# Energy Consumption Performance of a Class of Access Protocols for Mobile Data Networks*

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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 choice of media access protocols. We use the average number of correctly transmitted packets for a given amount of allocated energy as an appropriate metric. In particular, we study different versions of a wireless access protocol operating over a mobile radio channel using a finite energy source with a flat power profile. The mobile radio channel iteslf is characterized by a correlated Rayleigh fading process, the correlation in the fading process being dependent on the speed of the user terminal. We show that the access protocol with an *Error Detect* feature is energy efficient for pedestrian user speeds, whereas for vehicular speeds a *Retransmission* protocol is more efficient.**

## I. Introduction

Portable user terminals for mobile communications must rely on limited battery energy for their operation [1]-[6]. The design/choice of media access protocols in such applications must consider judicious use of the available energy resource. In this paper, we investigate the "bits per joule" rating of different media access protocols in a mobile radio environment. We extend an analytical perspective to the scope of the metrics that can be tracked in assessing the energy efficiency of various wireless access protocols. On a related topic, significant amount of work has been done in recent years on the development of new batteries and the characterization of battery discharge behavior [7],[8]. The battery performance metrics commonly reported are the constant power, constant current and constant load capacity. With most types of batteries these three capacities are not equal, implying that one can get more out of a given battery by draining it in the "right way". Particularly, the mobile radio channel is prone to correlated bursts of packet errors. These error correlations introduce memory which can, in principle, be exploited for a variety of purposes, including energy conservation.

In [1],[2], Bambos and Rulnick are concerned with the optimization of power control strategy to maximize the battery life (or, equivalently, to minimize the transmit power) under QoS constraints. In [3],[4], Zorzi and Rao studied energy constrained ARQ techniques. In this paper, we apply energy consumption constraints to media access protocols design in order to enhance energy efficiency under different channel conditions. We use a stochastic model for jointly tracking the evolution of the protocols and the available charge. 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. By appropriately defining the metrics and by studying the corresponding reward earned throughout the evolution of the process, we evaluate the energy efficiency of the protocols. Although the energy consumption issue addressed in this paper and in [1]-[4] originates from different perspectives (access mechanism versus power/error control), they lead to consistent conclusions about energy management strategies. In particular, persistence is not always a reasonable choice, and adaptive strategies which try to avoid transmission during bad channel periods yield much better energy efficiency.

## II. Wireless Access Protocols

In this section, we describe the wireless access protocol considered in this paper (we will refer to it as the *Basic* protocol), and two enhanced versions of it (*Error Detect* protocol and *Retransmission* protocol) [9],[10]. This protocol can be viewed as a hybrid protocol employing the slotted ALOHA and reservation concepts [11]. 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 uplink (mobile-to-base station link) channel is slotted to one packet duration. Transmission attempts are made by the mobiles only at the slot boundaries. 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 like destination address, number of packets in the data segment, etc. The data segment represents the actual traffic. It consists of a random number of data packets. A *busy/idle flag* indicating the activity on the uplink is made available to the mobiles at the beginning of each slot. This flag is broadcast by the base station, once every slot, on the downlink (base station-to-mobile link).

### A. Basic Protocol

As per the *Basic* protocol, once a mobile receives a message to be delivered to the base station, it first checks the status of the received busy/idle flag. If the flag is set to busy, it refrains from making a transmission attempt. If the flag is set to idle, then it makes a transmission attempt by first sending the header packet

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on the uplink slot. If the header packet is received successfully (without packet loss due to collision or fading), the base station broadcasts the ID of the successful mobile (capturing mobile in the event of collision among header packets from different mobiles), and sets the flag busy for the $X$ subsequent slots, where $X$ is the number of packets in the successful mobile's data segment. This allows only the successful mobile to send all its data packets continuously in those $X$ slots. The base station resets the flag back to the idle status once the message transmission is complete. On the other hand, if the header packet is lost (due to collision or fading), the base station will not respond with a busy flag, but will continue sending the idle flag. This is an indication to the mobile that the header packet was lost, and so it has to reschedule the transmission attempt to a later time.

It can be seen that the packet transmissions, as per the above feedback mechanism (when error-free), can experience fading, interference, and noise during header slots, whereas during data slots only fading and noise (no interference) are experienced. Thus, in case of error-free feedback to all the mobiles, collisions are possible only during the header packet transmission and not during the transmission of data packets. However, errors in the busy/idle flag reception will result in collisions, hence packet losses, during the transmission of data packets as well [12].

### B. Error Detect Protocol

In the *Basic* protocol described in Section II.A, the mobile is allowed to continuously transmit all the packets in the data segment of the message even if one or a block of those packets are lost due to channel fading. However, the memory in the fading process can be exploited to modify the data transmission strategy by using the knowledge about the channel status information. As an example, consider the following. Under slow fading conditions (where events in successive slots are expected to be highly correlated), the fact that the data packet in the current slot is received in error implies that the packet in the subsequent slot will also be received in error with high probability. Therefore, the protocol rules could be modified such that, when the base station detects such a "bad" channel condition during data packets transmission from a mobile, it could ask that mobile to abort transmission and release the channel. This would avoid the occurrence of possible subsequent errors, and allows other mobiles (which may, on the other hand, experience "good" channel conditions) to transmit. This leads to a value of the throughput which may even exceed the average rate of successful slots on the channel, due to the introduced dependence between admitted users and channel quality.

We call the protocol incorporating the above idea as the protocol with an error-detect (*ED*) feature. According to the *ED* protocol, if a packet in the data segment of the message is received in error, the base station sends out an idle flag in the next slot (instead of sending a busy flag in all $X$ data slots, as the *Basic* protocol would require) to prompt the mobile to terminate the ongoing data transmission. Such a strategy enables other mobiles to access the channel during those slots which otherwise could have witnessed loss of packets due to fading.

### C. Retransmission Protocol

The *Basic* protocol does not take any action in the event of data packet errors, i.e., data packets which get corrupted during transmission are just lost and the recovery of such errors is left to higher layer protocols. The *ED* protocol (in Section II.B), on the other hand, reacts to packet errors by aborting the ongoing message transmission. However, in the presence of rapidly varying channels, which result in low correlation between errors in consecutive slots, the strategy of *ED* protocol may be too wasteful, as it effectively reduces the message length and therefore decreases the overall efficiency. Another classic way of recovering errors in packet transmission is through *Retransmission* at the link level. Instead of ignoring packet errors (as in the *Basic* protocol) or aborting the message transmission altogether (as in the *ED* variation), a packet is retransmitted if it is received in error. In the local wireless environment under consideration, where the feedback is assumed to be instantaneous, a 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 user with header packets from other users.

### D. Energy Consumption Metric

In an energy constrained environment, when the channel is "bad" over a long period of time, continued transmission of data packets in a message (as in *Basic* protocol) or repeated transmission of data packets until success (as in *Retransmission* protocol) would lead to waste of energy due to many unsuccessful data packet transmissions. On the other hand, if the user witnesses a "rapidly" fading channel (experienced by a fast moving vehicular user), then the retransmission strategy may prove to be beneficial, since, in that case, consecutive data packet transmissions may succeed or fail independently from slot to slot. In order to compare the energy consumption of the various protocols under different fading scenarios using a unified metric, we study the *energy efficiency* of a protocol, $U$, which was introduced in [4] as

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

We adopt a first-order Markov approximation to the packet success/failure process on correlated fading channels [13],[14], and investigate how the throughput and the consumed energy depend on the protocol rules. We show that a good choice of the protocol can greatly improve the energy efficiency.

## III. Energy Efficiency Analysis

In order to analyze the energy efficiency of the protocols described in the previous section, we assume that the feedback from the base station (busy/idle/retransmit and the successful mobile ID) on the downlink is received instantaneously, and error-free by all the mobiles. The instantaneous feedback assumption is reasonable in cellular environments where the delays due to propagation and processing could be very small compared to one slot duration. The error-free feedback assumption is also reasonable because the feedback consists of a very few bits, and hence can be provided with adequate error protection. We also make the following assumptions on the message arrival process and the message length distribution: 1) the message arrival process at each mobile is Bernoulli with rate $\lambda$ per slot, and 2) the length of the data segment of the message, $X$, measured in integer number of packets, follows a geometric distribution with parameter $g_d$.

Based on the above assumptions, the evolution of the protocols on a Markov channel can be tracked by means of a Markov chain with finite number of states [9],[10]. By appropriately defining metrics on the transitions of this chain, renewal reward analysis allows to compute throughput and energy performance [4].

For the protocols considered here, an adequate choice for the state space $\Omega$ of the Markov chain consists of just five states, corresponding to 1) *idle* ($I$), 2) *header packet success* ($H_s$), 3) *header packet failure* ($H_f$), 4) *data packet success* ($D_s$), and 5) *data packet failure* ($D_f$). Once the state transition probabilities of the chain, $P_{ij}, i, j \in \Omega$, are determined, the steady-state probability vector, $\pi$, is given by the solution of the equation

$$\pi = \pi P, \qquad \sum_{j \in \Omega} \pi_j = 1. \tag{2}$$

It is possible to define various semi-Markov processes in which this Markov chain is embedded [15]. This formulation allows us to keep track of various events through a unified analytical tool. Specifically, let us consider packets which have been successfully transmitted. Let $R_i$ be the number of such successes associated with a visit to state $i$. The quantity $R_i$, which can be a random variable, is called a *reward function* associated with the Markov chain. The analytical framework in [15],[16] leads to the following simple expression for the average number of successes per slot:

$$\eta = \lim_{\tau \to \infty} \frac{R(\tau)}{\tau} = \frac{\sum_{i \in \Omega} \pi_i \overline{R}_i}{\sum_{i \in \Omega} \pi_i} \tag{3}$$

where $R(\tau)$ is the total reward earned in the time interval $[0, \tau]$, and $\overline{R}_i = E[R_i]$. By appropriately defining other "reward" functions, it is possible to compute the average values of other quantities of interest. For example, let $C_i$ be the amount of consumed energy associated with a visit to state $i$. Then, one can compute the average consumed energy per slot as

$$\lim_{\tau \to \infty} \frac{C(\tau)}{\tau} = \frac{\sum_{i \in \Omega} \pi_i \overline{C}_i}{\sum_{i \in \Omega} \pi_i}. \tag{4}$$

A more interesting quantity, for the purposes of this study, is the average number of successes per unit energy, introduced in (1). In this case $U$ evaluates to

$$U = \lim_{\tau \to \infty} \frac{R(\tau)}{C(\tau)} = \frac{\sum_{i \in \Omega} \pi_i \overline{R}_i}{\sum_{i \in \Omega} \pi_i \overline{C}_i}. \tag{5}$$

It is thus clear that the Markov approach allows us to compute directly a number of quantities of interest once (2) has been solved. In what follows, we solve (2) for the various protocols considered and compute their energy efficiency.

### A. Analysis of Basic Protocol

Based on the assumptions above, the state transition probability matrix, $P$, for the *Basic* protocol can be written as

$$P = \begin{bmatrix} X_0 & X_1 & X_2 & 0 & 0 \\ 0 & 0 & 0 & p & 1-p \\ X_0 & X_1 & X_2 & 0 & 0 \\ g_d X_0 & g_d X_1 & g_d X_2 & X_3 & X_4 \\ g_d X_0 & g_d X_1 & g_d X_2 & X_5 & X_6 \end{bmatrix}, \tag{6}$$

where $X_0 = p_0 = (1-\lambda)^N$, $X_1 = \sum_{k=1}^{N} p_k p_s^{(k)}$, $X_2 = 1 - X_0 - X_1$, $X_3 = (1-g_d)p$, $X_4 = (1-g_d)(1-p)$, $X_5 = (1-g_d)(1-q)$, and $X_6 = (1-g_d)q$. In the above, $p$ and $q$ are the parameters of the two-state Markov chain which is used to describe the packet success/failure process. In other words, $p$ and $1-q$ are the probabilities that the packet transmission in slot $j$ is successful, given that the transmission in slot $j-1$ was successful or unsuccessful, respectively. On a correlated Rayleigh fading channel, the parameters $p$ and $q$ depend on the link fading margin $F$, and the normalized Doppler bandwidth $f_D T$, where $f_D$ is the Doppler frequency and $T$ is the packet duration. Expressions for $p$, and $q$ are given in [13],[9]. As discussed in [10], the above matrix gives a conservative approximation, since the dependence of the transition probabilities from the *header success state* on the number of users involved in the collision is neglected. Further, $p_k$ is the probability that $k$ out of $N$ mobile users ($0 \le k \le N$) make a transmission attempt in a slot, which is given by the binomial expression $\binom{N}{k} \lambda^k (1-\lambda)^{N-k}$. The header packet capture probability $p_s^{(k)}$ is given by [10]

$$p_s^{(k)} = k e^{-1/F} \left( \frac{1}{1+b} \right)^{k-1}, \tag{7}$$

where $b$ is the capture threshold. There is no capture when $b \to \infty$, and there is perfect capture when $b = 1$.

As to the reward and energy consumption metrics, note that successful transmissions can only occur in the *data success* state (a header success is *not* counted as useful throughput in this context), whereas no successful transmission is possible in any other state, so that

$$\overline{R}_4 = 1, \qquad \overline{R}_1 = \overline{R}_2 = \overline{R}_3 = \overline{R}_5 = 0. \tag{8}$$

A single packet transmission occurs in a slot which is designated as *busy* (corresponding to a *data success* and *data failure*). On the other hand, if a slot is designated as *idle*, each user will generate a new message in that slot with probability $\lambda$, and therefore the average number of transmissions (which represents the consumed energy) is $N\lambda$. Therefore, we have in this case

$$\overline{C}_1 = \overline{C}_2 = \overline{C}_3 = N\lambda, \qquad \overline{C}_4 = \overline{C}_5 = 1. \tag{9}$$

The energy efficiency of the *Basic* protocol can be computed by using the above expressions in (5).

### B. Analysis of ED Protocol

Note that the transition probability matrix for the *ED* protocol, $P'$, will be the same as that of the *Basic* protocol (matrix $P$, given by (6)), except for the transition probabilities from state $D_f$. In fact, for the *ED* protocol, the transition probabilities from state $D_f$ will be same as those from the *idle* state. Accordingly, the transition probability matrix for the *ED* protocol is given by

$$P' = \begin{bmatrix} X_0 & X_1 & X_2 & 0 & 0 \\ 0 & 0 & 0 & p & 1-p \\ X_0 & X_1 & X_2 & 0 & 0 \\ g_d X_0 & g_d X_1 & g_d X_2 & X_3 & X_4 \\ X_0 & X_1 & X_2 & 0 & 0 \end{bmatrix}, \tag{10}$$

where $X_0$, $X_1$, $X_2$, $X_3$, and $X_4$ are as defined in Section III.A. The quantities $\overline{R}_i$ and $\overline{C}_i$ can be found as before, and the energy efficiency of the *ED* protocol can again be computed from (5).

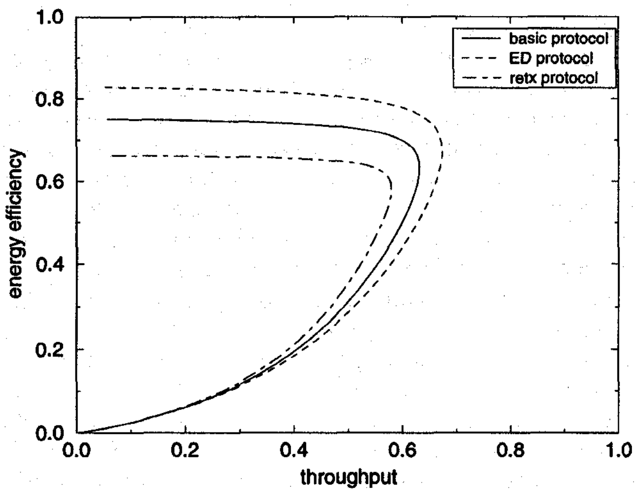


Fig. 1. Energy efficiency *vs* throughput for various protocols in *slow fading*, i.e., $f_DT = 0.02$. $N = 10$. $g_d = 0.1$. $b \to \infty$. $F = 5$ dB.

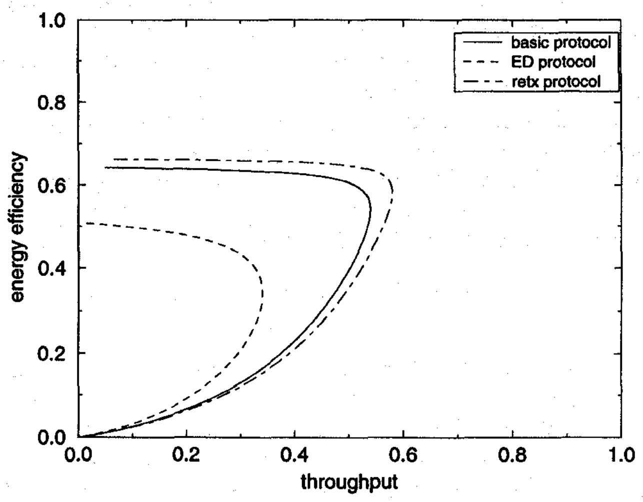


Fig. 2. Energy efficiency *vs* throughput for various protocols in *fast fading*, i.e., $f_DT = 0.64$. $N = 10$. $g_d = 0.1$. $b \to \infty$. $F = 5$ dB.

## C. Analysis of Retransmission Protocol

Since the use of retransmissions occurs only when a data packet is in error, the transition probability matrix for the *Retransmission* protocol is the same as for the *Basic* protocol, except for the last row (transitions from state $D_f$, which corresponds to a data packet in error). In fact, after an erroneous data packet, a retransmission attempt is performed and therefore only transitions to $D_s$ (with probability $1-q$) or $D_f$ (with probability $q$) are allowed.

Therefore, the analysis of the *Retransmission* protocol can again be performed using its transition probability matrix which is given by

$$P'' = \begin{bmatrix} X_0 & X_1 & X_2 & 0 & 0 \\ 0 & 0 & 0 & p & 1-p \\ X_0 & X_1 & X_2 & 0 & 0 \\ g_dX_0 & g_dX_1 & g_dX_2 & X_3 & X_4 \\ 0 & 0 & 0 & 1-q & q \end{bmatrix}. \quad (11)$$

## D. Results and Discussion

As an example of the obtained results, Figures 1 and 2 show the energy efficiency, $U$, as a function of the achievable throughput for the different versions of the access protocol. The parameters considered in the plots are: number of mobiles $N = 10$, fading margin $F = 5$ dB, $b \to \infty$, and $g_d = 0.1$. Figure 1 gives the performance when the fading process is very *slow*, i.e., the normalized Doppler bandwidth $f_DT = 0.02$. Figure 2 gives the results when the fading is *fast*, i.e., $f_DT = 0.64$. Note that at a carrier frequency of 900 MHz and a packet duration of 10 ms, the $f_DT$ values of 0.02 and 0.64 correspond to mobile user speeds of about 2.5 km/h (e.g., pedestrian user) and 80 km/h (e.g., vehicular user), respectively. The figures show that for very small arrival rate ($\lambda \to 0$) the throughput goes to zero whereas the energy efficiency is maximum (no collisions). As $\lambda$ is increased, corresponding to traveling clockwise along the curves, the energy efficiency is degraded, whereas throughput increases up to some optimal value of $\lambda$ (equal to $1/N$, as discussed in [10]), after which it decreases due to too many collisions. The knee of the curves is the desired operating point for the system, and it is seen from Figure 1 that for slow fading this leads to best throughput and best energy efficiency for the *ED* protocol, whereas the worst performance is achieved by the *Retransmission* protocol. This was to be expected, since, in the presence of significant correlation between successive errors, aborting the transmission may be the best thing to do. For example, if the average length of an error burst is comparable to the average message length, completing the message transmission after an error may lead to unsuccessful transmissions with consequent waste of bandwidth and energy; insisting on retransmission is of course the worst thing to do in this case. On the other hand, when the packet errors are almost independent, a single retransmission may lead to successful message completion, whereas the *ED* strategy may unnecessarily abort messages. In this case, as illustrated in Figure 2, the *Retransmission* protocol shows the best performance, and the *ED* protocol the worst. Therefore, we may conclude that the *ED* protocol is energy efficient for pedestrian user speeds, whereas the *Retransmission* protocol is more efficient for vehicular user speeds.

As a refinement to the *ED* and the *Retransmission* protocols, consider the following. Instead of terminating the data transmission at the first instance of a data packet failure (as in the *ED* protocol), or repeatedly sending a data packet until success (as in the *Retransmission* protocol), the base station could allow the mobile to resend a lost data packet only up to a certain number of times (defined as a parameter, $n_r$), after which the mobile is asked to abort the data transmission. As can be seen, this is a generalized form of the protocol, and both *ED* and *Retransmission* protocols can be thought of as special cases of this generalized form. That is, when $n_r = 0$, the protocol performs as the *ED* protocol, and when $n_r \to \infty$, the protocol performs as the *Retransmission* protocol. The transition probabilities for the generalized protocol can be written in the same way as for the *ED* protocol, except that the single $D_f$ state in the *ED* case is expanded into $(n_r + 1)$ different states, that is, $D_f(0), D_f(1), ..., D_f(n_r)$, where $D_f(j)$ corresponds to failure of the $(j+1)^{th}$ transmission of a data packet. Accordingly, the state transition probability matrix for the protocol with parameterized retransmission strategy, $P'''$, can be writ-

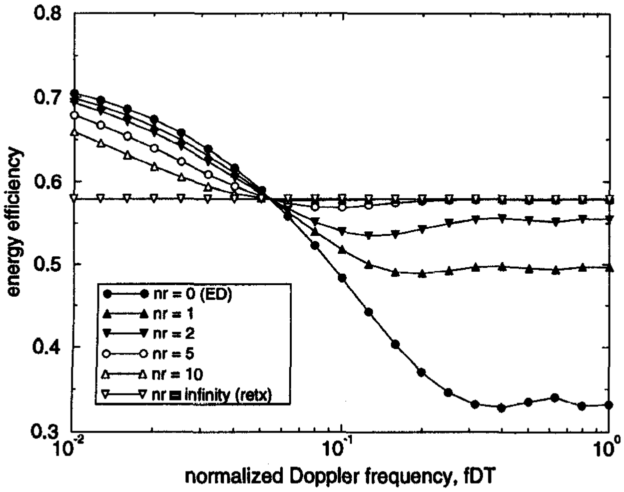


Fig. 3. Energy efficiency *vs* normalized Doppler bandwidth, $f_D T$. Parameterized retransmission ($n_r = 0, 1, 2, 5, 10, \infty$). $N = 10$. $g_d = 0.1$, $b \to \infty$. $F = 5$ dB, $\lambda = 1/N$.

ten as

$$P''' = \begin{bmatrix} X_0 & X_1 & X_2 & 0 & 0 & 0 & . & . & 0 \\ 0 & 0 & 0 & p & 1-p & 0 & . & . & 0 \\ X_0 & X_1 & X_2 & 0 & 0 & 0 & . & . & 0 \\ g_d X_0 & g_d X_1 & g_d X_2 & X_3 & X_4 & 0 & . & . & 0 \\ 0 & 0 & 0 & 1-q & 0 & q & . & . & 0 \\ 0 & 0 & 0 & 1-q & 0 & 0 & q & . & 0 \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ 0 & 0 & 0 & 1-q & 0 & 0 & 0 & . & q \\ X_0 & X_1 & X_2 & 0 & 0 & 0 & . & . & 0 \end{bmatrix}. \tag{12}$$

In Figure 3, the energy efficiency curves, for the maximum throughput performance point corresponding to $\lambda = 1/N$, are plotted for the parameterized retransmission strategy as a function of $f_D T$[1]. These curves are obtained by solving (12) for different values of the parameter $n_r$ (= 1, 2, 5, 10) and using the result in (5). The energy efficiency of the *ED* and the *Retransmission* protocols are also plotted as limiting cases when $n_r = 0$, and $n_r \to \infty$, respectively. It is observed that the energy efficiency performance of the *ED* protocol is best when the fading is slow, and worst when fading is fast. Under fast fading conditions (e.g., $f_D T > 0.1$), it is interesting to see that the energy efficiency improves significantly compared to the *ED* protocol even if only one retransmission attempt ($n_r = 1$) is allowed. In fact, just 3 to 5 retransmission attempts are adequate to establish the same energy efficiency performance as the *Retransmission* protocol under fast fading conditions. Even in slow fading ($f_D T < 0.1$), the parameterized retransmission strategy performs well, close to the *ED* protocol's performance which is best in slow fading. In summary, from an energy consumption point of view, the access protocol which allows a limited number of retransmission attempts results in good energy efficiency performance over a range of normalized Doppler bandwidths (or equivalently, mobile user speeds) of interest. For example, the curve for $n_r = 2$ is very close to the envelope of all curves in Figure 3, and can be seen as a reasonable compromise.

[1]Note that this Figure is the same as given in [10] for the throughput performance, since in this case where $\lambda = 1/N$ we have $\overline{C}_i = 1$ for all $i$, and throughput and energy efficiency coincide.

## IV. Conclusions

We analyzed the energy consumption performance of different versions of a media access protocol suitable for use in mobile data networks. The average number of correctly transmitted packets for a given amount of energy was used as the energy efficiency metric. With significant correlation in the channel fading process, the protocol with an *Error Detect* feature was shown to perform better, whereas as the fading process becomes rapid enough to be close to an i.i.d. process, the *Retransmission* protocol performed better. Interestingly, the access protocol with a parameterized retransmission strategy that allows a limited number of retransmission attempts was shown to result in good energy efficiency over the range of normalized Doppler bandwidths of interest. In general, the results lead to the conclusions that persistence is not always a reasonable choice, and adaptive strategies which try to avoid transmission during bad channel periods yield much better energy efficiency.

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