Energy-conserving Go-Back-N ARQ Protocols for Wireless Data Networks

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Abstract

Mobile computer communications fundamentally implies reliance on a self-contained, portable power source and communications over an error-prone fading radio channel. In this paper we propose two energy-conserving alternatives to the classical Go-Back-N automatic repeat request protocol which allow a substantial energy saving over the traditional approach by reducing the number of uplink acknowledgments required, while preserving good delay/throughput performance.

1 Introduction

It is common to consider energy conservation to be one of the top areas of necessary research in mobile computing today [6]. Energy efficient solutions are essential for reducing size and weight of mobile devices, lower maintenance, and a reduce environmental hazards.

Recently, methods for conserving energy by switching off the receiver during the times it is expected not to be in use have been proposed [4, 9, 11]. 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. All of these works assume an ideal channel, such that transmission of a packet from the base station, to a node whose receiver is “awake” is always successful.

However, the concept of mobile computing implies not only reliance on a portable, self-contained power source, but also an increased difficulty of communications in the highly-variable radio channel. 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 [8], it is important to realize that this can require substantial energy expenditure from the mobile node.

In this paper, we propose and evaluate two *energy-conserving* variants to the classical Go-Back-N ARQ protocol. When designing an energy-conserving ARQ scheme, we observe the following trade-off between energy, delay and throughput: If we allow a single acknowledgment to act as a reply to a large number of sent packets, acknowledgments will be sent more infrequently, resulting in a lower energy expenditure. However, errors on the channel can typically cause the retransmission of many more packets leading to a reduction in throughput and additional 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.

We next define our system model and the proposed protocols. We follow with an analysis of the maximum throughput and energy consumption of the protocols and present comparative performance results.

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. Our model consists of a single base station sending data to a single mobile node. However, it is easy to see that the same can be replicated, without restriction, in a multi-station environment each with multiple nodes. Communication is packet-oriented. We assume 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 ARQ protocol*. In these protocols, the mobile node conserves energy by acknowledging groups of packets sent by the base station with a single acknowledgment. The acknowledgments follow a Go-Back-N style of approach such that there is no buffering of out-of-order packets by the mobile node.

In the first type of energy-conserving ARQ protocol, *Windowed Feedback with Go-Back-N*, 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/NAKs 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. If the transmission of the last packet in the window (i.e.W) is not acknowledged, packet W is continuously retransmitted until such an event occurs.
- if no acknowledgment has been received during the last t slots, the last packet is retransmitted until an ACK is received.
- upon reception of an ACK(j), it goes back to packet j, retransmitting in order all packets from j. The window range is consistently updated (from j to $j + W$).

In the *Instantaneous Feedback with Go-Back-N* protocol the receiver acts as in the Windowed Feedback case, but also reacts to out-of-order packet receptions with a NAK transmission. The transmitter window is therefore updated by either a NAK or an ACK reception, and a time-out occurs at the mobile node (base station) when no type of acknowledgment was sent (received) during the previous t slots.

For conciseness in the ensuing analysis and simulation results we have considered 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 two ARQ protocols proposed we provide analytical models which evaluate them under different channel scenarios in terms of the energy consumption E, as well as the maximum throughput η:

$E-$ 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 [7]. The ability of this model to capture the behavior of a fading channel, independently of modulation, coding techniques or packet length, was assessed in [12]. 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. The transition probabilities matrices $M_D(x) = M_D^x$ and $M_U(x) = M_U^x$ are given by:

$$M_D = \begin{pmatrix} p & q \\ r & s \end{pmatrix}$$

$$M_U = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

where $p = 1 - q$ ($r = 1 - s$) is the probability that a packet transmitted in the current slot of the downlink channel would be received correctly given that a packet transmitted in the previous slot would have been received correctly (incorrectly). M_U similarly depicts these probabilities in reference to the uplink channel. 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 channel state xy to channel state wz

$$p_{xy,wz} = M_D[x,w]M_U[y,z]$$

Three semi-Markov processes can then be associated with an underlying Markov chain which tracks the channel/protocol state, similar to the approach in [12]. 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 η and E. From a fundamental theorem of renewal reward processes we have that[10]

$$\begin{aligned} \eta &= \lim_{\tau\to\infty} \frac{R(\tau)}{\tau} \\ &= \frac{E[R]}{E[D]} \end{aligned}$$

$$\begin{aligned} E &= \lim_{\tau\to\infty} \frac{A(\tau)}{\tau} \\ &= \frac{E[A]}{E[D]} \end{aligned}$$

where $R(\tau)$ and $A(\tau)$ are the number of correct receptions and the number of ACK/NAKs sent upto time τ. $E[A]$ 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/NAKs while in state i. Then we have

$$E[D] = \frac{\sum_i \pi_i D_i}{\pi_{s_r}}$$

$$\begin{aligned} E[R] &= \frac{\sum_i \pi_i R_i}{\pi_{s_r}} \\ E[A] &= \frac{\sum_i \pi_i A_i}{\pi_{s_r}} \end{aligned}$$

,where π_i is the steady-state probability of being in state i.

3.1 Analysis of the Windowed Feedback with Go-Back-N

The embedded Markov chain which models the protocol/channel behavior is described by Figure 1. The $2W+6$ 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 $\langle s'_f, W\rangle$, $s_f \in \{C/C, C/I, I/C, I/I\}$, 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. $Q^h_{xy/wz}$ denotes the probability of going from channel state xy to channel state wz in h steps, given that in the first step the packet channel was in error:

$$\begin{aligned} Q^h_{xy/wz} &= M_U[x,I]M_D[y,C](M_U^{h-1}[I,w]M_D^{h-1}[C,z])+ \\ &\quad M_U[x,I]M_D[y,I](M_U^{h-1}[I,w]M_D^{h-1}[I,z]) \end{aligned}$$

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 $\langle w/z\rangle$ of the group is given by $p_{xy,wz}$.

The protocol acts according to the following rules: Both the receiver and transmitter increase the "next packet" counter at each slot until the packet channel is correct, and there are still packets to be transmitted in the window (transition from states $\langle C/C, i\rangle$, $\langle C/I, i\rangle$ to states $\langle C/C, i+1\rangle$, $\langle C/I, i+1\rangle$). If the transmission of packet i fails, packets $i+1, ..., W$ are discarded as out-of-order and no action is performed until packet W is transmitted (transition from states $\langle C/C, i\rangle$, $\langle C/E, i\rangle$ to $\langle s'_f, W\rangle$ in $W-i$ slots). 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. When the successful reception of packet W is not followed by a successful ACK transmission (state $\langle C/I, W\rangle$) the protocol states denote that no new packet can be successfully received (transition to states $\langle s'_f, W\rangle$). Otherwise, the process of retransmitting packet W and attempting ACK transmissions in response to every correctly received packet is iteratively repeated (loop in either $\langle s_f, W\rangle$ or $\langle s'_f, W\rangle$) until an ACK is received at the base station (states $\langle C/C, W\rangle$ or $\langle C/C', W\rangle$). Transmitter and receiver windows then synchronize and the first packet in the new group is transmitted. If this transmission is successful (transition to states $\langle C/C, 1\rangle, \langle C/I, 1\rangle$) the receiver increases the next packet counter; otherwise (transition to group $\langle s'_f, W\rangle$ in W slots) subsequent correctly received packets are discarded and no action is performed until the last packet in the window is received.

Let us represent the set of possible states with the vector

$$\begin{gathered} (\langle C/C,1\rangle, \langle C/I,1\rangle, \langle C/C,2\rangle, \langle C/I,2\rangle, ..., \\ \langle C/C, W-1\rangle, \langle C/I, W-1\rangle, \langle C/C, W\rangle \\ , \langle C/I, W\rangle, \langle I/C, W\rangle, \langle I/I, W\rangle, \\ \langle C/C', W\rangle, \langle C/I', W\rangle, \langle I/C', W\rangle, \langle I/I', W\rangle) \end{gathered}$$

We observe that transitions to the $\langle C/C, i\rangle, \langle C/I, i\rangle$ states correspond to reception of a new packet, while an uplink transmission is associated with moving to a state that denotes the reception of packet W. Finally, every transition is performed in one slot, except for the ones from states $\langle C/C, i\rangle, \langle C/I, i\rangle$ to states $\langle s'_f, W\rangle$, which take place in $W-i$ slots, and the ones from states $\langle C/C, W\rangle$ and $\langle C/C', W\rangle$ to states $\langle s'_f, W\rangle$, which take W slots.

The average number of receptions R_i associated to state i can then be found by multiplying term-by-term matrix R, whose elements denote the number of received packets associated to each state transitions, and the transition probability matrix, and then summing the entries in row i of the resulting matrix. This corresponds to 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 and D_i we obtain:

$$\begin{aligned} R_{2i} &= R_{2i-1} = R_{2W-1} = R_{2W+3} = p && i \le W-1 \\ R_{2W+1} &= R_{2W+2} = r \\ R_{2W} &= R_{2W+4} = R_{2W+5} = R_{2W+6} = 0 \end{aligned}$$

$$\begin{aligned} A_{2i} &= Q^{W-i}_{CI/CC} + Q^{W-i}_{CI/CI} && i \le W-2 \\ A_{2i-1} &= Q^{W-i}_{CC/CC} + Q^{W-i}_{CC/CI} && i \le W-2 \\ A_{2W-3} &= A_{2W-2} = A_{2W} = A_{2W+4} = p \\ A_{2W-1} &= A_{2W+3} = Q^{W}_{CC/CC} + Q^{W}_{CC/CI} \\ A_{2W+1} &= A_{2W+2} = A_{2W+5} = A_{2W+6} = r \end{aligned}$$

$$\begin{aligned} D_1 &= ... = D_{2W-4} = p + q(W-i) \\ D_{2W-3} &= D_{2W-2} = D_{2W} = D_{2W+1} \\ &= D_{2W+2} = D_{2W+4} \\ &= D_{2W+5} = D_{2W+6} = 1 \\ D_{2W-1} &= D_{2W+3} = p + qW \end{aligned}$$

3.2 Analysis of the Instantaneous Feedback with Go-Back-N

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). In the Instantaneous Feedback

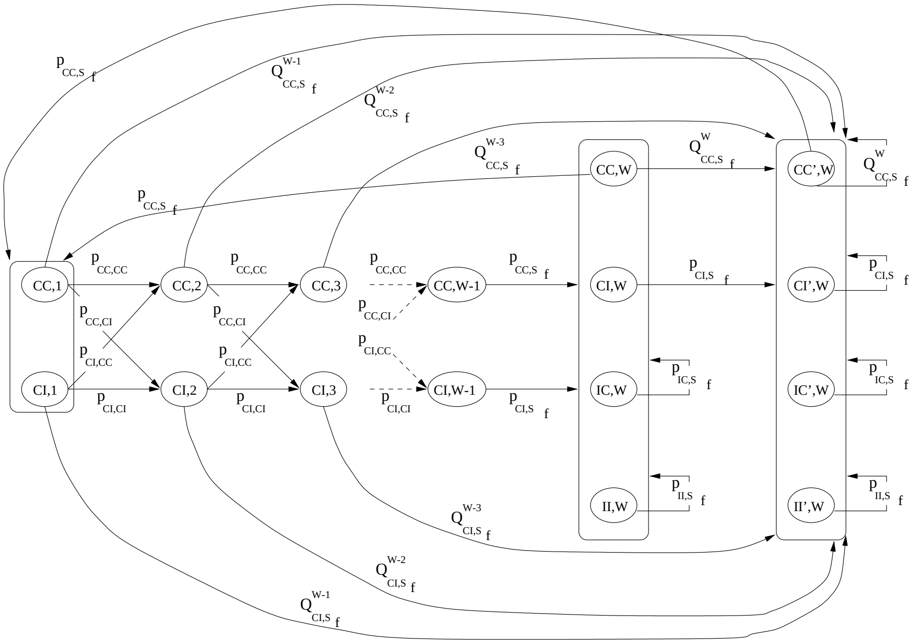

Figure 1: Windowed Feedback with Go-Back-N: flow graph

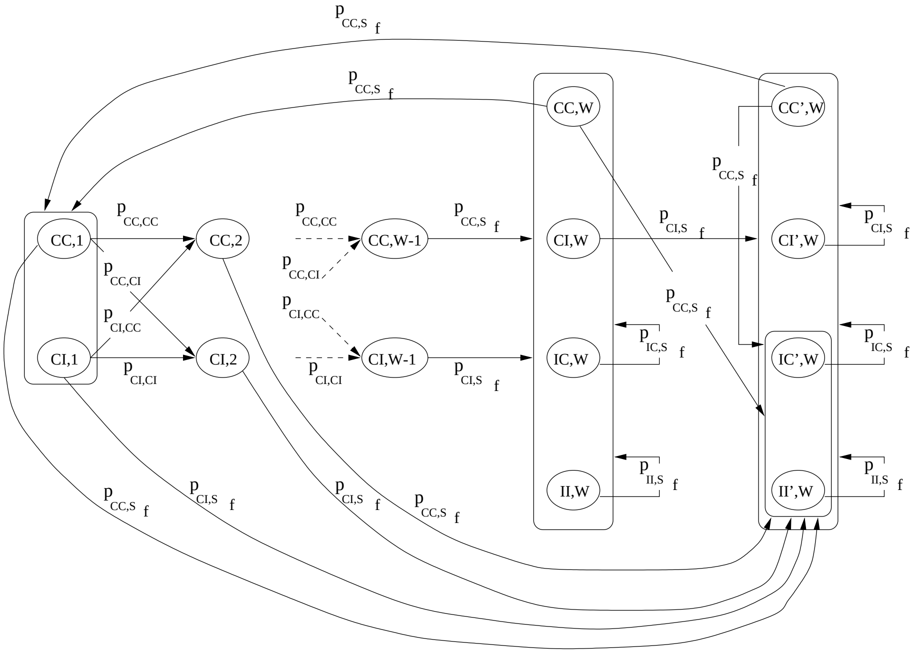

Figure 2: Instantaneous feedback with Go-Back-N: flow graph

model, a packet transmission failure results in the protocol immediately entering the ACK/NAK transmission cycle (states $\langle s_f, W\rangle$,$\langle s'_f, W\rangle$), which is not exited until a packet reception by the receiver is followed by either an ACK or NAK reception by the base station. The transmission of packets which belong to a new window is then started. If the first packet of this new window is successfully received (transition to state $\langle C/C, 1\rangle$, $\langle C/I, 1\rangle$), the receiver window is increased; otherwise the cycle is entered again (transition to states $\langle s'_f, W\rangle$ in one step).

We observe that, since all the transitions are performed in one slot, $D_i = 1 \forall i$, so that $\eta = \sum_i \pi_i R_i$ and $E = \sum_i \pi_i A_i$.

From all the above considerations and the flow graph we find:

$$\begin{aligned}
R_1 &= R_2 = \ldots = R_{2W-1} = R_{2W+3} = p \\
R_{2W+1} &= R_{2W+2} = r \\
R_{2W} &= R_{2W+4} = R_{2W+5} = R_{2W+6} = 0 \\
\\
A_{2W-3} &= A_{2W-2} = A_{2W} = A_{2W+4} = p \\
A_{2W+1} &= A_{2W+2} = A_{2W+5} = A_{2W+6} = r \\
A_1 &= A_2 = \ldots = A_{2W-4} = A_{2W-1} = A_{2W+3} = 0
\end{aligned}$$

4 Results

In order to compare the relative performance of the two protocols and their energy conserving abilities over the traditional Go-Back-N scheme, we studied the maximum throughput vs. energy (Figures 3 and 4) and delay vs. energy (Figures 5 and 6) trade-offs for fast and slow fading characteristics. The measurements for 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. 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 Hz. 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. The highest point in each of the graphs depicts the protocols with a window size of $W = 1$, which corresponds to a classical GBN ARQ protocol. It is easy to see the substantial decrease in energy usage these protocols achieve: picking nearly any point in the figures shows a protocol with a lower energy than the classical version without increasing the average packet delay beyond reasonable application delay constraints nor substantially reducing 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 performances of the Windowed and Instantaneous Feedback versions of the protocols 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 can potentially lead to higher energy conservation (up to 95% in fast fading and 91% in slow fading). However, since these savings occur from a reduced amount of feedback to the base station, the incorrectly received packets need to wait longer before being retransmitted, and the throughput capacity severely degrades. Meanwhile, for fast fading the Instantaneous Feedback Go-Back-N protocol achieves up to a 63% energy-conservation over the classical Go-Back-N protocols at the cost of a slightly reduced throughput capacity (12% reduction at $E = 0.27$). In slow fading, the maximum energy-conservation achievable by this protocol increases to 86%, since the reduced frequency of fading periods causes a smaller number of instantaneous ACKs to be sent. Additionally, the longer sequences of correct channel states results in an increased throughput capacity of 25%.

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. As when considering the throughput, the divergence in performance for the protocols depends upon the fading speed. In particular, in slower fading situations such as that shown in Figure 6, there seems to be an increased advantage of using the instantaneous ACK versions of the protocol over situations of fast fading such as that shown in Figure 5. Similar to the throughput performance, faster fading requires a higher energy consumption of the instantaneous protocols because of the increase in channel state transitions.

An increase in throughput capacity and decrease in delay despite a lower energy-consumption for situations of slow fading with small window sizes can be seen in Figure 6 and Figure 4. The base station relies on the uplink quality to determine when additional packet retransmissions should occur. In the presence of longer sequences of burst errors on the uplink, the increased reliance on feedback for a small window size can be seen to degrade the performance.

5 Conclusions

This paper introduced two new variations on the well known ARQ Go-Back-N (GBN) 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 acknowledgment transmission without sacrificing the timely reception of error-free data. In particular, under various conditions, both protocols were shown to achieve up to a 60% reduction in en-

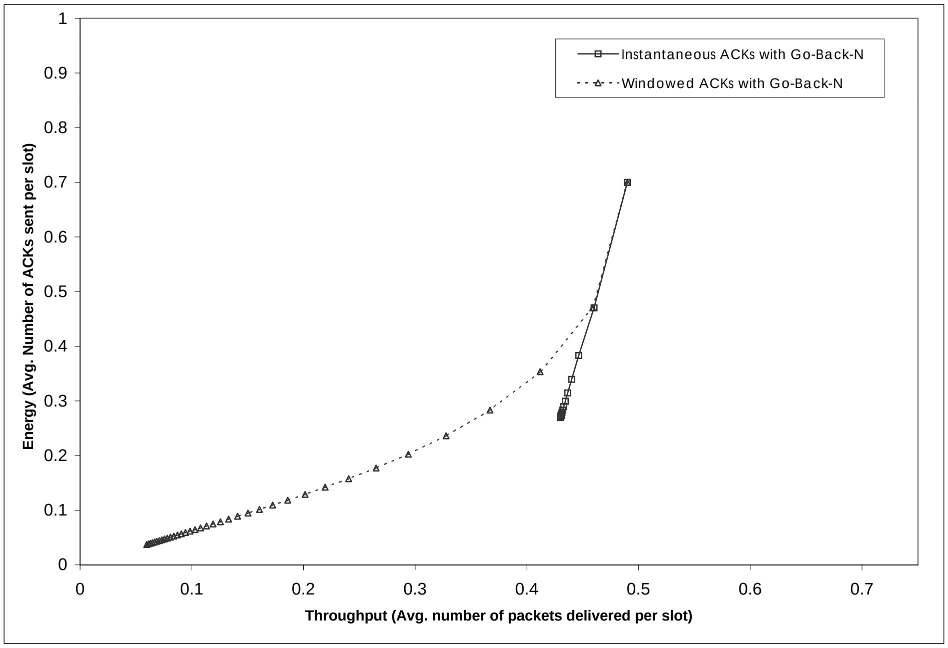

Figure 3: Maximum throughput performance of the four energy-conserving ARQ protocols. 500,000 packets for a single mobile node are generated at a single base station such that packets are always available for transmission. The state of the Gilbert uplink and downlink channels are independent but have identical steady state packet error rates of $\epsilon = 0.3$ and normalized Doppler fading rates of $f_D NT = 1.0$ (fast fading)

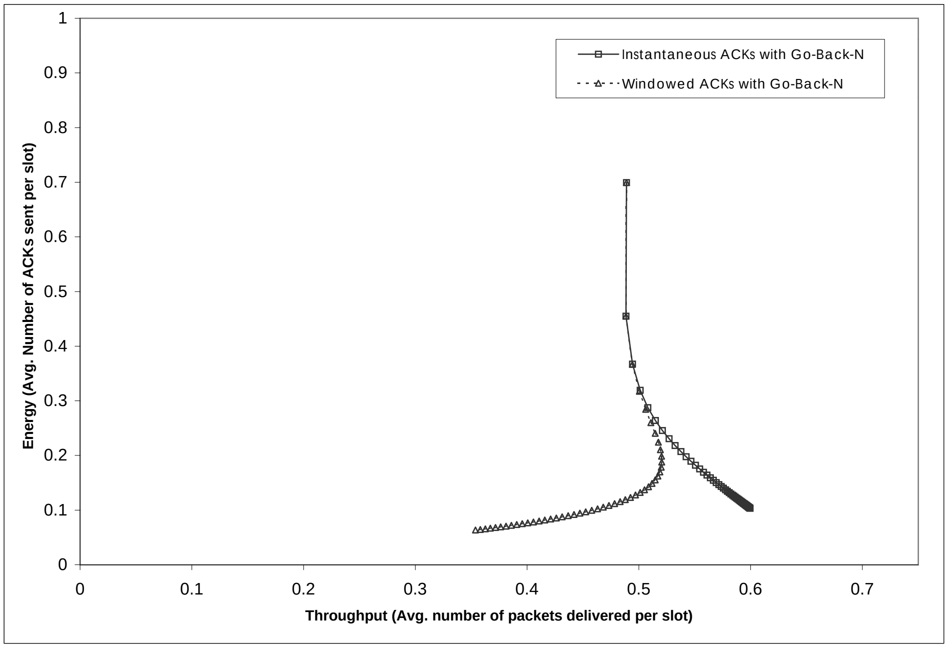

Figure 4: Maximum throughput performance of the four energy-conserving ARQ protocols. 500,000 packets for a single mobile node are generated at a single base station such that packets are always available for transmission. The state of the Gilbert uplink and downlink channels are independent but have identical steady state packet error rates of $\epsilon = 0.3$ and normalized Doppler fading rates of $f_D NT = 0.02$ (slow fading)

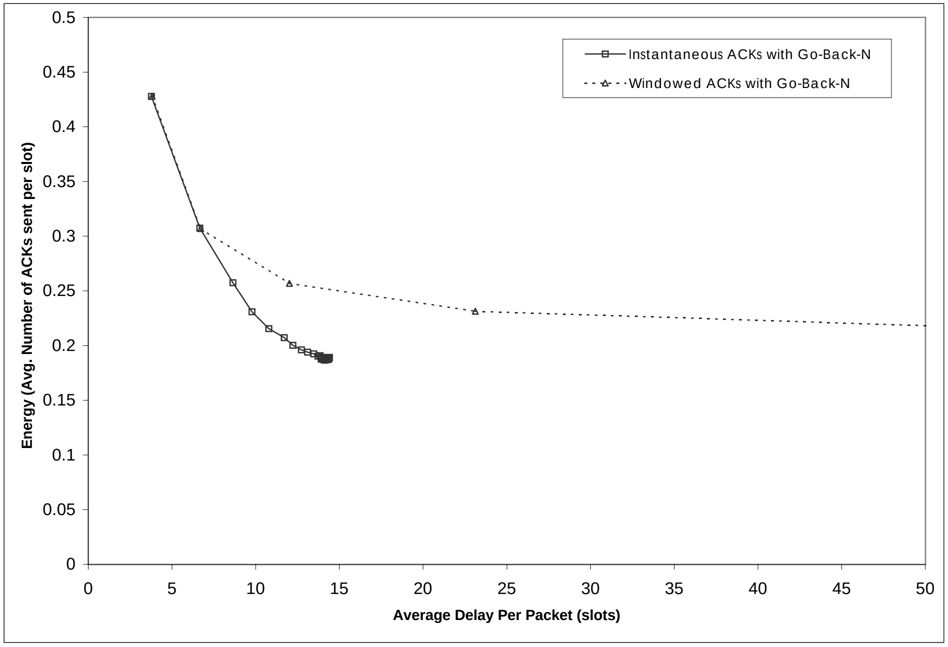

Figure 5: Energy vs. Delay performance of the four energy-conserving ARQ protocols. 500,000 packets for a single mobile node are generated at a single base station according to a Poisson arrival process with interarrival rate $\lambda = 0.3$. The state of the Gilbert uplink and downlink channels are independent but have identical steady state packet error rates of $\epsilon = 0.3$ and normalized Doppler fading rates of $f_D NT = 1.0$ (fast fading)

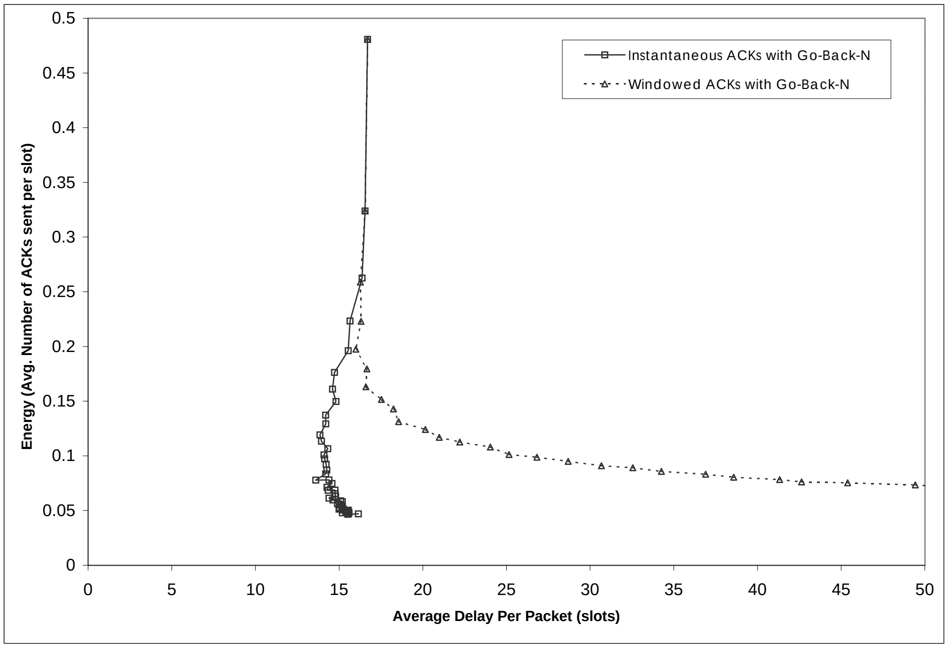

Figure 6: Energy vs. Delay performance of the four energy-conserving ARQ protocols. 500,000 packets for a single mobile node are generated at a single base station according to a Poisson arrival process with interarrival rate $\lambda = 0.3$. The state of the Gilbert uplink and downlink channels are independent but have identical steady state packet error rates of $\epsilon = 0.3$ and normalized Doppler fading rates of $f_D NT = 0.02$ (slow fading)

ergy usage over the classical GBN without significantly affecting either the access delay or the throughput capacity.

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