Analysis of a Media Access Protocol for Wireless Messaging Systems*

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Abstract

In this paper, we analyze the throughput performance of a wireless media access protocol taking into account the effect of capture in the presence of Rayleigh fading. For efficient access on the uplink (mobile-to-base), the protocol makes use of the uplink channel status information which is conveyed to the mobile through a *busy/idle flag* on the downlink (base-to-mobile link). The uplink is slotted such that each slot duration is equal to one ATM cell duration. Each message generated at the mobiles is assumed to consist of a multiple number of ATM cells. Analytical estimates of throughput are derived for capture under slow fading and i.i.d. fading conditions. Throughput estimates obtained through simulations at various Doppler bandwidths validate the analysis.

1 Introduction

Next generation wireless systems must support not only voice communications, but a range of multimedia services (including data, video, etc.) as well [1]. Asynchronous transfer mode (ATM) is widely being regarded as the enabling technology to realize this goal [2], [3]. ATM relies on packet switching where messages, irrespective of the nature of the message source (i.e., voice, data or video), will be segmented into fixed size (53 byte) packets (called cells) and transported across the network. Design and performance analysis of efficeient media access protocols for transporting ATM cells over wireless networks remains an important issue. Media access protocols play a vital role in determining the network efficiency in terms of throughput and delay performance when multiple mobile users share a common wireless medium. Classical random access protocols, for which extensive analyses have been carried out, are random ALOHA, slotted ALOHA, and carrier sense multiple access [4]. In this paper, we propose and analyze the performance of a media access protocol applicable to next generation wireless messaging systems. The proposed protocol uses the uplink (mobile-to-base station link) channel status information, which is conveyed to the mobile through the downlink (base station-to mobile link) broadcast from the base station by periodically inserting a busy/idle flag. In addition, the protocol uses a *header packet* for each message, and the access procedure is so designed that collisions (due to simultaneous transmissions from different mobiles) are possible only during the header packets transmission and not during the data packets transmission. This feature of the protocol improves the channel utilization efficiency. We analyze the throughput performance of this protocol in a fading environment taking into account the effect of capture.

Mobile radio channels are severely affected by time-varying losses due to distance, shadowing (blockage due to buildings, trees, etc.) and mutltipath fading [5]. While the variation in the losses due to distance and shadowing is relatively slow, the variation due to multipath fading is quite rapid. The fading envelope due to multipath follows a Rayleigh distribution, and the envelope squared (i.e., power) has an exponential distribution [5]. In this paper, we will consider a system in which different mobiles' transmissions are power controlled in a such a way that their slowly varying distance and shadow losses are perfectly compensated whereas the rapidly varying multipath fading remains uncompensated. Multipath fading encountered by different mobiles' transmissions are independent and random so that their received signal powers at the base station are different; this leads to the classical *capture* phenomenon[1]. Typically, capture results in better throughput performance. Several studies have investigated the effect of capture under different scenarios [7], [8], [9]. In fact, there are protocols that are proposed to explicitly exploit this effect for improved performance [10]. In this paper, we analyze the effect of capture due to fading on the performance of the proposed protocol. Capture under two different fading scenarios is considered to derive throughput performance improvement bounds. The first scenario considers the multipath fading to vary slowly (e.g., static user or users moving at pedestrian speed), and the second scenario considers multipath fading to vary rapidly (e.g., users moving at freeway speed). An i.i.d. fading model is used to characterize the fast multipath fading scenario. Simulation results are provided both to verify the analysis as well as to provide performance results at intermediate user speeds.

The rest of the paper is organized as follows. The proposed media access protocol is described in Section 2. In Section 3, the system model is described. Section 4 provides the throughput analysis,

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[1]The radio phenomenon by which when more than one signal arrive simultaneously at a receiver with unequal powers, the strongest one could be decoded correctly with a non-zero probability [6].

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results and discussions. Section 5 highlights the conclusions and scope for further work.

2 Protocol Description

In the following description of the media access protocol, it is assumed that the uplink (mobile-to-base) channel is slotted to one packet duration (one ATM cell duration), transmission attempts are made at the slot boundaries, and each message consists of a random number of data packets (ATM cells).

The mobile, once it receives a message to be delivered to the base station, first checks the status of the busy/idle flag which it receives periodically on the downlink from the base station. If the flag is set to busy, it refrains from making a transmission attempt, and reschedules the attempt to a later time. If the flag is set to idle, then it makes a transmission attempt by sending a header packet (which could contain the number of packets in the message, and other control information like source and destination addresses, etc.) in the immediately following slot on the uplink. The mobile expects the base station to respond to this header in the form of the busy/idle flag being set to busy, in the event of successful header packet reception. If this happens, the mobile transmits the data packets continuously on the uplink until all the packets in the message are sent. The base station sets the flag back to idle once the entire massage transmission is complete. In the event of the header packet loss (either due to collision or channel errors), the base station makes no response. Thus, the continued idle status of the flag prompts the mobiles to reschedule their transmission attempts to a later time.

Note that the purpose of the periodic busy/idle flag is twofold; one, it informs the status of the uplink to all the participating mobiles in the network, and two, it acts as an acknowledgement mechanism to inform a sender mobile about the successful reception of the header packet so that transmission of the data packets can follow. Thus, multiple transmissions from several mobiles (and, consequently, a collision) are possible only during the header packet transmission, and this makes the protocol more efficient.

3 System Model

The following system model is considered to analyze the throughput performance of the above protocol.

1. A single cell system with N mobile users trying to communicate with the base station.
2. All mobiles' transmissions are power controlled such that the distance and shadow losses are perfectly compensated and the multipath fading remains uncompensated.
3. All the mobiles receive the busy/idle flag instantaneous and error-free.
4. Message arrival process at each mobile is Bernoulli with rate λ.
5. Each message consists of a number of packets, and the message length (measured in integer number of packets) follows a geometric distribution with parameter g_m and pdf

$$\text{pr(msg. length}=x) = \begin{cases} g_m(1-g_m)^{x-1} & x = 1,2,3,... \\ 0 & \text{otherwise.} \end{cases}$$

Fading Channel Model

We consider a flat fading channel, whose analytical model is described in the following. In the literature, the flat fading channel is modeled as a multiplicative complex function, $\alpha(t)$, which is adequately described as a random process. A popular model considers a Gaussian random process with a given mean and covariance function [5]. On the time scale of the fading variations, the process can and will be considered as stationary. Therefore, with no loss in generality, we will normalize its power to 1. The real and imaginary axes can be chosen so that the mean, $\mu = E[\alpha(t)]$, is real. Also, for the future reference, we define the covariance function as

$$K(\tau) = E[(\alpha(t+\tau)-\mu)^*(\alpha(t)-\mu)]. \qquad (1)$$

Note that if $\mu = 0$, the envelope of $\alpha(t)$ is Rayleigh distributed for any t, and the envelope squared has an exponential distribution. On the other hand, when $\mu > 0$, we are in the presence of so-called *Rician fading*: this latter model accounts for the presence of a line-of-sight (LOS) component, and is often more accurate in micro- and picocells. When the LOS component is absent, or has negligible power, the Rician model degenerates into the Rayleigh one.

In a widely accepted model, the Gaussian process is assumed to have a bandlimited non-rational spectrum given by [5]

$$S(f) = S(0)\left[1-\left(\frac{f}{f_D}\right)^2\right]^{-1/2}, \quad \text{for } |f| < f_D, \qquad (2)$$

and zero otherwise. This spectrum corresponds to the covariance function

$$K(\tau) = J_0(2\pi f_D|\tau|), \qquad (3)$$

whose physical meaning has been investigated in [5]. $J_0(\cdot)$ is the modified Bessel function of the first kind and of zeroth order. The correlation properties of the fading process depend only on $f_D|\tau|$. When it is small (< 0.1), the process is very correlated ("slow" fading); on the other hand, for larger values of $f_D|\tau|$ (> 0.2), two samples of the channel are almost independent ("fast" fading).

Capture Model

We model the capture/no capture (i.e., packet success/failure) process as the outcome of a comparison of the instantaneous signal-to-noise ratio to a threshold value; if the received power is above the threhold, the packet is successfully decoded with probability 1; otherwise it is lost with probability 1. Consider simultaneous transmissions from 'n' number of mobile users in a slot, which are received with signal powers α_j^2, $j = 1,2,..,n$ at the base station. Capture is said to occur in favor of user 'i' if

$$\alpha_i^2 > b\left[\sum_{j=1, j\neq i}^{n} \alpha_j^2\right] + \frac{1}{F}, \qquad (4)$$

where b is defined as the capture threshold and F is the fading margin of the system. Fading margin is the amount of average excess power needed for a packet to be decoded correctly, taking into account the effect of fading, even in the absence of interference from other users. Note that there is no capture when $b \to \infty$, and there is perfect capture when $b = 1$.

4 Throughput Analysis

In this section, we analyze the protocol throughput performance. We consider two different fading scenarios; one corresponding to "slow" fading and the other corresponding to "fast" fading. These two scenarios set the bounds on the improvement in throughput due to capture, that is, static fading provides the maximum and i.i.d. fading gives the minimum improvement.

Slow fading

In analyzing slow fading capture, we assume that once a header packet of a given user is captured, all the data packets in the corresponding message are also captured. While this assumption is true for static users, it also turns out to be a reasonable assumption for slowly moving users (e.g., users moving at pedestrian speed).

Based on the above assumption, the system can be modelled as a two state Markov chain as shown in Figure 1, the defining states being IDLE state (state 1) and ACTIVE state (state 2). The state transition probabilities are given by

$$p_{11} = p_0 + \sum_{i=1}^{N} p_i(1 - p_s^{(i)}), \qquad (5)$$

$$p_{12} = \sum_{i=1}^{N} p_i p_s^{(i)}, \qquad (6)$$

$$p_{21} = g_m, \qquad (7)$$

and

$$p_{22} = 1 - g_m. \qquad (8)$$

p_i is the probability that 'i' users make a transmission attempt in a slot, and equals

$$p_i = \binom{N}{i} \lambda^i (1 - \lambda)^{N-i}. \qquad (9)$$

$p_s^{(i)}$ is the capture probability of any one user succeeding when it sees $(i-1)$ interfering users' transmissions in the slot. This capture probability can be derived as [11]

$$p_s^{(i)} = i e^{-1/F} \left(\frac{1}{1+b} \right)^{i-1}. \qquad (10)$$

Now the throughput is given by the expression

$$\eta = \frac{1 + E(A)}{E(I) + E(A)}, \qquad (11)$$

where $E(I)$ and $E(A)$ are the expected length of the idle and active segments, respectively. Note that, in the above, we are

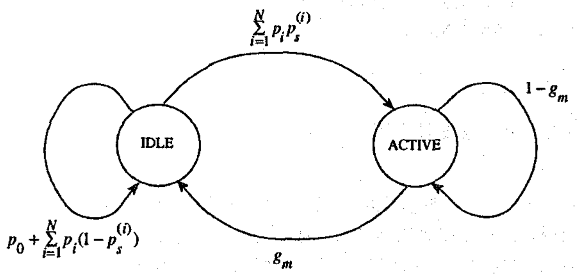

Figure 1: State transition diagram for slow fading

considering successful header packet transmissions also to contribute to the throughput computation. It is easy to see that

$$E(I) = \frac{1}{\sum_{i=1}^{N} p_i p_s^{(i)}}, \qquad (12)$$

and

$$E(A) = \frac{1}{g_m}. \qquad (13)$$

Combining Equations (9), (10), (11), (12), and (13), the throughput expression can be obtained in closed form as

$$\eta = \frac{(1 + g_m) e^{-1/F} N\lambda [1 + b(1-\lambda)]^{N-1}}{g_m (1+b)^{N-1} + e^{-1/F} N\lambda [1 + b(1-\lambda)]^{N-1}}. \qquad (14)$$

It can be seen from the above expression that, like any other random access protocol, the proposed protocol exhibits unstable behavior at high arrival rates, and the maximum throughput (η_{max}) occurs at the arrival rate (λ_{max}) given by

$$\lambda_{max} = \frac{1+b}{bN}. \qquad (15)$$

Note that when there is no capture (i.e., $b \to \infty$), λ_{max} becomes equal to $1/N$. When there is perfect capture ($b = 1$), η_{max} occurs when the arrival rate is $2/N$.

Results

In Figure 2, we plot the maximum throughput performance of the protocol as a function of different capture threshold values, b (in dB), for a 10 user ($N = 10$) network. A b value of 0 dB corresponds to perfect capture, and a large value of b (e.g., 50 dB) represents the no capture condition. A g_m value of 0.1, corresponding to an average message length of 10 packets per message (not including the header) is used. The curves are parameterized by the fading margin, F (in dB). The protocol is seen to provide a maximum throughput of around 0.65 even under conditions of small fading margins ($F = 0$ dB) and no capture (e.g., $b = 50$ dB). This throughput value improves to 0.82 when there is perfect capture ($b = 0$ dB), which is a 17 % improvement in capacity due to capture alone. The percentage improvement in capacity due to capture shows diminishing returns as the fading margin is increased. (Note that as $F \to \infty$ the channel becomes noiseless). For example, η_{max} improves from 0.75 to 0.89 (14 % improvement) when $F = 2.5$ dB, from 0.81 to 0.93 (12 % imrpovement) when $F = 5$ dB, and from 0.85 to 0.96 (11 % improvement) when $F = 10$ dB. When $F = 20$ dB (close to noiseless channel condition), the maximum throughput improves from 0.87 to 0.97, resulting in 10 % improvement in throughput due to capture. It can be seen from Equation (14) that the throughput improves as the message length is increased. However, the increased throughput for large message sizes comes at the expense of increased delay performance of the protocol, which needs to be studied.

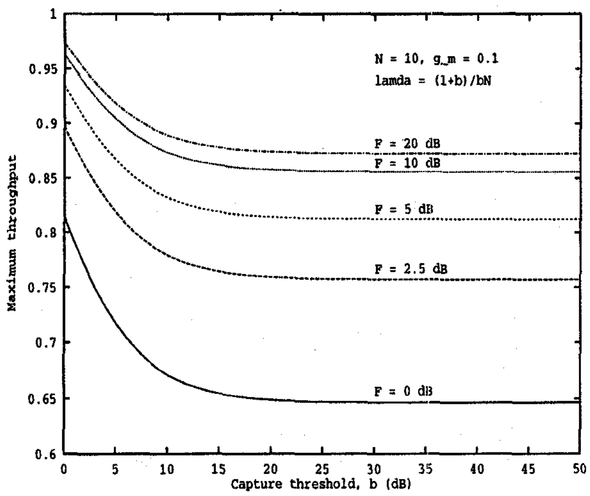

Figure 2: Effect of capture on the maximum throughput under *slow* Rayleigh fading. $N = 10$. $g_m = 0.1$. $\lambda = (1+b)/bN$.

Fast fading

Here we consider the "fast" fading scenario. The fading is assumed to be i.i.d., implying that knowledge of a capture in a particular slot does not say anything about the possibility of capture or otherwise in the subsequent slots. As will be seen later, this is a good model for fast moving users.

To analyze this scheme, it must be noted that the system can no longer be modelled as a simple two state Markov chain as we did for the slow fading case. On the contrary, a large number of states, which grows linearly with the number of users in the system, are needed to define the system. This is explained as follows. The system state space can be subdivided into 1) idle state, 2) header capture state set, 3) header loss state set, 4) data capture state set, and 5) data loss state set. State 1 (idle state where no user is transmitting in a slot) is unique. Capture (state sets 2 and 4) and lossy (state sets 3 and 5) state sets correspond to situations where one or more users transmit in a slot. With state sets 2 and 4, there will be a packet success due to capture, whereas there will be no capture (resulting in loss of packets) with state sets 3 and 5. State sets 2 to 5 each are comprised of N different sub-states (each corresponding to different number of users simulataneously transmitting in a slot), resulting in $(4N+1)$ total number of states. Thus, the individual states in the state sets 2 to 5 can be described by the (i, n_i) pair, where $i = 2,3,4,5$ and $n_i = 1,2,..,N$. Note the pair (1,0) represents the idle state. The various state transition probabilities can be derived as follows.

$$P_{(1,0)\to(k,l)} = \begin{cases} p_0 & k=1; l=0 \\ p_l p_s^{(l)} & k=2; l=1,2,..,N \\ p_l(1-p_s^{(l)}) & k=3; l=1,2,..N \\ 0 & \text{otherwise,} \end{cases}$$

where p_l and $p_s^{(l)}$ are as defined in (9), and (10), respectively. Other transition probabilities are derived as

$$P_{(2,j)\to(k,l)} = \begin{cases} p_s^{(l)} & j=1,2,..,N; k=4; l=j \\ 1-p_s^{(l)} & j=1,2,..,N; k=5; l=j \\ 0 & \text{otherwise,} \end{cases}$$

$$P_{(3,j)\to(k,l)} = \begin{cases} p_0 & j=1,2,..,N; k=1; l=0 \\ p_l p_s^{(l)} & j,l=1,2,..,N; k=2 \\ p_l(1-p_s^{(l)}) & j,l=1,2,..,N; k=3 \\ 0 & \text{otherwise,} \end{cases}$$

and

$$P_{(4,j)\to(k,l)} = \begin{cases} g_m p_0 & j=1,2,..,N; k=1; l=0 \\ g_m p_l p_s^{(l)} & j,l=1,2,..,N; k=2 \\ g_m p_l(1-p_s^{(l)}) & j,l=1,2,..,N; k=3 \\ (1-g_m)^l p_s^{(l)} & j=1,2,..,N, k=4,5; l=j \\ \binom{j-1}{l-1}(1-g_m)^l g_m^{j-l} p_s^{(l)} & j=1,2,..,N, k=4,5; l<j \\ 0 & \text{otherwise.} \end{cases}$$

The transition probabilities $P_{(5,j)\to(k,l)}$ are identical to the probabilities $P_{(4,j)\to(k,l)}$ as defined above. Since it is not easy to obtain the throughput expression in closed form, the system equations are solved using MatLab to obtain the steady state probabilities and hence the system throughput. The maximum throughput is obtained through an iterative procedure. The arrival rate (λ_{max}) at which the maximum throughput occurs is found to be different for different capture threshold values. Figure 3 shows the maximum throughput performance of the protocol with i.i.d. fading and capture. We use the same set of parameters that were selected for slow fading case ($N = 10$, $g_m = 0.1$, $F = 0$ to 20 dB). It is seen that the percentage improvement in throughput due to capture is always less under i.i.d. fading conditions than compared to slow fading conditions. Also, when fading is i.i.d., the maximum achievable throughput gets severely degraded at low fading margins (e.g., η_{max} of 0.32 with perfect capture when $F = 0$ dB). It must be emphasized that the analytical performance predictions presented above, both for slow as well as i.i.d. fading, were found to be accurate through simulations.

Simulations

Simulations are carried out at different vehicle speeds (equivalently, different Doppler bandwidths) to examine how close are the above analytical bounds to the actual performance. The correlated Rayleigh fading process defined in Section 3 is simulated by the technique proposed by Jakes in [5]. The different normalized Doppler bandwiths, f_dT, considered are 0.002, 0.02, 2. For a packet duration of about 16 msec (i.e., 1 ATM cell at 200 Kbps data rate), the f_dT value 0.002 corresponds to less than 1 Hz Doppler (1.5 km/hr user speed - a pedestrian user!) at 900 MHz carrier frequency. Similarly $f_dT = 2$ corresponds to a user moving at a speed of 150 km/hr (125 Hz Doppler). In Figure 4, we plot the analytical (for both slow and i.i.d. fading) and simulation throughput results at different capture threshold values,

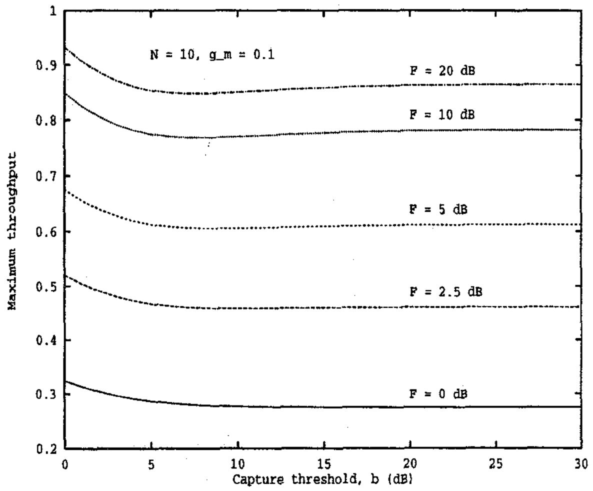

Figure 3: Effect of capture on the maximum throughput under *fast* Rayleigh fading. $N = 10$. $g_m = 0.1$.

for $N = 10$, $g_m = 0.1$, $F = 10$ dB, and $\lambda = 0.1$. Note that the simulation results for $f_d T = 2$ are close to the i.i.d. fading analytical results, implying that the i.i.d. model is accurate, but only at high Doppler bandwidths. The i.i.d. model turns out to be a poor model for low mobility users, as can be seen from plots for $f_d T = 0.02$ and 0.002. The slow fading model is seen to provide better a approxmiation to the low mobility users' performance.

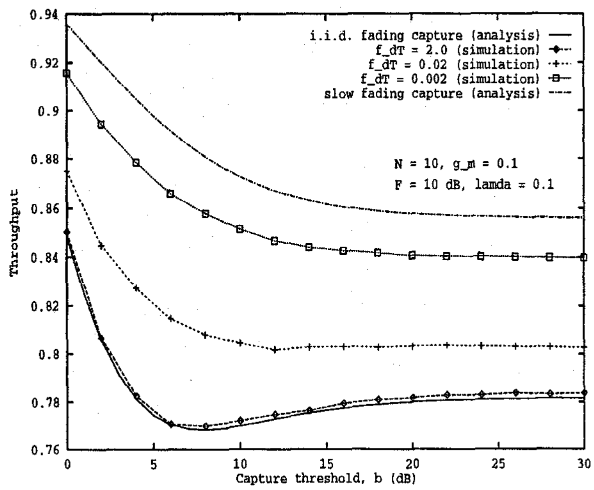

Figure 4: Comparison of analytical results *vs* simulation results at different Doppler bandwidths ($f_d T = 0.002, 0.02, 2.0$). $N = 10$. $g_m = 0.1$. $\lambda = 0.1$.

5 Conclusions

We proposed a new media access protocol, suitable for next generation wireless messaging systems, and analyzed its throughput performance in the presence of fading and capture. The improvement in throughput due to capture was shown to be better in slowly fading channels than compared to fast fading channels. Simulation results were presented to validate the analytical results. The current analysis could be extended to evaluate the performance of a non-power controlled system, taking into account the effect of shadowing and distance. Also, the effect of non-zero error rate of the busy/idle flag on the protocol performance, and the degree of error protection that may be needed, are possible future directions to this study. Further, a more detailed study of the performance, including a delay analysis, is needed, taking into account the details of modulation/coding schemes.

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