Energy Consumption of TCP in Ad Hoc Networks[*] [†]

H. Singh, S. Saxena, and S. Singh
Department of Computer Science
Portland State University
Portland, OR 97207

ABSTRACT

In this paper we study the *energy cost* (protocol processing and communication cost) and *goodput* of different flavors of TCP (Transmission Control Protocol) in ad hoc networks. We implemented a testbed and measured the actual energy cost as well as goodput of running TCP Reno, Newreno, SACK (Selective ACKnowledgement) and a version that combines Explicit Link Failure Notification (ELFN) [7] and Explicit Congestion Notification (ECN) [5] in Newreno. We see that the use of ECN & ELFN does yield higher goodput in most cases with a corresponding lower total energy cost. We see an energy savings of between 20% and 500% depending on the network conditions.

Categories & Subject Descriptors

C.4 [Performance of Systems]: Measurement Techniques; D.4.4 [Operating Systems]: Communications Management.

General Terms

Performance, Experimentation.

Keywords

Mobile, Protocol, TCP, Energy.

1. INTRODUCTION

In ad hoc networks, communication plays a significant role in the deployed applications and thus accounts for a large proportion of the overall energy usage. Since energy is the key constraint that determines the useful life of ad hoc networks, it is important to reduce the communication energy cost. Various techniques have been proposed for reducing the communication energy cost including transmission power control, using directional antennas, adapting data rates, MAC protocols that power the radio off, and routing protocols that use energy-based routing metrics. While all of these approaches clearly reduce the cost of communicating we believe that additional savings are possible at the TCP layer as well. In this paper we explore the energy cost of TCP connections by comparing four variations of TCP for reducing this cost.

The variants of TCP studied here are: Reno, Newreno, SACK, and a hybrid developed by us called TCP-ECN-ELFN. TCP-ECN-ELFN is based on previous proposals of ECN [5] and ELFN [7] developed by other researchers. In ELFN, the TCP timers at the sender are frozen in the event of routing failure until the network layer informs TCP that a new route has been found to the destination. ECN has been proposed as a mechanism to enable TCP senders to quickly respond to incipient congestion in the network. We studied the performance of these variations of TCP in a testbed. We measured the goodput of the protocols as well as the total energy and idealized energy consumed for ttcp data transfers. The idealized energy corresponds to the energy consumed by the sender when transmitting or receiving or processing but does not include the idle energy of the node. We observe that under most ad hoc networking scenarios, TCP-ECN-ELFN results in significantly lower energy consumption as compared with TCP-SACK, Reno, and Newreno, and it also has a higher goodput.

The remainder of the paper is organized as follows. In the next section we discuss related work; section 3 develops the energy model for characterizing protocol cost; section 4 presents a summary of the various TCP variants studied including the details of ECN and ELFN that we incorporated into TCP's implementation; we used a hybrid approach for measuring TCP's energy and this is described in section 5; results are presented in section 6.

2. RELATED WORK

There have only been a few papers dealing with the problem of TCP's energy consumption over wireless links. Some of these papers propose link layer solutions while others compare various versions of TCP with respect to the energy cost. The link layer approaches include [8] who consider the effect of ARQ, FEC and a combination of the two on energy consumed in ad hoc networks. Unlike our work here, however, this paper was primarily concerned with link layer schemes to improve TCP's energy behavior. [14] also considers the effect of ARQ strategies on energy consumption. The key idea is to suspend packet transmission when chan-

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nel conditions worsen and probing the channel state prior to packet transmission. When channel conditions improve, packet transmission is resumed.

[12] compares the energy and throughput-efficiency of TCP error control strategies for three implementations of TCP Tahoe, Reno, and New Reno. They implemented the three versions of TCP using the x-kernel protocol framework and their focus was to study heterogenous wired/wireless environments. [15] analyzes the energy consumption performance of various versions of TCP for bulk data transfer in an environment where channel errors are correlated. Interestingly, the energy cost is modeled as the ratio of the number of successful transmissions to the total number of transmissions. This paper does not consider processing or other costs associated with running a higher layer protocol. Furthermore, the paper only considers a one-hop wireless link with zero propagation delay.

In the recent past there have been simulation based studies [16, 3] of throughput and energy performance of TCP in wireless networks. These studies investigate the tradeoff of radio Power on the throughput of TCP. [16] concludes that increased trasmitted power is not always good as their study shows that increased transmitted power results in higher TCP throughput up to a breakpoint (because of better Signal to Interference Ratio), after which an increment of transmitted power actually leads to worse performance due to greater interference.

[1] studied the behavior of TCP over three different routing protocols and they conclude that frequency of route failures, routing overhead, and delay in route establishment are the primary determinants of TCP's performance. [2] proposed a heuristic called fixed RTO (Retransmit Time Out) to distinguish between route loss and network congestion. In their implementation, the same RTO value is used for consecutive timeouts because, they argue, losses are probably due to routing failure rather than congestion and increasing the timeout values only degrades performance. Finally, [6] studies the relationship between the MAC layer and TCP in multi-hop networks. They show that the interaction between TCP and MAC (Medium Access Control) backoff timers can cause severe unfairness. Furthermore, the interaction between TCP data packets and ACKs can result in very small congestion windows. Finally, they show how these problems can be overcome by protocols that include link layer ACKs.

Our study is different in many ways, first while all the previous studies were based on simulation, we measured energy using a wireless test-bed (3-hop ad hoc network) and a real TCP/IP stack (FreeBSD); second, in all the previous studies total energy is considered to be the primary metric. Unfortunately, total energy includes the energy consumed when the connection is idle and this can be the dominating factor in computing this metric. We therefore also measured the actual protocol processing energy, which excludes the connection idle periods.

3. ENERGY COST OF TCP

Figure 1 shows a simplified view of the evolution, in time, of the energy consumption of a TCP sender. In the figure, we plot the instantaneous current draw as a function of the time. As we show in the figure, the node consumes P_{Idle} amount of Power (watts) when idle (essentially waiting for packets or ACKs), P_{Tx} Power in *processing and transmitting*

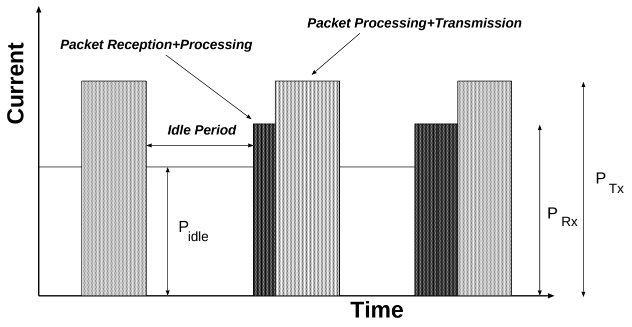

Figure 1: Simplified energy consumption profile.

TCP segments, and P_{Rx} Power in *receiving and processing* TCP ACKs. Let t_{total}, t_{Tx}, and t_{Rx} denote the total time of the connection, the time spent by the node in processing and transmitting packets, and the time spent in receiving and processing ACKs. Then, the total energy consumed by the TCP connection is[1],

$$\begin{aligned} E_A &= P_{\text{Idle}}(t_{\text{total}} - t_{Tx} - t_{Rx}) + P_{Tx}t_{Tx} + P_{Rx}t_{Rx} \\ &= P_{\text{Idle}}t_{\text{Idle}} + E_{Tx} + E_{Rx} \\ &= P_{\text{Idle}}t_{\text{Idle}} + E_I \end{aligned} \tag{1}$$

Where E_I denotes the energy consumed only for transmitting/receiving packets and the associated processing cost. In a sense, E_I denotes the *ideal* energy consumed if the node and the radio can be *powered off for exactly the duration of the idle periods.*

Next, assume that B bytes of data are sent during the lifetime of the connection at an average throughput of τ bytes/sec. If the transmission speed of the radio is r bytes/sec, we can write,

$$t_{\text{Idle}} \approx B/\tau - B/r - (64B)/(2Dr) \propto 1/\tau(sec)$$

where D is the packet size used, B/r is the time to transmit the packets, and $(64B)/(2Dr)$ is the time to receive the 64-byte ACKs (assuming one ACK is sent for every two packets). If we substitute $1/\tau$ for t_{Idle} in equation 1, we get,

$$E_A \propto P_{\text{Idle}}/\tau + E_I \propto E_{\text{Idle}} + E_I \tag{2}$$

As equation 2 shows, the total energy consumed by a TCP connection is inversely proportional to the connection's throughput and is proportional to the idealized energy E_I. In equation 2, we treat E_{Idle} as a constant but it is easy to see that its value has a significant impact on the measured total energy E_A. The value of E_{Idle} depends on the behavior of the node during periods when the node is idle. Typically, laptops and PDAs enter a sleep state when they have been idle for some period of time and wake up when an event occurs. The energy consumed when the node sleeps versus when it is idle but awake can be quite dramatic and can make a significant impact on any energy comparison.

4. OVERVIEW OF TCP VARIANTS

[1]The assumption here and in the remainder of the paper, is that there are no other applications running over which the energy cost can be amortized.

All the current TCP implementations are based on TCP Tahoe that incorporated algorithms for slow-start, congestion avoidance, fast retransmit. and modifications to the formula for estimating round-trip times (RTT), see [11]. TCP Reno is essentially similar to Tahoe but with a modified fast retransmit algorithm that includes fast recovery as well. When the sender receives three duplicate ACKs, it retransmits one segment and reduces its ssthresh by half (minimum of two segments). However, unlike Tahoe which performs slow-start, Reno increases its congestion window more rapidly by setting it to min(recvr_window, CWND + ndup). In other words, after retransmitting one segment and reducing ssthresh by one half, Reno sets ndup to 3 and increments it for every duplicate ACK received. When the sender receives an ACK for new data, it exits fast recovery by setting ndup to zero. It is easy to see that Reno's fast recovery algorithm is optimized for single packet losses from a window of data and will not perform well for multiple losses. In this case the retransmit timer will go off resulting in congestion avoidance and very low throughput.

TCP Newreno tries to overcome the shortcomings of Reno in the presence of bursty losses by using information contained in *partial* ACKs differently. A partial ACK is an ACK that acknowledges some but not all of the unacked packets in the sender's window. In Reno, a partial ACK takes the sender out of fast recovery. In Newreno, on the other hand, a partial ACK received during fast recovery is taken as an indication that the packet following the partial ACK was lost and should be retransmitted. Thus, in the presence of multiple losses from within a window, partial ACKs ensure that the lost packets are retransmitted without waiting for retransmit timers to go off. Newreno only comes out of fast recovery when all the packets that were in the window at the time fast recovery started are acknowledged.

TCP SACK, built on top of Newreno, adds an additional capability that allows faster recovery in the presence of multiple packet losses. When the receiver receives a block of data which is out of sequence, that data creates a hole in the receiver's buffer. This causes the receiver to generate a duplicate ACK for the segment preceding the hole. The receiver also includes the starting and ending sequence numbers of the data that was received out of sequence. This information is a SACK. The first block in a SACK option is required to report the data receiver's most recently received segment, and the additional SACK blocks repeat the most recently reported SACK blocks. This algorithm generally allows TCP to recover from multiple segment losses in a window of data within one RTT of loss detection.

When a sender detects a lost packet (via three duplicate ACKs), it retransmits one packet, cuts the congestion window by half, and enters fast recovery as in the case of Reno and Newreno. SACK maintains a variable called *pipe* that estimates the number of packets in flight. It is incremented for every transmission and is decremented when a duplicate ACK is received containing a new SACK. The sender maintains a list of segments deemed to be missing (based on all the SACKs received) and retransmits segments from this list when *pipe* is less than CWND. Finally, when partial ACKs are received, the sender decrements *pipe* by two rather than one (see [4] for a discussion of why). SACK exits fast recovery under the same conditions as Newreno.

Previous papers have compared the throughput of different versions of TCP. The results indicate that SACK has the highest throughput for a large percentage of network conditions. Based on equation (2), we can therefore predict that SACK would consume the *lowest* total energy (E_A). This is borne out in our measurements as we discuss in section 6. The discussion of SACK makes it clear that the sender needs to execute more code to maintain and use the SACK-related data structures. We had assumed that this added cost would be negligible. However, as section 6 shows, the idealized energy cost E_I of SACK is higher (and measurable) than Reno and Newreno for many cases.

4.1 TCP-ECN-ELFN

Table 1 summarizes the changes made to the operation of TCP to include ECN and ELFN. We note that our implementation goes beyond simply adding ELFN and ECN to TCP - we no longer treat timeouts and triple duplicate ACKs as indications of congestion. Rather, we rely exclusively on ECN to flag network congestion. The table also describes the intuition behind these changes.

Routing Failure: Using ELFN

[7] describes the interplay between routing failure (due to link outage or propagation of stale routes) and TCP throughput, in detail. Briefly, successive route failures (due to link failure) lead to timeouts hence resulting in a small congestion window.. Hence, the throughput of the connection is small. The fix proposed in [7] and used by us is as follows. A *route failure* message is propagated back to the TCP sender from the intermediate node that detects the route failure. This message has the effect of freezing TCP's state and initiating the transmission of probe packets. When there is a response to the probe packet (i.e., the route is up), TCP's state is unfrozen and transmission resumes. This solution ensures that there are no timeouts (and hence no unnecessary retransmissions), and that the TCP sender begins sending packets soon after the route is up.

Out-of-order Packets, Timeouts, & Triple Duplicate ACKs

Mobility of nodes can cause packets belonging to the same connection to be routed along different routes. This can result in the receiver getting out-of-order packets which causes duplicate ACKs to arrive at the sender. Likewise, packet loss due to link-layer errors can result in triple duplicate ACKs or timeouts. On receiving three duplicate ACKs, the sender reduces its congestion window by a half and retransmits the out-of-sequence packet while in the case of timeouts, the window is reduced to one or two segments. This congestion avoidance behavior has the net effect of reducing the throughput of the connection (due to the smaller congestion window) and thus increasing overall energy consumption. We believe that the appropriate fix for this problem is for the TCP sender to retransmit the offending packet but *not adjust its congestion window.* We made this modification to TCP-ECN-ELFN in our implementation.

Network Congestion: Using ECN

A problem with our approach above is that if the triple duplicates (or timeout) were generated as a result of packet drops due to congestion, then the solution of simply retransmitting the packet without reducing the congestion window will have negative consequences (this is the reason why TCP reduces its congestion window). In our design, we rely on *explicit congestion notification* [5] to signal imminent congestion along a route[2]. Here, a node whose buffer occupancy

[2]ECN has been proposed as RFC 2481 to the IETF and has

Event	*TCP's Behavior*	*TCP-ECN-ELFN*
Routing Failure	Timeout, CWND ← 1 Retransmissions Exponential backoff timer	Freeze state Probe network Unfreeze when route restored
Triple Duplicate (TD) ACKs	Retransmit packet CWND ← CWND/2 + 3	Retransmit packet
Timeout	CWND ← 1 Retransmit Exponential backoff timer	Retransmit packet
Explicit Congestion Notification	No action	CWND ← CWND/2

Table 1: Summary of changes made to TCP.

crosses some threshold, sets a bit (the CE bit) in all data packets it sees. Receivers reflect this flag back in the ACKs they generate by setting the ECN-ECHO bit. Upon receiving an ACK with the ECN-ECHO bit set, TCP senders enter a recovery phase in which they reduce the congestion window by a half. The sender sets a CWR (Congestion Window Reduced) bit in new data packets. If the receiver sees another CE bit set in a future packet and sees that the sender had sent a CWR bit, this indicates that there is still congestion in the network. The receiver again sets the ECN-ECHO bit in new ACKs thus forcing the sender to enter another recovery phase. This can go on until the sender's window has shrunk to one or two segments.

5. MEASURING ENERGY

Most of the research in ad hoc networking uses the ns2 simulator and to a lesser extent other simulators like glomosim [13]) to run experiments. The benefit of this approach is that researchers can build upon the work of others and use a standard platform to check competing ideas. While ns2 is a good tool for measuring traditional networking metrics such as throughput, loss, and delay, it is ill-suited to measure energy consumption of a protocol like TCP. This is because the energy consumed includes not only the radio costs (which are modeled to some extent in ns2) but the node-level protocol processing and data copy costs. An alternative idea would be to use a node-level energy simulator/emulator that gives fairly accurate energy readings for processing code. The problem, however, is that these tools do not simulate the ad hoc network environment. Thus, an idealized simulator would be one which combined a detailed node-level emulator and ns2. However, we are not aware of any such simulator that we could have used.

Given the above constraints, we decided to use a hybrid approach to measure the node-level TCP energy. Specifically, we used a 4-node network (see Figure 3) in which we measured the energy of the sender node directly using two Agilent 34401A multimetes (resolution of 1msec) – one measured the total system energy while the second measured the radio-level energy alone (Figure 2 shows a sample data trace). We also ensured that there is no other traffic was present on the channel. Each node in the network is a Toshiba laptop that has a Lucent 802.11 Silver (11 Mbps) WaveLAN DSSS PC card. Further, the two intermediate nodes are set up to act as routers. To simulate multi-hop ad hoc network behavior, we ran Dummynet [10] at node C. Dummynet is a freely available kernel-level patch that allows us to control a wide-variety of network behaviors such as delay, loss, and bandwidth. For instance, Dummynet can add delays to packets to simulate variable RTT, drop packets to simulate lossy networks, vary the bandwidth, and implement different queuing mechanisms[3]. We ran Dummynet with a setting of HZ = 1000, a kernel option that gives us a time granularity of 1msec. We also implemented RED (Random Early Detection) for AQM (Active Queue Management) to detect and report incipient congestion in order to implement ECN. All of the implementation was done in FreeBSD. *Ad hoc mode of these WaveLAN PC cards do not allow Transmit Power control or explicit data rate control, and hence we did not not investigate the impact of these on TCP throughput.*

been put forward as a Proposed Standard for use over the Internet.

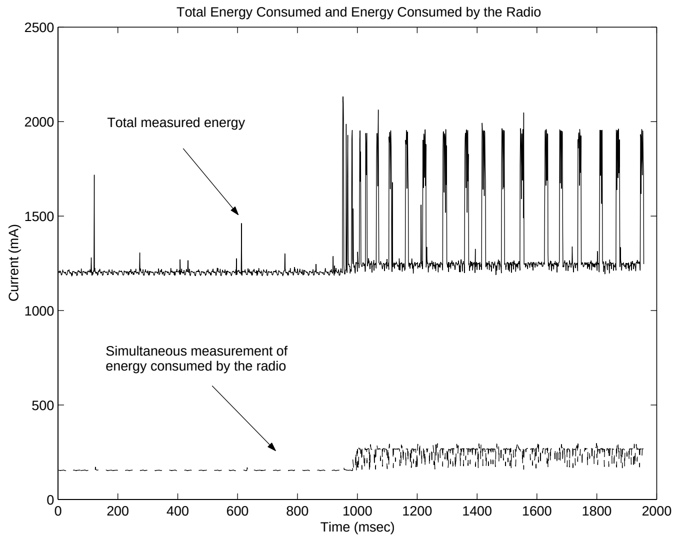

Figure 2: Sample energy trace: note simultaneous measurement of radio and system-level energy cost.

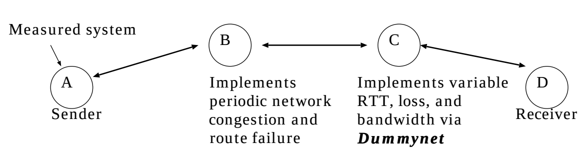
All nodes are laptops with 802.11b 11Mbps cards.
Measured system
A
Sender
B
Implements periodic network congestion and route failure
C
Implements variable RTT, loss, and bandwidth via Dummynet
D
Receiver

Figure 3: Measurement setup.

[3]The overhead of running Dummynet on network parameters like RTT etc., is negligible because Dummynet does not perform data copies, it works with pointers only.

6. EXPERIMENTAL RESULTS

Since our ad hoc network is emulated as in Figure 3, we needed to feed appropriate values for various parameters such as bandwidth, loss probability, and RTT range into Dummynet. In addition, we needed to generate out-of-order packets and congestion scenarios to model similar scenarios in ns2-based simulations. To this end, we conducted simulations in ns2 and used the results of others to determine appropriate values for these various parameters. The final selection of parameter values was somewhat optimistic but seemed to cover a wide range of ad hoc network behavior. These values are summarized in Tables 2 and 3.

All experiments were conducted at least ten times and we computed 95% confidence intervals (which are also shown in the figures). Furthermore, in order to get statistically significant results, we transmitted 5M of data (TTCP flow) for each run (transmitting smaller amounts of data resulted in high measurement error due to the 1msec granularity of the multimeter). We measured E_A, E_I, and goodput for the connections. One note about the figures. We normalize the total energy measured (E_I or E_A) by the data transferred and plot the energy in units of micro-Joules per bit. The x-axis in all plots is the average RTT value.

The remainder of this section is broken in three: in section 6.1 we look at the impact of mobility-induced factors on protocol performance; in section 6.2 we consider the relative protocol performance when nodes do not move; finally, we summarize the main results in section 6.

6.1 Mobile ad hoc network case: *impact of mobility*

6.1.1 Routing Failure Case

We simulated routing failure by breaking the route for 5 seconds after every 15 seconds during the run. This was done for the three packet loss probabilities of 1%, 5%, and 10% and for all the different RTT ranges. Figure 4 plots the energy E_I and E_A for different RTTs. We have left out the 5% loss case from the energy graphs for clarity. We also left out the plots for Reno and Newreno because their performance falls far below that of the other two variants. We see that the TCP-ECN-ELFN protocol outperforms TCP-SACK on all measured metrics because of two reasons:

- Due to route failure, TCP-SACK has a very poor throughput (and goodput) due to many timeouts. In the TCP-ECN-ELFN protocol, on the other hand, an ICMP route failure packet has the effect of freezing TCP state and resuming it when the route is up. Thus, the goodput and energy E_A of the TCP-ECN-ELFN are better than TCP-SACK.
- TCP-SACK having no mechanism of detecting route failure ends up retransmitting many packets and it has to do extra processing in maintaining SACK blocks thus has a higher *idealized enrgy* cost E_I as well. Further, this cost of maintaing SACK blocks becomes significant at higher losses. TCP-ECN-ELFN on the other hand will send a zero window probes in freeze state.
- At a 10% loss, the idealized energy for TCP-SACK is 2.5x greater than that for TCP-ECN-ELFN and the awake energy is 5x greater! However, at a 1% loss, the difference is quite small.

Total transmissions	MTU 512		MTU 1500	
	1%	5%	1%	5%
TCP-SACK	11142	11149	3607	3608
TCP-ECN-ELFN	11173	11181	3614	3647

Table 4: Number of transmissions for the reorder case.

It is interesting to note that there is an order of magnitude difference between E_I and E_A values for both protocols (we considered the cost of freezing TCP state and sending zero window probes in TCP-ECN-ELFN). This is because E_A includes the idle energy while E_I does not and, in this case, the idle energy (and idle time) are quite large because of route failure. We note that Awake Energy and goodput are inversly related. However, we note a contradition in Figure 4 at rtt 100msec and 130 msec. At rtt 100 msec TCP-SACK has higher Goodput but it also has a higher Awake Energy. The reason for this is that at rtt 100 msec the number of timeouts are relatively fewer (23) and TCP-SACK mainatins a higher cwnd and processes more SACK blocks (39), hence it achieves a higher goodput, however, the cost of processing these SACK blocks contributes to the higher energy cost. At rtt 130 msec TCP-SACK has more timeouts and has less SACK processing because in the event of timeouts, all SACK blocks are discarded. Further, due to invocaction of slow start in quick succession it achieves lower goodput. Finally, note that packet loss has a non-trivial impact on the performance of the different protocols. We examine the effect of loss in detail in section 6.2.1.

6.1.2 Packet Reorder Case

Dummynet was configured to reorder 1% and 5% packets randomly in its buffer. In Figures 5 and 6 we plot the idealized and awake energies consumed by all four variants of TCP. In general we note that Reno has the highest idealized as well as awake energy consumption followed by Newreno (for both MTU sizes). SACK performs better than Reno and Newreno because when the sender receives three duplicate ACKs (that also contain information about holes in the receiver's buffer), the sender retransmits one segment and then retransmits the segments that corresponded to holes in the receiver's buffer as and when *pipe* is less than CWND. Newreno, on the other hand, sequentially retransmits segments on receipt of partial ACKs. This results in some packets not being retransmitted early enough and we get timeout events. In our experiments, we noted that SACK never had any timeouts for the reorder experiments while both Reno and Newreno had timeout events (Reno more than Newreno).

Let us next compare the relative behaviors of TCP-SACK and TCP-ECN-ELFN. In the 1% case, we note that TCP-SACK has a lower idealized energy cost (at lower RTTs) than the TCP-ECN-ELFN protocol. This is due to the fact that the TCP-ECN-ELFN protocol retransmits[4] more packets than TCP-SACK (see Table 4). Interestingly, at a 5% reorder rate, we see that TCP-SACK has a *higher* idealized energy than the TCP-ECN-ELFN protocol even though it retransmits fewer packets! The explanation is that the additional reception and processing cost of SACKs becomes appreciable at the 5% reorder level and thus increases the

[4]We used tcpdump and netstat before and after each run to gather these statistics.

Parameter	*Values*	*Comments*
RTT	10-20ms, 30-50ms, 60-80ms, 90-110ms, 120-140ms	For a given experiment, we use one of the RTT ranges; each packet had a RTT randomly uniformly selected from this range
MTU size	512 and 1500 bytes	These extreme values explore the dependence of energy on MTU size
RTS/CTS	ON or OFF	We performed experiments with both cases but show graphs for the OFF case only (the ON case was similar)
Protocols studied	Reno, Newreno, SACK and ECN-ELFN	SACK implemented in FreeBSD4.3 based on RFC2018; the TCP-ECN-ELFN also implemented in FreeBSD4.3

Table 2: Experimental parameters for all experiments.

Experimental Factors	*Values*	*Comments*
	Mobile ad hoc networks	
Route failure	Route down for 5 sec every 15 sec	These values are very optimistic and were selected because even at these values TCP's energy cost is significantly higher than the cost of the TCP-ECN-ELFN protocol
Packet reordering	1% and 5% packets reordered	Packets as well as ACKs reordered randomly; these values are dependent on the routing protocol and could be higher
	Static ad hoc networks	
End-to-end Packet Loss	1%, 5%, 10%	This range is somewhat optimistic and ignores some high loss cases
Bursty loss	85% loss for 1 sec every 12 sec	Models the case when the route fails at a node that has a buffer full of packets
Congestion	Router B congested for 5 sec every 30 sec	Two RTTs used:15 ms and 130 ms; this case shows that the TCP-ECN-ELFN protocol reacts correctly to congestion

Table 3: Summary of ad hoc network conditions studied.

E_I value ([9] also contemplates the additional cost of using SACK). SACK is a TCP option in which the receiver can specify up to three blocks of out-of-order data it has received. Each block is specified by the starting and ending 32-bit sequence number. Thus, specifying each block consumes eight bytes. In the case of a 5% packet reordering, the number of duplicate ACKs is larger and each duplicate ACK will contain a SACK that can contribute between ten and twenty four bytes of additional information. The sender also needs to maintain additional data structures to process SACKs. The cost of receiving more data coupled with the cost of processing and storing SACK data structures increases the overall idealized energy cost for TCP-SACK. The TCP-ECN-ELFN protocol has none of this overhead and thus has a lower idealized energy cost. In the 1% reorder case, the number of duplicate ACKs is much smaller and hence the SACK overhead is minimal.

Returning to the 1% reorder case, the SACK-associated cost is not significant here because of two reasons. First, the number of duplicate ACKs is much smaller than the 5% case (thus, the receiving and processing cost of SACK is much smaller). Second, SACK *clears* its data structures when it receives an in sequence ACK. In the 1% reorder case, the the probability that more than one packet was out-of-order (in a window) at the receiver is small and hence when it is ACK'ed, the SACK data structures can be cleared. In the 5% reorder case, on the other hand, more than one packet can be out of order within a window and thus the SACK data structures (indicating received blocks) need to be maintained for longer times.

6.2 Static ad hoc network case: *impact of loss*

6.2.1 Random Packet Loss Case

One of the primary contributors to lowered protocol performance in static ad hoc networks is packet loss resulting from link-layer errors and congestion. In order to study the impact of packet loss on protocol behavior, we used three values for packet loss (1%, 5%, and 10%), for the five values for RTT and two different MTU values (see Table 2). Figure 7 plots the idealized energy cost E_I as a function of RTT for both MTU values (1% and 10% loss); Figure 8 plots the awake energy cost E_A and Figure 9 plots the goodput. We can make the following observations:

- In general, smaller MTUs are better (i.e., consume less energy E_I and E_A) at higher loss rates whereas larger MTUs are better at low loss rates. This observation has been made by several previous researchers when throughput was the metric studied.

- If we only look at the idealized energy consumption (Figure 7), then we see clearly that either Reno or Newreno are the best performing protocol with the appropriate MTU size. This is because, unlike TCP-SACK, Reno and Newreno do not incur the extra processing overhead and unlike TCP-ECN-ELFN, they do not needlessly retransmit packets.

  At a loss of 1%, the idealized energy of the TCP-ECN-ELFN protocol is *higher* than that of TCP-SACK, Reno and Newreno. The reason for this is that the TCP-ECN-ELFN protocol actually retransmits many more packets than the other protocols. This is because if a packet is lost, on receipt of triple duplicate ACKs the TCP-ECN-ELFN protocol retransmits that packet but does not shrink its congestion window. Thus, it is sometimes the case (when the sender has a lot of data to send) that the same packet may receive another set of triple duplicate ACKs (sent in response to new packets arriving at the receiver) thus prompting a second (unnecessary) retransmission. TCP-SACK, Reno, and Newreno, on the other hand, shrink their congestion windows on receipt of triple duplicate ACKs. This reduces the probability of receiving a new set of triple duplicate ACKs for the same packet (and hence we avoid an unnecessary second retransmission). Table 5 summarizes the total number of transmissions for the TCP-SACK and TCP-ECN-ELFN (averaged over all RTTs). As we can see, for a MTU of 1500, the TCP-ECN-ELFN protocol transmits 425 more packets than TCP-SACK.

- At a loss of 10%, we note that the TCP-ECN-ELFN protocol still transmits more packets than TCP-SACK but it has a lower idealized energy cost. The reason for this dichotomy is the dependence of energy cost on the both the transmission/reception cost as well as on the *processing cost*. At a 10% loss rate, TCP-SACK will see a large number of duplicate ACKs containing SACKs for blocks received out-of-order. As we discussed in section 6.1.2, the added cost of processing, storing, and receiving these SACKs is non-trivial and accounts for the higher idealized energy E_I value for TCP-SACK. At a 1% loss rate, however, the number of SACKs is significantly smaller and the energy associated with SACK processing is not statistically significant and thus does not affect the relative values of E_I for TCP-SACK and the TCP-ECN-ELFN protocol.

- Consider Figure 8 where we plot the awake energy E_A costs. Here, we see that TCP-ECN-ELFN is the winner in both loss cases and it consumed the least amount of energy. The reason for this (in contrast to its performance with respect to the E_I metric) is that by retransmitting more packets, ECN-ELFN maintains a much higher goodput (see Figure 9) and thus the data transmission concludes earlier. The other protocols take longer to send the data and the idle energy costs begin to dominate the total awake energy cost.

- For the 1% loss case with a MTU of 512 bytes, TCP-SACK has a higher goodput than the TCP-ECN-ELFN protocol for cases when the RTT < 100 ms. The reason the goodput of TCP-SACK is higher for these cases is two-fold: first, the TCP-ECN-ELFN protocol has a higher number of retransmissions (for the reason explained earlier) and second, TCP-SACK can recover from multiple losses occurring in a window within one RTT thus maintaining its throughut.

  However, at a high RTT (e.g., 100ms), we see that the goodput of the TCP-ECN-ELFN protocol overtakes that of TCP-SACK. This is because the TCP-ECN-ELFN protocol does not shrink its congestion window on receipt of triple duplicate ACKs (as TCP-SACK does) thus it maintains a high throughput. At a low RTT, TCP-SACK is able to quickly build up its congestion window to maintain high throughput but at high RTT this process takes much longer and we therefore see the TCP-ECN-ELFN protocol pulling ahead! For an MTU of 1500 bytes the trend is the same for identical reasons. However, the crossover point occurs at lower RTTs due to the larger MTU.

- For the 10% loss case, the TCP-ECN-ELFN protocol has a higher goodput (and thus a lower E_A) as compared with TCP-SACK because, unlike TCP-SACK, the TCP-ECN-ELFN protocol does not reduce its congestion window on receipt of triple duplicate ACKs or timeouts. At a loss probability of 10%, we see multiple losses within a window due to which TCP-SACK's congestion window does not grow much thus keeping the goodput small.

Total transmissions	MTU 512		MTU 1500	
(Timeouts)	1%	10%	1%	10%
TCP-SACK	11004 (0.51)	11538 (104)	3642 (0.64)	4111 (340)
TCP-ECN-ELFN	11661 (0.52)	14150 (6.48)	4067 (0.16)	5551 (40)

Table 5: Number of transmissions (and timeouts) for the loss case.

6.2.2 *Bursty Loss Case*

Figure 10 plots the energy and gooodput for the bursty loss case. First, comparing Reno, Newreno, and SACK, we see that SACK has the lowest awake energy while Newreno has the lowest ideal energy (Reno has the highest energy cost). The reason for this difference in Newreno and SACK is that in the case of a bursty loss, Newreno will retransmit lost packets without waiting for the retransmit timers to go off (based on partial ACKs received). SACK, likewise will retransmit these packets as well (as indicated by the SACKs) but it also has the added overhead of maintaining SACK-related data. This additional cost results in SACK having a higher idealized energy cost even though its goodput is the highest.

If we compare TCP-SACK and TCP-ECN-ELFN, we note that ECN-ELFN has a lower E_I as well as a lower E_A. The reason is that while both protocols retransmit missing packets when the sender receives triple duplicate ACKs, ECN-ELFN does not shrink its congestion window while SACK does. Thus, the goodput of the TCP-ECN-ELFN protocol is higher and its awake energy E_A & idealized energy E_I are lower than that of TCP-SACK. Interestingly, as shown in Figure 10, the idealized energy E_I for the TCP-ECN-ELFN protocol is quite close to that of the awake energy. This is due to the fact that in these experiments the only loss suffered was due to bursty loss (i.e., no random packet loss was simulated) and there was no network congestion or route failure. Thus, the TCP-ECN-ELFN protocol operated at the maximum possible rate resulting in minimal idle time. This causes the values of E_A and E_I to be quite close. In the case of TCP-SACK, on the other hand, the congestion window shrinks every time there is a triple duplicate ACK or timeout that causes the goodput and E_A to fall. Thus, there is a larger difference between the idealized and awake energy for TCP-SACK. Overall, we see a 2x improvement

Ntwk condition	*Lower E_I*	*Higher Goodput*
Mobile ad hoc networks		
Route failure	ECN-ELFN	ECN-ELFN
Pkt reordering	ECN-ELFN	ECN-ELFN
Static ad hoc networks		
Packet Loss	Newreno	ECN-ELFN
Bursty loss	ECN-ELFN	ECN-ELFN
Congestion	ECN-ELFN	ECN-ELFN

Table 6: Summary of results.

in E_A when using ECN-ELFN and a 10 – 25% improvement in E_I.

6.2.3 Congestion Case

In this set of experiments we wanted to investigate the effects of congestion on TCP-ECN-ELFN and TCP-SACK. Using packet traces we observed that TCP-ECN-ELFN did indeed respond to congestion appropriately, the sender reduced its congestion window in response to one or more ECNs and build up its congestion window when it no longer received the ECNs. In this section we examine the energy consumed by the two protocols under study for the case when congestion occurs every 30 seconds and lasts for 5 seconds. We ran the experiments for two cases when the average RTT was 15 msec and 130 msec. For each of these RTT values we had background packet loss of 1%, 5%, and 10%.

Figure 11 plots the idealized and awake energy consumed by the two protocols. It is interesting to observe that the idealized energy consumed is the same for the two RTT values for TCP-SACK and for the TCP-ECN-ELFN protocol with an RTT of 130 msec. However, the idealized energy for the TCP-ECN-ELFN protocol at an RTT of 15 msec is the smallest by far. In the case of TCP-SACK, the periodic congestion coupled with packet loss ensures that its congestion window is always small (for both RTTs) and thus the idealized energy consumed is almost the same (i.e., on the average the same number of SACKs are processed and the same number of packets are retransmitted). In the case of the TCP-ECN-ELFN protocol, however, the idealized energy is higher for the larger RTT case because the protocol mistakenly retransmits more packets at a higher RTT. Recall from our discussion in section 6.2.1 that the TCP-ECN-ELFN protocol may retransmit the same packet more than once because it may receive multiple cases of triple duplicate ACKs – the probability of this happening is higher at a larger RTT.

7. CONCLUSIONS

In this paper we have characterized the energy cost of TCP Reno, Newreno, SACK and a modified version of TCP (ECN-ELFN) that appears to be better suited for operation in ad hoc networks. The TCP-ECN-ELFN protocol relies on explicit routing failure notifications to freeze TCP state allowing faster recovery when the route is back up. In addition, it uses ECN to respond to network congestion. We showed that the TCP-ECN-ELFN protocol uses less energy and delivers a higher goodput as compared with the other three TCP variants in all cases but one where Newreno performs better (see Table 6). One of the areas of concern in using the TCP-ECN-ELFN protocol, however, is the issue of fairness. That is, will this protocol share bandwidth fairly between multiple connections? This question is fairly complex and is presently being studied in a ns2 simulation.

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8. REFERENCES

[1] Ashish Ahuja, Sulabh Agarwal, Jatinder Pal Singh, and Rajeev Shorey. Performance of tcp over different routing protocols in mobile ad-hoc networks. In *IEEE Vehicular Technology Conference (VTC 2000), Tokyo, Japan*, May 2000.

[2] Thomas D. Dyer and Rajendra V. Boppana. A comparison of tcp performance over three routing protocols for mobile ad hoc networks. In *ACM Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC)*, October 2001.

[3] Sorav Bansal et.al. Energy efficiency and throughput for tcp traffic in multi-hop wireless networks. In *Proceedings INFOCOM 2002, New York, NY*, 2002.

[4] K. Fall and S. Floyd. Simulation-based comparison of tahoe, reno, and sack tcp. *ACM Computer Communications Review*, 26(3):5 – 21, July 1996.

[5] S. Floyd. TCP and explicit congestion notification. *ACM Computer Communication Review*, 24(5):10–23, 1994.

[6] M. Gerla, K. Tang, and R. Bagrodia. Tcp performance in wireless multi-hop networks. In *IEEE WMCSA'99, (New Orleans, LA)*, Feb. 1999.

[7] Gavin Holland and Nitin H. Vaidya. Analysis of TCP performance over mobile ad hoc networks. In *ACM Mobile Computing and Networking (MOBICOM'99)*, pages 219–230, 1999.

[8] M. Srivastava P. Lettieri, C. Schurgers. Adaptive link layer strategies for energy efficient wireless networking. In *Wireless Networks*, volume 5, pages 339 – 355, 1999.

[9] L. Rizzo. Issues in the implementation of selective acknowledgements for tcp, 1996.

[10] L. Rizzo. Dummynet: a simple approach to the evaluation of network protocols. *ACM Computer Communication Review*, 27(1), January 1997.

[11] W. Richard Stevens. *TCP/IP Illustrated, Volume I: The Protocols*. Addison Wesley, 1994.

[12] V. Tsaoussidis, H. Badr, X. Ge, and K. Pentikousis. Energy/throughput tradeoffs of tcp error control strategies. In *In Proceedings of the 5th IEEE Symposium on Computers and Communications, France*, July 2000.

[13] Xiang Zeng, Rajive Bagrodia, and Mario Gerla. Glomosim: a library for parallel simulation of large-scale wireless networks. In *Proceedings of the 12th Workshop on Parallel and Distributed Simulations – PADS '98*, May 26-29 1998.

[14] M. Zorzi and R.R. Rao. Error control and energy consumption in communications for nomadic computing. In *IEEE Transactions on Computers*, March 1997.

[15] M. Zorzi and R.R. Rao. Is tcp energy efficient? In *Proceedings IEEE MoMuC*, November 1999.

[16] M. Zorzi, M. Rossi, and G. Mazzini. Throughput and energy performance of tcp on a wideband cdma air interface. In *Journal of Wireless Communications and Mobile Computing, Wiley 2002*, 2002.

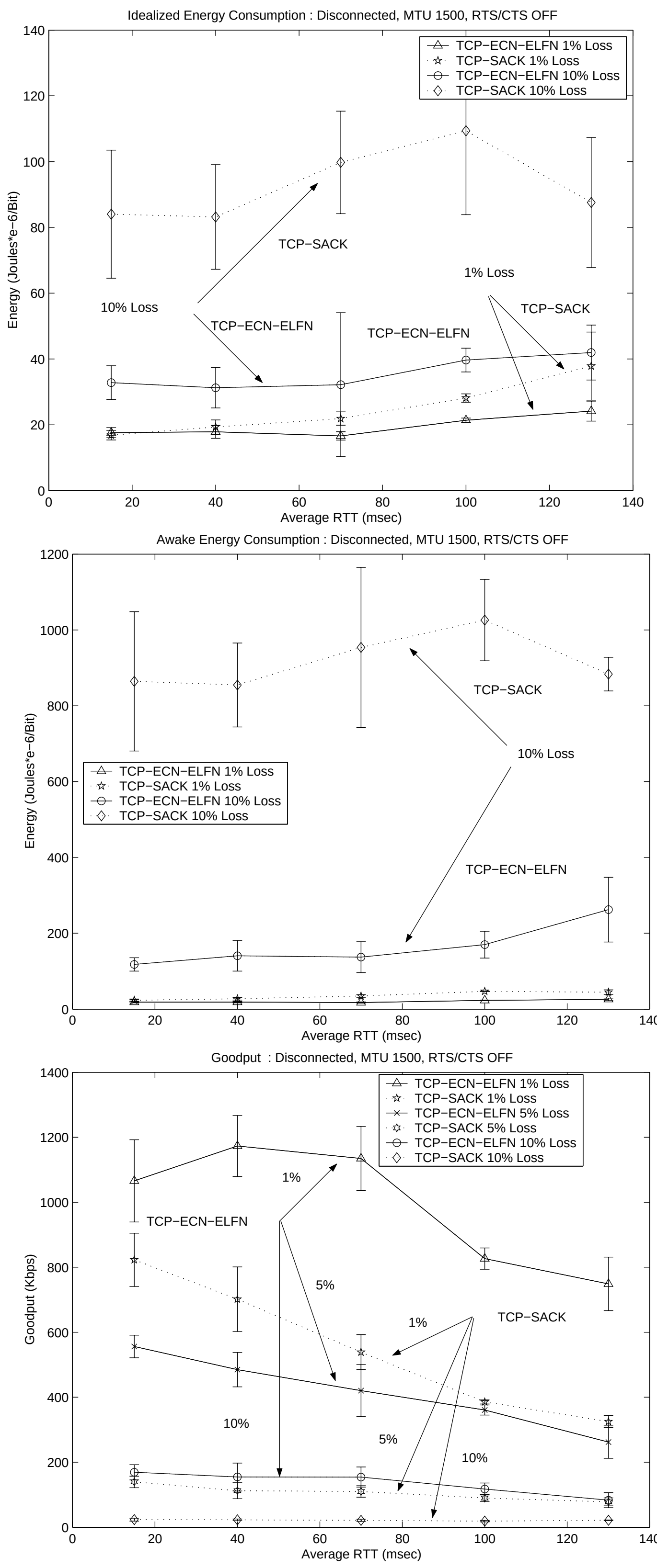


Figure 4: Idealized and awake energy cost for the route failure case.

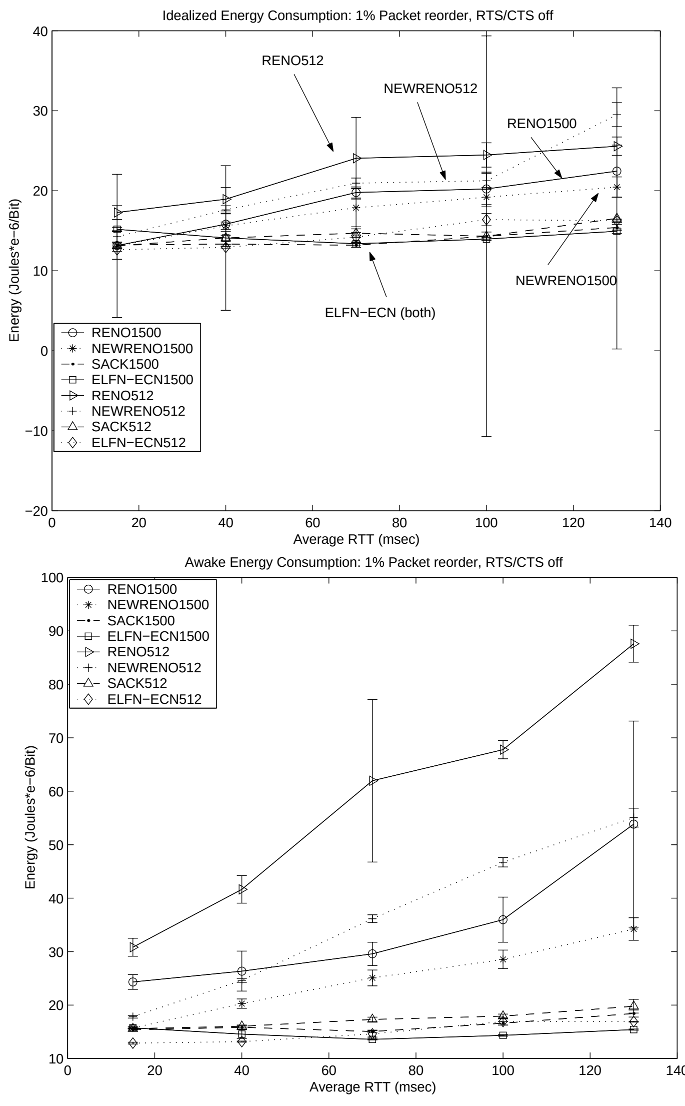


Figure 5: Idealized and awake energy for 1% packet reordering.

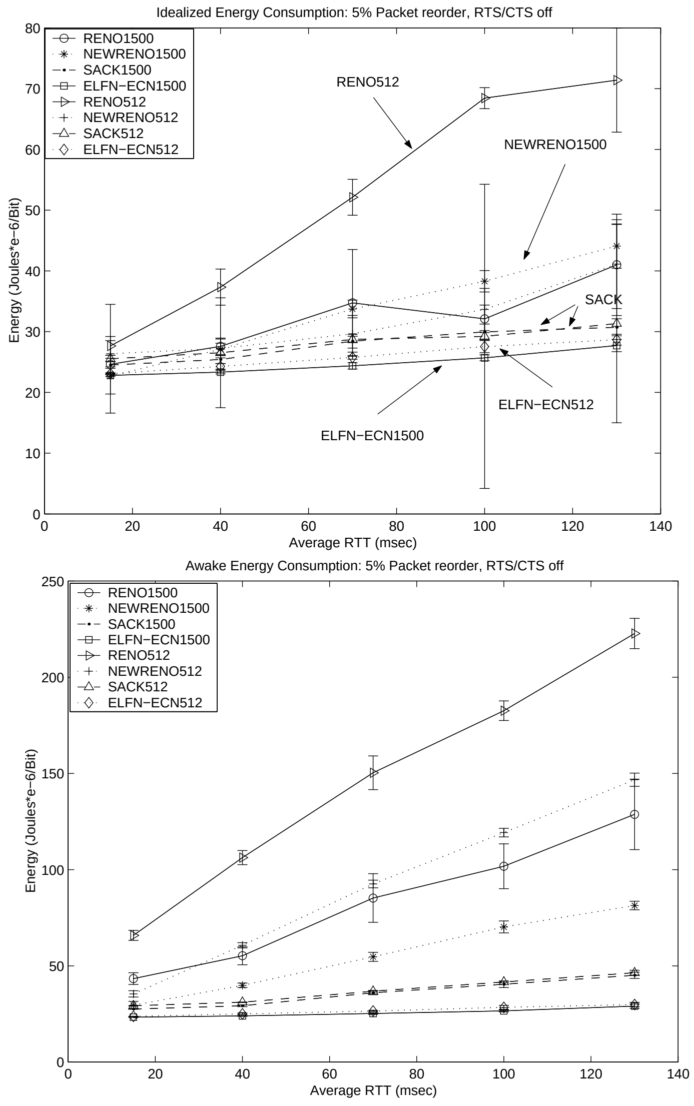


Figure 6: Idealized and awake energy for 5% packet reordering.

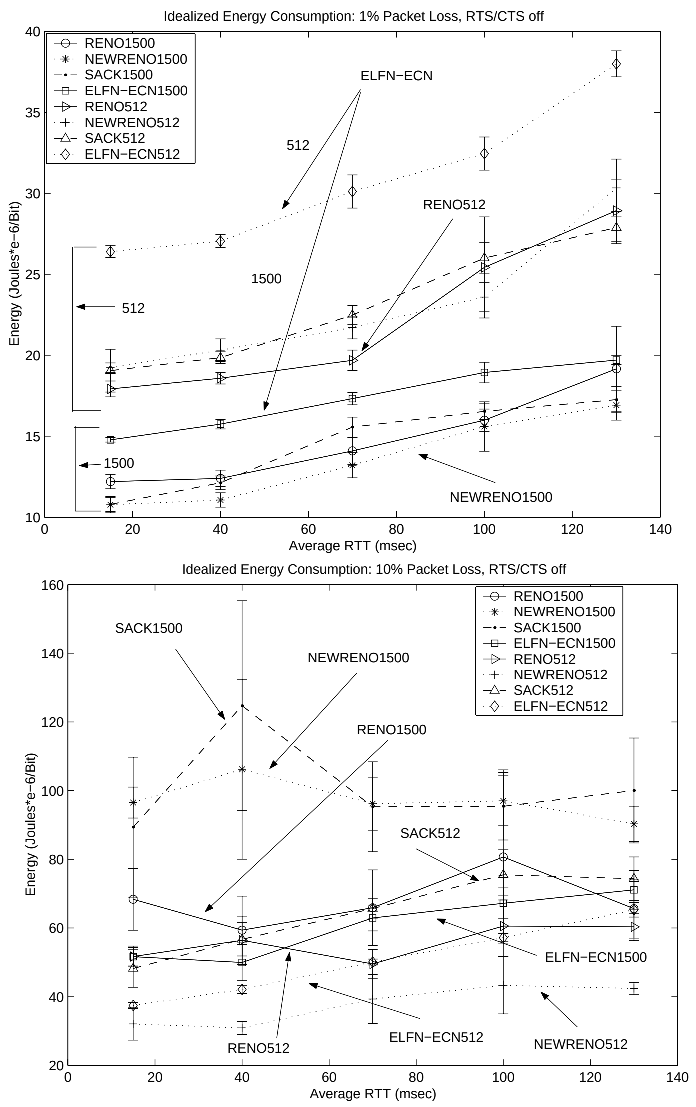


Figure 7: Idealized energy cost for loss case.

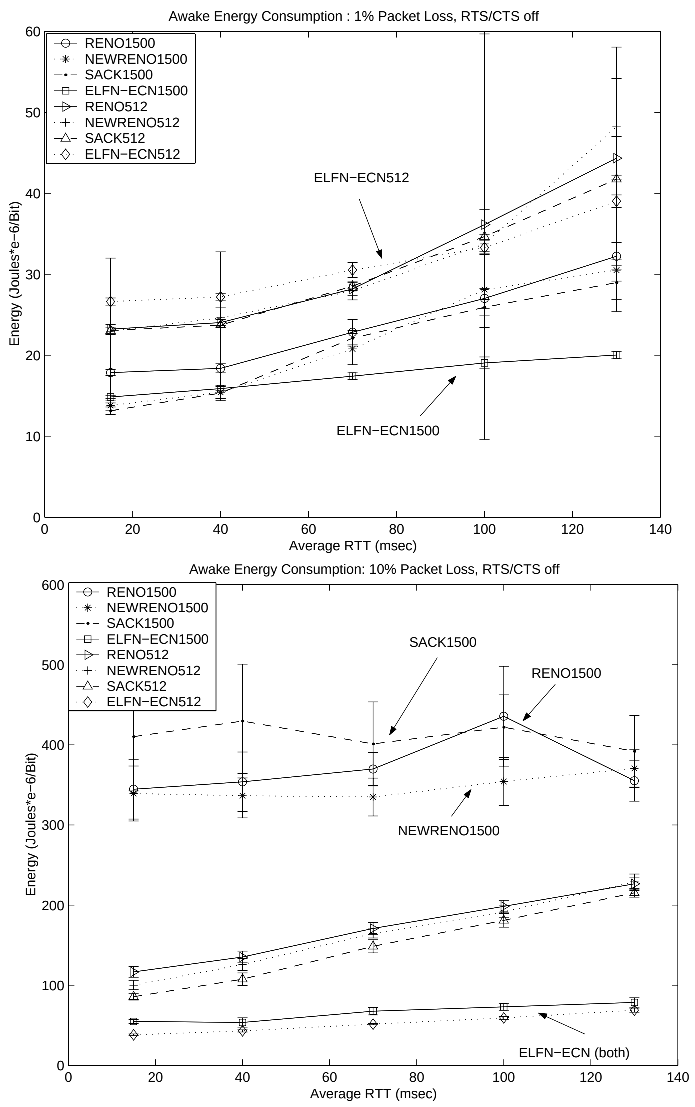


Figure 8: Awake energy cost for loss case.

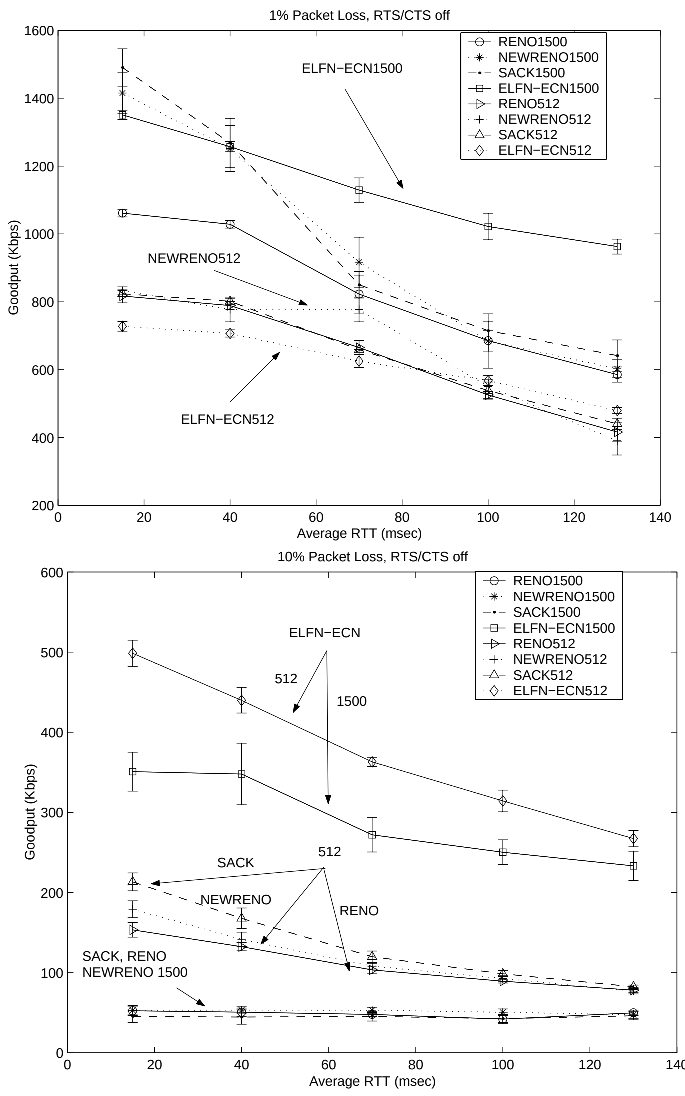


Figure 9: Goodput for loss case.

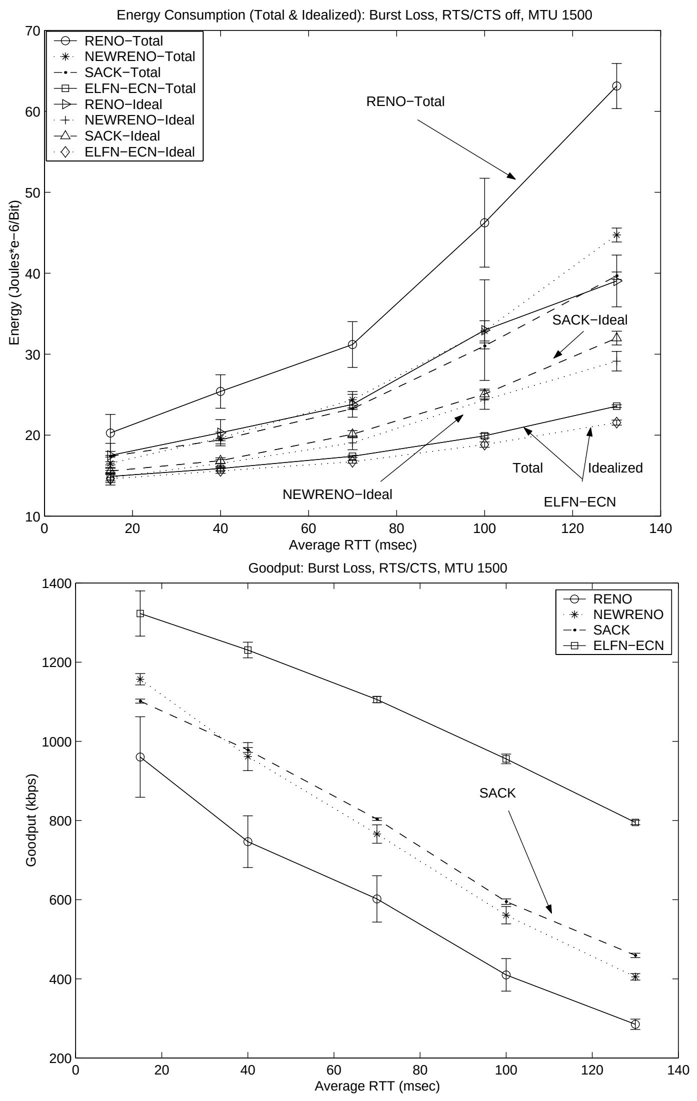
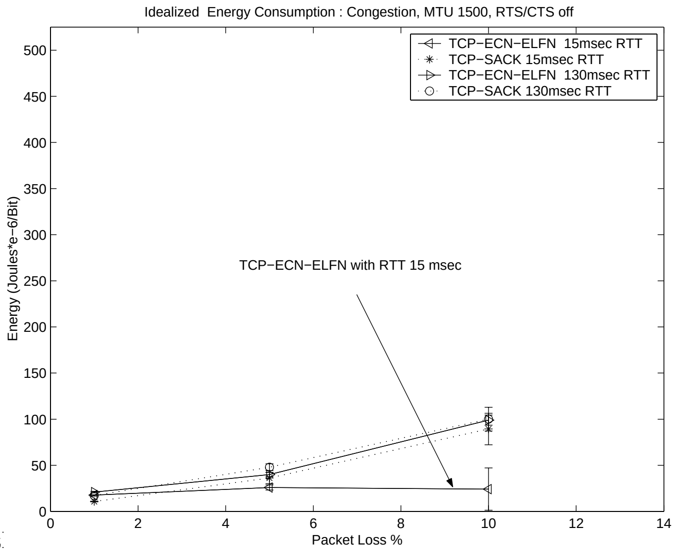


Figure 10: Energy and goodput for bursty losses.



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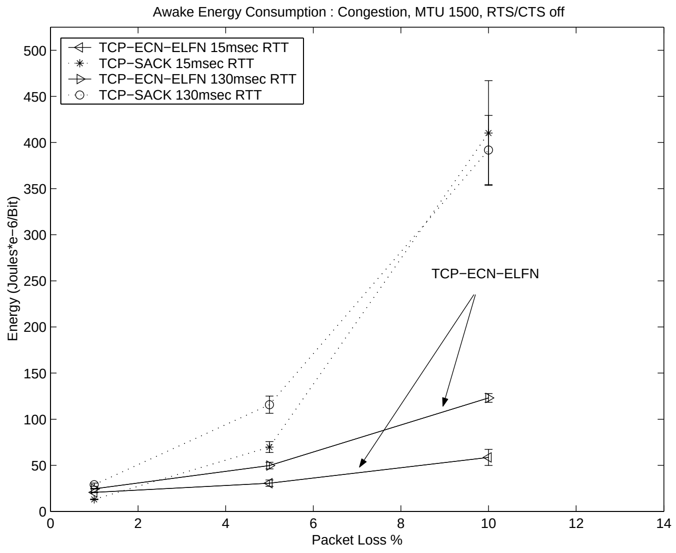

Figure 11: Idealized and awake energy for the congestion case.