

# Energy-conserving Selective Repeat ARQ Protocols for Wireless Data Networks

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## Abstract

Mobile communications implies reliance on a self-contained, portable power source, error-prone fading radio channels and subsequent need for acknowledgments. We propose two energy-conserving variants of the Selective Repeat ARQ protocol, which reduce the number of acknowledgments sent by the mobile node. The protocols are compared to previously described energy-conserving Go-Back-N ARQ protocols as well as classical approaches and shown to maintain favorable delay and throughput performances.

## 1 Introduction

It is widely recognized that energy management is one of the most important research areas in mobile computing today. Energy efficient solutions possess many advantages, such as reduced size and weight of the device, lower maintenance costs, and a reduced environmental hazard.

A number of energy conserving access protocols have been recently proposed. [4] presents an overview of many of these protocols. These methods focus on the energy savings available by reducing the amount of time the mobile receiver is "ON", while attempting to not significantly add to the time required to receive the data. Access protocols rely on acknowledgments to verify the successful reception of messages. Mobile computing increases the difficulty of communications due to the highly-variable properties of radio channels.

In order to ensure reliable, verified error-free delivery of data in the presence of multipath fading, automatic repeat request (ARQ) schemes are used to synchronize and acknowledge the transmission of data between the base station and the mobile node. As uplink transmission can typically use twice as much energy as reception [7], it is important to realize that this can require substantial energy expenditure from the mobile node. Since mobile nodes are portable and use a self-contained power source, ARQ schemes need to be found which minimize the amount of energy (transmissions) spent on verification of message reception.

In this paper we propose two new *energy-conserving* variants to the classical Selective Repeat ARQ protocol, designed for reducing the amount of energy required by a mobile node. In designing an energy-conserving ARQ scheme, we observe

that there is a trade-off between energy, maximum throughput and delay. If we allow a single acknowledgment to act as a reply to a large number of sent packets, acknowledgments will be sent less frequently, resulting in a lower energy expenditure. Although buffering at the mobile node allows the throughput capacity to be unaffected by the reduced amount of feedback in the presence of errors, this energy-conserving approach can however result in additional access delay to packets queued at the base station.

The traditional transmission of one acknowledgment for every packet makes classical sliding window schemes inappropriate for energy conservation over the base station to mobile node link. The idea of combining multiple outstanding acknowledgments into one acknowledgment has been introduced previously to combat TCP/IP performance problems in an asymmetric channel [2, 3]. These studies did not take into account the energy saved by reducing the number of acknowledgments, and generally were used by the mobile nodes to simply remove redundant acknowledgments from backlogged uplink queues. [1] proposed a completely new link-level wireless protocol which described combining acknowledgments for multiple packets for the purpose of energy conservation but did not explicitly consider the energy vs. delay or energy vs. throughput trade-offs, nor evaluate the effects of varying the number of packets acknowledged at once.

## 2 System Model and Protocols Description

We consider a system where a base station communicates with a mobile node through a radio channel of bandwidth  $B$ . The model is easily generalized to represent a multi-station environment each with multiple nodes, by replicating, without restriction, the single base station model. We assume the communication to be packet-oriented, the time to be slotted and the base station's transmissions to be synchronized to the beginnings of slots. The packet length  $c$  is constant, and exactly one packet can be transmitted during one slot. To mitigate the adverse effects on performance due to time-correlated multipath fading while limiting the energy used for uplink communication, the mobile node acknowledges the packet transmission status (correct/incorrect) and the base station retransmits

the lost packets according to an *energy-conserving Selective Repeat ARQ protocol*. In this protocol, the mobile node conserves energy by acknowledging groups of packets sent by the base station with a single acknowledgment. The acknowledgments follow a Selective Repeat style of approach such that they include a bit-map denoting the reception status of all the packets transmitted since the last ACK. The base station therefore only retransmits the incorrectly received packets.

In the first type of energy-conserving ARQ protocol, *Windowed Feedback with Selective Repeat*, acknowledgments are sent in response to a group (or "window") of  $W$  packets, a duplicate packet reception, or the occurrence of a time-out. Since packet buffer space at the base station should not be freed until it is known that the packet was received error-free at the mobile node, these time-outs are set to occur when the time between two *ACK/NAK*s exceeds a fixed threshold  $t$ , either because of extremely light traffic or extremely bad channel conditions. For this protocol, the transmitter acts according to the following rules:

- it sends packets in order, as long as they belong to the current window. When a window has been completely transmitted or a time-out occurs, the most recently transmitted packet is continuously retransmitted until an ACK is received.
- upon reception of an ACK, the buffers associated to the correctly received packets are freed. The transmitter window is then updated to the next  $W$  unacknowledged packets.

In the *Instantaneous Feedback with Selective Repeat* protocol, both the mobile node and the base station act as in the Windowed Feedback case, however, the mobile node also uses negative acknowledgments to reply to out-of-order packet receptions. The reception of a NAK triggers both the retransmission of the erroneously received packets as well as an update of the transmitter window.

The behavior of the proposed protocols differs from the *Windowed Feedback* and *Instantaneous Feedback Go-Back-N* protocols proposed in [5] by the actions performed by the base station in response to an *ACK/NAK* reception. A GBN style of approach assumes indeed that no buffering is available at the mobile node, in that each *ACK/NAK* contains the sequence number  $j$  of the first incorrectly received packet in the window. Upon reception of an acknowledgment the base station then retransmits, in order, all packets starting from packet  $j$ .

For conciseness, the following analysis and simulation consider  $t$  to be large enough such that a time-out never occurs. An analysis which includes time-out considerations is covered in [5].

### 3 Analysis of the Energy-Conserving ARQ Protocols

To compare the performance of the proposed energy-conserving Selective Repeat protocols we next provide analyt-

ical models which evaluate the protocols under different channel scenarios in terms of the energy consumption  $E$  and the maximum throughput  $\eta$ :

$E$  – the average percentage of slots in which an acknowledgment is transmitted.

$\eta$  – the average number of new packets received per slot by the mobile node in a scenario where the base station always has packets to send.

We model both the downlink and uplink channels as Gilbert channels [6]. The ability of this model to capture the behavior of a fading channel, independently of modulation, coding techniques or packet length, was assessed in [9]. The pattern of feedback and packet errors is then described by two independent first-order Markov models. Two states  $C$  (*correct*) and  $I$  (*incorrect*) represent the status of the channel during the current slot, while the transition probabilities can be easily computed and only depend on the normalized Doppler frequency and the steady-state packet error rate. We introduce the following notation:

$p_{xy,wz}$  – is the probability of moving from downlink channel state  $x$  to state  $w$  and from uplink channel state  $y$  to state  $z$  in one slot.

The technique we use is similar to that adopted by Zorzi and Rao [9] and utilizes results of renewal reward processes and discrete-time semi-Markov processes [8]. Three semi-Markov processes can be associated with an underlying Markov chain which tracks the channel/protocol state. The first semi-Markov process tracks the time spent in each state, while the second and third track the number of successful packet receptions and attempted uplink transmissions. In the following we choose as a reference (renewal) an arbitrary state  $s_r$  of the Markov chain and use classic semi-Markov process theory to compute the values of  $\eta$  and  $E$ . From a fundamental theorem of renewal reward processes we have that

$$\eta = \lim_{\tau \rightarrow \infty} \frac{R(\tau)}{\tau} = \frac{E[R]}{E[D]} \quad (1)$$

$$E = \lim_{\tau \rightarrow \infty} \frac{A(\tau)}{\tau} = \frac{E[A]}{E[D]} \quad (2)$$

where  $R(\tau)$  and  $A(\tau)$  are the number of correct receptions and the number of *ACK/NAK*s sent upto time  $\tau$ .  $E[A]$  and  $E[R]$  are therefore the average number of uplink and successful downlink transmissions per cycle, while  $E[D]$  denotes the average length of a cycle. Let  $D_i$ ,  $R_i$  and  $A_i$  denote the average time spent, the average number of receptions and the average number of transmitted *ACK/NAK*s while in state  $i$ .  $E[A]$ ,  $E[R]$  and  $E[D]$  can then be computed by averaging  $A_i$ ,  $R_i$  and  $D_i$  over the steady-state probability of being in state  $i$ , and dividing the result by the steady-state probability of being in the reference state.

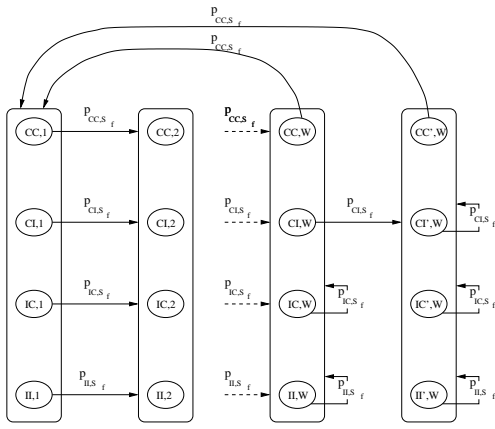


Figure 1: Windowed Feedback with Selective Repeat: flow graph

### 3.1 Analysis of the Windowed Feedback with Selective Repeat

The embedded Markov chain which models the protocol/channel behavior is described by Fig. 1. The  $4W + 4$  states are labeled by the current uplink and downlink channel states as well as the number of transmitted packets in the current window. To take into account the case when all the packets in the window have been transmitted and the transmitter is waiting for an acknowledgment, states  $\langle s_f, W \rangle$  and  $\langle s'_f, W \rangle$ ,  $s_f \in \{CC, CI, IC, II\}$ , are introduced. States  $\langle s_f, W \rangle$  are entered when all the packets in the window, except for  $W$ , were successfully received, so that a correct reception of  $W$  increases the counter of successfully received packets. In contrast, states  $\langle s'_f, W \rangle$  correspond to the situation in which no new packets will be accepted by the receiver and the only state of interest is a reception of packet  $W$  followed by successful ACK transmission.

We mark the state transitions with the corresponding transition probabilities. The transition from one state to a group of states indicates that a transition exists from that state to each state in the group. The corresponding transition probabilities  $p_{xy, s_f}$  consistently denote that the transition probability between the source state and state  $\langle wz \rangle$  of the group is given by  $p_{xy, wz}$ .

The protocol acts according to the following rules: When less than  $W$  packets have been transmitted, a packet transmission simply increases the counter of sent packets (transition from  $\langle s_f, i \rangle$  to  $\langle s_f, i + 1 \rangle$ ). States  $\langle s_f, W \rangle$ ,  $\langle s'_f, W \rangle$  correspond to a cycle during which packet  $W$  is transmitted and ACKs are sent in response to every correct packet reception. If an ACK is received (states  $\langle CC, W \rangle$ ,  $\langle CC', W \rangle$ ), the transmitter updates its window and starts sending the packets of a new window (transition to  $\langle s_f, 1 \rangle$ ). Otherwise, packet  $W$  is continuously retransmitted (loop in  $\langle s_f, W \rangle$ ,  $\langle s'_f, W \rangle$ ). After the first correct reception of  $W$ , no further packets can be received (loop in  $\langle s'_f, W \rangle$ ).

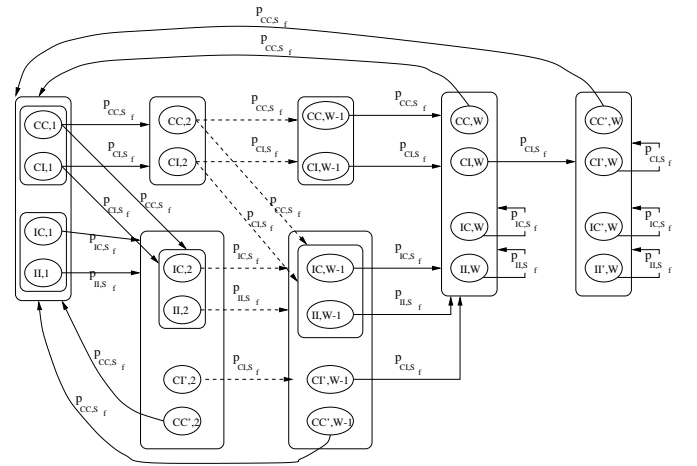


Figure 2: Instantaneous Feedback with Selective Repeat: flow graph

We represent the set of possible states with the vector

$$\langle \langle CC, 1 \rangle, \langle CI, 1 \rangle, \langle IC, 1 \rangle, \langle II, 1 \rangle, \dots, \langle CC, W \rangle, \langle CI, W \rangle, \langle IC, W \rangle, \langle II, W \rangle, \langle CC', W \rangle, \langle CI', W \rangle, \langle IC', W \rangle, \langle II', W \rangle \rangle$$

All the state transitions are performed in 1 slot, so that  $D_i = 1 \forall i$ . We observe that any transition to  $\langle CC, i \rangle$ ,  $\langle CI, i \rangle$  corresponds to a new packet reception, while an ACK transmission is attempted only after a  $W$  reception.

The average number of receptions  $R_i$  associated to state  $i$  can then be found by averaging the receptions associated to the transitions from state  $i$  over the conditional distribution of the destinations.

Applying a similar procedure to compute  $A_i$  we obtain:

$$\begin{aligned} R_{4i-2} &= R_{4i-3} = R_{4W-3} = R_{4W+1} = p & i \leq W-1 \\ R_{4i} &= R_{4i-1} = R_{4W-1} = R_{4W} = r & i \leq W-1 \\ R_{4W-2} &= R_{4W+2} = R_{4W+3} = R_{4W+4} = 0 \end{aligned}$$

$$\begin{aligned} A_{4W-7} &= A_{4W-6} = A_{4W-2} = A_{4W+2} \\ &= p \\ A_{4W-5+4j} &= A_{4W-4+4j} = r & 0 \leq j \leq 2 \\ A_1 &= A_2 = \dots = A_{4W-8} = A_{4W-3} \\ &= A_{4W+1} = 0 \end{aligned}$$

### 3.2 Instantaneous Feedback with Selective Repeat

The different actions performed by the Instantaneous Feedback version of the protocol when a packet transmission is unsuccessful are reflected in the Markov chain which models the protocol behavior (Figure 2). Two more states  $\langle CC', i \rangle$ ,  $\langle CI', i \rangle$  are added for each value of the sent packets counter in  $\{2, \dots, W-1\}$ . These new states represent the case of a correct packet channel status in the event that one of the previous unacknowledged transmissions was unsuccessful.

If all the packets transmitted up until the current slot were successfully received (states  $\langle CC, i \rangle$ ,  $\langle CI, i \rangle$ ) and the packet sent in the current slot is also successfully received, the counter of received packets is incremented (transition to  $\langle CC, i + 1 \rangle$ ,  $\langle CI, i + 1 \rangle$ ). Otherwise, a *NAK* transmission cycle is entered (transition to states  $\langle CC', i + 1 \rangle$ ,  $\langle CI', i + 1 \rangle$ ,  $\langle IC, i + 1 \rangle$ ,  $\langle II, i + 1 \rangle$ ). If a *NAK* is received (state  $\langle CC', i \rangle$ ) the transmitter window is updated (transition to states  $\langle CC, 1 \rangle, \dots, \langle II, 1 \rangle$ ). When the last packet in the window is transmitted, a cycle is entered where the protocol acts independently of the previous history: A correct/correct state starts a new window transmission, while a correct packet channel initiates an uplink transmission.

Let us represent the set of possible states with the vector

$$\begin{aligned} & (\langle CC, 1 \rangle, \langle CI, 1 \rangle, \langle IC, 1 \rangle, \langle II, 1 \rangle, \langle CC, 2 \rangle, \langle CI, 2 \rangle, \\ & \langle IC, 2 \rangle, \langle II, 2 \rangle, \langle CI', 2 \rangle, \langle CC', 2 \rangle, \langle CC, W \rangle, \langle CI, W \rangle, \\ & \langle IC, W \rangle, \langle II, W \rangle, \langle CC', W \rangle, \langle CI', W \rangle, \langle IC', W \rangle, \langle II', W \rangle) \end{aligned}$$

All the transitions take place in one slot. Since an *ACK/NAK* transmission is attempted whenever in  $\langle CC, W \rangle$ ,  $\langle CI, W \rangle$ ,  $\langle CC', i \rangle$ ,  $\langle CI', i \rangle$ , and a new packet is received every time the packet channel is correct and not all the packets in the window have been received, we obtain:

$$\begin{aligned} R_1 &= R_2 = R_{6i-1} = R_{6i} = R_{6i+3} \\ &= R_{6i+4} = R_{6W-7} \\ &= R_{6W-3} = p & 1 \leq i \leq W-2 \\ R_3 &= R_4 = R_{6i+1} = R_{6i+2} \\ &= R_{6W-5} = R_{6W-4} = r & 1 \leq i \leq W-2 \\ R_{6W-6} &= R_{6W-2} = R_{6W-1} = R_{6W} = 0 \\ A_{6i+3} &= A_{6W-13} = A_{6W-12} = A_{6W-9} \\ &= A_{6W-6} = A_{6W-2} = p & 1 \leq i \leq W-3 \\ A_3 &= A_4 = A_{6i+1} = A_{6i+2} \\ &= A_{6W-11} = A_{6W-10} = A_{6W-5} \\ &= A_{6W-4} = A_{6W-1} = A_{6W} = r & 1 \leq i \leq W-3 \\ A_1 &= A_2 = A_{6i-1} = A_{6i} = A_{6i+4} \\ &= A_{6W-8} = A_{6W-7} = A_{6W-3} \\ &= 0 & 1 \leq i \leq W-3 \end{aligned}$$

## 4 Results

In order to compare the relative performance of the two proposed protocols and their energy conserving properties over both their energy-conserving GBN counterparts and the traditional ARQ schemes, we study the maximum throughput vs. energy (Figures 3 and 4) and delay vs. energy (Figures 5 and 6) trade-offs for varying traffic load and fading characteristics.

The plots displaying the maximum throughput performance were generated from numerical evaluation of the analytical models, while simulation of the reception of 500,000 packets arriving according to a Poisson process with a rate of  $\lambda = 0.3$  was used to address delay considerations. For validation purposes, we ran simulations using an assumption of infinite packet availability which matched computationally derived analysis results to within 2% of all values.

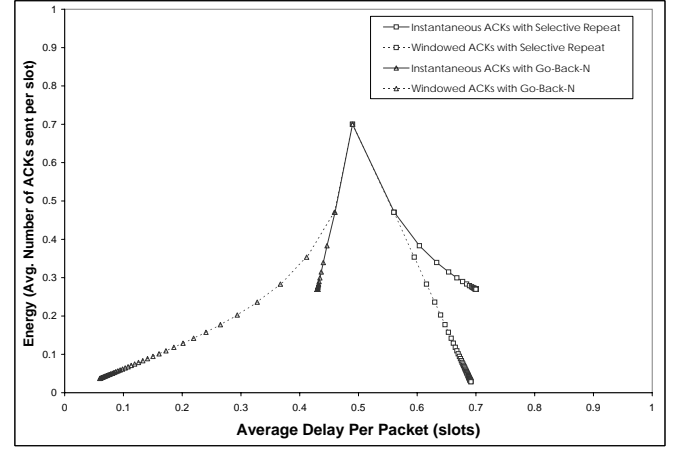


Figure 3: Maximum throughput performance of the Selective Repeat and GBN energy-conserving ARQ protocols in fast fading.

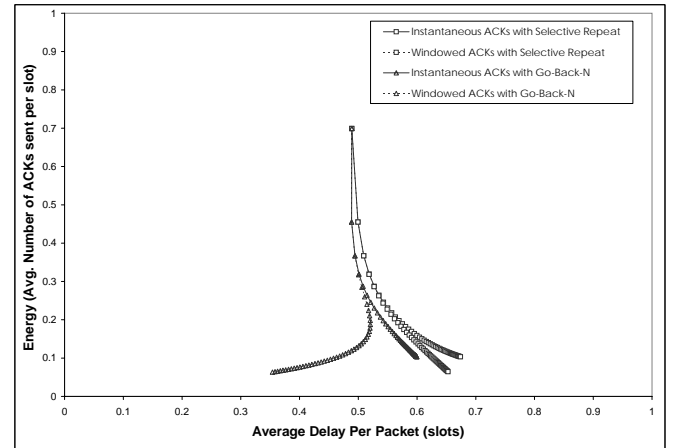


Figure 4: Maximum throughput performance of the Selective Repeat and GBN energy-conserving ARQ protocols in slow fading.

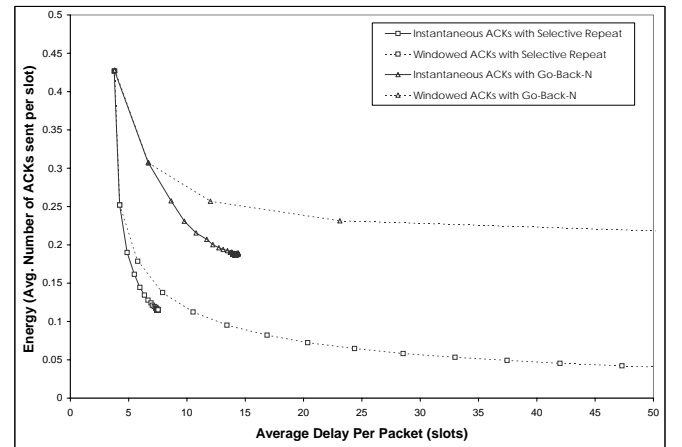


Figure 5: Energy vs. Delay performance of the Selective Repeat and GBN energy-conserving ARQ protocols in fast fading

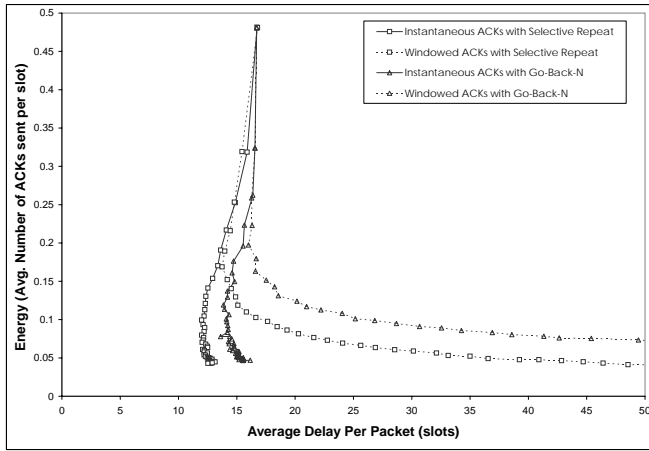


Figure 6: Energy vs. Delay performance of the Selective Repeat and GBN energy-conserving ARQ protocols in slow fading

The fading environments displayed in the figures are characterized by a steady-state packet error rate of  $\epsilon = 0.3$  and normalized Doppler frequencies of 1.0 and 0.02. These values have been used previously in the literature and experimentally verified to be reasonable. In a wireless network operating at 900Mhz, with packets of length 1000 bits, and a bit rate of 100kbps, these values correspond to a mobile node moving at speeds of 33 m/s (fast fading) and 0.67 m/s (slow fading). The propagation delay is assumed to be negligible. The access delay, as plotted along the x-axis of Figures 5 and 6, is defined as the number of slots between the arrival of the packet at the base station and the time when it is successfully received in-order by the mobile node.

Individual points on each of the lines in the plots were generated by changing the size of window, such that each point represents the next consecutive window size. It is easy to see how both the two protocols achieve a substantial decrease in energy consumption over the classical version ( $W = 1$ ) without increasing the average packet delay beyond reasonable application delay constraints nor substantially affecting the throughput capacity.

In Figures 3 and 4 we can see that the trade-off between energy conservation and throughput for each of the protocols varies with the fading speed. The Selective Repeat energy-conserving protocols show a higher throughput capacity for higher values of  $W$ , since we are requiring retransmission only of the packets in error while reducing the likelihood of needless retransmissions at the end of a window due to lost acknowledgments. The performances of the Windowed and Instantaneous Feedback versions of the Selective Repeat protocol are similar for small window sizes (and therefore lower energy-conservation) and then diverge as a greater number of instantaneous ACKs become warranted through errors occurring in the packets of the window. In these cases we see that the Windowed Feedback version leads to higher energy conservation (96% vs. 61% in fast fading and 90% vs. 85% in slow fading), at the cost of less than a 3% difference in the throughput capacity. The reduced difference in slow fading is due to the

reduced frequency of fading periods, which causes a smaller number of instantaneous ACKs to be sent. It is easy to see how a Selective Repeat style of approach results in significantly improved performances over the GBN case (62% throughput capacity increase of the Instantaneous Selective Repeat over the Instantaneous GBN at  $E = 0.26$  and in fast fading). In slow fading the performance difference between these two approaches decreases since the longer periods of deep fades of the downlink result in less frequent buffering of out-of-order packets.

If we consider the average packet delay we see that both protocols can achieve a similar reduction in energy over the classical ARQ scheme while not strongly affecting the time necessary to deliver the packets. In particular, as we move from fast fading (Figure 5) to slow fading (Figure 6), we can see an increased performance advantage of using the instantaneous ACK versions of the protocols over the windowed version with the fast fading. Similar to the throughput performance, faster fading requires a higher energy consumption of the instantaneous protocols because of the increase in channel state transitions. The Selective Repeat protocols always outperform the energy-conserving GBN variants, though the difference decreases when the fading speed decreases.

## 5 Conclusions

In this paper we have proposed two variants of the Selective Repeat (SR) acknowledgment protocol designed for energy conservation at the mobile node. It was shown that it is possible to save a substantial amount of the energy used for the transmission of acknowledgments without sacrificing the timely reception of error-free data. In particular, it was shown that under a variety of conditions, the proposed protocols reduce the energy consumption by more than 80% over the classical Selective Repeat without substantially affecting either the access delay or the throughput capacity.

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