + SIFS + H + ACK + DIFS + 4\tau,$$

$$T_{e} = H + RTS + SIFS + H + CTS + SIFS + H + M$$

$$+PL + ACK_{timeout} + 2\tau.$$
(12)

Finally, the normalized throughput S can be represented as the fraction of time the channel is used to successfully transmit user data. The analysis of *S* results in a non-linear equation system dependent on the probabilities presented above, and given as

$$S = \frac{P_t P_s (1 - P_e) E\{PL\}}{E\{S_{ts}\}}.$$
 (13)

IV. RESULTS

Numerical results are presented in the following. In particular, throughput figures for two-way and four-way mechanisms are considered. The network parameters are used according to the IEEE 802.11 protocol: Channel bit rate = 1 Mbps, Packet payload = 1020 bytes, MAC header = 34 bytes, PHY header = 24 bytes, ACK frame = 14 bytes, ACK timeout = 300 μ s, Slot time = 20 μ s, DIFS = 50 μ s, SIFS = 10 μ s, $\tau = 0.2 \ \mu$ s, m = 5 and $W_{min} = 8$. Numerical results for the throughput are offered in Figs. 2 and 3, with the calculation performed with the help of the mathematical tool Mathematica [21]. Note that without loss of generality, it is assumed that $\kappa = \kappa_s = \kappa_n$, $\mu = \mu_s = \mu_n$ and $\hat{\omega}_s^2 = \hat{\omega}_n^2 = 1$.

Fig. 2 depicts the throughput for two-way access mechanism. It can be observed that the curves are characterized by two well-defined zones, separated by a peak. In the first part, the throughput increases linearly with the increasing packet rate, and in the second part there is a saturation region, where the variation of the data packet rate has little influence over the channel throughput. It can be seen that, in general, a decrease in the channel throughput is observed just after the peak.



Fig. 2. Throughput *S* for IEEE 802.11 DCF on a κ - μ fading environment with incoherent addition of interfering signals, and 2-way handshaking. Solid lines correspond to variation of parameters κ and μ , dashed lines correspond to variation of \tilde{z}_0 and P_e , and dotted lines are specials curves for less generalized distributions; curve 11 depicts One-Sided Gaussian channel and Nakagami-*m* channel with m = 0.5, and curve 12 illustrates Rice channel.

Varying the number of stations cause the curves to change considerably due to increased traffic. The greater the number of stations N, the steeper the growth of the linear region of the curves, as expected (compare curves 1, 4 and 7 in Fig. 2). The channel error probability P_e also influences the channel throughput, as illustrated for the the pairs of curves 2 and 3, and 9 and 10 in Fig. 2. Comparing curves 1 and 2, there is a throughput decrease with the increase of parameters κ

and μ . This happens because the larger the values of these parameters, the more deterministic the scenario becomes. On the other hand, if the capture threshold is reduced, a throughput growth is observed. This occurs because reducing the threshold indicates an improvement of the ability of the receiver to detect the desired signal (compare pair of curves 4 and 5, and 7 and 8). As mentioned in the previous section, the κ - μ fading model may represent less generalized distributions. In the figure, curve 11 represents One-Sided Gaussian channel and Nakagami-*m* channel with m = 0.5, and curve 12 represents a Rice channel.



Fig. 3. Throughput for IEEE 802.11 DCF on 4-way handshaking over κ - μ fading environment with incoherent addition of interfering signals. There are variations on the parameters N, κ , μ , \tilde{z}_0 and P_e .

Fig. 3 illustrates the throughput results for four-way handshaking access mechanism. In a similar way to the simpler handshaking, the four-way has two well-defines zones (growth and saturation region), but due to the use of control packet (RTS/CTS) the decrease of channel throughput just after the peak is almost non-existent. It can also be observed that: the number of stations change considerably the curves; and the P_e is influential only in the saturation region (see curves 2 and 3 in Fig. 3). On the other hand, changing parameters κ , μ and \tilde{z}_0 has a subtle influence over the throughput, as illustrated by the pair of curves 1 and 2, 3 and 4, 5 and 6, and 7 and 8.

It is interesting to note that more severe fading seems to benefit the throughput performance. For instance, comparing results presented here with those appearing in [8] indicate the conclusion above. The reason behind it might be that less interference is produced in such situations.

V. CONCLUSION

This letter investigates the throughput of the IEEE 802.11 DCF using two-way and four-way handshaking access mechanisms over κ - μ fading environment with uniform attenuation for all terminals and incoherent addition of interfering signals. It is considered a non-saturated traffic condition, as the one proposed in [7]. Numerical, statistical and analytical methods were employed to obtain the results. The analysis presents the channel throughput for the cited protocol and how it is the influenced by the model's parameters. The use of the κ - μ model in the scenario considered here are unprecedented.

ACKNOWLEDGMENT

This work was supported by CNPq (in Portuguese: Conselho Nacional de Pesquisa).

REFERENCES

- A. S. Tanenbaum, and D. J. Wetherall, "Computer Networks", *Pearson*, 2013, isbn: 9781292024226.
- [2] A. Gohil, H. Modi, and S. K. Patel, "5G technology of mobile communication: A survey," *in Proc. Int. Conf. Intell. Syst. Signal Process. (ISSP)* 2013, Gujarat, pp. 288-292. doi: 10.1109/ISSP.2013.6526920.
- [3] Y. Yang, J. Xu, G. Shi, and CX. Wang, "5G Wireless Systems: Simulation and Evaluation Techniques", *Springer*, 2017, isbn: 9783319618692.
- [4] IEEE Standard 802.11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, 2016 Edition, url: https://standards.ieee.org/standard/802_11-2016.html.
- [5] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function", *IEEE J. Sel. Areas Commun.*, 2000, 18, pp. 535-547, doi: 10.1109/49.840210.
- [6] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, "Unsaturated Throughput Analysis of IEEE 802.11 in Presence of Non Ideal Transmission Channel and Capture Effects", *IEEE Trans. Wireless Commun.*, 2008, 7, pp. 1276-1286, doi: 10.1109/TWC.2008.060859.
- [7] E. J. Leonardo, and M. D. Yacoub, "Exact Formulations for the Throughput of IEEE 802.11 DCF in Hoyt, Rice, and Nakagami-*m* Fading Channels", *IEEE Trans. Wireless Commun.*, 2013, **12**, pp. 2261-2271, doi: 10.1109/TWC.2013.032513.120859.
- [8] H. R. da Silva, R. A. Pedriali, and E. J. Leonardo "Unsaturated Throughput Analysis of IEEE 802.11 DCF Under η μ Fading Channel" J. Commun. Inf. Syst., 2016, **31**, pp. 236-241, doi: 10.14209/JCIS.2016.21.
- [9] M. D. Yacoub, "The κ-μ distribution and the η-μ distribution", *IEEE Antennas Propag. Mag.*, 2007, **49**, pp. 68-81, doi: 10.1109/MAP.2007.370983.
- [10] H. Wen, C. Lin, Z. J. Chen, H. Yin, T. He, and E. Dutkiewicz, "An Improved Markov Model for IEEE 802.15.4 Slotted CSMA/CA Mechanism", *J. Comput. Sci. Technol*, 2009, **24**, pp. 495-504, doi: 10.1007/s11390-009-9240-5.
- [11] S. Ullah, M. Chen, and K. S. Kwak, "Throughput and Delay Analysis of IEEE 802.15.6-based CSMA/CA Protocol", J. Med. Syst., 2012, 36, pp. 3875-3891, doi: 10.1007/s10916-012-9860-0.
- [12] E. J. Leonardo, and M. D. Yacoub, "Throughput of CSMA in κ-μ Fading Channels", Simp. Brasileiro de Telecomun., 2011, 1, pp. 537-542.
- [13] Z. Chen, Y. Liu, R. Liu, J. Yuan, and D. Han, "Improved CSMA/CA Algorithm Based on Alternative Channel of Power Line and Wireless and First-Time Idle First Acquisition," *IEEE Access*, 2019, 7, pp. 41380-41394, doi: 10.1109/ACCESS.2019.2907705.
- [14] S. M. Soares, and M. M. Carvalho, "Throughput Analytical Modeling of IEEE 802.11ah Wireless Networks", in Proc. 16th IEEE Annual Consum. Commun. Netw. Conf. (CCNC), 2019, pp. 1-4, doi: 10.1109/CCNC.2019.8651805.
- [15] X. Yuan, C. Li, Q. Ye, K. Zhang, N. Cheng, N. Zhang, and X. Shen, "Performance Analysis of IEEE 802.15.6-Based Coexisting Mobile WBANs With Prioritized Traffic and Dynamic Interference", *IEEE Trans. Wireless Commun.*, 2018, **17**, pp. 5637-5652, doi: 10.1109/TWC.2018.2848223.
- [16] S. Panic, M. Stefanovic, J. Anastasov and P. Spalevic "Fading and Interference Mitigation in Wireless Communications", *CRC Press*, 2013, isbn: 9781466508415.

- [17] Z. Li, Z. Tian, M. Zhou, Z. Zhang and Y. Jin, "Awareness of Line-of-Sight Propagation for Indoor Localization Using Hopkins Statistic", *IEEE Sensors J.*, 2018, **18**, pp. 3864-3874, doi: 10.1109/JSEN.2018.2816586.
- [18] H. Rasheed and N. Rajatheva, "Spectrum sensing for cognitive vehicular networksover composite fading", *Int. J. of Veh. Technol.*, 2011, 2011, pp. 676–680, doi:10.1155/2011/630467.
- [19] F. W. J. Olver, "NIST Handbook of Mathematical Functions", Cambridge University Press, 2010, isbn: 9780521192255.
- [20] C. R. N. Da Silva, N. Simmons, E. J. Leonardo, S. L. Cotton and M. D. Yacoub, "Ratio of Two Envelopes Taken From α-μ, η-μ, and κ-μ Variates and Some Practical Applications", *IEEE Access*, 7, pp. 54449-54463, 2019, doi: 10.1109/ACCESS.2019.2907891.
- [21] Wolfram Research, Inc., Mathematica, Version 11.0, Champaign, IL, 2019.



Rafael A. Pedriali was born in Maringa, PR, Brazil, in 1993. He received the B.S. degree in Electrical Engineering from the State University of Maringa, in 2016 and M.Sc. degree in Electrical Engineering at the State University of Campinas, Brazil, in 2019. Currently he is pursuing the Ph.D. degree from the School of Electrical and Computer Engineering of the State University of Campinas at the State University of Campinas, working with wireless communications and fading channels.



Heber R. da Silva was born in Mundo Novo, MS, Brazil, in 1981. He received the B.S. degree in Production Engineering and M.Sc. in Computer Science from the State University of Maringa, Brazil, in 2008 and 2016, respectively. His research activities include wireless communications and fading communication channels.



Elvio J. Leonardo was born in Maringá, Brazil, in 1961. He received the B.S., M.Sc. and Ph.D. degrees in Electrical Engineering from the School of Electrical and Computer Engineering of the State University of Campinas, Brazil, in 1984, 1992, and 2013, respectively. From 1985 to 1992, Mr. Leonardo worked as an Engineer at the Research and Development Center of Telebrás, the then holding of the Brazilian state owned telephone operators. In 1992 he moved to Australia, where he first worked as a Research Assistant at the Sydney University,

joining later the Motorola Australia Software Centre as a Software Engineer. In 1998 he moved to Libertyville, USA, still working for Motorola, where he helped the development of cellular phones. In 2002 he moved back to Brazil, where he started his academic career. Currently he is an Assistant Professor at the State University of Maringá. His general research interests include embedded systems and wireless communications.