Throughput of CSMA in κ-μ Fading Channels

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***Resumo*— Este artigo apresenta resultados de desempenho do CSMA (*carrier sense multiple access*) em canais com desvanecimento κ-μ. A abordagem considerada inclui o modelo de captura do sinal com adi cão incoerente de sinais interferentes. O caso de atenua cão uniforme para todos os terminais (ou equivalentemente de controle perfeito de potência) é estudado. Resultados analáticos e numéricos são apresentados.**

***Palavras-Chave*— Comunica cão sem fio, CSMA, desvanecimento κ-μ.**

***Abstract*— This paper investigates the throughput performance of carrier sense multiple access (CSMA) in κ-μ fading channels. The approach considered includes the signal capture model with incoherent addition of interfering signals. The case of uniform attenuation for all terminals (or perfect power control) is studied. Analytical and numerical results are presented.**

***Keywords*— Wireless communication, CSMA, κ-μ fading.**

I. INTRODUCTION

Wireless local area networks (WLANs) are experiencing rapid development in part stimulated by the deployment of systems compatible to the IEEE 802.11 standards. They offer data communication between terminals within radio range while allowing a certain degree of mobility.

In order to serve terminals exhibiting bursty traffic behaviour, WLANs make use of packet radio techniques with random access to a transmission channel shared by multiple users. Specifically, variations of carrier sense multiple access (CSMA) are generally used to access the wireless medium [1], [2], [3], [4]. The capacity of the channel is then influenced by the probability of packet collision and by the signal degradation due to mutual interference and signal attenuation. In other words, it is influenced by the medium contention resolution algorithm and by the channel characteristics.

Intuitively one might expect that original (wireline) CSMA systems show better system performance than wireless systems because of more hostile channel characteristics found in the latter. However, this is not necessarily the case. For instance, in a channel model that takes into account the effects of fading, competing packets arriving at a common radio receiver antenna will not always destroy each other because they may show different and independent fading and attenuation levels [5], [6]. This leads to expect that wireless systems may actually exhibit successful reception rate higher than that of original (wireline) systems. In fact, Arnbak and Blitterswijk have shown this to happen with slotted Aloha over Rayleigh fading channels [7].

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In this paper, we investigate the throughput performance of CSMA in a packet radio network with κ-μ fading environment. The performance of the original (wireline) CSMA is presented in [8] and is here extended to this fading scenario. The κ-μ fading environment is relevant to model a situation where the random multipath signals are superimposed on a nonfading dominant signal, for instance, when a line-of-sight (LOS) component is present [9]. The distribution has the Rice (Nakagami-n), the Nakagami-m, the Rayleigh, and the One-Sided Gaussian distributions as special cases.

This paper is organized as follows. Section II describes the analytical model and considers the incoherent packet addition at the receiver's antenna. Section III presents the results obtained. Comments and conclusions are given in Section IV.

II. ANALYTICAL MODEL

A. Nonpersistent CSMA

For nonpersisting CSMA, a terminal ready to transmit first senses the channel. If it senses the channel idle, it transmits the packet. Otherwise, it schedules the (re)transmission of the packet to a later time according to some randomly distributed retransmission delay. After the retransmission delay has elapsed, the terminal repeats the procedure described above. In this paper, the channel is considered to be memoryless, i.e., failures to capture the channel and future attempts are uncorrelated. In addition, all packets are assumed to have fixed length and to require p seconds to transmit. Finally, each packet is assumed to have a single destination.

B. Probability of Capture

Given the transmission of an arbitrary test packet over a wireline channel, it is generally assumed that a successful reception can only occur if no other transmission attempt is made during the test packet reception, i.e., if there is no signal overlap at the receiver. However, in wireless systems the radio receiver may be able to be captured by a test packet, even in the presence of n interfering packets, provided the power ratio between the test signal and the joint interfering signal exceeds a certain threshold during a given portion of the transmission period t_w, $0 < t_w < p$, to lock the receiver [10], [11]. In such a case, a test packet is only destroyed if

$$\frac{w_s}{w_n} \leq z \quad \text{during } t_w \text{, with } n > 0, \tag{1}$$

where z is the capture ratio, and w_s and w_n are the test packet power and the joint interference power at the receiver's antenna, respectively. Values for z and the capture window t_w depend on the modulation and the coding employed by the network, among other things. For a typical narrowband FM receiver, a z value of 6 dB is suggested in [12]. The details about estimation of the values of z and t_w are beyond the scope of this paper.

Let the random variable Z be defined as the signal-to-interference ratio (SIR)

$$Z \triangleq \frac{W_s}{W_n}, \quad Z \geq 0 \tag{2}$$

where $W_s \geq 0$ and $W_n \geq 0$ are random variables representing the desired signal power and the interference power, respectively. Assuming that W_s and W_n are statistically independent, the resulting cumulative distribution function (CDF) can be expressed as [13]

$$\begin{aligned} F_Z(z_0) &= \text{Prob}\left\{\frac{W_s}{W_n} \leq z_0\right\} \\ &= \int_0^{z_0} dz \int_0^{\infty} y f_{W_s}(zy) f_{W_n}(y) dy \end{aligned} \tag{3}$$

where $f_{W_s}(.)$ and $f_{W_n}(.)$ are the probability density functions (PDFs) of the desired signal power and the interference power, respectively.

Let the number of packets generated in the network for new messages plus retransmissions be Poisson distributed, with mean generation rate of λ packets per second. The mean offered traffic is then expressed as $G = p\lambda$ packets per transmission period. Given the transmission of an arbitrary test packet, the probability of it being overlap by n other packets is given by [13]

$$R_n = \frac{(G\tilde{\tau})^n}{n!} e^{-G\tilde{\tau}} \tag{4}$$

where τ is the worst case propagation delay and $\tilde{\tau} = \tau/p$ its normalised version. Finally, the unconditional probability of a test packet being able to capture the receiver in an arbitrary transmission period may be expressed by

$$P_{capt}(z_0) = 1 - \sum_{n=1}^{\infty} R_n F_Z(z_0). \tag{5}$$

C. Channel Throughput

Let U, B and I be random variables representing, respectively, the duration of the successful transmission, the duration of the busy period and the duration of the idle period. Let E{U}, E{B} and E{I} be their respective expected values. Clearly, the channel throughput can be expressed by

$$S = \frac{E\{U\}}{E\{B\} + E\{I\}}. \tag{6}$$

For nonpersistent CSMA, Kleinrock and Tobagi have shown that [8]

$$E\{B\} = p + 2\tau - \frac{p}{G}\left(1 - e^{-G\tilde{\tau}}\right) \tag{7}$$

and

$$E\{I\} = \frac{p}{G}. \tag{8}$$

It can also be seen that

$$E\{U\} = p\, P_{capt}(z_0) \tag{9}$$

where $P_{capt}(.)$ is the probability of receiver's capture and also it represents the probability of a successful transmission. Using the results of (7)-(9), the throughput can be written as

$$S = \frac{G P_{capt}(z_0)}{G(1+2\tilde{\tau}) + e^{-G\tilde{\tau}}} \tag{10}$$

D. κ-μ Fading Channel

The κ-μ fading model [9] considers clusters of multipath waves propagating in a nonhomogeneous environment. The probability density function (PDF) of the signal envelope r may be expressed as

$$\begin{aligned} f_R(r) =& \frac{2\mu(\kappa+1)^{\frac{\mu+1}{2}}}{\hat{r}\kappa^{\frac{\mu-1}{2}} e^{\kappa\mu}} \left(\frac{r}{\hat{r}}\right)^{\mu} \exp\left[-\mu(\kappa+1)\left(\frac{r}{\hat{r}}\right)^2\right] \\ & \times I_{\mu-1}\left[2\mu\sqrt{\kappa(\kappa+1)}\frac{r}{\hat{r}}\right] \end{aligned} \tag{11}$$

where $\hat{r} = \sqrt{E(R^2)}$ is the rms value of R, $I_\nu(.)$ is the modified Bessel function of the first kind and ν-th order [14, Eq. 9.6.10], $\kappa > 0$ is the ratio between the total power of the dominant components and the total power of the scattered waves, $\mu > 0$ is given by $\mu \triangleq \frac{E^2(R^2)(2\kappa+1)}{V(R^2)(\kappa+1)^2}$, and $E(.)$ and $V(.)$ are the expectation and variance operator, respectively.

Let $W = R^2$ be the signal power and $\overline{w} = \hat{r}^2$ its average value. The signal power PDF may be expressed as

$$\begin{aligned} f_W(w) =& \frac{\mu(\kappa+1)^{\frac{\mu+1}{2}}}{\overline{w}\kappa^{\frac{\mu-1}{2}} e^{\kappa\mu}} \left(\frac{w}{\overline{w}}\right)^{\frac{\mu-1}{2}} \exp\left[-\mu(\kappa+1)\frac{w}{\overline{w}}\right] \\ & \times I_{\mu-1}\left[2\mu\sqrt{\kappa(\kappa+1)\frac{w}{\overline{w}}}\right]. \end{aligned} \tag{12}$$

E. Interference Signal

In a wireless system, interference typically results from signals arriving at the receiver's antenna from multiple transmitters. Depending on how these random signals combine during the observation interval, one of two scenarios might occur [15]: coherent addition or incoherent addition.

Coherent addition occurs if the carrier frequencies are equal and if the random phase fluctuations are small during the capture time t_w. The conditions for the coherent addition of signals to occur are difficult to meet, which makes it a rather unlikely scenario, and will not be considered at this moment.

Incoherent addition occurs if the phases of the individual signals fluctuate significantly due to mutually independent modulation [7], [16]. In this case, the interference power W_n experienced during the observation interval is the sum of the individual signals' powers W_i, i.e.,

$$W_n = \sum_{i=1}^{n} W_i = \sum_{i=1}^{n} \overline{X_i(t) X_i^*(t)} \tag{13}$$

where $X_i^*(.)$ is the complex conjugate of phasor $X_i(.)$. Considering the current work, where the signal power is a random variable, the PDF of the joint interference power is therefore the convolution of the PDFs of all contributing signal powers. If the individual components are independent and identically distributed (i.i.d.), then the interference power is expressed as the n-fold convolution of the PDF of the individual signal power.

TABLE I

RELATION BETWEEN NUMBER OF TERMS AND ACCURACY IN THE INFINITE SUMMATION OF (16).

Parameters					smallest J for accuracy of	
μ_s	μ_n	κ_s	κ_n	$\tilde{z}_0$	3-decimal-place	6-decimal-place
0.5	0.5	0.01	0.01	0.1	3	5
				1.0	9	19
				5.0	34	70
			1.0	1.0	8	15
			10.0	1.0	5	9
		1.0	0.01	1.0	15	31
			1.0	1.0	13	24
			10.0	1.0	8	13
		10.0	0.01	1.0	70	145
			1.0	1.0	54	103
			10.0	1.0	26	41
0.5	1.0	0.01	0.01	1.0	7	13
			1.0	1.0	6	11
			10.0	1.0	5	8
		1.0	0.01	1.0	11	21
			1.0	1.0	10	17
			10.0	1.0	7	11
		10.0	0.01	1.0	45	87
			1.0	1.0	37	65
			10.0	1.0	21	32
	10.0	1.0	1.0	1.0	6	10
1.0	0.5	1.0	1.0	1.0	21	41
	1.0	1.0	1.0	1.0	15	28
	10.0	1.0	1.0	1.0	9	14
10.0	0.5	1.0	1.0	1.0	178	345
	1.0	1.0	1.0	1.0	114	207
	10.0	1.0	1.0	1.0	40	60

III. RESULTS

For the calculations presented in this section, let (12) represent the desired signal power PDF as well as, with different parameters, the signal power PDF of an individual component of the interference signal. Also, for the remaining of this paper and wherever applicable, the subscripts s, i and n are used to represent the desired signal variables, the interference signal's individual component variables, and the joint interference signal variables, respectively. Finally, let $\tilde{z}_0$ be defined as $\tilde{z}_0 \triangleq z_0/(\overline{w}_s/\overline{w}_n)$ where the ratio $\overline{w}_s/\overline{w}_n$ is commonly denoted as average SIR.

For the incoherent addition, assume that the interference signal is composed of n i.i.d. variables. As a result, the joint interference signal power PDF is the n-fold convolution of the individual signal power PDF which, on its turn, is expressed by (12). If the Laplace transform of the PDF is used, then the n-fold convolution can be converted to a n-times product. Using [14, Eqs. 29.2.12 and 29.3.81], the Laplace transform $F_W(s) = L[f_W(w)]$ of (12) can be calculated as

$$F_W(s) = e^{-\kappa\mu}\left(\frac{a}{s+a}\right)^{\mu}\exp\left(\frac{k}{s+a}\right) \tag{14}$$

where $a \triangleq \frac{\mu(\kappa+1)}{\overline{w}}$ and $k \triangleq \frac{\mu^2\kappa(\kappa+1)}{\overline{w}}$. Raising (14) to the n-th power and using [14, Eqs. 29.2.12 and 29.3.81] to calculate its inverse Laplace transform gives the joint interference signal power PDF, which can be expressed as

$$\begin{aligned} f_{W_n}(w_n) =& \frac{\mu_n(\kappa_n+1)^{\frac{\mu_n+1}{2}}}{\overline{w}_n\kappa_n^{\frac{\mu_n-1}{2}}e^{\kappa_n\mu_n}}\left(\frac{w_n}{\overline{w}_n}\right)^{\frac{\mu_n-1}{2}} \\ &\times\exp\left[-\mu_n(\kappa_n+1)\frac{w_n}{\overline{w}_n}\right] \\ &\times I_{\mu_n-1}\left[2\mu_n\sqrt{\kappa_n(\kappa_n+1)\frac{w_n}{\overline{w}_n}}\right]. \end{aligned} \tag{15}$$

It can be seen that the joint interference signal power PDF and the individual signal power PDF follow the same distribution, with $\mu_n = n\mu_i$, $\kappa_n = \kappa_i$ and $\overline{w}_n = n\overline{w}_i$.

Using the appropriated expressions in (3), and after some manipulation (see Appendix), the signal-to-interference CDF may be expressed as

$$\begin{aligned} F_Z(\tilde{z}_0) = \frac{u^{\mu_n}}{e^{\kappa_n\mu_n}}\sum_{j=0}^{\infty}&\frac{(1-u)^{j+\mu_s}Q(j+1,\kappa_s\mu_s)}{(j+\mu_s)B(j+\mu_s,\mu_n)} \\ &\times {}_1F_1(j+\mu_s+\mu_n,\mu_n,\kappa_n\mu_n u) \end{aligned} \tag{16}$$

where $B(.)$ is the beta function [14, Eq. 6.2.2], ${}_1F_1(.)$ is the Kummer confluent hypergeometric function [14, Eq. 13.1.2], $Q(.)$ is the regularized incomplete gamma function defined as $Q(a,b) \triangleq \frac{\Gamma(a,b)}{\Gamma(a)}$, $\Gamma(.)$ is the gamma function [14, Eq. 6.1.1], $\Gamma(.,.)$ is the incomplete gamma function [14, Eq. 6.5.3], and

$$u = \frac{\mu_n(\kappa_n+1)}{\mu_n(\kappa_n+1)+\mu_s(\kappa_s+1)\tilde{z}_0}. \tag{17}$$

If $\mu_s = 1$ and $\mu_n = n$, where $n > 0$ is an integer, the result in (16) simplifies to the case of Rice channel model described in [17]. In addition, if both κ_s and κ_n are set to zero in (16), the CDF simplifies to the Rayleigh channel model and it can be expressed as

$$F_Z(\tilde{z}_0) = 1 - \left(\frac{n}{n+\tilde{z}_0}\right)^n. \tag{18}$$

Finally, if the result above is further simplified by assuming that $\overline{w}_s = \overline{w}_i = \overline{w}_n/n$, then the same expression presented in [7] is found.

Although (16) includes an infinite summation, the evaluation of the CDF converges rapidly for most cases of interest. Let J be defined as the number of terms in a truncated summation, i.e., $0 \leq j < J$. Table I gives the value of J necessary to obtain a three-decimal-place accuracy (error < 0.0005) and a six-decimal-place accuracy (error < 0.0000005) for the infinite summation of (16).

Fig. 1 depicts the CDF of (16) for $\mu = \mu_s = \mu_i = \mu_n/n$ and $\kappa = \kappa_s = \kappa_i = \kappa_n$ and a couple of values of n. The curves for Rice and Rayleigh channels are indicated. The Rayleigh channel is obtained when [9] $\mu = 1$ and $\kappa = 0$, and the Rice channel is obtained when $\mu = 1$ with the Ricean parameter k given by $k = \kappa$. First, it can be seen that larger values of μ concentrate the random outcomes around $\tilde{z}_0 = 1$. This is indicated by the sharp increase of the CDF around this value. Also, larger values of n tend to produce a distribution with lower variance. This is indicated by the steeper climb from zero that curves with larger n experience.

With the results obtained so far, using (5), (10) and (16), it is now possible to calculate the channel throughput, which are

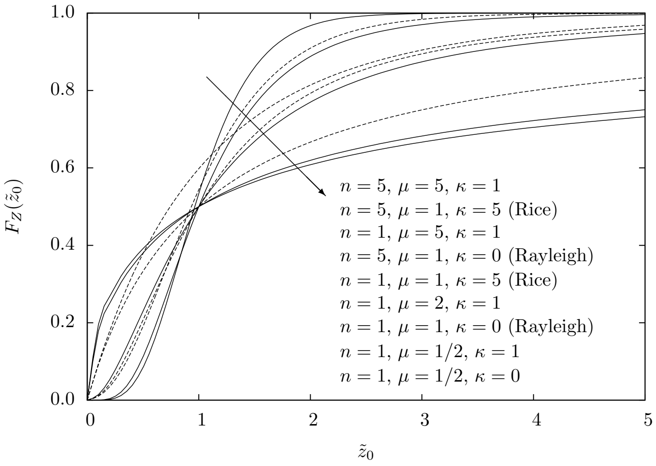

Fig. 1. CDF of (16) with $\mu = \mu_s = \mu_i = \mu_n/n$ and $\kappa = \kappa_s = \kappa_i = \kappa_n$. The dashed lines correspond to the Rice and Rayleigh channels, as indicated.

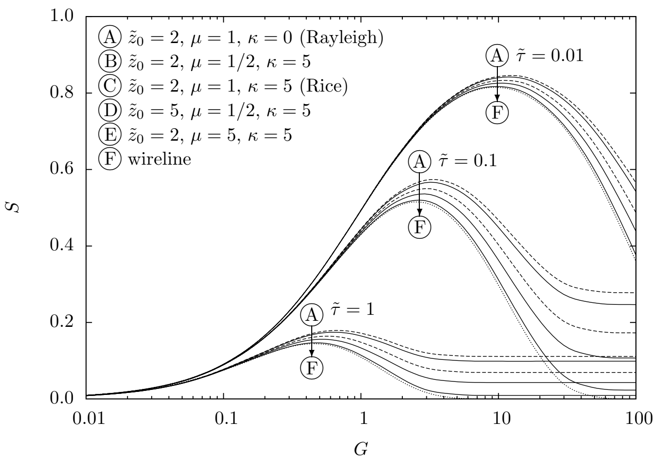

Fig. 2. Throughput S for incoherent $\kappa-\mu$ channel with $\mu = \mu_s = \mu_i = \mu_n/n$ and $\kappa = \kappa_s = \kappa_i = \kappa_n$. The dashed lines correspond to the Rice and Rayleigh channels, as indicated. The dotted lines correspond to the wireline channel ($z_0 \to \infty$).

presented in Fig. 2. The graphics clearly indicate the important role the normalised worst case propagation delay $\tilde{\tau}$ plays to determine the channel throughput. Also, the higher the capture threshold is (indicated by higher $\tilde{z}_0$), the lower the throughput is, which is expected since it indicates a diminished ability of receiver detection of the intended signal among the interfering signals. The fading intensity may be the reason behind the influence of μ, where lower values of μ (i.e., higher fading intensity) produce higher throughput. The parameter κ plays a somewhat smaller influence on the throughput. It can be seen that lower values of κ produce higher fading intensity and, as a result, higher throughput.

IV. Conclusion

This paper investigates the throughput performance of CSMA in a packet radio network and η-μ fading environment. Analytical and numerical results are presented considering the signal capture model with incoherent addition of interfering signals. The approach used here includes the signal capture model with uniform attenuation for all terminals (or perfect power control). The results indicate that higher fading intensity, lower capture threshold or lower propagation delay contributes to higher channel throughput.

Appendix

The calculation presented below refers to the incoherent addition of n interfering signals. Let (12) and (15) be used to describe the desired signal power and the interference power, respectively. With (3), changing the integration order, using [14, Eq. 9.6.10] and integrating over z (see [18, Eqs. 3.381.1, 8.356.3]) leads to

$$\begin{aligned} F_Z(z_0) = &\sum_{k=0}^{\infty} \int_0^{\infty} \frac{(\mu_s\kappa_s)^k \mu_n \kappa_n^{\frac{-\mu_n+1}{2}}}{k!\, e^{\kappa_n\mu_n+\kappa_s\mu_s}} \left(\frac{\kappa_n+1}{\overline{w}_n}\right)^{\frac{\mu_n+1}{2}} \\ &\times y^{\frac{\mu_n-1}{2}} e^{-\frac{\kappa_n+1}{\overline{w}_n}\mu_n y} \\ &\times I_{\mu_n-1}\left(2\mu_n\sqrt{\kappa_n\frac{\kappa_n+1}{\overline{w}_n}y}\right) \\ &\times \left[1 - Q\left(k+\mu_s, \frac{\kappa_s+1}{\overline{w}_s}\mu_s z_0 y\right)\right] dy. \end{aligned} \tag{19}$$

Applying [18, Eq. 8.356.2] recursively, and [14, Eqs. 6.5.3, 6.5.4, 6.5.29], it can be seen that

$$Q(\alpha+n, x) = Q(\alpha, x) + \frac{x^\alpha}{e^x}\sum_{j=0}^{n-1}\frac{x^j}{\Gamma(\alpha+j+1)} \tag{20a}$$

$$= 1 - \frac{x^\alpha}{e^x}\sum_{j=n}^{\infty}\frac{x^j}{\Gamma(\alpha+j+1)}. \tag{20b}$$

Using (20b) in (19) leads to

$$\begin{aligned} F_Z(z_0) = &\sum_{k=0}^{\infty}\sum_{j=k}^{\infty} \int_0^{\infty} \frac{\mu_s^{j+k+\mu_s}\kappa_s^k \mu_n \kappa_n^{\frac{-\mu_n+1}{2}}}{k!\,\Gamma(j+\mu_s+1)\, e^{\kappa_n\mu_n+\kappa_s\mu_s}} \\ &\times \left(\frac{\kappa_s+1}{\overline{w}_s}z_0\right)^{j+\mu_s} \left(\frac{\kappa_n+1}{\overline{w}_n}\right)^{\frac{\mu_n+1}{2}} \\ &\times y^{j+\mu_s+\frac{\mu_n-1}{2}} e^{-\left(\frac{\kappa_s+1}{\overline{w}_s}\mu_s z_0 + \frac{\kappa_n+1}{\overline{w}_n}\mu_n\right)y} \\ &\times I_{\mu_n-1}\left(2\mu_n\sqrt{\kappa_n\frac{\kappa_n+1}{\overline{w}_n}y}\right) dy. \end{aligned} \tag{21}$$

Solving the integral over y (see [18, Eqs. 6.643.2, 9.220.2]) results

$$\begin{aligned} F_Z(z_0) = &\sum_{k=0}^{\infty}\sum_{j=k}^{\infty} \frac{(\mu_s\kappa_s)^k (1-u)^{j+\mu_s} u^{\mu_n}}{k!\, e^{\kappa_n\mu_n+\kappa_s\mu_s}} \\ &\times \frac{\Gamma(j+\mu_s+\mu_n)}{\Gamma(j+\mu_s+1)\Gamma(\mu_n)} \\ &\times {}_1F_1\left(j+\mu_s+\mu_n, \mu_n, \mu_n\kappa_n u\right) \end{aligned} \tag{22}$$

where u is given by (17). Changing the summation order and using [18, Eq. 8.352.2] eliminates the summation on k. From here (16) is easily obtained.

References

[1] R. Verdone, F. Fabbri, C. Buratti, "Area Throughput for CSMA based Wireless Sensor Networks," *19th Intern. Symp. on Personal, Indoor and Mobile Radio Commun.*, PIMRC 2008, 15-18 Sep. 2008, pp. 1-6.

[2] L. Jiang, J. Walrand, "A distributed CSMA algorithm for throughput and utility maximization in wireless networks," *6th Annual Allerton Conf. on Commun., Control, and Computing* 23-26 Sep. 2008, pp. 1511-1519.

[3] H. Kwon, H. Seo, S. Kim, B. Gi Lee, "Generalized CSMA/CA for OFDMA systems: protocol design, throughput analysis, and implementation issues," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 4176-4187, Aug. 2009.

[4] C. Woo Pyo, H. Harada, "Throughput analysis and improvement of hybrid multiple access in IEEE 802.15.3c mm-wave WPAN," *IEEE J. Select Areas Commun.*, vol. 27, pp. 1414-1424, Oct. 2009.

[5] S. A. Qasmi, K. T. Wong, "The probability distribution of the carrier-to-interference ratio (CIR) of a CSMA/CA ad hoc wireless network," *IEEE Military Commun. Conf.*. MILCOM 2005, 17-20 Oct. 2005, pp. 996-1001, vol. 2.

[6] S. Choudhury, J. D. Gibson, "Payload Length and Rate Adaptation for Throughput Optimization in Wireless LANs," *IEEE 63rd. Vehicular Technology Conf.*, VTC 2006-Spring, 7-10 May 2006, pp. 2444-2448, vol. 5.

[7] J. C. Arnbak, W. V. Blitterswijk, "Capacity of Slotted ALOHA in Rayleigh-Fading Channels," *IEEE J. Select Areas Commun.*, vol. 5, pp. 261-269, Feb. 1987.

[8] L. Kleinrock, F. A. Tobagi, "Packet Switching in Radio Channels: Part I — Carrier Sence Multiple-Access Modes and Their Throughput-Delay Characteristics," *IEEE Trans. Commun.*, vol. 23, pp. 1400-1416, Dec. 1975.

[9] M. D. Yacoub, "The κ-μ Distribution and the η-μ Distribution," *IEEE Ant. Propag. Mag.*, vol. 49, n. 1, pp. 68-81, Feb. 2007.

[10] J. H. Kim, J. K. Lee, "Capture effects of wireless CSMA/CA protocols in Rayleigh and shadow fading channels," *IEEE Trans. Veh. Technol.*, vol. 48, n. 4, pp. 1277-1286, Jul. 1999.

[11] B. Zhang *et al.*, "Exploiting multiuser diversity in random reservation access," *IEEE Trans. Wireless Commun.*, vol. 5, pp. 2548-2554, Sep. 2006.

[12] J.-P. Linnartz *et al.*, "Near-far effects in land mobile random access networks with narrow-band Rayleigh fading channels," *IEEE Trans. Veh. Technol.*, vol. 41, pp. 77-90, Feb. 1992.

[13] A. Papoulis, *Probability, random variables, and stochastic processes*, 3rd. ed., New York, McGraw-Hill, 1991.

[14] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions*, 10th. print., Washington, National Bureau of standards, 1972.

[15] J.-P. Linnartz, *Narrowband land-mobile radio network*, Norwood, Artech House, 1993.

[16] R. Prasad and A. Kegel, "Improved Assessment of Interference Limits in Cellular Radio Performance," *IEEE Trans. Veh. Technol.*, vol. 40, pp. 412-419, May 1991.

[17] E. J. Leonardo, M. D. Yacoub, "Throughput of CSMA in Rice fading channels," *4th Intern. Conf. Signal Proc. Commun. Systems*, 13-15 Dec. 2010, pp. 1-5.

[18] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 5th. ed., San Diego, Academic Press, 1994.