# Interference distribution in the Nakagami fading wireless CDMA ad hoc networks with multi-code multi-packet transmission (MCMPT)

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# Interference Distribution in the Nakagami Fading Wireless CDMA Ad Hoc
# Networks with Multi-Code Multi-Packet Transmission (MCMPT)

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**Abstract**

In this paper, we derive the distribution of Multiple Access Interference (MAI) power for wireless Code Division Multiple Access (CDMA) ad hoc networks operating in a general Nakagami-m fading channel model. Furthermore, we propose a Multi-Code Multi-Packet Transmission (MCMPT) scheme for it to increase the performance, in terms of the expected forward progress. Based on the instantaneous good channel conditions in a Nakagami-m fading channel, a node can initiate flexible number of parallel transmission of multiple packets on multiple codes. Numerical results show that adaptive MCMPT considering varying channel conditions not only outperforms the nonadaptive Conventional Packet Transmission (CPT), but also achieves better progress improvement with the increasing values of parameter m in a slowly-varying Nakagami-m fading channel.

## 1. Introduction

There is serious fading and interference phenomena in wireless CDMA ad hoc networks, which causes time-varying channel conditions. Therefore, a key problem for such a network is to maintain the acceptable MAI performance over wireless channels experiencing fading with as more as possible simultaneous packet transmission. To date, expected forward progress per hop, which considers both the local throughput and the number of hops, has been investigated in the literatures [2] [3] [4] [5] as an important performance measure of packet forward in wireless CDMA ad hoc networks. Previous work [3] derived the optimum transmission range for a CDMA multihop network over an additive white Gaussian noise (AWGN) channel to maximize the expected progress per hop. [4] extended the channel model by considering both fading and shadowing to evaluate the optimum transmission range. Furthermore, [5] derived the distribution of the interference power for a Rayleigh fading channel and explored the benefit of route diversity in such a channel. However, the existing work only gives the interference distribution in the special cases of non-fading AWGN channel and Rayleigh fading channel instead of a general fading channel. Moreover, none of the existing work considers the progress improvement by exploiting the varying channel conditions in a fading channel.

Adaptive techniques considering the varying channel conditions have been the promising

approaches to increase wireless spectral efficiency. So far, much interest has been paid on the adaptive modulation and coding [18], and packet length [10] [11] under varying channel conditions in *wireless networks*. Recently, [19] investigated the benefit of adaptive modulation by considering varying channel state information in *CDMA multihop packet radio network*. However, none of them considers a flexible number of parallel packet transmission based on the varying channel conditions in wireless CDMA ad hoc networks. Although a framework of simultaneous MAC packet transmission (SMPT) is proposed in [6] to stabilize the link-layer throughput, it focused on automatic request repeat (ARQ) component and only studied the link-layer buffer occupancy and code usage.

In this paper, firstly we generalize the fading model and derive the *probability density distribution* (pdf) of MAI power in the wireless CDMA ad hoc networks under a Nakagami-m fading channel. Secondly, we propose MCMPT scheme [16] for wireless CDMA ad hoc networks operating in a Nakagami-m fading channel and investigate the benefit of MCMPT for the varying parameter *m*. Under the instantaneous good channel conditions, more number of parallel transmission can be initiated simultaneously while satisfy required *signal to interference plus noise ratio* (SINR) for the correct packet reception and recovery.

The rest of the paper is organized as follows. Section 2 explains the system model. Section 3 derives the pdf of MAI power at a given node for the Nakagami-m fading model. Section 4 introduces the MCMPT and analytically examines the performance, in terms of the expected forward progress, by utilizing the Markov model. Section 5 gives the numerical results and compares it with the CPT. Section 6 concludes the paper.

## 2. System Model

Let us consider a wireless CDMA ad hoc network operating under heavy traffic conditions, where nodes are randomly distributed in the plane according to a two-dimensional Poisson point process with average density $\lambda$. Then the probability of finding $k$ nodes within the region with radius $a$ is

$$\frac{e^{-\lambda \pi a^2} (\lambda \pi a^2)^k}{k!}$$

The system is slotted and each node transmits data independently with transmission probability $p$ in each slot.

We assume that the system operates in an asynchronous direct sequence scheme of binary phase shift keying (DS/BPSK) with rectangular chip pulse, and that nodes transmit at the same transmission power. Following [1] [3], SINR $\mu$ is represented as,

$$\mu = \left(\frac{2Y}{3GP_r} + \frac{1}{\mu_0}\right)^{-1}$$

(1)

where $P_r$ is the received signal power, $Y$ is the total interference power, $G$ is the processing gain and $\mu_0$ is the SINR at the receiver in the absence of MAI. The total MAI power $Y$ is assumed to be a Gaussian random variable.

Let $\mu_t$ denote the threshold value of SINR for successful packet reception. Then, according to [3], the unconditional packet success probability can be given by

$$
\begin{aligned}
P_s &= \int_0^\infty p_c(x) f_\mu(x) dx \\
&= \int_0^\infty p_c'(x)(1 - F_\mu(x)) dx \\
&= 1 - F_\mu(\mu_t)
\end{aligned}
\tag{2}
$$

where $f_\mu(x)$ and $F_\mu(x)$ are respectively the pdf and *cumulative distribution function* (cdf) of the random variable $\mu$, and the packet success probability $p_c(x)$ is a step function

$$
p_c(x) = \begin{cases} 1, & x \geq \mu_t \\ 0, & x < \mu_t \end{cases}
\tag{3}
$$

We use a complex channel model, which considers both large-scale path loss with path loss exponent $n$ and multi-path fading. We use a general Nakagami-m fading distribution to characterize the multi-path fading, since it is a two-parameter distribution with parameter $m$ and $\Omega$ and it can give the best fit to the statistics of signals transmitted over multipath channels in a land-mobile and indoor-mobile environments via the m parameters. We consider the slowly-varying flat fading and hence the channel remains roughly constant over a time slot. Let $P_t$ and $P_r$ denote respectively the transmission power and the receiving signal strength. Then, we have

$$
P_r = \frac{\alpha^2 P_t}{d^n}
$$

where $\alpha$ is the channel fading amplitude and $d$ is the distance between the transmitter and receiver. The channel fading amplitude $\alpha$ is a Nakagami fading random variable, whose pdf [14] is given by

$$
p_\alpha(\alpha) = 2\left(\frac{m}{\Omega}\right)^m \frac{\alpha^{2m-1}}{\Gamma(m)} e^{-m\alpha^2/\Omega}, \alpha \geq 0
\tag{4}
$$

where $\Omega$ is the average received power, $m$ is the Nakagami fading parameter ($m \geq 1/2$) and $\Gamma(.)$ is the gamma function defined by

$$
\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt, z \geq 0
$$

The parameter $m$ characterizes the severity of the fading. As $m$ increases, the fading becomes less severe. As a special case of $m = 1$, the Nakagami-m distribution represents the Rayleigh distribution. The case $m = 1/2$ gives the one-side Gaussian fading which is the fading in the worst case. Moreover, the Nakagami-m distribution can approximate Rice and lognormal distribution when $m > 1$ [20].

Performance is measured in terms of the expected progress per hop $\sqrt{\lambda}Z = \sqrt{\lambda}\zeta R$ [2] [3], where $\zeta$ is the one-hop throughput of a transmitter and $R$ is the distance between the transmitter and receiver. The previous result (see [3] Equa. (27)) shows that $\zeta$ is the product of the probability of successful packet transmission $P_s$ and the tendency of two nodes to pair up, which is given by $\zeta = (1 - p)(1 - e^{-P})P_s$. Define $N$ as the average number of nodes that are closer to the receiver than transmitter, then we have $N = \lambda \pi R^2$. Hence, the expected progress per hop can be expressed as

$$
\begin{aligned}
\sqrt{\lambda}Z \\
= \sqrt{N/\pi}(1 - p)(1 - e^{-P})P_s \\
= \sqrt{N/\pi}(1 - p)(1 - e^{-P})(1 - F_\mu(\mu_t))
\end{aligned}
\tag{5}
$$

and this result will be used in Section $IV$.

## 3. MAI power distribution in a general Nakagami-m fading channel

Referring to the previous work [3] [5] that derive the MAI power distribution under the non-fading AWGN channels and Rayleigh fading channels respectively, in this section, we will derive the MAI power distribution of wireless CDMA ad hoc networks in a general Nakagami-m fading channel.

Since we assume that nodes transmit at the same transmission power, we have the normalized interference power $g(r_i)$ from a node $i$ expressed as $g(r_i) = \alpha^2 P_t / r_i^n$, where $r_i$ is the distance between node $i$ and the given receiver. Then we have total interference $Y_a$ at the given node within the disk $D_a$ with radius $a$ expressed as

$$
Y_a = \sum_{r_i \leq a} g(r_i)
\tag{6}
$$

Let $\phi_{Ya}$ be the characteristic function of $Y_a$, then we have

$$
\phi_{Y_a}(\omega) = E(e^{j\omega Y_a})
\tag{7}
$$

According to the conditional expectations, Eq. 7 can be expressed as

$$\phi_{Y_a}(\omega) = E(e^{j\omega Y_a})$$
$$= E(E(e^{j\omega Y_a}/k \text{ nodes in } D_a))$$
$$= \sum_{k=0}^{\infty} \frac{e^{-\lambda_t \pi a^2}(\lambda_t \pi a^2)^k}{k!} E(e^{j\omega Y_a}/k \text{ nodes in } D_a) \tag{8}$$

where $\lambda_t = \lambda_p$. Let $r$ denote the distance between an interferer and a given node. Considering that nodes are uniformly distributed, we have the pdf of the random variable $r$ given by

$$f(r) = \frac{2r}{a^2}, 0 < r \le a$$

With the assumption that the fading attenuation of each interferer is *independent and identically distributed* (i.i.d), Eq. 8 can be further expressed as

$$\phi_{Y_a}(\omega) = \sum_{k=0}^{\infty} \frac{e^{-\lambda_t \pi a^2}(\lambda_t \pi a^2)^k}{k!} \{E(e^{j\omega g(r)})\}^k \tag{9}$$

where

$$E(e^{j\omega g(r)}) = \int_0^a \int_0^{\infty} e^{j\omega a^2/r^n} f_{r,\alpha}(r,\alpha) d\alpha dr \tag{10}$$

Assuming that the fading is independent of the distance, Eq. 10 can be written as

$$E(e^{j\omega a^2/r^n})$$
$$= \int_0^a \int_0^{\infty} e^{j\omega a^2/r^n} f_r(r) dr f_\alpha(\alpha) d\alpha$$
$$= \int_0^a \frac{2r}{a^2} \int_0^{\infty} 2(\frac{m}{\Omega})^m \frac{\alpha^{2m-1}}{\Gamma(m)} e^{-m\alpha^2/\Omega} e^{j\omega a^2/r^n} d\alpha dr \tag{11}$$

$$E(e^{j\omega a^2/r^n}) = \begin{cases} \frac{a^2 - (1-j)\sigma\sqrt{\omega} ArcTan[\frac{a^2(1+j)}{2\sigma\sqrt{\omega}}]}{a^2}, & m = 1 \\ \frac{2a^8 - j3a^2\sigma^2\omega + 3(-1)^{1/4}\sigma\sqrt{\omega}(ja^4 + \sigma^2\omega) ArcTan[\frac{(-1)^{1/4}a^2}{\sigma\sqrt{\omega}}]}{2a(a^5 - ja\sigma^2\omega)}, & m = 2 \\ \frac{6a^2(12a^8 - j25a^4\sigma^2\omega - 10\sigma^4\omega^2) + 5(1-j)\sigma\sqrt{3\omega}(j3a^4 + 2\sigma^2\omega)^2 ArcTan[\frac{\sqrt{3}(1+j)a^2}{2\sigma\sqrt{\omega}}]}{8a^2(3a^4 - j2\sigma^2\omega)^2}, & m = 3 \\ \frac{2a^2(384a^{12} - j924a^8\sigma^2\omega - 560a^4\sigma^4\omega^2 + j1056\sigma^6\omega^3) - 105(1+j)\sigma\sqrt{\omega}(j2a^4 + \sigma^2\omega)^3 ArcTan[\frac{(1+j)a^2}{\sigma\sqrt{\omega}}]}{96a^2(2a^4 - j\sigma^2\omega)^3}, & m - 4 \end{cases} \tag{12}$$

$$\phi_{Y_a}(\omega) = \begin{cases} e^{-\lambda_t \pi (1-j)\sigma\sqrt{\omega}ArcTan[\frac{a^2(1-j)}{2\sigma\sqrt{\omega}}]}, & m=1 \\[2mm] e^{-\lambda_t \pi a^2 + \lambda_t \pi \frac{(2a^6 - j3c^2\sigma^2\omega + 3(-1)^{1/4}\sigma\sqrt{\omega}(ja^4+\sigma^2\omega)ArcTan[\frac{(-1)^{1/4}a^2}{\sigma\sqrt{\omega}}])}{2(a^4 - jc^2\omega)}}, & m-2 \\[2mm] e^{-\lambda_t \pi a^2 + \lambda_t \pi \frac{(6a^2(12a^8 - j25a^4\sigma^2\omega - 10\sigma^4\omega^2) + 5(1-j)\sigma\sqrt{3\omega}(j3a^4+2\sigma^2\omega)^2 ArcTan[\frac{\sqrt{3}(1+j)a^2}{2\sigma\sqrt{\omega}}])}{8(3a^4 - j2\sigma^2\omega)^2}}, & m=3 \\[2mm] e^{-\lambda_t \pi a^2 + \lambda_t \pi \frac{(2a^2(384a^{12} - j924a^8\sigma^2\omega - 560a^4\sigma^4\omega^2 + j1056\sigma^6\omega^3) - 105(1+j)\sigma\sqrt{\omega}(j2\sigma^4+\sigma^2\omega)^3 ArcTan[\frac{(1+j)a^2}{\sigma\sqrt{\omega}}])}{96a^2(2a^4 - j\sigma^2\omega)^3}}, & m=4 \end{cases}$$

$$(13)$$

As noted in [3], only the path loss exponent $n = 4$ can give the closed-form expression of density. Hence, we use $n = 4$ thereafter. Note that $\phi_{Ya}(\omega)$ is not convergent for $m < 1$ when $a \rightarrow \infty$. Therefore, we obtain $E(e^{j\omega a^2/r^n})$ for the typical values of $m = 1, 2, 3$ and 4 (referring to $m$ values used by Proakis [14] and Alouini [18]) in Eq. 12 respectively, where $m = 1$ represents Rayleigh fading.

Substituting it for Eq. 9, we obtain $\phi_{Ya}(\omega)$ in Eq. 13, where $\beta = e^{-\lambda_t \pi \alpha^2}$. Since we have the total MAI power $Y$ at a given node

$$Y = lim_{a\longrightarrow\infty}Y_a,$$

correspondingly, we have the characteristic function of Y

$$\phi_Y(\omega) = lim_{a\longrightarrow\infty}\phi_{Y_a}(\omega)$$

which one can show as

$$\phi_Y(\omega) = \begin{cases} e^{-\lambda_t \pi^2 \sigma\sqrt{\omega/2}e^{-j\pi/4}}, & m=1 \\[2mm] e^{-\frac{3}{4}\lambda_t \pi^2 \sigma\sqrt{\omega}e^{-j\pi/4}}, & m=2 \\[2mm] e^{-\frac{5}{8}\lambda_t \pi^2 \sigma\sqrt{3\omega/2}e^{-j\pi/4}}, & m=3 \\[2mm] e^{-\frac{35}{32}\lambda_t \pi^2 \sigma\sqrt{\omega/2}e^{-j\pi/4}}, & m=4 \end{cases}$$

$$(14)$$

As a result, using the inverse Fourier transform, one can obtain the pdf and cdf of $Y$ respectively as

$$f_Y(y) = \begin{cases} \lambda_t \sigma \left(\frac{\pi}{2y}\right)^{3/2} e^{-\lambda_t^2 \pi^4 \sigma^2 / 8y}, & m = 1 \\ \frac{3}{8} \lambda_t \sigma \left(\frac{\pi}{y}\right)^{3/2} e^{-9\lambda_t^2 \pi^4 \sigma^2 / 64y}, & m = 2 \\ \frac{5}{8} \sqrt{3} \lambda_t \sigma \left(\frac{\pi}{2y}\right)^{3/2} e^{-75\lambda_t^2 \pi^4 \sigma^2 / 512y}, & m = 3 \\ \frac{35}{32} \lambda_t \sigma \left(\frac{\pi}{2y}\right)^{3/2} e^{-1225\lambda_t^2 \pi^4 \sigma^2 / 8192y}, & m = 4 \end{cases} \tag{15}$$

and

$$F_Y(y) = \begin{cases} Erfc\left(\frac{\lambda_t \pi^2 \sigma}{2\sqrt{2y}}\right), & m = 1 \\ Erfc\left(\frac{3\lambda_t \pi^2 \sigma}{8\sqrt{y}}\right), & m = 2 \\ Erfc\left(\frac{5\sqrt{3}\lambda_t \pi^2 \sigma}{16\sqrt{2y}}\right), & m = 3 \\ Erfc\left(\frac{35\lambda_t \pi^2 \sigma}{64\sqrt{2y}}\right), & m = 4 \end{cases} \tag{16}$$

for $y > 0$. We observe that Eq. 16 is consistent with Sousa's result in [3] with an additional factor $\eta$ illustrated in Table 1 for different values of parameter $m$. We also observe that the result when $m = 1$ is complying with Souryal's result of Rayleigh fading in [5].

## 4. MCMPT

There is a trade off between more number of simultaneous transmission and increased MAI. In MCMPT, based on the instantaneous good channel conditions and acceptable MAI, the sequential transmission of packets in CPT is transformed into a flexible number of parallel transmission of multiple packets on multiple codes according to the fading conditions to increase the expected forward progress. We consider slow Nakagami-m fading channel. Thus, CPT that does not consider fading conditions can be evolved into adaptive MCMPT according to varying channel conditions of Nakagami-m fading channels.

### 4.1. Markov Model for Nakagami-m Fading Channels

In MCMPT, we use $Q+1-$state Markov model as shown in Fig. 1, where $Q$ is the partitioned number of good channel conditions of a Nakagami-m fading channel and additional 1 is for the bad channel conditions. Denote $\alpha_q^l$ and $\alpha_q^u$ respectively as the lower and upper threshold values of $\alpha$ for the $q$ ($q = 0, 1, ..., Q$) channel state interval, where $q = 0$ denotes the bad channel state and incremental $q$ means better channel conditions. For each good channel state, there is corresponding number of parallel packet transmission to maximize the expected progress per hop. Note that for the bad channel state, no packets are transmitted. The thresholds of the partitioned channel states will be determined later.

### 4.2. Analysis of Expected Progress Per Hop

Let $\kappa$ denote the flexible number of parallel transmission in MCMPT from a node which is active with the attempt probability $p$ at a slot, we have the actual SINR

$$\mu = \left(\frac{2(\kappa Y + (\kappa - 1)P_r)}{3GP_r} + \frac{1}{\mu_0}\right)^{-1}$$

(17)

where for simplification we only consider the case that $\kappa$ is the same. Substituting Eq. 17 in Eq. 16 in terms of $Y$, we can obtain the conditional cdf of $\mu$ on $\alpha$ as

$$
F_{\mu|\alpha}(\mu|\alpha)
= \begin{cases}
1 - F_Y\left[\frac{3G}{2\kappa R^4}\left(\frac{\alpha^2}{\mu} - \frac{1}{\mu_0} - \frac{2\alpha^2(\kappa-1)}{3G}\right)\right], & \mu < \alpha^2\mu_0 \\
1, & \mu \geq \alpha^2\mu_0
\end{cases}
$$

where $\alpha$ follows a Nakagami-m probability distribution.

Define the multiple-access capability

$$K(\mu, \alpha, \kappa) = \frac{3G}{2\kappa}\left(\frac{\alpha^2}{\mu} - \frac{1}{\mu_0} - \frac{2\alpha^2(\kappa-1)}{3G}\right)$$

Thus, we can obtain

$$
\begin{aligned}
F_\mu(\mu) &= \int_0^\infty F_{\mu|\alpha}(\mu|\alpha)f_\alpha(\alpha)d\alpha \\
&= \int_0^{\sqrt{\mu/\mu_0}} f_\alpha(\alpha)dr + \int_{\sqrt{\mu/\mu_0}}^\infty (1 - F_Y[\frac{1}{R^4}K(\mu,\alpha,\kappa)]) \\
&\quad \cdot f_\alpha(\alpha)d\alpha \\
&= 1 - \sum_{q=0}^Q \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R^4}K(\mu,\alpha,\kappa)]f_\alpha(\alpha)d\alpha
\end{aligned}
$$

(18)

where $\alpha_q^u = \alpha_{q+1}^l$. Note that $\alpha_q^l = min\{\alpha_q^l, \sqrt{\mu/\mu_0}\}$.

As a result, the expected progress per hop can be expressed as

$$
\begin{aligned}
\sqrt{\lambda}Z &= \sqrt{N/\pi}\kappa(1-p)(1-e^{-P})(1-F_\mu(\mu_t)) \\
&= \sqrt{N/\pi}\kappa(1-p)(1-e^{-P})\sum_{q=0}^Q \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R^4}K(\mu,\alpha,\kappa)] \\
&\quad \cdot f_\alpha(\alpha)d\alpha
\end{aligned}
$$

(19)

Therefore, the adaptation mechanism can be defined as

$$arg_{\forall(\kappa_q, p_q)} max\{\sqrt{\lambda Z}\}$$
$$= \sum_{q=0}^{Q} arg_{\forall(\kappa_q, p_q)} max\{\sqrt{N/\pi}\kappa(1-p)(1-e^{-P})$$
$$\cdot \int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R^4}K(\mu, \alpha, \kappa)]f_\alpha(\alpha)d\alpha\}$$

(20)

where $\kappa_q$ and $p_q$ are respectively the variables $\kappa$ and $p$ in the $q$-th channel state. Define

$$(\sqrt{\lambda Z})_q$$
$$= \sqrt{N/\pi}\kappa(1-p)(1-e^{-P})\int_{\alpha_q^l}^{\alpha_q^u} F_Y[\frac{1}{R^4}K(\mu, \alpha, \kappa)]f_\alpha(\alpha)d\alpha$$

(21)

Eq. 21 is a concave function in the variables $p$ and $\kappa$ and hence there exists an optimum $(\kappa_q, p_q)$ pair to maximize $(\sqrt{\lambda Z})_q$. Therefore, we can find the optimum $(\kappa, p)$ pair for each channel state to maximize $\sqrt{\lambda Z}$ in Eq. 20 such that transmitter can initiate $\kappa$ parallel packet transmission with acceptable MAI to any ongoing transmission to achieve the maximum expected progress per hop. For the special case of $m = 1$ and $\kappa = 1$, we observe that Eq. 20 is consistent with Souryal's result in [5].

### 4.3. Determination of Thresholds

We know that the steady state probability of channel conditions can be derived as

$$Pr[\alpha_q^l < \alpha \leq \alpha_q^u]$$
$$= \int_{\alpha_q^l}^{\alpha_q^u} p_\alpha(\alpha)d\alpha$$
$$= (\Gamma(m, \frac{m\alpha_q^{l2}}{\Omega}) - \Gamma(m, \frac{m\alpha_q^{u2}}{\Omega}))/\Gamma(m)$$

(22)

There are many partitioning schemes for determining the thresholds of state intervals in the finite-state Markov channel [8] [9]. In the following numerical results, we simply apply equally probable partition [7] of channel states. Taking the case $m = 1$ as the reference, we determine the thresholds according to

$$Pr[\alpha_q^l < \alpha \leq \alpha_q^u] = \frac{1}{Q+1}$$

(23)

where $\alpha_0^l = 0$ and $\alpha_Q^u = 3$.

### 4.4. Implementation Issues

The adaptation of appropriate number in MCMPT is based on the estimation of channel states, which is feedback by the receiver to the transmitter by comparing the measured signal attenuation to a set of channel gain thresholds in a separate control channel. Existing work has investigated the impact of channel estimation and suggests that it is practical. Existing work [10]

[11] has investigated the impact of channel estimation and suggests that it is practical. Moreover, as explained in [6], many existing systems are multi-code CDMA systems, which allows the transmitter to transmit multiple packets to the receiver by using multiple code channels. [20] argued that simultaneous multi-packet transmission is advantageous when IP packets are considered. Our previous work [17] also investigated the efficient code assignment scheme in wireless CDMA ad hoc networks.

## 5. Numerical results

Referring to the direct-sequence mobile packet radio network [12] [13], we choose the same system parameters $\mu_t = 6.6dB$ (required BER $= 10^{-5}$ and CRC code gain$= 1dB$), $\mu_0 = 26.6dB$ and $G = 128$. According to [5], the parameter $\sigma$ is set to be $1/\sqrt{2}$. Hence, $\Omega = 2\sigma^2 = 1$. The thresholds for the partitioned channel state intervals are illustrated in Table 2, where we replace $\alpha_0^l = 0$ with $\alpha_0^l = \sqrt{\mu_t/\mu_0} = 0.1$ as noted in Eq. 18. Thereafter, unless specifically mentioned, the expected progress per hop in MCMPT is obtained through adopting the optimum number of parallel packet transmission in each channel state for each transmission probability.

Fig. 2 and Fig. 3 show that expected progress per hop versus transmission probability $p$ under varying number of state partitions of Nakagami-m fading channels respectively in the cases of $m = 1$ and $m = 2$ when $N = 7$ and $G = 128$. Obviously, when we consider the varying channel conditions and adapt the optimum number of parallel packets transmission, there is significant improvement of expected progress per hop than that of CPT. With more number of partitions of channel states, there is better expected progress per hop due to more accurate channel states. However, the increasing slope becomes less, which is attributed to more number of partition approximates the perfect estimation of the instantaneous channel states. There exists an optimum value of $p$ under the different number of state partitions of Rayleigh fading channel in MCMPT, in agreement with CPT. The result in the case of $m = 1$ is consistent with that of MCMPT in the Rayleigh fading channels [16]. With the increasing values of parameter $m$, there is better $\sqrt{\lambda}Z$ under the same other parameters, due to less severe fading.

## 6. Conclusions and Future Work

In this paper, the pdf of MAI power in wireless CDMA ad hoc networks is derived for a general Nakagami-m fading channel. Furthermore, an adaptive parallel packet transmission scheme named as MCMPT is proposed for wireless CDMA ad hoc networks operating in a slow Nakagami-m fading channel by considering varying channel conditions. Performance is analyzed in terms of the expected progress per hop and it is shown that MCMPT outperforms CPT and with increasing values of $m$ there is better benefit of packet progress.

In the future, the impact of imperfect channel estimation in MCMPT will be investigated. Moreover, cross-layer design of MCMPT by considering higher layer can be further investigated.

## 7. Acknowledgements

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| m | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $\eta$ | $\sqrt{\frac{\pi}{2}}\sigma$ | $\frac{3}{4}\sqrt{\pi}\sigma$ | $\frac{5}{8}\sqrt{\frac{3\pi}{2}}\sigma$ | $\frac{35}{32}\sqrt{\frac{\pi}{2}}\sigma$ |

Table 1

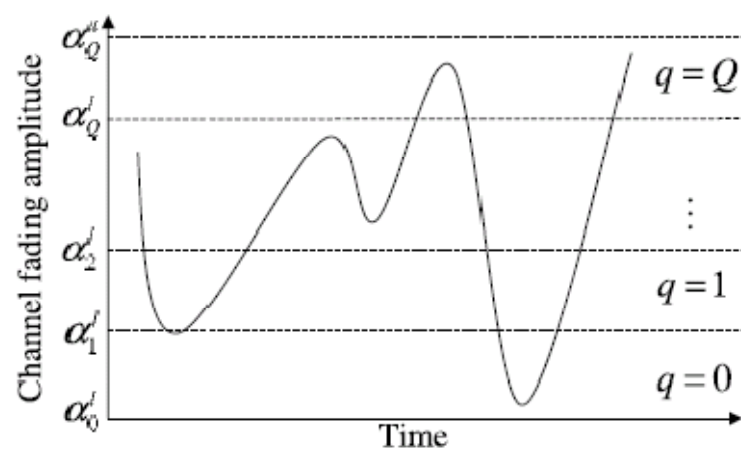| Q | $\alpha_0^l$ | $\alpha_0^u(\alpha_1^l)$ | $\alpha_1^u(\alpha_2^l)$ | $\alpha_2^u(\alpha_3^l)$ | $\alpha_3^u(\alpha_4^l)$ | $\alpha_4^u$ |
|---|---|---|---|---|---|---|
| 1 | 0.1 | 0.8325 | 3 | - | - | - |
| 2 | 0.1 | 0.6367 | 1.048 | 3 | - | - |
| 3 | 0.1 | 0.5364 | 0.8326 | 1.1777 | 3 | |
| 4 | 0.1 | 0.4730 | 0.7168 | 0.9646 | 1.2878 | 3 |

Table 2

Figure 1

Figure 2

Figure 3