Energy Efficiency Analysis of a Multichannel Wireless Access Protocol*

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ABSTRACT

When user terminals powered by a finite battery source are used for wireless communications, energy constraints are likely to influence the design/choice of media access protocols. In this paper, we analyze the energy efficiency of a multichannel wireless access protocol using a finite energy source in a mobile radio environment. The average number of correctly transmitted packets for a given amount of allocated energy is used as the appropriate energy efficiency metric. The mobile radio channel itself is characterized by a correlated Rayleigh fading process, whose memory parameters depend on the speed of the user terminal, the data rate, and the physics of the channel. We show that the protocol which recovers erroneous data packets through retransmission is more energy efficient at low channel correlations.

I. INTRODUCTION

Portable user terminals for mobile communications must rely on limited battery energy for their operation. The design/choice of media access protocols in such applications must consider judicious use of the available energy resources, and should exploit the characteristics of the wireless environment towards improved efficiency. It has been recognized that energy conservation is a task which should be performed at all levels of the protocol stack (and not only limited to the search for better batteries or lower-power circuits), so that it should be an objective in the design of a communications system as a whole. In [1], Bambos and Rulnick study the optimization of power control strategies to maximize the battery life under QoS constraints. Energy performance of error control schemes is studied by Zorzi and Rao in [2], and by Lettieri *et al.* in [3].

In this paper, we focus on energy efficiency analysis of access protocols in wireless networks. The issue of energy consumption of media access protocols has been addressed in [4], and a protocol design following energy conservation principles has been proposed in [5]. In [6], it has been shown that error correlation (naturally present in wireless channels) can be exploited to conserve energy by devising access protocol rules that take into account the fading characteristics of the wireless channel. In this paper, based on Markov analysis and on the theory of renewal reward processes, we analyze the energy efficiency of a *multichannel* wireless access protocol in a mobile radio environment. In multichannel systems, there are several independent, orthogonal channels, and a user can transmit on any of these channels based on a suitable access protocol [7],[8].

We use a stochastic model for jointly tracking the evolution of the protocol and the available energy. By considering a discrete-time process which tracks the protocol evolution by means of a state machine, it is possible to define a set of metrics associated with the state transitions. We evaluate the energy efficiency of the protocol by appropriately defining the metrics and by studying the corresponding reward earned throughout the evolution of the process.

II. ENERGY EFFICIENCY

In order to evaluate the energy performance of access protocols under different fading scenarios using a unified metric, we define the *energy efficiency* of a protocol, which was introduced in [2], as

$$U = \frac{\text{total amount of data delivered}}{\text{total energy consumed}}. \tag{1}$$

We assume here that the protocol evolution can be tracked by means of a Markov chain with finite state space Ω. By appropriately defining metrics on the transitions of this chain, renewal reward analysis allows to compute throughput and energy performance [2],[10].

Let P_{ij} be the transition probability from state i to state j, and let π_i be the steady-state probability of the chain being in state $i \in \Omega$. It is possible to define various semi-Markov processes in which this Markov chain is embedded [10]. In general, consider two reward functions, $R^{(1)}$ and $R^{(2)}$, where $R_{ij}^{(1)}, R_{ij}^{(2)}$ are quantities associated with transition ij, and let $R^{(1)}(\tau), R^{(2)}(\tau)$ be the cumulative values of those functions, i.e., the total reward earned through the system evolution in the time interval $[0, \tau]$. From renewal theory [11], we have the following fundamental result:

$$\lim_{\tau\to\infty} \frac{R^{(1)}(\tau)}{R^{(2)}(\tau)} = \frac{\sum_{i\in\Omega} \pi_i \sum_{j\in\Omega} P_{ij} R_{ij}^{(1)}}{\sum_{i\in\Omega} \pi_i \sum_{j\in\Omega} P_{ij} R_{ij}^{(2)}}, \tag{2}$$

which can be easily computed for a number of cases of interest. For example, let S_{ij}, C_{ij} and D_{ij} be the average number of successfully received packets, amount of consumed energy, and time delay associated with transition ij, respectively. Then, if $R^{(2)} = D$, evaluation of (2) for $R^{(1)} = S$ and $R^{(1)} = C$ gives

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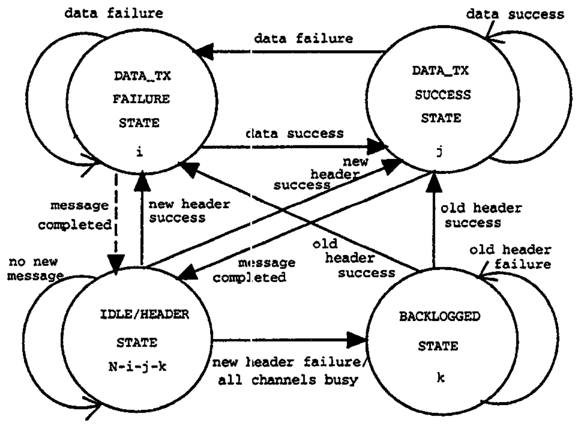

Fig. 1. Mobile state transition diagram (in Markov fading)

the average throughput and energy consumption, respectively (ergodicity of all processes involved will be assumed throughout). On the other hand, the choice $R^{(1)} = S$ and $R^{(2)} = C$ yields the energy efficiency of the protocol. Therefore, once the Markov chain for the protocol evolution has been found, all the relevant performance metrics can be easily computed from the above.

III. Multichannel Protocol Performance

In this section, we present the energy efficiency analysis of a multichannel wireless access protocol, which can be viewed as a hybrid protocol employing the slotted ALOHA and reservation concepts, based on the throughput-delay analysis for the same multichannel wireless access protocol [8]. 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 collisions are restricted to occur only among header packet transmissions. Refer to [8] for a detailed description of the protocol, the system model, and the fading channel model. The mobile state transition diagram is shown in Figure 1.

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 in [8]). In the *idle/header_tx* state, the mobile remains idle with probability $1 - \lambda$ or generates a new message with probability λ. In the latter case, it randomly chooses an idle uplink channel (if available), and transmits the header packet in the uplink slot. If the header packet transmission is successful, then the mobile moves from the *idle/header_tx* state to either *data_tx_success* state or *data_tx_failure* state. In the data transmit state, the mobile transmits the data packets continuously until all the packets in the message are sent, and then moves back to the *idle/header_tx* state. During the transmission of data packets, the mobile moves from *data_tx_success* state to either *data_tx_success* state or *data_tx_failure* state, with probability p and $1 - p$, respectively. Similarly, from *data_tx_failure* state, the mobile moves to *data_tx_success* state and *data_tx_failure* state with probability $1 - q$ and q, respectively. The mobile moves from the *idle/header_tx* state to a *backlogged* state if all the uplink channels are found busy upon arrival of a message. Similarly, if the header packet is lost due to collision or bad channel conditions, the mobile moves from the *idle/header_tx* state to the *backlogged* state. In the *backlogged* state, the mobile rechecks the status of the uplink channels after a random number of slots. The rescheduled transmission attempt delay is assumed to be geometrically distributed with parameter g_r. If a mobile in the *backlogged* state fails to transmit its header packet successfully, it stays in this state until its header packet transmission is successful, after which it moves to either *data_tx_success* state or *data_tx_failure* state.

A. Throughput

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, $P_{i_1 j_1 k_1, i_2 j_2 k_2}$, 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 Eq. (5) in [8]. Let $\boldsymbol{P} = (P_{i_1 j_1 k_1, i_2 j_2 k_2})$ be the probability transition matrix and let $\boldsymbol{\Pi} = \{\pi_{i_1 j_1 k_1}\}$, $0 \leq i_1 \leq M, 0 \leq j_1 \leq M - i_1$, $0 \leq k_1 \leq N - i_1 - j_1$, 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 equal to the number of users in the *data_tx_success* state, so that the average number of successes per slot is given by

$$E\{S_d\} = \sum_{i_1=0}^{M} \sum_{j_1=0}^{M-i_1} \sum_{k_1=0}^{N-i_1-j_1} j_1 \pi_{i_1 j_1 k_1}. \tag{3}$$

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

$$\eta_c = \frac{E\{S_d\}}{M}. \tag{4}$$

B. Delay

As derived in [8], the average delay experienced by a message is given by

$$E\{D\} = 1 + \frac{E\{\nu\}}{\Lambda}, \tag{5}$$

where $E\{\nu\}$ is the average number of users which either are in the transmission mode or are backlogged, i.e.,

$$E\{\nu\} = \sum_{i_1=0}^{M} \sum_{j_1=0}^{M-i_1} \sum_{k_1=0}^{N-i_1-j_1} (i_1 + j_1 + k_1)\pi_{i_1 j_1 k_1}, \qquad (6)$$

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

C. Energy Efficiency

Let the system be in state (i_1, j_1, k_1) in a given slot (i.e., i_1 users experience data failure, j_1 users experience data success, k_1 users are backlogged and $N - i_1 - j_1 - k_1$ users are idle). Users in the data transmission state (both successful and unsuccessful) will transmit one packet with probability one in that slot. If $i_1 + j_1 < M$ (i.e., not all channels are occupied), users in the backlogged state will each attempt transmission with probability g_r, and idle users will each attempt transmission with probability λ, so that the average number of packet transmissions in the slot is given by $i_1 + j_1 + k_1 g_r + (N - i_1 - j_1 - k_1)\lambda$. On the other hand, if $i_1 + j_1 = M$ (i.e., all channels are busy), backlogged and idle users will not attempt transmission and the number of transmissions will be equal to M.

From the above expressions for the probability distribution of the Markov chain, it is then possible to compute the average number of transmitted packets in a slot (whioch is defined to be the average energy consumption) as

$$\varepsilon = \sum_{i_1=0}^{M-1} \sum_{j_1=0}^{M-i_1-1} \sum_{k_1=0}^{N-i_1-j_1} [i_1 + j_1 + k_1 g_r + (N - i_1 - j_1 - k_1)\lambda] + \sum_{i_1+j_1=M} M\pi_{i_1 j_1 0}. \qquad (7)$$

The energy efficiency of the scheme, defined as the average number of successful transmissions per unit energy, can be computed as

$$U = \frac{E\{S_d\}}{\varepsilon}, \qquad (8)$$

where the energy unit is assumed to be equal to one packet transmission.

IV. 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*. 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, the expressions for the expected value of the effective length of the message and the one step transition probability need to be modified as given in Section V of [8].

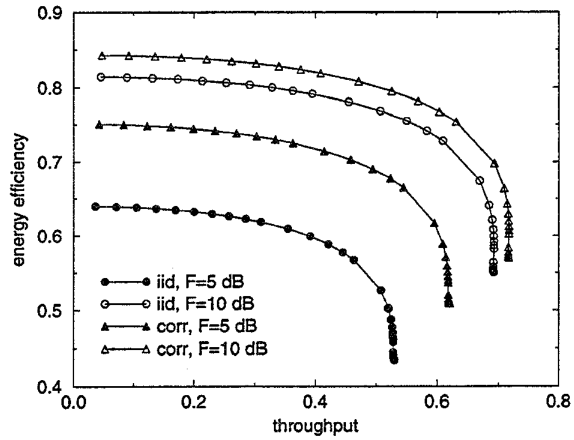

Fig. 2. Energy efficiency vs. throughput for i.i.d. fading and correlated Rayleigh fading with $f_D T = 0.02$, for varying λ. Different points correspond to different λ. $M = 3, N = 15, F = 5$ and 10 dB. No retransmission. No capture.

V. Results and Discussion

Numerical results are obtained from the analysis presented above for $M = 3$, $N = 15$, $g_d = 0.1$, $g_r = 0.1$, and a normalized Doppler bandwidth of $f_D T = 0.02$, where f_D is the maximum Doppler shift and T is the packet duration. 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 values of the fading margin[1], F, considered are 5 and 10 dB, and no capture is assumed (plots showing the effect of capture are not presented here due to lack of space, even though the analysis presented here would make that calculation possible). We also found good agreement between analytical and simulation results.

Average per-channel throughput, average message delay, and energy efficiency are computed using (4), (5), and (8), respectively. The performance in i.i.d. fading is also plotted for comparison. Figure 2 shows the energy efficiency vs. throughput (different points on the curve correspond to different values of the per-user message arrival rate, λ). It can be seen that the relationship between the two performance metrics implies a trade-off, since any throughput increase results in a loss in energy efficiency. Note that in this case, when the traffic load is increased, throughput is increased (as shown in [8]), but the number of transmissions per slot also increases, and the latter effect is seen to always be more significant than the former. From Figure 2, it is also seen that the correlated fading case performs better than the i.i.d. fading case, as the latter curve always lies below the former. This had been observed for throughput in [8], and is seen here to be true for energy efficiency as well (in fact, the improvement in energy efficiency induced by error correlation is even more significant than that in throughput). Similar behavior is exhibited by the throughput/delay trade-off (see Figure 3).

[1] The fading margin is the maximum tolerable attenuation which still guarantees good reception quality.

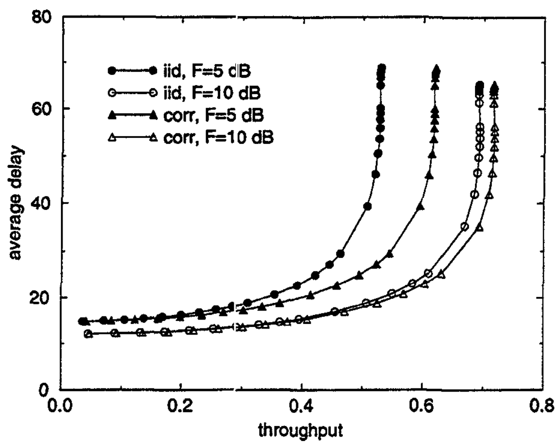

Fig. 3. Average message delay vs. throughput for i.i.d. fading and correlated Rayleigh fading with $f_D T = 0.02$, for varying λ. Different points correspond to different λ. $M = 3, N = 15, F = 5$ and 10 dB. No retransmission. No capture.

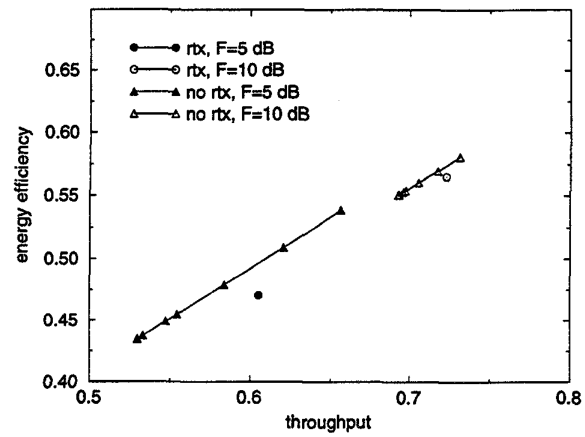

Fig. 5. Energy efficiency vs. throughput for varying $f_D T$ and $\lambda = 1$. Different points correspond to different $f_D T$. $M = 3, N = 15, F = 5$ and 10 dB. Protocols with and without retransmission. No capture.

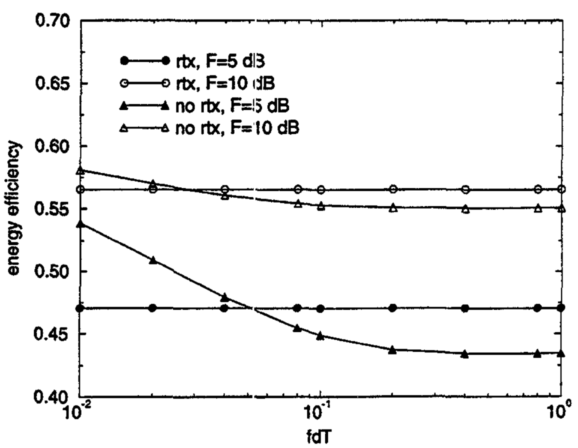

Fig. 4. Energy efficiency vs. $f_D T$ for $\lambda = 1$. $M = 3, N = 15, F = 5$ and 10 dB. Protocols with and without retransmission. No capture.

As the performance metrics depend on the channel correlation, it is of interest to study in more detail this dependence. Figure 4 shows the energy efficiency vs. the normalized Doppler bandwidth, $f_D T$, for $\lambda = 1$. Two cases are considered in this figure, namely the protocol with retransmission and without retransmission. It is seen that in the case of the protocol with retransmission the energy efficiency is actually independent of the channel correlation. This is consistent with the throughput results reported in [8] and with the fact that at the considered value of λ the average number of packet transmissions per slot is close to 1 and only weakly dependent on $f_D T$. On the other hand, when retransmission is not used, throughput is no longer independent of $f_D T$. In particular, in highly correlated channels (small $f_D T$), the protocol without retransmission is more energy efficient than the protocol with retransmission. On the other hand, when the channel correlation is very low (large $f_D T$), the protocol with retransmission is more energy efficient than the protocol without retransmission. This performance variation over $f_D T$ suggests that it is possible to devise more efficient versions of the protocol that could exploit the memory in the channel fading process for better energy performance. For example, if the base station detects a data packet error from a mobile, it can simply ask the mobile to terminate its on-going data transmission and release the channel. Such a scheme is expected to give good results in the presence of significant channel burstiness (i.e., slow fading), as it avoids insisting on transmission in slots which are likely to be in error, and lets other mobiles (whose channel conditions might be good) access and use the channel. On the other hand, the above strategy could be wasteful in fast fading conditions where packet errors could occur independently from slot to slot. In such fast fading conditions, error recovery by retransmission would be preferred.

The relationship between throughput and energy efficiency as the channel correlation changes is illustrated in Figure 5, which shows the energy efficiency vs. the average throughput for various values of $f_D T$ and for $\lambda = 1$. The energy consumption is always independent of $f_D T$, since in our model users attempting transmission of a header packet experience steady-state channel conditions. This accounts for the linear relationship between throughput and energy efficiency (given by throughput divided by the constant energy consumption), which reduces to a single point for the case in which retransmission is used (throughput is also independent of $f_D T$ in this case).

Finally, a comparison between the multichannel and single channel cases is provided in Figure 6, which shows results for $N = 1, M = 5$ and for $N = 3, M = 15$ (the number of users per channel is kept fixed for a fair comparison). It can be seen that the

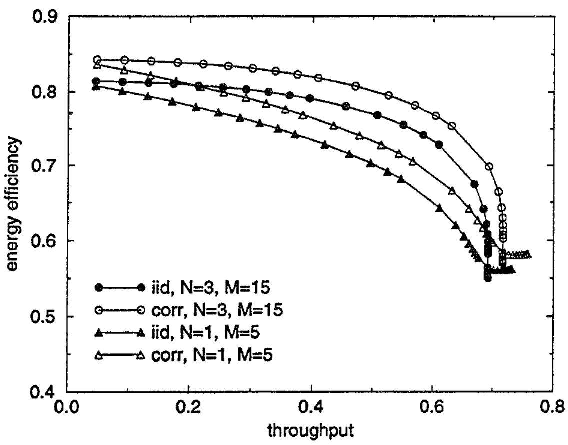

Fig. 6. Energy efficiency vs. throughput for i.i.d. fading and correlated Rayleigh fading with $f_D T = 0.02$, for varying λ. Different points correspond to different λ. $M = 3, N = 15$ and $M = 1, N = 5$ compared. $F = 10$ dB. No retransmission. No capture.

multichannel case yields slightly better throughput in most cases, as one would expect due to statistical multiplexing. Also, significantly better energy efficiency is achieved in the multichannel case, which is to be ascribed to the decreased collision rate. In fact, in the absence of capture, for a single channel a header success can only occur when a single user attempts transmission (i.e., if two or more users simultaneously attempt, the probability of header success is zero), whereas in the multichannel case there is always a positive (although possibly small) probability that a user succeeds. The fact that in the multichannel case users choose channels at random when trying to gain access also accounts for the performance crossover at high arrival rates. In fact, in this case, if, for example, three users attempt transmission and there are three idle channels, there is no guarantee that no collision will occur, as more than one user may end up choosing the same channel, resulting in collisions on some channels and in some other channels being idle.

VI. Conclusions

We analyzed the effect of packet error burstiness caused by the correlation in the multipath fading process on the throughput-delay and energy efficiency performance of a multichannel wireless access protocol. The packet error burstiness was modeled using a first-order Markov chain whose parameters were defined as a function of the normalized Doppler bandwidth and the fading margin. Following Markov analysis and renewal reward analysis, expressions for the average per channel throughput, average message transfer delay and energy efficiency were derived. Numerical and simulation results showed that the correlated fading model resulted in better performance than the i.i.d. fading model. A simple 'persist-until-success' retransmission strategy to recover erroneous data packets 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) than the protocol with retransmission. However, the protocol with retransmission performed better in fast fading channels (e.g., vehicular user speeds). The gains in throughput are paralleled by even more significant gains in terms of energy efficiency. We recognize that, in networks comprising battery-powered devices, maximizing throughput alone may not be the primary concern. The results shown, as well as others which can be obtained from the analysis presented, can help the designer tune the protocol parameters to trade-off throughput for energy efficiency.

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