PERFORMANCE ANALYSIS OF MULTICHANNEL WIRELESS ACCESS PROTOCOL IN THE PRESENCE OF BURSTY PACKET LOSSES*

Weiping Xu, A. Chockalingam,† and Laurence B. Milstein

Department of Electrical and Computer Engineering, University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0407, USA
Email: ypxu@ece.ucsd.edu, milstein@ece.ucsd.edu

ABSTRACT

In this paper, we analyze the effect of bursty packet losses caused by correlation in the multipath fading process on the throughput and delay performance of a multichannel wireless access protocol. We model the channel memory as a first-order Markov chain whose parameters are defined as a function of the fading margin and the normalized Doppler bandwidth. Following a Markov chain analysis, we derive the analytical expressions for the average per channel throughput and the mean message transfer delay. It is shown that the multichannel protocol with a 'persist-until-success' retransmission strategy at the link level to recover erroneous data packets performs better on fast fading channels (low correlation), whereas the protocol without retransmission at the link level performs better on slow fading channels (high correlation).

INTRODUCTION

Next generation wireless networks are envisaged to support high data rates, packet oriented transport, and multimedia traffic. The design of efficient and robust wireless media access protocols, and the evaluation of their performance in the presence of physical layer impairments, are key technical issues [1]. Mobile radio channels are affected by time-varying losses due to distance, shadowing, and multipath fading. The fading envelope due to multipath is assumed to follow a Rayleigh distribution whose autocorrelation function depends on the normalized Doppler bandwidth, which in turn varies as a function of the mobile user velocity [2].

In [3], we presented and analyzed a *multichannel* wireless access protocol which can be viewed as a hybrid protocol employing the slotted ALOHA and reservation concepts [4]. M equal-capacity, orthogonal, traffic channels are shared by N mobile users ($N \geq M$) on the uplink (mobile-to-base station link). A header packet is sent on a contention basis first, following which data packets are sent on a reservation basis. By this approach, packet losses due to collision are restricted to occur only among header packet transmissions. The analysis in [3] assumed the multipath Rayleigh fading to be independent and identically distributed (i.i.d.). However, the multipath fading process in mobile radio environments can typically be considered to be slowly varying, at least for the usual values of the carrier frequency (i.e., 900-1800 MHz) and for typical mobile speeds, in the sense that the dependence between transmissions of consecutive packets of data cannot be neglected [2]. In particular, the assumption that the successes/failures of data packets constitute an i.i.d. process is far from reality, since correlation in the multipath fading behavior introduces burstiness (memory) in the packet error process, which can affect the protocol performance.

In this paper, we analyze the effect of the burstiness of packet errors due to correlation in the multipath fading on the multichannel protocol performance. We do this by modeling the channel memory as a first-order Markov chain whose parameters depend on the fading margin and the Doppler bandwidth. Following a Markov chain analysis, we derive the expressions for the average per channel throughput and the mean message transfer delay. Simulations are carried out to verify the analysis. We also analyze the performance of the multichannel protocol with a 'persist-until-success' *retransmission* strategy at the link level to recover erroneous data packets.

MULTICHANNEL WIRELESS ACCESS PROTOCOL

Consider a packet communication wireless network where N mobile users share M equal-capacity, orthogonal, traffic channels ($N \geq M$) on the uplink to communicate with the base station. All the uplink channels are synchronized and slotted to one packet duration. All the mobiles in the network can use any of the M different channels following the access rules. The base station is provided with M receivers to demodulate all the uplink channels' traffic. Based on the busy/idle status of the M receivers, the base station broadcasts an M-bit *busy/idle word*, in every slot, on the downlink. The busy/idle flag corresponding to each channel is set or reset depending on whether or not data packets are being transmitted on that channel.

Each message generated at the mobiles consists of two segments, namely the *header segment* and the *data segment*. The header segment is of one packet length. It carries control information, e.g., the destination address and the number of packets in the data segment. The data segment, which represents the actual traffic, consists of a random number of packets. Transmission attempts are made by the mobiles only at the slot boundaries by sending the header packet.

The mobile, once it receives a message to be sent to the base station, first checks the status of the busy/idle word which it periodically receives from the base station on the downlink. If all the M busy/idle flags indicate busy status, the mobile refrains from making a transmission attempt, and reschedules the attempt to a later time. If one or more flags indicate an idle status, then the mobile *randomly* picks one of these idle channels, and makes a transmission attempt by sending a header packet on the uplink

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†A. Chockalingam is presently with Qualcomm, Inc., 6455 Lusk Boulevard, San Diego, CA 92121. E-mail: achockal@qualcomm.com

slot of the chosen channel. If the header packet is received successfully, without packet loss due to fading or collision, the base station broadcasts the channel ID and the successful mobile ID (capturing mobile in the event of collision among header packets from different mobiles), and sets the corresponding channel's flag *busy* for the X subsequent slots, where X is the number of packets in the data segment of the successful mobile. This allows only the successful mobile to send its data packets in those X slots on that channel. During these X slots, other mobiles would receive a busy status flag for this channel and so they would not make transmission attempts on it. The base station resets the flag back to idle status after X slots. If the header packet is lost (due to collision or fading), then the base station will not respond with a busy status flag, but will continue to send the corresponding channel's flag as *idle*. This is an indication to the mobile that the header packet was lost, and so it has to reschedule its transmission attempt to a later time.

CORRELATED RAYLEIGH FADING MODEL

We consider a system where all the mobiles' transmissions are power controlled so that the slowly varying distance and shadow losses are perfectly compensated, whereas the rapidly varying multipath fading remains uncompensated. The multipath fading in a mobile radio channel is considered to follow a Rayleigh distribution [2]. As in [5], we model the channel memory using a simple two-state Markov chain whose transition probability matrix is given by

$$M_c = \begin{pmatrix} p & 1-p \\ 1-q & q \end{pmatrix}, \tag{1}$$

where p and $1-q$ are the probabilities that the packet transmission in slot j is successful, given that the packet transmission in slot $j-1$ was successful or unsuccessful, respectively. The steady-state probability that a packet error occurs, P_E, is

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

Note that $(1-q)^{-1}$ represents the average length of a burst of errors, which is described by a geometric random variable. Also, for a Rayleigh fading channel with fading margin F, the average packet error rate can be found as [6],

$$P_E = 1 - e^{-1/F}. \tag{3}$$

The expression for the parameter q ss a function of the normalized Doppler bandwidth $f_d T$, and fading margin F is given in [5].

PERFORMANCE ANALYSIS

In the following analysis, a single cell system with no inter-cell interference is considered. We assume that the busy/idle word on the downlink is received instantaneously, and error-free by all the mobiles. Header packets from different mobiles can collide in a slot and the probability of *capture* [7] under such conditions needs to be computed to carry out the throughput analysis. From [8], the probability that there is a header packet success when n simultaneously colliding header packet transmissions are present

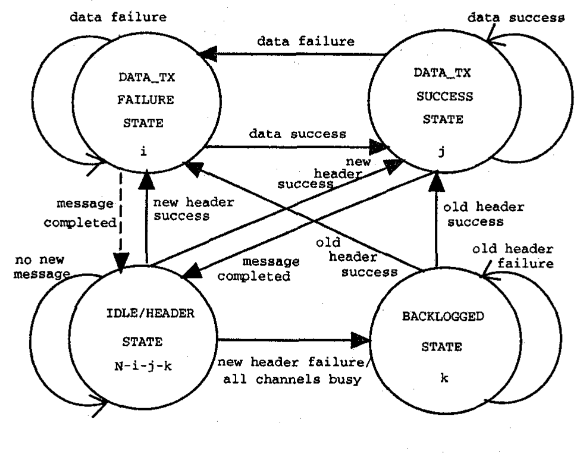

Fig. 1. Mobile state transition diagram (in Markov fading)

in a slot, $p_s^{(n)}$, is given by

$$p_s^{(n)} = ne^{-1/F}\left(\frac{1}{1+B}\right)^{n-1}, \quad n \geq 0, \tag{4}$$

where B is defined as the capture threshold.

A. Throughput Performance

A new message is assumed to arrive at each mobile with probability λ in each slot (Bernoulli arrival process). The mobile accepts a newly arriving message for transmission only when it has no message to send, and does not generate new messages when it already has a message to send. The length of the data segment of each message, X, measured in integer number of packets, is assumed to follow a geometric distribution with parameter g_d.

Each mobile, in any given slot, can be in any one of four states, namely, *idle/header_tx* state, *data_tx_success* state, *data_tx_failure* state, and *backlogged* state (see Figure 1). Note that the data transmit state is divided into *success* and *failure* substates in order to account for the one slot channel memory (defined by a first-order Markov chain with parameters p and q). The rescheduled transmission attempt delay in the *backlogged* state is assumed to be geometrically distributed with parameter g_r.

Let x_t be the number of mobiles in the *data_tx_failure* state, y_t be the number of mobiles in the *data_tx_success* state, and z_t be the number of mobiles in the *backlogged* state at the beginning of slot t. The three dimensional random process $\{x_t, y_t, z_t\}$ can be modeled as a finite state Markov chain. Based on the conditional probability that n mobiles simultaneously transmit header packets and c_s of those packets are successfully received at the base station, the one step transition probability that the system moves from $(x_t = i_1, y_t = j_1, z_t = k_1)$ at time slot t to $(x_{t+1} = i_2, y_{t+1} = j_2, z_{t+l} = k_2)$ at time slot $t+1$ is given by

$$P_{i_1 j_1 k_1, i_2 j_2 k_2} = \sum_{n=0}^{N-i_1-j_1} \sum_{c_s=0}^{min(M-i_1-j_1,n)} \sum_{s_j=0}^{c_s} \sum_{s_f=0}^{i_2-c_s+s_j} \sum_{f_s=0}^{j_2-s_j}$$

$$\cdot \binom{N-i_1-j_1-k_1}{a}\lambda^a(1-\lambda)^{N-i_1-j_1-k_1-a}$$
$$\cdot \binom{k_1}{n-a} g_r^{n-a}(1-g_r)^{k_1-n+a}$$
$$\cdot \binom{j_1}{b_j} g_d^{j_1-b_j}(1-g_d)^{b_j}\binom{b_j}{s_f}(1-p)^{s_f}p^{b_j-s_f}$$
$$\cdot \binom{i_1}{b_i} g_d^{i_1-b_i}(1-g_d)^{b_i}\binom{b_i}{f_s}(1-q)^{f_s}q^{b_i-f_s}$$
$$\cdot \binom{c_s}{s_j} p^{s_j}(1-p)^{c_s-s_j} f(c_s|n, M-i_1-j_1), \quad (5)$$

where M is the total number of uplink channels, N is the total number of mobiles, $N \geq M$, $0 \leq i_1 \leq M$, $0 \leq j_1 \leq M - i_1$, $0 \leq k_1 \leq N - i_1 - j_1$, $0 \leq i_2 \leq M$, $0 \leq j_2 \leq M - i_2$, $0 \leq k_2 \leq N - i_2 - j_2$, $a = k_2 - k_1 + c_s$, $b_j = j_2 - s_j - f_s + s_f$, $b_i = i_2 - c_s + s_j - s_f + f_s$, $f_s \leq b_i$, $s_f \leq b_j$, and the conditional probability $f(c_s|n, m_f)$ is defined as the probability that c_s header packets are successfully received conditioned on n mobiles transmit header packets over m_f channels, which can be evaluated by a recursive expression as

$$f(c_s|n, m_f) = \sum_{i=0}^{n} \binom{n}{i}\left(1-\frac{1}{m_f}\right)^{n-i}\left(\frac{1}{m_f}\right)^{i}$$
$$\cdot\left\{f(c_s|n-i, m_f-1)(1-p_s^{(i)}) + f(c_s-1|n-i, m_f-1)p_s^{(i)}\right\} \quad (6)$$

The initial conditions for $f(c_s|n, m_f)$ are given by

$$f(c_s|n, 0) = \begin{cases} 1 & \text{if } c_s = 0 \text{ and any } n \\ 0 & \text{if } c_s > 0 \text{ and any } n \end{cases}, \quad (7)$$

$$f(c_s|0, m_f) = \begin{cases} 1 & \text{if } c_s = 0 \text{ and any } m_f \\ 0 & \text{if } c_s > 0 \text{ and any } m_f \end{cases}, \quad (8)$$

$$f(c_s|1, m_f) = \begin{cases} 1 - p_s^{(1)} & \text{if } c_s = 0 \text{ and } m_f \geq 1 \\ p_s^{(1)} & \text{if } c_s = 1 \text{ and } m_f \geq 1 \\ 0 & \text{if } c_s > 1 \text{ and } m_f \geq 1 \end{cases}, \quad (9)$$

$$f(c_s|n, 1) = \begin{cases} 1 - p_s^{(n)} & \text{if } c_s = 0 \text{ and } n > 1 \\ p_s^{(n)} & \text{if } c_s = 1 \text{ and } n > 1 \\ 0 & \text{if } c_s > 1 \text{ and } n > 1 \end{cases}, \quad (10)$$

and

$$f(c_s|n, m_f) = 0 \text{ if } c_s < 0. \quad (11)$$

Note that, in the above, we assumed that header packet transmissions do not have any correlation with their previous header or data packet transmissions. Also, the probability of moving from header capture to *data_tx_success* state is assumed to be p. Simulations show that these are good approximations.

Let $\boldsymbol{P} = (P_{i_1j_1k_1,i_2j_2k_2})$ be the probability transition matrix and let $\boldsymbol{\Pi} = \{\pi_{i_1j_1k_1}\}$, $0 \leq i_1 \leq M$, $0 \leq j_1 \leq M - i_1$, $0 \leq k_1 \leq N - i_1 - j_1$, denote the steady-state probability vector. The vector $\boldsymbol{\Pi}$ can be calculated by solving the linear equations $\boldsymbol{\Pi} = \boldsymbol{\Pi P}$ and using the unity conservation relationship. The number of successful data packets in a slot is, in this case, equal to the number of users in the *data_tx_success* state, so that the average number of successes per slot is given by

$$E\{S_d\} = \sum_{i_1=0}^{M}\sum_{j_1=0}^{M-i_1}\sum_{k_1=0}^{N-i_1-j_1} j_1\pi_{i_1j_1k_1}. \quad (12)$$

The average per channel throughput, defined as the average number of packets (excluding the header packets) successfully received per slot per channel, is then given by

$$\eta_c = \frac{E\{S_d\}}{M}. \quad (13)$$

B. Delay Performance

Consider a system containing all mobiles which are either in the *backlogged* state, the *data_tx_success* state or in the *data_tx_failure* state. The number of users in that system is $\nu = i_1 + j_1 + k_1$, so that

$$E\{\nu\} = \sum_{i_1=0}^{M}\sum_{j_1=0}^{M-i_1}\sum_{k_1=0}^{N-i_1-j_1} (i_1 + j_1 + k_1)\pi_{i_1j_1k_1}. \quad (14)$$

On the other hand, the number of users which are not in the system is $N - \nu$, each generating a message in a slot with probability λ. Whenever a mobile generates a message, it joins the system one slot later. Therefore, the average arrival rate to that system is given by

$$\Lambda = \lambda(N - E\{\nu\}). \quad (15)$$

From Little's formula, the average time which each user spends in the system is given by the ratio between the average number of users in the system and the arrival rate. In our case, the average delay is one slot larger, since a user is assumed to join the system only after the slot in which the message is generated (which is not counted in the above calculation). Therefore, the average delay experienced by a message is given by

$$E\{D\} = 1 + \frac{E\{\nu\}}{\Lambda}. \quad (16)$$

RETRANSMISSION OF ERRONEOUS DATA PACKETS

In the multichannel protocol analyzed above, packets which get corrupted during the data segment transmission are lost and the recovery of such errors is left to the higher layer protocols. A classic way of recovering errors in packet transmission is through *retransmission* at the link level. Instead of ignoring the packet errors, a data packet is retransmitted if it is received in error. In the local wireless environment under consideration, where the feedback is assumed to be practically instantaneous, a data packet in error can be retransmitted in the immediately following slot. In this case, the base station would need to send a non-binary feedback (busy/idle/retransmit) in order to avoid a collision among retransmission packets from a mobile with header packets from other mobiles. Thus, with the 'persist-until-success' retransmission strategy, a geometric length message of X packets (with $E\{X\} = 1/g_d$) will take X' slots to finally get through, due to possible retransmissions. Therefore, we will have

$$X' = \sum_{i=1}^{X} Y_i, \quad (17)$$

where Y_i is an integer random variable equal to the number of transmissions it takes data packet i to be successfully received. If the fading is i.i.d., each packet transmission can experience an

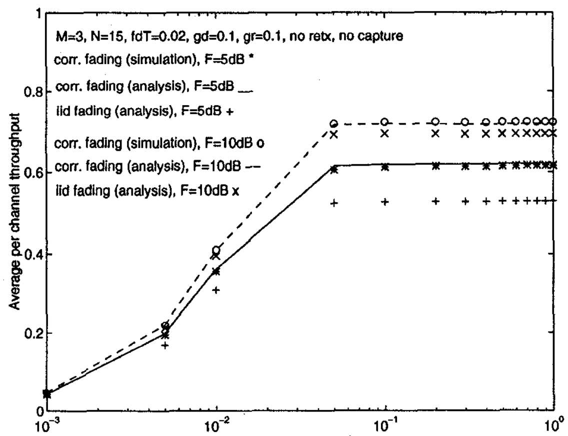

Fig. 2. Average per channel throughput η_c versus new message arrival rate λ. No retransmission. $M = 3$, $N = 15$, $g_d = 0.1$, $g_r = 0.1$, no capture, $f_D T = 0.02$, $F = 5$, 10 dB.

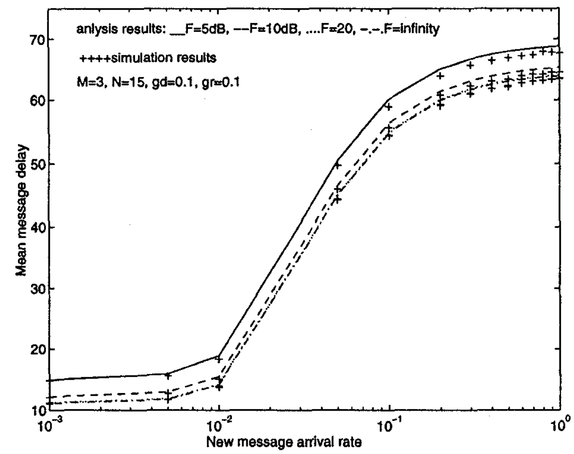

Fig. 3. Mean message delay verus new message arrival rate λ. No retransmission. $M = 3$, $N = 15$, $g_d = 0.1$, $g_r = 0.1$, no capture, $F = 5$, 10, 20 dB.

error with probability P_E, and the random variable Y_i will have a geometric distribution with parameter $(1 - P_E)$. In the correlated fading channel, Y_i will have a distribution given by

$$P[Y_i = y] = \begin{cases} p & y = 1 \\ (1-p)q^{y-2}(1-q) & y \geq 2 \end{cases} . \quad (18)$$

In both cases, it can be shown that $E\{Y_i\} = 1/(1 - P_E)$. Thus, the expected value of the effective length of the message (including the retransmission slots) is given by

$$E\{X'\} = \frac{1}{g_d(1 - P_E)}. \quad (19)$$

It can be seen that in the protocol with the 'persist-until-success' retransmission strategy, the mobile cannot directly move from the *data_tx_failure* state to the *idle/header_tx* state. Thus, in the case of the protocol with retransmission, the probability term $\binom{i_1}{b_i} g_d^{i_1 - b_i}(1 - g_d)^{b_i} \binom{b_i}{f_s}(1-q)^{f_s} q^{b_i - f_s}$ in (5) is modified to $\binom{i_1}{f_s}(1-q)^{f_s} q^{b_i - f_s}$, and $b_i = i_1 = i_2 - c_s + s_j - s_f + f_s$, in order to account for the fact that, with retransmission of erroneous data packets at the link level, the message transmission cannot end in a *data_tx_failure* state. Also, the parameter g_d in the term $\binom{j_1}{b_j} g_d^{j_1 - b_j}(1 - g_d)^{b_j}$ gets replaced with $g_d(1 - P_E)$.

RESULTS AND DISCUSSION

Numerical results for the average per channel throughput of the multichannel protocol without retransmission obtained from (13) for $M = 3$, $N = 15$, $g_d = 0.1$, $g_r = 0.1$, and no capture (i.e., $B \to \infty$) are plotted in Figure 2 for a normalized Doppler bandwidth of $f_D T = 0.02$. At a carrier frequency of 900 MHz and a packet duration of 10 ms, the $f_D T$ value of 0.02 represents slow fading (i.e., high correlation in fading) corresponding to the user moving at a speed of 2.5 km/h. The various values of the fading margin considered are 5 and 10 dB. The performance in i.i.d. fading is also plotted for comparison. The g_d value of 0.1 corresponds to an average message length of 10 data packets. Likewise, the parameter $g_r = 0.1$ means that the average time between rescheduled transmission attempts is 10 slots. In addition to the analysis, the multichannel protocol was simulated as well, and the performance collected in over one million slots of simulation runs is also shown in Figure 2. The correlated Rayleigh fading channel was simulated using the method proposed by Jakes [2].

Figure 2 shows that the i.i.d. fading model provides a pessimistic performance prediction when the fading is slow (i.e., when there is significant burstiness in packet errors due to high correlation in fading). Also, in Figure 2, both the analytical and the simulation results are found to be in close agreement, thus validating the analysis. For the same set of parameters, the mean message transfer delay performance of the multichannel protocol is shown in Figure 3. The curves represent the average delay values, in number of slots, obtained from (16). For the protocol without retransmission, the delay performance remains the same for both i.i.d. and correlated fading cases, because 1) the average header success slots remains independent of parameters p and q, and 2) since there is no retransmission at the link level, the delay due to data segment transmission is $1/g_d$. We also observed from numerical results that the header packet capture phenomenon due to multipath fading offers a per channel throughput improvement of about 10 to 15%, and a similar order of improvement in the delay performance.

Figure 4 shows the throughput performance of the multichannel protocol, both with and without retransmission, as a function of the normalized Doppler bandwidth, $f_D T$, for $\lambda = 1$, $M = 3$, $N = 15$, $g_d = 0.1$, $g_r = 0.1$, and no capture. The range of $f_D T$ values shown corresponds to very slow fading at one end ($f_D T = 0.01$), and close to i.i.d. fading at the other ($f_D T = 1$). For the protocol without retransmission, when $F = 5$ dB, the throughput increases from 0.53 to 0.66 (an increase of about 24%) when the $f_D T$ value is decreased from 1 to 0.01. However, the throughput performance of the protocol with retransmission of erroneous data packets remains independent of the value of $f_D T$. At low values of $f_D T$ (e.g., $f_D T < 0.02$ at $F = 5$ dB), the protocol without retransmission gives better throughput performance than the protocol with retransmission, whereas at high values of

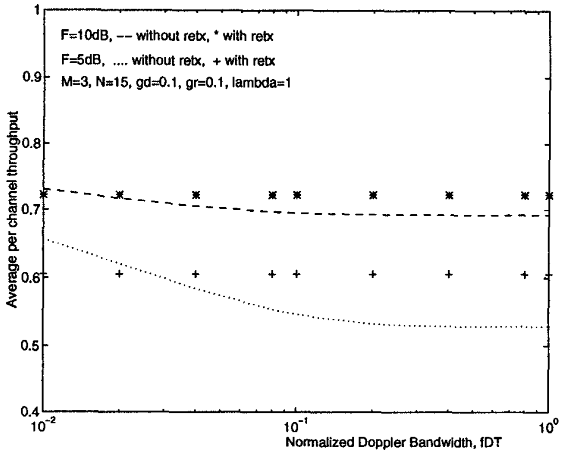

Fig. 4. Average per channel throughput η_c versus normalized Doppler bandwidth f_DT a) with retransmission and b) without retransmission. $\lambda = 1$. $M = 3$, $N = 15$, $g_d = 0.1$, $g_r = 0.1$, no capture, $F = 5$, 10 dB.

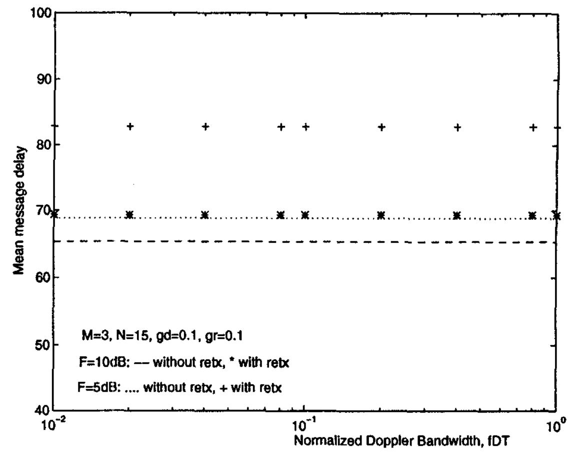

Fig. 5. Mean message delay versus normalized Doppler bandwidth f_DT a) with retransmission and b) without retransmission. $\lambda = 1$. $M = 3$, $N = 15$, $g_d = 0.1$, $g_r = 0.1$, no capture, $F = 5$, 10 dB.

f_DT ($f_DT > 0.02$ at $F = 5$ dB) the protocol with retransmission performs better. This performance variation over f_DT suggests that it is possible to devise more efficient versions of this protocol that could exploit the memory in the channel fading process for better performance.

We also see from Figure 4 that the delay performance remains independent of f_DT even in the case of the protocol with 'persist-until-success' retransmission. This is because with retransmission, the delay due to data segment transmission is just $1/g_d(1-P_E)$. So both the protocols with and without retransmission will exhibit delay performance independent of f_DT. However, the protocol with retransmission results in larger delays than the protocol without retransmission.

CONCLUSIONS

We analyzed the effect of packet error burstiness, caused by the correlation in the multipath fading process, on the throughput-delay performance of a multichannel wireless access protocol. Numerical and simulation results showed that the correlated fading model resulted in better performance than the i.i.d. fading model. Header packet capture due to multipath fading was shown to offer a per channel throughput improvement of about 10 to 15%, and a similar order of improvement was observed in the delay performance. A simple 'persist-until-success' retransmission strategy to recover erroneous data packets at the link level was also analyzed. It was shown that the protocol without retransmission benefited from highly correlated fading. It was observed that the multichannel protocol without retransmission performed better on slow fading channels (e.g., pedestrian user speeds), whereas the protocol with retransmission performed better in fast fading channels (e.g., vehicular user speeds). For the protocols both with and without retransmission, the average delay performance was shown to remain independent of the packet error burstiness. However, the protocol with retransmission resulted in larger delays than the protocol without retransmission. The improved reliability achieved through retransmissions at the link level, even though realized at the expense of significant delay performance, is expected to result in better performance at the upper layers of the protocol stack (e.g., TCP layer) in a wireless environment. It was also pointed out that more efficient versions of this protocol could be devised to exploit the memory in the channel fading behavior for better performance. Finally, the effect of non-zero propagation and processing delays and unreliable feedback on the protocol performance are topics for further investigation.

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