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Multi-Code Multi-Packet Transmission (MCMPT) in Wireless CDMA Ad Hoc Networks under Rayleigh Fading Channels

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Abstract

In this letter, we introduce a Multi-Code Multi-Packet Transmission (MCMPT) scheme for wireless Code Division Multiple Access (CDMA) ad hoc networks to increase the performance, in terms of the expected forward progress, by considering varying channel conditions in the Rayleigh fading channels. We develop an analytical model to examine the maximum expected progress per hop and optimum number of parallel transmission in MCMPT. Numerical results show that adaptive MCMPT considering varying channel conditions achieves significant progress improvement over the nonadaptive Conventional Packet Transmission (CPT) in a slow Rayleigh fading channel.

Index Terms

Wireless CDMA ad hoc networks, Rayleigh fading channel, MCMPT.

1. Introduction

It is well known that in wireless CDMA ad hoc networks, fading can seriously affect the channel conditions. Therefore, a key problem for such a network is to maintain the acceptable multiple access interference (MAI) performance over time-varying wireless channels experiencing fading with simultaneous packet transmission. To date, expected progress per hop has been investigated in the literatures [1] [2] [3] as an important performance measure of packet forward in wireless CDMA ad hoc networks. None of the existing works consider the progress improvement by exploiting a flexible number of parallel packet transmission based on the varying channel conditions. Recently, [4] proposed a framework of simultaneous MAC packet transmission (SMPT) to stabilize the link-layer throughput. However, SMPT focused on automatic request repeat (ARQ) component and only studied the link-layer buffer occupancy and code usage.

In this letter, we introduce MCMPT scheme for wireless CDMA ad hoc networks operating in a Rayleigh fading channel. We seek to maximize the expected progress per hop by adapting the number of parallel transmission of multiple packets on multiple codes according to varying channel conditions. Under the instantaneous good channel conditions,

an increase in the number of parallel transmission can be initiated simultaneously while satisfying the required signal to interference plus noise ratio (SINR) for the correct packet reception and recovery. We observe that there is an optimum number of parallel packet transmission under a certain channel condition to maximize the expected forward progress per hop.

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 λ . 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 binary phase shift keying (DS/BPSK) scheme with a rectangular chip pulse, and that nodes transmit at the same transmission power. Following [1], SINR μ is represented as,

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

where P_r is the received signal power, Y is the total interference power, G is the processing gain and μ_0 is the SINR at the receiver in the absence of MAI. The total interference power Y is assumed to be a Gaussian random variable.

Let μ_t denote the threshold value of SINR for successful packet reception. Then, according to [1], the unconditional packet success probability can be given as

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

where $f_\mu(x)$ and $F_\mu(x)$ are the probability density distribution (pdf) and cumulative distribution function (cdf) of the random variable μ , respectively, and the packet success probability $p_c(x)$ is a step function at a threshold of $x = \mu_t$.

Let us consider a flat and slowly-varying Rayleigh fading channel. For the sake of simplicity, we consider the special case that the path loss exponent is 4. The pdf of Rayleigh-distributed variable r is given by

$$f_r(r) = \begin{cases} \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), & 0 \leq r \leq \infty \\ 0, & r < 0 \end{cases}$$

with σ being the rms value of the received signal strength before the envelope detection, and according to [3] the cdf of interference power Y is given by

$$F_Y(y) = \text{erfc}\left(\frac{\lambda_t \pi^2 \sigma}{2\sqrt{2y}}\right), y > 0 \quad (3)$$

where $\lambda_t = \lambda_p$ and $\text{erfc}(\cdot)$ is the complementary errorfunction.

Performance is measured in terms of the expected progress per hop $\sqrt{\lambda}Z = \sqrt{\lambda}\zeta R$ [1], where $\zeta = (1 - p)(1 - e^{-p})P_s$ is the one-hop throughput of a transmitter and R is the distance between the transmitter and receiver. Define N as the average number of nodes that are closer to the receiver than transmitter, then we have $N = \lambda\pi R^2$.

3. MCMPT

There is a tradeoff 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 using multiple codes to increase the expected forward progress. Thus, CPT that does not consider fading conditions can be evolved into adaptive MCMPT according to varying channel conditions of Rayleigh fading channels.

A. Markov Model for Rayleigh Fading Channels

In MCMPT, we use $Q+1$ - state Markov model, where Q is the partitioned number of good channel conditions of a Rayleigh fading channel and additional 1 is for the bad channel conditions. For each good channel state, there is a 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.

B. Analysis of Expected Progress Per Hop

Let κ 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

$$\mu = \left(\frac{2(\kappa Y + (\kappa - 1)P_r)}{3GP_r} + \frac{1}{\mu_0} \right)^{-1} \quad (4)$$

where for simplification we only consider the case that κ is the same. By substituting Y in Eq. 4 for Eq. 3, one can show the conditional cdf of μ on r as

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

where r follows a Rayleigh probability distribution.

Define the multiple-access capability

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

Thus, we can obtain

$$\begin{aligned} & F_\mu(\mu) \\ &= \int_0^\infty F_{\mu|r}(\mu|r) f_r(r) dr \\ &= \int_0^{\sqrt{\mu/\mu_0}} f_r(r) dr + \int_{\sqrt{\mu/\mu_0}}^\infty (1 - F_Y[\frac{1}{R^4} K(\mu, r, \kappa)]) f_r(r) dr. \end{aligned} \quad (5)$$

Let r_q^l and r_q^u denote respectively the lower and upper threshold values of r for the q ($q = 0, 1, \dots, Q$) channel state interval, where $q = 0$ denotes the bad channel state and incremental q means better channel conditions. Then, we have

$$F_\mu(\mu) = 1 - \sum_{q=0}^Q \int_{r_q^l}^{r_q^u} F_Y[\frac{1}{R^4} K(\mu, r, \kappa)] f_r(r) dr. \quad (6)$$

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

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

$$\begin{aligned} & \sqrt{\lambda} Z \\ &= \sqrt{N/\pi\kappa} (1-p)(1-e^{-p})(1-F_\mu(\mu_t)) \\ &= \sqrt{N/\pi\kappa} (1-p)(1-e^{-p}) \sum_{q=0}^Q \int_{r_q^l}^{r_q^u} F_Y[\frac{1}{R^4} K(\mu, r, \kappa)] f_r(r) dr. \end{aligned} \quad (7)$$

Therefore, the adaptation mechanism can be defined as

$$\begin{aligned} & \arg_{\forall(\kappa_q, p_q)} \max\{\sqrt{\lambda} Z\} \\ &= \sum_{q=0}^Q \arg_{\forall(\kappa_q, p_q)} \max\left\{ \sqrt{N/\pi\kappa} (1-p)(1-e^{-p}) \right. \\ & \quad \left. \int_{r_q^l}^{r_q^u} F_Y[\frac{1}{R^4} K(\mu, r, \kappa)] f_r(r) dr \right\} \end{aligned} \quad (8)$$

where κ_q and p_q are respectively the variables κ and p in the q -th channel state. Define

$$(\sqrt{\lambda} Z)_q = \sqrt{N/\pi\kappa} (1-p)(1-e^{-p}) \int_{r_q^l}^{r_q^u} F_Y[\frac{1}{R^4} K(\mu, r, \kappa)] f_r(r) dr.$$

Since Eq. 8 is a concave function in the variables p and κ , there exists an optimal (κ_q, p_q) pair to maximize $(\sqrt{\lambda} Z)_q$. Transmitter can initiate κ parallel packet transmission with acceptable MAI to any ongoing transmission to achieve the maximum expected progress per hop. For the special

case of $\kappa = 1$, we observe that Eq. 8 is consistent with Souryal's result in [3].

C. Determination of Thresholds

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

$$\begin{aligned} Pr[r_q^l < r \leq r_q^u] &= \int_{r_q^l}^{r_q^u} p_r(r) dr \\ &= \exp\left(-\frac{r_q^{l2}}{2\sigma^2}\right) - \exp\left(-\frac{r_q^{u2}}{2\sigma^2}\right). \end{aligned} \quad (9)$$

There are many partitioning schemes for determining the thresholds of state intervals in the finite-state Markov channel. In the following numerical results, we apply equally probable partition [5] of channel states and determine the thresholds according to

$$Pr[r_q^l < r \leq r_q^u] = \frac{1}{Q+1}, \quad (10)$$

where $r_0^l = 0$ and $r_Q^u = 3$.

D. 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 in a separate control channel by comparing the measured signal attenuation to a set of channel gain thresholds. Existing work [6] has investigated the impact of channel estimation and suggests that it is practical. Therefore, in MCMPT the transmitter can select appropriate (κ, p) pair to maximize the expected progress per hop based on the instantaneous estimations of channel state information. Moreover, as noted in [4], many existing systems are multi-code CDMA systems, which allows the transmitter to transmit multiple packets to the receiver by using multiple code channels.

4. Numerical Results

We choose the same system parameters $\mu_t = 6.6\text{dB}$, $\mu_0 = 26.6\text{dB}$ and $G = 128$ with reference to the direct-sequence mobile packet radio network [7]. According to [3], the parameter σ is set to be $1/\sqrt{2}$. We choose $Q = 3$ as an example. The thresholds for the partitioned channel state intervals are illustrated in Table I, where we replace $r_0^l = 0$ with $r_0^l = \sqrt{\mu_t/\mu_0} = 0.1$ as noted in Eq. 6.

In Fig. 1, we vary the transmission probability to observe the benefit of MCMPT over CPT under varying number of nodes N when $G = 128$ and $Q = 3$. 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. There is significant improvement of $\sqrt{\lambda}Z$ in MCMPT. We observe that, as in the case of CPT, under different transmission probability, there is different optimum value of N which maximizes the expected progress per

hop. As shown in Fig. 1, the illustrated values of $N = 20, 10, 7$ and 3 show the maximum $\sqrt{\lambda}Z$ within the corresponding interval of $p \in [0, 0.04), [0.04, 0.07), [0.07, 0.12)$ and $[0.12, 1)$ respectively. With the increasing transmission probability p and N , there is no much progress benefit due to limited multiple-access capability. Instead, there is even worse $\sqrt{\lambda}Z$ under high transmission probability in MCMPT than that in CPT, which is further attributed to the supposition in MCMPT that there is no packet transmission when $q = 0$.

Fig. 2 shows the optimum κ for different channel states of $Q = 3$ in MCMPT for the optimum transmission probability $p = 0.27$ of CPT when $N = 7$ and $G = 128$. There exists an optimum κ to maximize $\sqrt{\lambda}Z$ for each channel state, which can be obtained by differentiating $(\sqrt{\lambda}Z)_q$ with respect to κ . As q increases, the optimum κ increases due to the better channel conditions.

5. Conclusion and Future Work

In this letter, an adaptive parallel packet transmission scheme named as MCMPT is proposed for wireless CDMA ad hoc networks operating in a slow Rayleigh fading channel. It is shown that MCMPT considering varying channel conditions outperforms CPT in terms of the expected progress per hop and there is an optimum number of parallel packet transmission under a certain channel condition to maximize the expected progress per hop. Generalized fading model will be examined in the future work.

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Table I

Q	r_0^l	$r_0^u(r_1^l)$	$r_1^u(r_2^l)$	$r_2^u(r_3^l)$	r_3^u
3	0.1	0.5364	0.8326	1.1777	3

Figure 1

Figure 2