Is TCP energy efficient?*

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Abstract—
We analyze the energy consumption performance of various versions of TCP, for bulk data transfer in an environment where channel errors are correlated. We focus on a single wireless TCP connection and model the packet loss or error process as a first-order Markov chain. We compute the throughput and energy performance of various versions of TCP. The main findings of this study are that 1) error correlations significantly affect the energy performance of TCP (consistent with analogous conclusions for throughput; and 2) the congestion control mechanism implemented by TCP does a good job at saving energy as well, by backing off and idling during error bursts. An interesting conclusion is that, unlike throughput, the energy efficiency metric may be very sensitive to the TCP version used and to the choice of the protocol parameters.

I. INTRODUCTION

Rapid advances in the area of wireless communications and the popularity of the Internet call for provision of packet data services for applications like e-mail, web browsing and mobile computing over wireless channels. Transport Control Protocol (TCP) is a reliable, end-to-end, transport protocol that is widely used to support applications like telnet, ftp, and http [2].

TCP was designed for wireline networks where the channel error rates are very low and congestion is the primary cause of packet loss. Since its original deployment, several modifications to TCP, including Reno, NewReno, and Vegas have been proposed and their performance analyzed in wireline networks [1, 3]. Reno's loss recovery algorithm is optimized for the case when a single packet is lost in a window of data. Hence, Reno can suffer performance problems when multiple packets are lost in a window [1]. NewReno addresses this problem by improving the loss recovery phase to handle this situation [1, 4].

The wireless environment often involves portable devices which rely on batteries as their energy supplies. In this scenario, a key objective is the efficient usage of limited power sources. Much of the effort in this respect has been focusing on battery technology (a slowly improving field) and on low-power circuitry. As better performance is achieved by the RF components, other sources of data losses are congestion and buffer overflow. There-
metric may be very sensitive to the TCP version used and to the choice of the protocol parameters, so that large gains appear possible.

II. SYSTEM MODEL AND ASSUMPTIONS

A detailed description of the receive and transmit processes in TCP OldTahoe, Tahoe, Reno and NewReno can be found in [4, 9].

In this paper, we are primarily interested in the performance of TCP during a bulk data transfer. Consequently, we consider only the data transfer phase of the protocol, which dominates the overall performance in this case, and neglect connection set up and tear down phases. We consider a single transmitter-receiver pair running TCP on a 1.5-Mbps dedicated link with zero propagation delay and perfect feedback. The transmitter is assumed to have an infinite supply of packets to send.

We assume a TCP packet size of 1400 bytes. At 1.5 Mbps rate, this corresponds to a packet transmission time $T$ of about 7.5 ms. As discussed in [11], the error process caused by the Rayleigh fading effects is approximated by means of a two-state Markov process. The average packet error rate depends on the value of the fading margin, $F$. In addition, the memory of the process is affected by the normalized value of the Doppler frequency, $f_D$, normalized by multiplying it by the packet length, $T$. By choosing different values of $f_D T$, we can establish fading channel models with different degrees of correlation in the fading process. When $f_D T$ is small, the fading process is very correlated (long bursts of packet errors); on the other hand, for larger values of $f_D T$, successive samples of the channel are almost independent (short bursts of packet errors). The case of independent and identically distributed (iid) errors will be considered for comparison.

We stress the fact that, although motivated by the behavior of the wireless channel, the loss model considered here applies to any environment where packet loss process exhibits memory, e.g., due to congestion. IID loss models do not capture this dimension, whereas Markov models are a natural choice in this case.

The analytical approach is based on a Markov/renewal reward approach. The window evolution can be tracked by a Markov process, whose state is given by the values of four variables, i.e., the window size, $W$, the slow start threshold, $W_1$, the number of outstanding packets and the channel state. In principle, it is then possible to define a Markov model and to compute the quantities of interest from it.

A potential problem with this approach is that the number of states can be very large. An alternative is to sample the chain in a way that reduces the state space. If sampled appropriately, a Markov chain results in a semi-Markov process (as defined in [13, Ch. 10]). Each transition needs to be labeled appropriately to track the quantities of interest associated with the transition from $i$ to $j$ (in particular, number of slots, $N_i$, number of transmissions, $N_t$, and number of successful transmissions, $N_s$). Once these quantities have been defined, from the theory of renewal reward processes we can find the steady-state average of the "reward" earned during a slot. In the case of $N_t$, we find the average number of transmissions per slot (which is directly related to the energy consumption of the protocol), whereas by using $N_s$ we find the throughput performance. Details of the approach can be found in [12, 9].

The energy efficiency of the protocol was defined in [10] as the average number of successful transmission per energy unit used. Under the above assumptions, this quantity can be computed as

\[ \text{energy efficiency} = \frac{\sum_{i \in G_X} \pi_i \sum_{j \in G_X} P_{ij} N_s}{F} \]

III. NUMERICAL RESULTS

In our investigation, we considered various values of the different parameters. Specifically, we studied the following: normalized Doppler frequency, $f_D T$, (iid, 0.01, 0.08, and 0.64); TCP version (OldTahoe, Tahoe, Reno and NewReno); fast retransmit threshold, $K$ (1, 2, and 3); maximum window size, $W_{max}$ (6 and 24).

An extensive set of results can be found in [12]. Here, we limit ourselves to showing what we see as the most interesting way to present the energy efficiency results, i.e., through the energy efficiency vs. throughput tradeoff. This representation gives a clear understanding of how instantaneous rate of data delivery (in good packets per slots) can be traded off for better usage of the energy source, and may help in assessing the energy savings achievable according to the application’s requirements. Not surprisingly, higher throughput comes at the expense of reduced energy efficiency.

It is clear in fact that by transmitting higher power one would achieve higher throughput but might incur in reduced energy efficiency due to higher energy consumption. This is confirmed by the results presented, where different points on the curves correspond to different values of the fading margin (specifically, moving along the curves towards the right-hand side of the plots corresponds to increasing the fading margin).

Figure 1 compares Tahoe and Reno for $W_{max} = 24$. Using TCP Reno instead of TCP Tahoe in this case may lead to some throughput degradation. The energy efficiency degradation is much more significant, and may be as large as a factor of 10 for 90% throughput and correlated fading. That is, under these conditions, using Tahoe instead of Reno leads to a tenfold improvement in battery life! In Figure 2, TCP NewReno is considered for two different values of $W_{max}$. Again, for the case of correlated fading and for a 90% throughput, using $W_{max} = 24$ instead of $W_{max} = 6$ leads to a threefold improvement in the energy efficiency. These sample results show that using the right version of TCP and/or the appropriate parameters may lead to very significant energy savings.

The conclusions we can draw from these results and from others not shown here (see [12]) are the following: TCP Tahoe performs better than TCP Reno; correlated fading is more benign than iid errors (all figures); a larger advertised maximum window, $W_{max}$, allows to fully exploit the advantages of correlated errors; the advantage of using NewReno instead of Tahoe vanishes as error correlation is increased; the advantage of using smaller $K$ (number

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1. Here we make the somewhat simplistic assumption that all energy goes into transmitted power, so that the energy consumption is directly proportional to the fading margin (this assumption is discussed in more detail in Section 5). Also, we arbitrarily define one energy unit as corresponding to the transmission of a packet with a fading margin of 0 dB.
of duplicate ACKs after which a retransmission is triggered) vanishes as error correlation is increased.

We may conclude that if choosing the "right" TCP version may lead to some incremental performance advantage in terms of throughput, the energy efficiency performance can be dramatically increased by the appropriate choice of the protocol and its parameters.

IV. SUMMARY

In this paper, we presented some results on the energy consumption performance of various versions of TCP for bulk data transfer in an environment where channel errors are correlated. We investigated the performance of a single wireless TCP connection by modeling the correlated packet loss/error process as a first-order Markov chain. The main findings of our study were that 1) error correlations significantly affect the energy performance of TCP (consistent with analogous conclusions for throughput), and in particular they result in considerably better performance for Tahoe and NewReno than iid errors; and 2) the congestion control mechanism implemented by TCP does a good job at saving energy as well, by backing off and idling during error bursts. An interesting conclusion is that, unlike throughput, the energy efficiency metric may be very sensitive to the TCP version used and to the choice of the protocol parameters, so that large gains appear possible.

Topics of ongoing investigation include the study of the effect of using a link-layer FEC/ARQ scheme, and the effect of other physical layer parameters (e.g., packet size) on the overall TCP performance. Other performance metrics besides throughput (e.g., delay) are also being considered.

REFERENCES


Fig. 1. Energy efficiency and throughput performance of TCO Reno and Tahoe a) i.i.d. b) $f_{DT} = 0.01$. $W_{max} = 24$. $K = 3$. $MTO = 100$.

Fig. 2. Energy efficiency and throughput performance of TCO NewReno a) i.i.d. b) $f_{DT} = 0.01$. $W_{max} = 6$ and 24. $K = 3$. $MTO = 100$. 