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Differential Maximum Ratio Combining (MRC)-Based Throughput Analysis on Dual-Fading Models of Slotted-Aloha CDMA Systems

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Abstract In this paper we investigate throughputs of Slotted-ALOHA code division multiple access systems with differential detection upon ***L***-branch antenna by means of maximum ratio combining (MRC) diversity technique. We investigate the effects of co-channel interference by employing two different fading models (i.e. between the desired signals and its interferences.) We consider systems under Nakagami/Nakagami and Rician/Nakagami fading environments. The purpose of employing MRC diversity and differential phase shift keying with ***L***-branch antenna is to overcome multipath fading interference in order to enhance the performance of the systems. Our research indicates that the implementation of ***L***-branch antenna in the receiver have reasonably increased the throughputs of the systems. Furthermore, we also investigate the inverse relation between interference signal and the throughputs of the systems. We further point out that the value of Nakagami fading parameter ***M*** and Rician factor ***K*** are proportional to the achievable throughputs of the systems.

Keywords Slotted-ALOHA code division multiple access systems · Maximum ratio combining · Differential phase shift keying · Nakagami and Rician fading models

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1 Introduction

Multipath fading and interference adversely affects data packet being transmitted via wireless communication channels. Not only can they suppress the quality of the received signal but they also can cause interference due to the implementation of the frequency reuse within cellular communication systems. In mobile communication systems, co-channel interference due to the use of frequency reuse is a real disturbance. Given the nature of adverse fading environment, the desired signals and its interference may have different fading characteristics [1].

The performance of S-ALOHA systems over fading channel is well- studied. Interested readers can refer to the prior researches due to Sheikh et al. [2]. The performance analysis of S-ALOHA over Rayleigh fading channels was conducted by Roberts and Healy [3] and Anbark and Van Blitterswijk [4]. Similarly, the performance of S-ALOHA systems over Nakagami/Nakagami fading channels with the same value of parameters for test and interfering packets was investigated by Al-semari and Mohsen Guizani [5]. Furthermore, bit error rate (BER) calculation could be performed on CDMA systems by taking various models of channels i.e. Rayleigh-based fading model that already takes Rician and Nakagami into account. Also, Hafez and Alagoz [6] analysed the up/down link CDMA receiver using maximum ratio combining (MRC) diversity technique with coherent detection and differential detection affected by multiple access interference (MAI). Meanwhile, in [7], the desired signal and the interference were conditioned under Rayleigh fading. Also, [8] modelled the desired signal using Rician fading model and interference signal employing Rayleigh fading condition.

In order to overcome co-channel interference, Yao and Sheik [9] proposed the use of diversity technique selection and represented the channel condition using Nakagami/Nakagami model. Damar proposed the use of single MRC diversity antenna technique and employed Nakagami/Nakagami fading model [10]. Meanwhile, Gunawan applied diversity technique MRC upon ***L***-branch antenna and employed Nakagami/Nakagami and Rician/Nakagami models to represent the condition of the channel [11].

Our main contribution in this paper, extending our previous work in [12, 13], is to investigate the throughputs of differential MRC-based CDMA ALOHA systems over two fading models under Nakagami/Nakagami and Rician/Nakagami fading channels. We believe our approach is the first in the literature that is easy to compute and feasible for practical implementation. We further proceed as follows. While Sect. 2 depicts the model of the system, our discussion in Sect. 3 delineates our mathematical model and analysis. Lastly, conclusions will be subsequently drawn in Sect. 4.

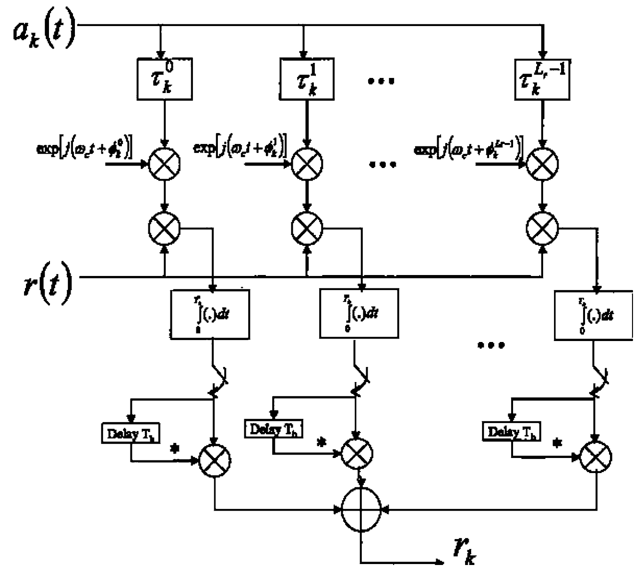

Fig. 1 Differential detection based MRC receiver [5]

2 Mathematical Mobels of the Systems

2.1 Model of the Transmitter

To model the dynamics of the transmitter, we consider the following scenario. Each user shall transmit the average power P_k $(1 \leq k \leq K)$, on the carrier frequency $f_c = \frac{\omega_c}{2\pi}$ with data rate $R_b = \frac{1}{T_b}$ and chip rate $R_c = \frac{1}{T_c}$. Every user is also assigned a unique spreading code sequence, $a_{k,j} \in \{-1, +1\}$ with waveform code given by:

$$a_k(t) = \sum_{j=-\infty}^{\infty} a_{k,j} p_{T_c}(t - jT_c) \tag{1}$$

The mathematical expression of kth data user signal that carry data element $b_{k,j} \in \{-1, +1\}$ is given by:

$$b_k(t) = \sum_{j=-\infty}^{\infty} b_{k,j} p_{T_b}(t - jT_b), \tag{2}$$

in which, $\rho_T(t)$ is a unit rectangular pulse within the duration of T, the chip duration is denoted by T_c, and bit duration is denoted by T_b, while $\eta = \frac{T_b}{T_c}$ is the processing gain.

Furthermore, the transmitted signal by kth user is given by:

$$S_k(t) = \sqrt{2P_k} a_k(t) b_k(t) \cos(\omega_c t + \Phi_k), \tag{3}$$

in which phase angle Φ_k is assumed to be uniformly distributed within $[0, 2\pi]$. S_T (t) is the sum of all existing signals over k user in the system and can be mathematically represented by:

$$S_T(t) = \sum_{k=1}^{K} S_k(t). \tag{4}$$

2.2 Model of the Channel

In our research, fading is represented by a linear filter where the characteristic of kth user in regards to a complex-valued low-pass equivalent impulse response is given by:

$$h_k(t) = \sum_{l=0}^{L_K-1} \beta_k^l e^{-j\theta_k^l} \delta(t - \tau_k^l) \tag{5}$$

where β_k^l is the attenuation factor, τ_k^l is the delay, θ_k^l is the phase angle, L_k is the path of kth user channel, $\delta(.)$ is the dirac delta function.

2.3 Model of the Receiver

We employ differential detection-based receiver as illustrated in Fig. 1. The output signal is calculated by a time convolution between S(t) and h(t) it and can be mathematically depicted as follows:

$$r(t) = \sum_{k=1}^{K} \sum_{l=0}^{L_k-1} \beta_k^l \sqrt{2P_k} a_k(t - \tau_k^l) b_k(t - \tau_k^l) \cos(\omega_c t + \varphi_k^l) + n(t) \tag{6}$$

where n(t) is the AWGN with zero mean and has two sided power spectral density $N_0/2$.

Given ***L***-branch antenna, the total SNR of MRC due to the co-channel interference signal can be mathematically expressed by [14]:

$$r = \frac{\sum_{p=1}^{L} \Omega_j^p}{1 + \sum_{q=1}^{I} \Omega_i^q} = \frac{X}{1+Y} = \frac{X}{\omega} \tag{7}$$

where Ω_j^p represents average SNR of the jth desired signal in the pth branch, Ω_t^q indicates average tth INR rata–rata in the qth branch, $X = \sum_{p=1}^{L} \Omega_j^p$ shows total SNR of the desired signal and $Y = \sum_{q=1}^{I} \Omega_t^q$ is the total INR interference signal in each branch of the antenna.

Moreover, the positive definite function (pdf) of signal-to-interference-plus-noise ratio (SINR) of MRC is given by [14]:

$$f_r(r) = \int_0^\infty (\omega + 1) f_X((\omega + 1)r) f_Y(\omega) d\omega \tag{8}$$

2.4 Bit Error Rate (BER) of Dual Fading Models

In order to measure the performance of the system, the mathematical expression of BER will be derived by means of dual fading models. It turns out that the desired signal and the interferences have different fading conditions. Given $X = \sum_{p=1}^{L} \Omega_j^p$ is the total SNR of the desired signal, Ω_j is the average SNR of each branch of the antenna, and $\Gamma(.)$ is the gamma function, the pdf of the desired Rayleigh distributed signal expressed by [15] can be represented by:

$$f_X(x) = \frac{x^{L-1}}{(\Omega_j)^L \Gamma(L)} e^{-\frac{x}{\Omega_j}} \tag{9}$$

The pdf of the desired signal which follows Nakagami model can be obtained as follows [15]:

$$f_X(x) = \left(\frac{m_j}{\Omega_j}\right)^{m_j L} \frac{x^{m_j L - 1}}{\Gamma(m_j L)} e^{-\frac{m_j}{\Omega_j} x} \tag{10}$$

where m_j is the Nakagami parameter of the desired signal.

The Ricianly-distributed pdf of the desired signal can be mathematically given as follows [15]:

$$f_X(x) = \frac{(K_j + 1)}{\Omega_j} \left(\frac{x(K_j + 1)}{K_j.L.\Omega_j}\right)^{\frac{L-1}{2}} \mathrm{e}^{\left(-K_j.L - \frac{(K_j+1)}{\Omega_j} x\right)} I_{L-1} \times \left(2\sqrt{\frac{K_j.L.(K_j + 1)}{\Omega_j} x}\right). \tag{11}$$

where Kj is the Rician of the desired signal and $\mathbf{I_n(.)}$ is the nth order modified Bessel function.

Moreover, $Y = \sum_{q=1}^{I} \Omega_t^q$ represents the total INR of the interference signal, Ω_t denotes the average interference-to-noise ratio (INR) of the interference signal, and $\Gamma(.)$ is the gamma function. Accordingly, the pdf of the interference signal which is Rayleigly distributed is expressed by [15]:

$$f_Y(y) = \frac{y^{I-1}}{(\Omega_t)^I \Gamma(I)} e^{-\frac{y}{\Omega_t}} \tag{12}$$

Also, the pdf of the interference signal which is Nakagamily distributed given m_t is the Nakagami parameter of the interference signal can be expressed by [15]:

$$f_Y(y) = \left(\frac{m_t}{\Omega_t}\right)^{m_t I} \frac{y^{m_t I - 1}}{\Gamma(m_t I)} e^{-\frac{m_t}{\Omega_t} y} \tag{13}$$

Given K_t is the Rician factor of the interference signal, and $\mathbf{I_n(.)}$ is the nth order of modified Bessel function, the pdf of the interference signal which is Ricianly distributed can be mathematically expressed by:

$$f_Y(y) = \frac{(K_t + 1)}{\Omega_t} \left(\frac{y(K_t + 1)}{K_t.I.\Omega_t}\right)^{\frac{I-1}{2}} \mathrm{e}^{\left(-K_t.I - \frac{(K_t+1)}{\Omega_t} y\right)} I_{I-1} \times \left(2\sqrt{\frac{K_t.M.(K_t + 1)}{\Omega_t} y}\right) \tag{14}$$

Furthermore, the general equation to compute BER is given by [6]:

$$P_e = \int_0^\infty f_r(r) P(r) dr \tag{15}$$

where $f_r(r)$ is the pdf of SINR, $P(r)$ is the bit error probability from the detection scheme on AWGN channel.

Subsequently, the mathematical expression of the receiver employing the differential detection differential phase shift keying (DPSK) over AWGN channel its mathematical expression is given by:

$$P(r) = \left(\frac{1}{2}\right)^{2L-1} e^{-r} \sum_{k=0}^{L-1} b_k r^k \tag{16}$$

in which,

$$b_k = \frac{1}{k!} \sum_{j=0}^{L-1-k} \binom{2L-1}{j} \tag{17}$$

2.4.1 *Rayleigh/Rayleigh Model*

In order to compute the BER of Rayleigh/Rayleigh model, we firstly determine the pdf of SINR of Rayleigh/Rayleigh model i.e. by substituting (9) and (12) to (8) and (16) such that the following equation is obtained:

$$Pe = \frac{1}{(\Omega_j)^L \Gamma(L) \Gamma(I)} \left(\frac{1}{2}\right)^{2L-1} \sum_{k=0}^{L-1} b_k \Gamma(L+k) \times \sum_{i=1}^{N} w_i (\Omega_I x_i + 1)^L x_i^{I-1} \left(\frac{(\Omega_t x_i + 1)}{\Omega_j} + 1\right)^{-L-k} \tag{18}$$

2.4.2 Rayleigh/Nakagami Model

The pdf of SINR under Rayleigh/Nakagami fading model can be calculated by substituting the Eqs. (9) and (13) to Eqs. (8) and (16), such that [16], [17] are obtained.

$$Pe = \frac{1}{(\Omega_j)^L \Gamma(L)\Gamma(m_t I)} \left(\frac{1}{2}\right)^{2L-1} \sum_{k=0}^{L-1} b_k \Gamma(L+k) \times \sum_{i=1}^{N} w_i \left(\frac{\Omega_t}{m_t} x_i + 1\right)^L x_i^{m_t I-1} \left(\frac{\left(\frac{\Omega_t}{m_t} x_i + 1\right)}{\Omega_j} + 1\right)^{-L-k} \quad (19)$$

Equation (19) is the BER equation of the system over Rayleigh/Nakagami model. Moreover, given $m_t = I$ the systems will be transformed into Rayleigh/Rayleigh fading model (18).

2.4.3 Nakagami/Rayleigh

The pdf of SINR under Nakagami/Rayleigh can be obtained by substituting (10) and (12) into (8) and (16) as follows:

$$Pe = \left(\frac{m_j}{\Omega_j}\right)^{m_j L} \frac{1}{\Gamma(m_j L)\Gamma(I)} \left(\frac{1}{2}\right)^{2L-1} \sum_{k=0}^{L-1} b_k \Gamma(m_j L + k) \times \sum_{i=1}^{N} w_i (\Omega_t x_i + 1)^{m_j L} x_i^{I-1} \left(\frac{m_j(\Omega_t x_i + 1)}{\Omega_j} + 1\right)^{-m_j L-k} \quad (20)$$

Equation (20) represents the BER of the system over Nakagami/Rayleigh channel.

2.4.4 Nakagami/Nakagami

Furthermore, the Pdf of SINR under Nakagami/Nakagami condition can be computed by substituting (10) and (13) into (8) and (16), as follows

$$Pe = \left(\frac{m_j}{\Omega_j}\right)^{m_j L} \frac{1}{\Gamma(m_j L)\Gamma(m_t I)} \left(\frac{1}{2}\right)^{2L-1} \sum_{k=0}^{L-1} b_k \Gamma(m_j L + k) \times \sum_{i=1}^{N} w_i x_i^{m_t I-1} \left(\frac{\Omega_t}{m_t} x_i + 1\right)^{m_j L} \left(\frac{m_j \left(\frac{\Omega_t}{m_t} x_i + 1\right)}{\Omega_j} + 1\right)^{-m_j L-k} \quad (21)$$

Equation (21) is the mathematical representation of the BER of the system over Nakagami/Nakagami fading channel.

2.4.5 Rician/Rayleigh

The pdf of SINR under Rician/Rayleigh can be computed by combining Eqs. (11) and (12) into Eqs. (8) and (16) to arrive the following equation:

$$Pe = \left(\frac{(K_j+1)}{\Omega_j}\right)^L e^{-K_j.L} \frac{1}{\Gamma(I)\Gamma(L)} \left(\frac{1}{2}\right)^{2L-1} \sum_{k=0}^{L-1} b_k \Gamma(L+k) \times \sum_{i=1}^{N} w_i (\Omega_t x_i + 1)^L x_i^{I-1} \left(\frac{(K_j+1)(\Omega_t x_i + 1)}{\Omega_j} + 1\right)^{-L-k} \times {}_1F_1\left(L+k, L, \frac{K_j L (K_j+1)(\Omega_t x_i + 1)}{(1 + \Omega_j + \Omega_t x_i + K_j \Omega_t x_i)}\right) \quad (22)$$

where, ${}_1F_1(a;b;z)$ is the Kummer confluent hyper-geometric function [8]. Equation (22) is the BER of the system under Rician/Rayleigh fading models. If we set $K_j = 0$, the system will be fully transformed into Rayleigh/Rayleigh fading model (18).

2.4.6 Rician/Nakagami

The pdf of SINR under Rician/Nakagami fading model can be calculated by substituting (11) and (13) into (8) and (16) as follows:

$$Pe = \left(\frac{(K_j+1)}{\Omega_j}\right)^L \frac{1}{\Gamma(m_t I)\Gamma(L)} e^{-K_j.L} \left(\frac{1}{2}\right)^{2L-1} \sum_{k=0}^{L-1} b_k \Gamma(L+k) \times \sum_{i=1}^{N} w_i \left(\frac{\Omega_t}{m_t} x_i + 1\right)^L x_i^{m_t I-1} \left(\frac{(K_j+1)\left(\frac{\Omega_t}{m_t} x_i + 1\right)}{\Omega_j} + 1\right)^{-L-k} \times F_1\left(L+k, L, \frac{K_j L (K_j+1)\left(\frac{\gamma_L}{m_t} x_i + 1\right)}{\left(1 + \Omega_j + \frac{\Omega_t x_i}{m_t} + \frac{K_j \Omega_t x_i}{m_t}\right)}\right) \quad (23)$$

Equation (23) is the BER of Rician/Nakagami. Given the value of $K_j = 0$, and $m_t = 1$ the systems will be simplified into Rayleigh/Rayleigh fading model (18).

2.5 Throughputs of S-ALOHA DS-CDMA

Accordingly, the throughput of S-ALOHA CDMA over multipath fading channel due to [4], [5] and [6] can be represented by Eq. (24):

$$S = G\left(\sum_{n=1}^{\infty} P_n(n)\right) \cdot (1 - P_e)^{L_b}, \quad (24)$$

in which, L_b is the length of the packet, the probability of the frames obtained within a particular time frame on S-ALOHA can be modelled using Poisson distribution:

$$P_n(n) = \frac{G^n e^{-G}}{n!}. \quad (25)$$

2.6 Analysis and Results

Figure 2 indicates the throughputs of S-ALOHA CDMA system under Rayleigh/Rayleigh fading channel for various number of receiving antennas (***L = 1, 2, 4, 6, 8, 10***). The

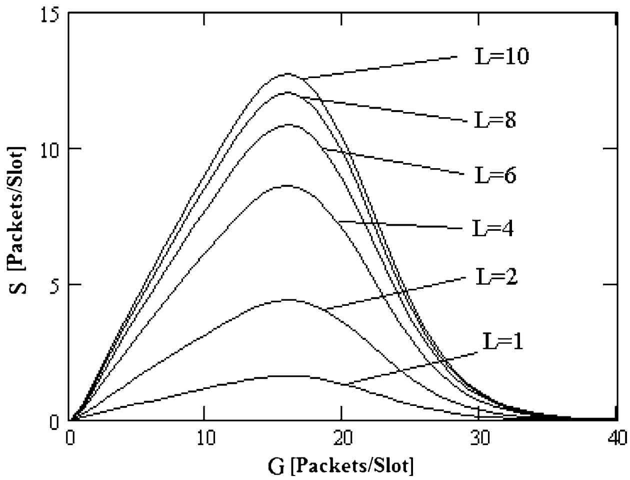

Fig. 2 Throughputs S-ALOHA CDMA for rayleigh/rayleigh fading channels with average SNR = 10 dB and average INR = 2 dB

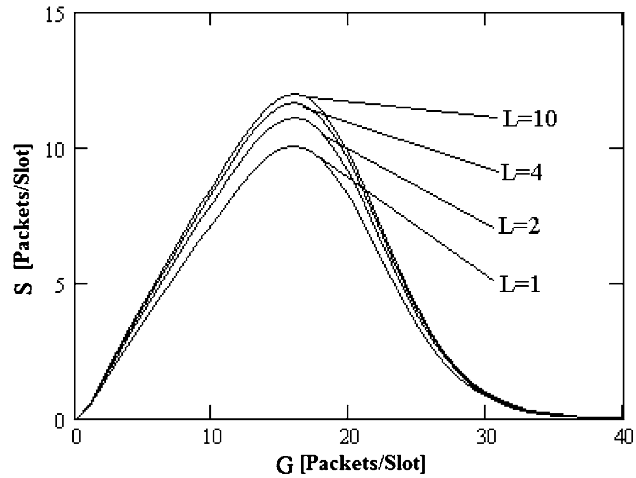

Fig. 4 Throughputs of S-ALOHA CDMA for Rayleigh/Nakagami fading channel with average INR = 2 dB, $I = 2$ and $L = 6$

calculation was performed under average INR = 1 dB. As can be seen, the throughputs of S-ALOHA CDMA systems can be substantially improved by employing more antennas in the receiver ***L***. The more antennas employed in the system; the higher the throughputs and the less noise exists in the systems. The number of antennas employed shall affect the performance of the system as it reflects the quality of the desired signals. Those signals will be combined using MRC diversity technique such that the optimal throughput is obtained.

Figure 3 indicates the throughputs of S-ALOHA CDMA on Nakagami/Rayleigh fading channel with variation in the number of receiver's antenna. Calculation was performed using Nakagami-$m = 2$, average SNR = 4 dB and average INR = 1 dB. Figure 3 depicts the effects of employing ***L***-branch antenna on the throughput of the system. Although

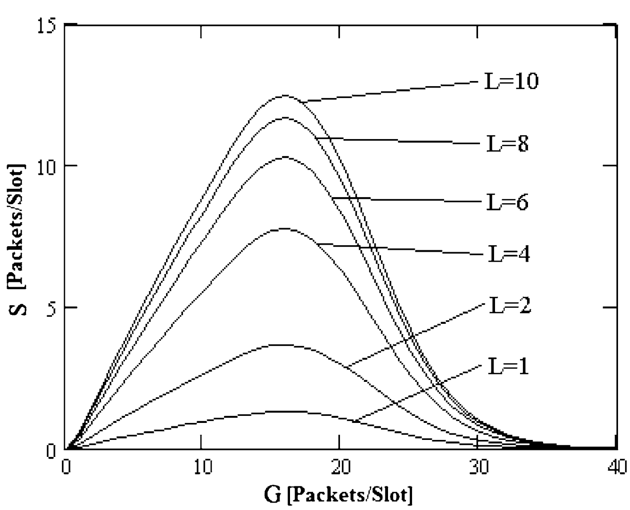

Fig. 3 Throughputs of S-ALOHA CDMA on Nakagami/Rayleigh channel with $m_j = 2$, average SNR = 4 dB and average INR = 1 dB

Fig. 3 looks superficially similar to Fig. 2, in Fig. 3 the desired fading signal was depicted using Nakagami model while Rayleigh model was employed to depict the interference signal.

Figure 4 depicts the throughputs of S-ALOHA CDMA system on Rayleigh/Nakagami channel given variation in the number of antennas in the receiver. Calculation was performed using Nakagami-$m = 2$, average SNR = 4 dB and average INR = 1 dB. Figure 4 depicts the effect of the ***L***-branch antenna with respect to the throughput of the system. As can be seen, the more antennas we used as reflected by the value of ***L,*** the more throughputs were obtained. Because of the interference, the change of the throughputs of the system under Rayleigh/Nakagami model was less significant.

Moreover, Fig. 5 depicts the throughputs of S-ALOHA CDMA for Nakagami/Nakagami fading channel under various interference signals m_t. It is shown that the higher the value of the Nakagami's parameter, the higher the value of the throughputs. This fact is in line to the theory that state the bigger the value of Nakagami fading channel, the smaller the existing fading signal in the systems. Meanwhile, if the value of m_t continuously increases until it reaches infinity, we can assume that the channel is a typical non-fading one.

Figure 6 indicates the throughput of S-ALOHA CDMA for Rician/Nakagami fading channel. Calculation was performed using average INR = 2 dB, the number of the antenna in the receiver $L = 6$, the number of the interference signal $I = 2$, and the Nakagami fading model of the interference signal $m_t = 2$. Furthermore it also depicts the effect of fading on the throughputs of the system. The higher the Rician factor ($\mathbf{K_j}$), the more LOS signals exist, thus, the higher the throughputs of the system.

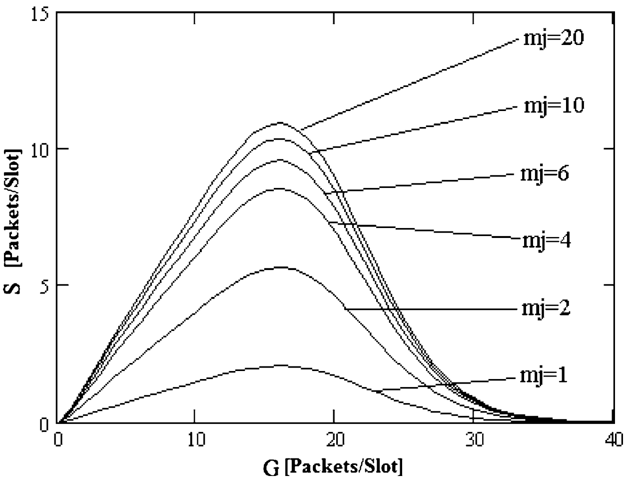

Fig. 5 Throughputs of S-ALOHA CDMA for Nakagami/Nakagami fading channel with INR = 1 dB, SNR = 10 dB, $m_t = 2$, and $L = 2$

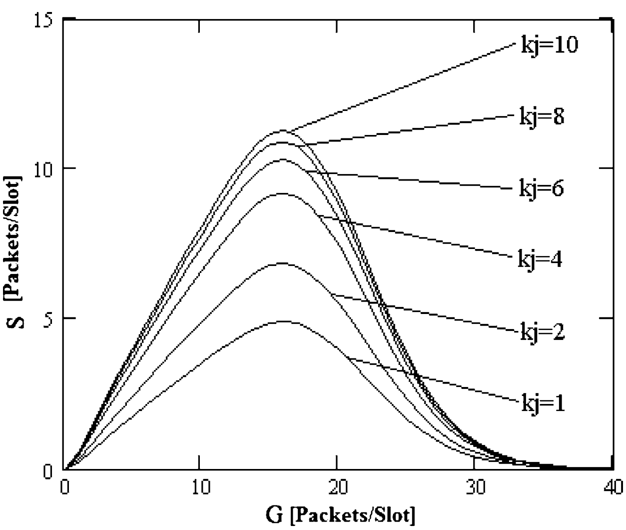

Fig. 6 Throughputs of S-ALOHA CDMA for Rician/Nakagami fading channel with INR average = 2 dB, $L = 6$, $I = 2$ and $m_t = 2$

This fact is understandable because the bigger the value of $\mathbf{K_j}$, the less amount of fading exists in the channel. If we keep increasing the value of $\mathbf{K_j}$ until it reaches infinity then we will end up with non-fading channel. In this condition, the increase of Rician factor ($\mathbf{K_j}$) will no longer affect the performance of the system.

3 Concluding Remarks

The performance of S-ALOHA CDMA systems (using MRC diversity and differential detection by means of two models of fading channels) has been analysed. To model the adverse fading environments, we employed Nakagami/Nakagami and Rician/Nakagami fading models. Our research indicates that the throughputs of the systems proportionally increase to the number of the antennas in the receiver. Moreover, higher value of fading parameters (Nakagami and Rician) will lead to increased value of the throughputs of the systems.

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