A First-Order Markov Model for Correlated Nakagami-m Fading Channels

A. Ramesh*, A. Chockalingam† and L. B. Milstein‡
* Wireless and Broadband Communications
Synopsys (India) Pvt. Ltd., Bangalore 560095, INDIA
† Department of Electrical Communication Engineering
Indian Institute of Science, Bangalore 560012, INDIA
‡ Department of Electrical and Computer Engineering
University of California, San Diego, La Jolla, CA 92093, U.S.A

***Abstract*— In this paper, we propose a first-order Markov model for generalized Nakagami-m flat fading channels. Using a moment generating function (MGF) approach, we derive the parameters of the proposed model for any value of the fading severity index $m \geq 0.5$. The proposed model is a generalized version of the one proposed earlier by Zorzi *et al* for flat Rayleigh fading channels. For $m = 1$, we show that our generalized model gives the same parameter values obtained using Zorzi's approach. Our generalized model thus encompasses Zorzi's model as a special case. We illustrate the usefulness of our proposed Markov model by applying it to the analysis of the throughput and energy efficiency performance of a link layer (LL) protocol with backoff on wireless fading links with different values of the m-parameter ($= 0.5, 1, 4$).**

***Keywords* – Nakagami-m fading, Markov model, LL protocols.**

I. Introduction

Recently, there has been a growing interest in developing simple, finite-state Markovian models to represent wireless fading channels [1]-[5]. The motivation has been the resulting tractability of performance analysis of complex protocols on wireless channels, design of channel prediction based protocols for wireless, and design of low complexity channel simulators. A popular idea in this regard is to develop first-order Markov representations of fading channels [1],[2]. Efforts to develop K-state Markov models have also been reported [3],[5]. The approaches that are typical in deriving Markov channel models have been based on $a)$ a mutual information theoretic approach [1],[2],[3], which involves the derivation of joint pdf of successive samples in the fading process, and $b)$ level crossing rates [6],[7].

In [1], Wang investigated the accuracy of a first-order Markov process in modeling data transmission on a flat Rayleigh fading channel. The process he refers to is the sequence of fade amplitudes in a correlated Rayleigh fading process (i.e., the envelope of the complex Gaussian process used to model the multiplicative effect of the channel). Zorzi *et al*, in [2], pointed out that the success/failure process of data blocks on a fading channel is important, and developed a first-order binary Markov model for the packet success/failure process on flat Rayleigh fading channels. The Markov model parameters were derived in terms of the normalized Doppler bandwidth and the channel fading margin. In Zorzi's approach, the computation of Markov parameters involve evaluation of the Marcum-Q function.

This work was supported in part by the Office of Naval Research under grant N00014-98-1-0875, and by the TRW foundation.

The Markov model in [2] has been used in the design and performance analysis of various wireless protocols. For example, in [8], the performance of a wireless access protocol on Rayleigh fading has been analyzed using the Markov channel model in [2]. The energy efficiency of this protocol is analyzed in [9], where the Markov channel model provided a simple and tractable mechanism to analyze and compare the performance of different versions of the protocol. Further, the throughput analysis of TCP on fading channels with memory in [10] also adopted the first-order Markov model in [2].

In this paper, we extend the Markov channel model proposed by Zorzi *et al* in [2] to a correlated Nakagami-m fading channel. While [2] provides the Markov model for a flat Rayleigh fading channel, we, in this paper, derive a first-order Markov model for generalized Nakagami-m fading channels, using a moment generating function (MGF) approach. We derive the parameters of the proposed model for any value of the fading severity index $m \geq 0.5$. The computation of the model parameters in our approach does not involve evaluation of the Marcum-Q function as in [2]. For $m = 1$, we show that our generalized model gives the same parameter values obtained using Zorzi's approach in [2]. Our generalized model thus encompasses Zorzi's model as a special case of $m = 1$. We also illustrate the usefulness of our proposed Markov model by applying it to the analysis of the throughput and energy efficiency performance of a link layer protocol with backoff on wireless fading links with different values of the m-parameter ($= 0.5, 1, 4$).

The rest of the paper is organized as follows. In Section II, the Markov modeling of the Nakagami-m fading channel is presented. The derivation of the model parameters is given in

Section III. An illustration of the application of the proposed model to the analysis of a link layer protocol with backoff is presented in Section IV. Conclusions are provided in Section V.

II. Markov Modeling of Fading Channel

We assume that the channel fading process, $\alpha(t)$, is frequency non-selective (flat) and slowly fading. $\alpha(t)$ is assumed to be Nakagami-m distributed and the marginal density function of the associated random variable, α, at time t (i.e., $\alpha = \alpha(t)$) is given by

$$f_\alpha(x) = \frac{2m^m}{\Gamma(m)} e^{-mx^2} x^{2m-1}, \quad x \geq 0, \tag{1}$$

where $\Gamma(\cdot)$ is the standard Gamma function [11] and m is the fading severity index [12]. In Eqn. (1) we normalized the second moment of the fading process to unity (i.e., $E(\alpha^2) = 1$). Furthermore, the joint density function of two Nakagami-m random variables, $\alpha(t)$ and $\alpha(t+\tau)$, separated by τ units apart, is given by [12]

$$\begin{aligned} f_{\alpha(t),\alpha(t+\tau)}(x,y) &= \frac{4m^{m+1}(xy)^m}{\Gamma(m)(1-\rho)(\rho)^{\frac{m-1}{2}}} e^{-\frac{m}{1-\rho}(x^2+y^2)} \\ &\quad \cdot I_{m-1}\left(\frac{2\sqrt{\rho}}{1-\rho} xym\right), \end{aligned} \tag{2}$$

where ρ is the correlation coefficient between $\alpha^2(t)$ and $\alpha^2(t+\tau)$ and is expressed as

$$\rho = \frac{\text{cov}(\alpha^2(t), \alpha^2(t+\tau))}{\sqrt{\text{var}(\alpha^2(t))\text{var}(\alpha^2(t+\tau))}}. \tag{3}$$

In general, the correlation coefficient ρ depends on the channel parameters like the Doppler bandwidth, f_d, and the time interval under consideration, T [13]. As in [14], [7], we take the correlation factor, ρ, in the fading process to be $J_0^2(2\pi f_d T)$, where $J_0(\cdot)$ is the zeroth order Bessel function of the first kind.

We assume that the fading process is time-discretized in units of one data block interval, i.e., $\alpha_n = \alpha(nT)$, where T is the data block (packet) duration. The amplitude of the fading process is partitioned into two disjoint sets, $(0, \Delta)$ and (Δ, ∞). Since the fading process is correlated, we use a memory based model to characterize its evolution. In particular, we use a first-order Markov model to characterize the successes/failures in packet transmissions. We define S_n, $n = 0, 1, \ldots$, $S_n \in \{0, 1\}$, as the success-failure process of the packet transmissions on the fading channel. Let $S_n = 1$ and 0 denote the success and failure, respectively, of a packet at time instant nT. $S_n = 1 \Leftrightarrow \alpha_n \in (\Delta,\ \infty)$ and $S_n = 0 \Leftrightarrow \alpha_n \in (0,\ \Delta)$. It is noted that the threshold to compare the received signal power for making the packet success/failure decision is given by $1/C_{FM}$ [2], where C_{FM} is the channel fade margin. Accordingly, Δ is related to C_{FM} as $\Delta^2 = 1/C_{FM}$. The transition probabilities of the above described chain are given by

$$\begin{aligned} p &= \text{Prob}(S_n = \text{success}|S_{n-1} = \text{success}) \\ &= \frac{\text{Prob}(S_n = \text{success}, S_{n-1} = \text{success})}{\text{Prob}(S_{n-1} = \text{success})}, \\ &= \frac{\int\limits_{x=\Delta}^{\infty}\int\limits_{y=\Delta}^{\infty} f_{\alpha_{n-1},\alpha_n}(x,y)dxdy}{\int\limits_{x=\Delta}^{\infty} f_{\alpha_{n-1}}(x)dx}, \end{aligned} \tag{4}$$

and

$$\begin{aligned} q &= \text{Prob}(S_n = \text{failure}|S_{n-1} = \text{failure}) \\ &= \frac{\text{Prob}(S_n = \text{failure}, S_{n-1} = \text{failure})}{\text{Prob}(S_{n-1} = \text{failure})}, \\ &= \frac{\int\limits_{x=0}^{\Delta}\int\limits_{y=0}^{\Delta} f_{\alpha_{n-1},\alpha_n}(x,y)dxdy}{\int\limits_{x=0}^{\Delta} f_{\alpha_{n-1}}(x)dx}. \end{aligned} \tag{5}$$

Define $F_\alpha(x)$, the marginal cumulative distribution function (cdf) of r.v α_n (or α_{n-1}), and $F_{\alpha_{n-1},\alpha_n}(x,y)$, the joint cdf of r.v's α_n and α_{n-1}. With this notation, Eqns. (4) and (5) can be simplified as

$$p = \frac{1 - F_{\alpha_n}(\Delta) - F_{\alpha_{n-1}}(\Delta) + F_{\alpha_{n-1},\alpha_n}(\Delta,\Delta)}{1 - F_{\alpha_{n-1}}(\Delta)}, \tag{6}$$

and

$$q = \frac{F_{\alpha_{n-1},\alpha_n}(\Delta,\Delta)}{F_{\alpha_{n-1}}(\Delta)}. \tag{7}$$

The Markov parameters p and q for a Nakagami-m fading channel are computed in Section III. We define $\underline{\pi} = [\pi_b, \pi_g]$ as the steady-state probability vector, where π_b and π_g are the steady-state probabilities of being in packet failure state and success state, respectively. Assuming stationarity of the Markov chain, the $\underline{\pi}$ vector can be obtained by solving $\underline{\pi} = \underline{\pi}\mathbf{P}$, where $\mathbf{P}$ is the transition probability matrix, which is given by

$$\mathbf{P} = \begin{bmatrix} q & 1-q \\ 1-p & p \end{bmatrix}. \tag{8}$$

The steady-state probabilities can be computed as

$$\pi_b = \frac{1-p}{2-p-q}, \tag{9}$$

and

$$\pi_g = \frac{1-q}{2-p-q}. \tag{10}$$

The average probability of error is given by $\epsilon = \pi_b = \frac{1-p}{2-p-q}$ and the average length of burst errors, L_e, is given by $L_e = (1-q)^{-1}$.

III. Computation of Model Parameters

In this section, we derive the Markov model parameters p and q for Nakagami-m fading channels. In [15], Tellambura *et al* presented a unified approach to calculate the error probability and outage probability of binary and M-ary signals on dual-branch selection diversity Nakagami-m fading channels. Their approach is based on contour integral representation of the generalized Marcum-Q function [11] and application of the moment generating function approach. Their results are valid for correlation coefficient, $\rho, \neq \{0,1\}$ and for $m \geq 0.5$. In our approach to calculate the Markov parameters p and q, we make use of a result derived in [15]. In particular, we use the joint CDF of two space-correlated r.v's to obtain $F_{\alpha_{n-1},\alpha_n}(\Delta,\Delta)$ required in Eqn. (6) and (7). This is described as follows.

Let r_1 and r_2 be the fade r.v's on the first and second antenna, respectively, and r be the output of the selection diversity combiner (i.e., $r = \max(r_1, r_2)$). Denoting the CDF of r as $F_R()$, we have the following:

$$\begin{aligned} F_R(u) &= \text{Prob}(r \leq u) \\ &= \text{Prob}(max(r_1, r_2) \leq u) \\ &= \text{Prob}(r_1 \leq u, r_2 \leq u) \\ &= F_{R_1,R_2}(u,u). \end{aligned} \quad (11)$$

Now, if we replace u by Δ in the above and let $R_1 = \alpha_{n-1}$ and $R_2 = \alpha_n$, we get the desired CDF $F_{\alpha_{n-1},\alpha_n}(\Delta,\Delta)$. In what follows, we follow the notations in [15] for the derivation of $F_{\alpha_{n-1},\alpha_n}(\Delta,\Delta)$. We write $F_{\alpha_{n-1},\alpha_n}(\Delta,\Delta)$ as [15]

$$\begin{aligned} F_{\alpha_{n-1},\alpha_n}(\Delta,\Delta) &= \text{Prob}(\alpha_{n-1} \leq \Delta, \alpha_n \leq \Delta) \\ &= \text{Prob}(\max(\alpha_{n-1}, \alpha_n) \leq \Delta) \\ &= \text{Prob}(\beta \leq \Delta^2) \end{aligned}$$

$$= \frac{1}{2} - \frac{2}{\pi} \int_{\theta=0}^{\frac{\pi}{2}} \textbf{Im}\left[\phi_\beta(-j\tan\theta) e^{-j\Delta^2 \tan\theta}\right] \frac{1}{\sin 2\theta} d\theta, \quad (12)$$

where $\beta = \max(\alpha_{n-1}^2, \alpha_n^2)$, $\phi_\beta(s) = E[e^{-s\beta}]$ is the moment generating function of the r.v β. ¿From [15], $\phi_\beta(s)$ can be computed as

$$\begin{aligned} \phi_\beta(s) = & \frac{2^{2m+1}\Gamma(2m)}{\Gamma(m)\Gamma(m+1)} \frac{(A^2(s)m)^m}{[(1+B(s))B(s)]^m} \\ & \cdot 2^{F_1}\left(1-m, m, ; 1+m, \frac{1 - \frac{1}{B(s)}}{2}\right), \end{aligned} \quad (13)$$

where $2^{F_1}(\cdot,\cdot;\cdot;\cdot)$ is the Gauss hypergeometric function [16], and $A(s)$ and $B(s)$ are defined as

$$A(s) = \frac{1}{s}\sqrt{\frac{m}{2(1-\rho)}}, \quad (14)$$

and

$$B(s) = \frac{\sqrt{[s(1-\rho)+2m]^2 - 4m^2\rho}}{s(1-\rho)}, \quad (15)$$

respectively. For $m = 1/2$ and $m = 1$, $\phi_\beta(s)$ reduces to the following, much simpler to compute, expressions

$$\phi_\beta(s) = \frac{8\sqrt{2}}{\pi} \frac{A(s)}{\sqrt{B^2(s)-1}} \sin^{-1}\left(\sqrt{\frac{B(s)-1}{2B(s)}}\right), \quad (16)$$

and

$$\phi_\beta(s) = \frac{8A^2(s)}{B(s)(1+B(s))}, \quad (17)$$

respectively.

The marginal cdf, $F_\alpha(\Delta)$, can be derived as follows.

$$\begin{aligned} F_\alpha(\Delta) &= \int_{x=0}^{\Delta} \frac{2m^m}{\Gamma(m)} e^{-mx^2} x^{2m-1} dx \\ &= \frac{\Gamma(m\Delta^2, m)}{\Gamma(m)}, \end{aligned} \quad (18)$$

where

$$\Gamma(u,n) = \int_{x=0}^{u} e^{-x} x^{n-1} dx. \quad (19)$$

Substituting Eqns. (18) and (12) into Eqns. (6) and (7), for the desired value of m, we get the parameters $\mathbf{P}$, L_e, and ϵ of the first-order Markov model of the Nakagami-m fading channel, in terms of the normalized Doppler bandwidth, $f_d T$, and the channel fade margin, C_{FM}.

Table I gives the Markov model parameters p and q computed as per Eqns. (6) and (7), for different values of the Nakagami-m parameter ($m = 0.5, 1, 4$), normalized Doppler bandwidth ($f_d T = 0.01, 0.08, 0.64$), and channel fade margin (C_{FM} = 30,20,10 dB). The average packet error probability, ϵ, and the burst error length, L_e, are also given. Note that $m = 1$ corresponds to Rayleigh fading, $m = 0.5$ characterizes a severe, one-sided Gaussian distributed fading process, and $m = 4$ characterizes light fading conditions which are typical of a Ricean distribution with a line-of-sight path in addition to diffused paths [11]. Also, an $f_d T$ value of 0.01 represents a highly correlated fading process (low mobile speeds), whereas an $f_d T$ value of 0.64 represents a less correlated fading process (high mobile speeds).

We point out that the p and q parameters for $m = 1$ in Table I are exactly the same as those obtained through Zorzi's model in [2] (see Table I, pp. 1292 in [10]). This validates our moment generating function approach to compute the model parameters. Our generalized approach thus encompasses Zorzi's model as a special case for $m = 1$. In addition, our MGF approach provides the parameter values for any value of $m \geq 0.5$. From Table I, it is further noted that

m	f_dT	C_{FM} (dB)	p	q	ϵ	L_e
4.0	0.01	29.99	0.9999	0.0570	1.065e-11	1.0605
		19.98	0.9999	0.5338	1.053e-07	2.1453
		9.77	0.9998	0.8591	9.405e-04	7.0973
	0.08	29.99	0.9999	3.27e-3	1.065e-11	1.0032
		19.98	0.9999	3.18e-4	1.053e-07	1.0003
		9.77	0.9992	1.59e-1	9.405e-04	1.1894
	0.64	29.99	0.9999	3.71e-3	1.065e-11	1.0037
		19.98	0.9999	5.78e-7	1.053e-07	1.0000
		9.77	0.9990	1.65e-3	9.405e-04	1.0016
1.0	0.01	29.99	0.9993	0.3294	1.000e-03	1.4913
		19.98	0.9975	0.7543	1.000e-02	4.0701
		9.77	0.9918	0.9268	1.000e-01	13.6708
	0.08	29.99	0.9990	0.0082	1.000e-03	1.0083
		19.98	0.9906	0.0772	1.000e-02	1.0837
		9.77	0.9403	0.4631	1.000e-01	1.8628
	0.64	29.99	0.9990	0.0011	1.000e-03	1.0023
		19.98	0.9900	0.0118	1.000e-02	1.0119
		9.77	0.9018	0.1163	1.000e-01	1.1317
0.5	0.01	29.99	0.9877	0.5268	2.523e-02	2.1133
		19.98	0.9870	0.8594	7.985e-02	7.1165
		9.77	0.9812	0.9450	2.545e-01	18.1862
	0.08	29.99	0.9761	0.0077	2.523e-02	1.0841
		19.98	0.9331	0.2291	7.985e-02	1.2972
		9.77	0.8611	0.5933	2.545e-01	2.4593
	0.64	29.99	0.9748	0.0293	2.523e-02	1.0302
		19.98	0.9209	0.0886	7.985e-02	1.0972
		9.77	0.7525	0.2751	2.545e-01	1.3795

TABLE I

MARKOV MODEL PARAMETERS p AND q FOR DIFFERENT VALUES OF m, f_dT, AND C_{FM}.

the burst error length, L_e, gets increasingly large as the fading gets severe (i.e., small values of m) and as the correlation gets larger (i.e., small values of f_dT). For example, when $f_dT = 0.01$, L_e is 18.2 for $m = 0.5$, 13.7 for $m = 1$, and 7.1 for $m = 4$, which is expected. Also, as f_dT gets large, the channel behaves almost like an i.i.d channel (i.e., $L_e \approx 1.0$) for $f_dT = 0.08$ and 0.64 in the case of $m = 4$, and for $f_dT = 0.64$ in the case of $m = 0.5$. We can also observe that for a given fade margin, C_{FM}, the average packet error rate, ϵ, decreases with increasing values of m. This again is expected because the intensity of fading is less for large m.

IV. APPLICATION OF MARKOV MODEL TO LL PROTOCOL PERFORMANCE ANALYSIS

In this section, we apply the proposed first-order Markov model to analyze the performance of link layer protocols on Nakagami-m fading channels. We consider two protocols, namely, 1) an ideal selective repeat (SR) ARQ protocol, and 2) an ARQ protocol with geometric backoff (GBO), which is proposed and analyzed in [17].

A. Selective Repeat ARQ (SR)

In this protocol, the receiver asks for the retransmission of only those LL packets which are detected to be in error. The throughput of the ideal SR ARQ protocol is given by $\eta_{SR} = 1 - \epsilon$ [18]. We define one energy unit as the energy spent in the transmission of a LL packet at a fade margin, C_{FM}, of 0 dB. Accordingly, the energy efficiency, ξ, is defined as the ratio of successful packet transmissions to the total number of packet transmissions, normalized by the fade margin. The energy efficiency of the SR ARQ protocol is given by $\xi_{SR} = (1-\epsilon)/C_{FM}$.

B. ARQ with Geometric Backoff (GBO)

In this scheme [17], we define a parameter g, $0 < g \leq 1$, called the *geometric backoff factor*. Following an idle or LL packet failure, the LL leaves the channel idle in the next slot with probability g (or equivalently, the LL transmits a packet with probability $1-g$). With this scheme, the expected number of backoff (idle) slots following a packet failure is given by $g/(1-g)$ [17]. The motivation for the above backoff strategy is to save energy by not transmitting packets during deep fade conditions.

Assuming the proposed first-order Markov model for the fading channel, and due to the memoryless property of the geometric backoff, we can model the system with a finite state Markov-chain. The system status in a slot can be in any one of *success*, *failure*, *idle with possible success* and *idle with possible failure* states. We denote these states by s, f, i_s and i_f, and their the steady-state probabilities by π_s, π_f, π_{is} and π_{if}, respectively. Denoting the steady state-probability vector $\pi_{gbo} = [\pi_s \, \pi_f \, \pi_{is} \, \pi_{if}]$, π_{gbo} can be obtained by solving $\pi_{gbo} = \pi_{gbo}\mathbf{T}$, where $\mathbf{T}$ is the transition probability matrix of the GBO system, which can be written as [17]

$$\mathbf{T} = \begin{bmatrix} p & (1-p) & 0 & 0 \\ (1-g)(1-q) & (1-g)q & g(1-q) & gq \\ (1-g)p & (1-g)(1-p) & gp & g(1-p) \\ (1-g)(1-q) & (1-g)q & g(1-q) & gq \end{bmatrix}. \quad (20)$$

Solving $\pi_{gbo} = \pi_{gbo}\mathbf{T}$, the expressions of of π_s, π_f, π_{is}, and π_{if} can be obtained as [17]

$$\pi_s = \frac{(1-g)(1-q)}{(2-p-q)(1-gp)}, \quad (21)$$

$$\pi_f = \frac{(1-p)(g^2(p+q-1) - g(p+q) + 1)}{(2-p-q)(1-gp)} \quad (22)$$

and

$$\pi_i = \pi_{i_s} + \pi_{i_f} = 1 - \pi_s - \pi_f. \quad (23)$$

The throughput of the GBO scheme, η_{gbo} is given by π_s and the energy efficiency of this scheme can be computed as $\xi_{gbo} = \frac{1}{C_{FM}} \cdot \frac{\pi_s}{\pi_s + \pi_f}$.

The throughput performance of the SR and GBO protocols are computed for $m = 0.5, 1$, and 4, and plotted as a function of fade margin in Figs. 1, for a fixed normalized Doppler bandwidth $f_dT = 0.001$. The required p and q values to be used in Eqns. (20) are obtained from the Markov model parameter computation derived in Sections II and III. The parameter g for the GBO is taken to be 0.2. At 900 MHz carrier frequency, $f_dT = 0.001$ corresponds to mobile speed of 1.2 Kmph, link speed of 1 Mbps and LL packet size of 1000 bits. As expected, the throughput performance is better for $m = 4$

compared to $m = 1$ and 0.5. The results for $m = 1$ match with the results in [17] for Rayleigh fading channels. In Fig. 2, the energy efficiency versus throughput performance is plotted. It is observed that the GBO backoff protocol gives appreciable energy savings without much loss in throughput performance compared to the ideal SR protocol. The energy savings due to backoff is larger for severe fading conditions ($m = 0.5$).

V. CONCLUSION

In this paper, we proposed a first-order Markov model for generalized Nakagami-m flat fading channels. Using a moment generating function MGF approach, we derived the parameters of the proposed model for any value of the Nakagami-m parameter $m \geq 0.5$. The proposed model is a generalized version of the one proposed earlier by Zorzi *et al* for flat Rayleigh fading channels. We showed that, for $m = 1$, our generalized model gives the same parameter values as obtained using Zorzi's approach. We also applied the proposed Markov model to the analysis of the throughput and energy efficiency performance of link layer protocols on wireless fading links with different values of the m-parameter.

REFERENCES

[1] H. S. Wang, "On verifying the first-order Markovian assumption for a Rayleigh fading channel model," *Proc. ICUPC'94*, pp. 160-164, September 1994. Also in *IEEE Trans. on Veh. Tech.*, vol. 45, pp. 353-357, May 1996.

[2] M. Zorzi, R. R. Rao, and L. B. Milstein, "On the accuracy of first-order Markov model for data transmission on fading channels," *Proc. IEEE ICUPC'95*, pp. 211-215, November 1995.

[3] H. S. Wang and N. Moayeri, "Finite-state Markov channel – A useful model for radio communication channels," *IEEE Trans. on Veh. Tech.*, vol. 44, pp. 163-171, February 1995.

[4] F. Babich, G. Lombardi, "A Markov model for the mobile propagation channel," *IEEE Trans. Veh. Tech.*, vol. 49, no. 1, pp. 63-73, January 2000.

[5] C. C. Tan and N. C. Beaulieu, "On first-order Markov modeling for the Rayleigh fading channel," *IEEE Trans. on Commun.*, vol. 48, no. 12, pp. 2032-2040, December 2000

[6] M. D. Yacoub, E. V. Bautista, and L. Guerra de Rezende Guedes, "On higher order statistics of the Nakagami-m distribution," *IEEE Trans. on Veh. Tech.*, vol. 48 no. 3, pp. 790-794, May 1999.

[7] T. T. Tjhung and C. C. Chai, "Fade statistics in Nakagami-Lognormal channels," *IEEE Trans. on Commun.*, vol. 47, no. 12, pp. 1769-1772, December 1999.

[8] A. Chockalingam, M. Zorzi, L. B. Milstein, and P. Venkataram, "Performance of a wireless access protocol on correlated Rayleigh-fading channels with capture," *IEEE Trans. on Commun.*, vol. 46, no. 5, May 1998.

[9] A. Chockalingam and M. Zorzi, "Energy efficiency of media access protocols for mobile data networks," *IEEE Trans. on Commun.*, vol. 46, no.11, pp. 1418-1421, November 1998.

[10] M. Zorzi, A. Chockalingam, and R. R. Rao, "Throughput analysis of TCP with memory," *IEEE Jl. Sel. Areas in Commun.*, vol. 18, no. 7, pp. 1289-1300, July 2000.

[11] J. G. Proakis, *Digital Communications*, McGraw-Hill, 1995.

[12] M. Nakagami, "The m-distribution- A general formula of intensity distribution of rapid fading," *Statistical Methods in Radio Wave Propagation*, pp. 3-36, Pregamon Press, Oxford, U. K., 1960.

[13] W. C. Jakes, *Microwave Mobile Communications*, IEEE Press, 1974.

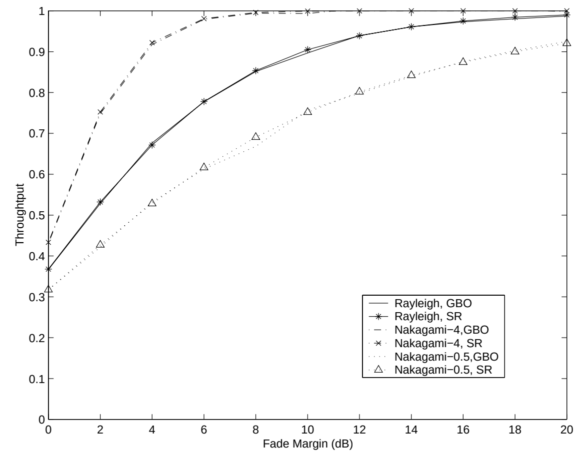

Fig. 1. LL throughput vs fade margin performance of SR and GBO ARQ protocols. $f_d T = 0.001$, $g = 0.2$, $m = 0.5, 1, 4$.

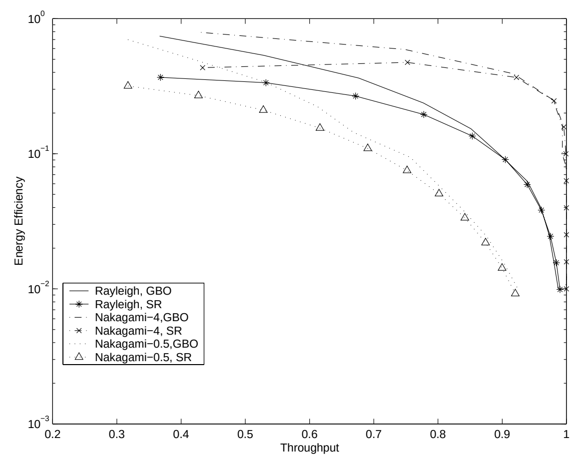

Fig. 2. Energy efficiency vs throughput performance of SR and GBO ARQ protocols. $f_d T = 0.001$, $g = 0.2$, $m = 0.5, 1, 4$.

[14] N. B. Mehta and A. Goldsmith, "Performance analysis of link adaptation in wireless data networks," *Proc. IEEE GLOBECOM'2000*, San Francisco, 2000.

[15] C. Tellambura, A. Annamalai, and V. K. Bhargava, "Contour integral representation for generalized Marcum-Q function and its application to unified analysis of dual-branch selection diversity over correlated Nakagami-m fading channels," *Proc. IEEE VTC'2000*, pp. 1031-1034, 2000.

[16] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions with formulas, graphs, and mathematical tables*, New York: Dover, 1968.

[17] P. M. Soni and A. Chockalingam, "Analysis of link layer backoff schemes on point-to-point Markov fading Links," *Proc. PIMRC'2000. Also accepted in IEEE. Trans. on Commun.*

[18] D. Bertesakas and R. Gallager, *Data Networks*, Prentice-Hall, Englewood Cliffs, New Jersey, 1987.