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Abstract— **The TCP-Friendly Rate Control (TFRC) is used as a streaming media transport protocol. Using the TCP congestion response function and current network conditions, TFRC adjusts its transmission rate to yield the maximum TCP-Friendly throughput when sharing capacity with TCP flows. Since TFRC was designed for wired networks, it does not achieve the maximum TCP-Friendly throughput in multihop ad hoc wireless networks. The reduced wireless spatial channel reuse due to hidden terminals in multihop wireless networks induces TFRC throughput reductions. Specifically, TFRC is unaware of MAC layer transmission delays due to collisions, retransmissions and MAC layer congestion. This paper illustrates that an unmodified TFRC's sending rate overloads the multihop wireless MAC layer, leading to increased round-trip times, higher loss event rates, and lower throughput. We propose an enhancement to TFRC, called RE TFRC, that uses measurements of the current round-trip time and a model of wireless delay to restrict TFRC bitrates from overloading the MAC layer, while retaining desirable TCP-Friendly characteristics. RE TFRC requires minimal changes to TFRC and no changes to the MAC layer and evaluation of RE TFRC show substantial improvements over TFRC for some wireless scenarios.**

Keywords—**TCP-Friendly, TFRC, IEEE 802.11, MAC, Ad Hoc, Multihop, Wireless**

I. Introduction

The Transmission Control Protocol (TCP) is the current de facto transport layer protocol used in wireless ad hoc networks. Designed to operate over wired networks, TCP can perform poorly in 802.11 wireless networks, as demonstrated by recent research [1], [2], [3], [4], [5], [6], [7].

The TCP-Friendly Rate Control (TFRC) protocol [8],[1] which was designed to support rate-based streaming multimedia and telephony applications over wired networks, faces challenges similar to that of TCP in wireless ad hoc networks. However, to date, there has been very little TFRC-related work done for wireless networks.

At the core of TCP/TRFC's wireless challenge is the wireless Media Access Control (MAC) layer of IEEE 802.11. 802.11 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and a Request-to-Send/Clear-to-Send (RTS/CTS) mechanism to reduce hidden terminal collisions. However, when the MAC layer is saturated, contention delays and retransmissions caused by the RTS/CTS mechanism become the major cause of TCP/TFRC performance degradation. These effects are referred to as RTS/CTS jamming [9] or RTS/CTS-induced congestion [10]. Furthermore, since TFRC observes loss events after the MAC contention phase, TFRC is unaware of MAC layer congestion and does not compensate for it. Consequently, TFRC overestimates the maximum sending rate, overloads the MAC layer and exacerbates MAC layer congestion. Eventually, a stable state is reached in which throughput and round-trip times are sub-optimal.

Previous research in TCP performance improvements over wireless ad hoc network include investigating link breakage and routing failure issues [1], [2], [4], link layer solutions [3], [7], MAC layer solutions [5], and TCP protocol modifications [6]. A few recent papers have focused on methodologies to improve TCP throughput by controlling the total number of packets in flight. Fu *et al* [7] present a link layer approach named Link-RED (LRED) that reduces MAC layer collisions by limiting TCP's sending window, while Cali *et al* [5] limit TCP window sizes directly. While these solutions share a common goal with our research, as window-based approaches they are not applicable to TFRC, a rate-based protocol. Moreover, none of these studies consider packet round-trip time and packet loss as metrics in their optimizations.

Our investigation focuses on solving the problem of the mis-interaction between TFRC and the MAC layer. Specifically, the objective is to make TFRC aware of RTS/CTS-induced congestion such that it chooses a near-optimal sending rate that avoids MAC layer saturation. A

[1] The Datagram Congestion Control Protocol (DCCP) has proposed to use TFRC as its congestion control mechanism. See http://www.ietf.cnri.reston.va.us/html.charters/dccp-charter.html.

major contribution of this paper is introducing a new Rate Estimation (RE) algorithm in the TFRC protocol to estimate the saturation capacity of the MAC layer. This involves creating a model for round-trip time during MAC layer saturation and deriving a composite TFRC loss event rate that reflects the current MAC layer congestion level. By limiting the sending rate to a value that is lower than the estimated rate, RE TFRC avoids MAC layer congestion. NS-2 simulation results presented in this report comparing RE TFRC with TFRC indicate a 5% to 40% reduction on round-trip times, a 8% to 80% reduction in the loss event rate, and a 5% improvement in overall throughput. Given that TFRC is intended for multimedia applications, large delay reductions with slight throughput improvements for the RE TFRC implies this scheme can improve performance for streaming flows in wireless networks.

The rest of this paper is organized as follows: Section II provides a brief introduction to TFRC and the hidden terminal problem in ad hoc networks; Section III analyzes TFRC behavior in wireless ad hoc networks and investigates the relationship between performance and a constrained sending rate; Section IV details the RE TFRC algorithm; Section V evaluates our RE TFRC algorithm in several wireless ad hoc network scenarios; Section VI summarizes our conclusions and Section VII presents possible future work.

II. Background

A. TFRC

TCP-Friendly Rate Control (TFRC)[2] [8] is a rate-based protocol designed for unicast flows that co-exist with TCP traffic over the Internet. TFRC uses a throughput equation to estimate the maximum allowable sending rate as a function of the loss event rate and the round-trip time. To compete fairly with TCP for available capacity, TFRC's throughput equation is based on a bitrate response function of TCP. Generally speaking, TFRC's congestion control mechanism works as follows:

- The receiver measures the loss event rate and periodically sends this information back to the sender.
- The timing of these feedback messages is used by the sender to measure the round-trip time.
- The loss event rate and round-trip time are then fed into TFRC's throughput equation, giving the acceptable sending rate.

The throughput equation currently recommended for TFRC is a version of the throughput equation for a conformant TCP Reno flow:

$$X = \frac{s}{r\sqrt{\frac{2bp}{3}} + 3p(t_{rto}(1+32p^2)\sqrt{\frac{3bp}{8}})} \tag{1}$$

where X is the transmission rate in bytes/second, s is the packet size in bytes, r is the round-trip time in seconds, p is the loss event rate (0.0 to 1.0) which is the number of loss events as a fraction of the number of packets transmitted, t_{rto} is the TCP retransmission timeout value in seconds, and b is the number of packets acknowledged by a single TCP acknowledgment.

B. Hidden Terminals

Figure 1 illustrates the hidden terminal problem in IEEE 802.11 wireless Local Area Networks. Node 1 and node 3 are within the transmission (or power) range of node 2, but are out of range of each other. Hence, while they can both receive transmissions from node 2, they cannot receive each other's transmissions. If node 1 and node 3 simultaneously start transmission to node 2, their transmissions collide.

To mitigate the hidden terminal effect, 802.11 [11] mandates an RTS-CTS pre-exchange before any data packets can be sent. In the above scenario, if node 1 senses an idle channel and sends an RTS to node 2, its intended destination node, all nodes within its range hear its transmission and backoff. When node 2 responds with a CTS message, all nodes within its range, including node 3, become aware of the imminent data transmission and also back off, thus solving the hidden terminal problem. RTS and CTS frames also contain duration information, called a Net Allocation Vector (NAV), on how long the data exchange will take. This allows other nodes that hear either the RTS or CTS frames to determine how long the channel will be busy, and hence back off accordingly.

An RTS sender may receive no CTS because its RTS packet collided with another transmission at the receiver or because the receiver's NAV indicated that the network is not available. The sender of the RTS packet eventually times out and does an exponential backoff before resending the RTS, up to a limit of seven times, as prescribed by the 802.11 standard.

Since RTS and CTS packets are small in comparison to data packets, the wasted bandwidth incurred when RTS and CTS packets collide is minimal. However, RTS collisions increase network load which ultimately results in larger contention delays due to repeated exponential backoffs and RTS contention drops when the number of retransmissions exceeds the specified threshold of seven.

[2]Online at: http://www.icir.org/tfrc/

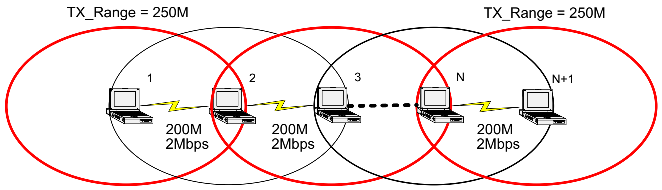

Fig. 1. Simulation Topology

III. TFRC Performance Analysis

While the RTS/CTS collision avoidance mechanism reduces hidden terminal collisions in the 802.11 MAC layer, repeated MAC layer backoffs may cause transport layer timeouts, leading to sub-optimal transport layer performance in wireless environments. Fu *et al* [7] demonstrates the impact of hidden terminals on the transport layer protocol.

In TCP-Friendly transport protocols, the sender responds to network congestion by adjusting its transmission rate or window size, based on packet loss information gathered from the network and peers. In 802.11 wireless networks, packet loss rates and the round-trip time (RTT) observed at the sender include the effects of the RTS/CTS mechanism, MAC layer backoffs and retransmissions, as well as network layer congestion, and hence cannot be used unmodified as congestion hints. Our goal was to characterize the effects of the 802.11 MAC layer on TFRC, and hence adapt the TFRC sending rate over 802.11 wireless LANs.

The first phase of this research simulates (via NS-2 [12]) TFRC over an 802.11 wireless network and analyzes the effects of the RTS/CTS mechanism on round-trip time and loss. The second phase uses TFRC with a constrained sending rate to explore the relationship between the TFRC throughput, round-trip time and loss event rate in multihop 802.11 ad hoc networks.

A. *Characterization of TFRC over 802.11 Ad Hoc Network*

To simplify the analysis in this section, we use a chain topology in our simulation as shown in Figure 1. By setting inter-node distance to the allowed maximum of 200 meters, interference between nodes is minimized as discussed in Section II. In order to minimize the effect of the routing protocol and simplify the analysis, all nodes are assumed to be static in our simulation and the default NS-2 parameter settings for 802.11 are used. The key parameters are summarized in table I. Although the NS error model is enabled, we did not apply any bit errors except in simulating the effects of bit errors.

Capacity research in [13] establishes that the maximum throughput for an ad hoc network is approximately $1/5 - 1/7$ of link capacity. As shown in Figure 2, the maximum throughput that TFRC can achieve over a multihop wireless network is much lower than the line capacity. Beyond 7 hops, the throughput of TFRC is about 0.25 Mbps (about 1/8 of the link capacity of 2Mbit/s), which is slightly lower than the expected range. This may be attributed to over saturation in the MAC layer, since the throughput of the 802.11 MAC protocol decreases when the offered load exceeds the saturation threshold [14]. This phenomenon is also known as MAC layer RTS/CTS congestion [10].

Figure 3 shows that in networks with a few hops, the offered load is significantly higher than the throughput, which implies that some transmitted packets are dropped. These losses are due to MAC layer congestion and not transport layer congestion. While TFRC detects and reacts to transport layer losses, it is unaware of MAC layer congestion, and hence does not reduce its sending rate accordingly. As the number of hops increases, the difference

TABLE I
SIMULATION SETUP

Parameters	Setting
Physical interface	Default DSSS
Link capacity	2 Mbits/s
Propagation	TwoRayGround
Transmit range	250 Meters
Error model	Uniform
MAC protocol	802_11
Routing portocol	AODV
Tranport portocol	Default TFRC
Packet Size	1460 bytes
NS-2 version	2.1b8[old]/2.24[new]

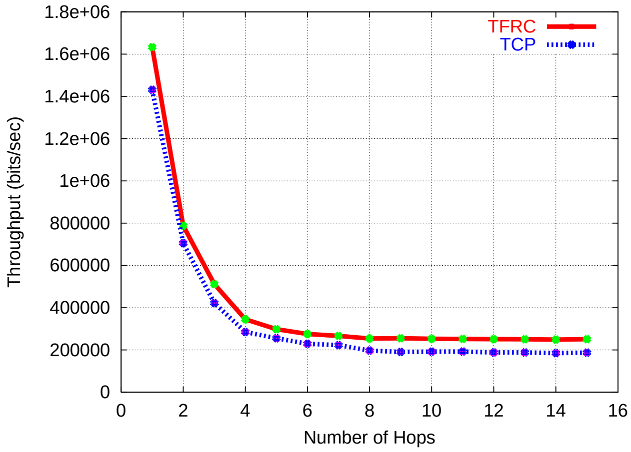

Fig. 2. TFRC throughput over ad hoc network

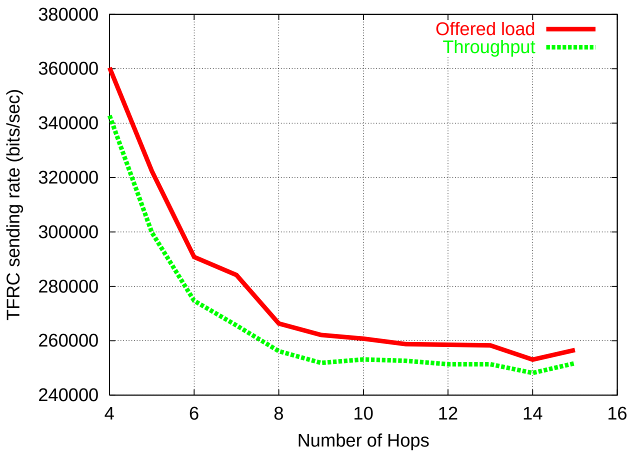

Fig. 3. TFRC offered load and throughput

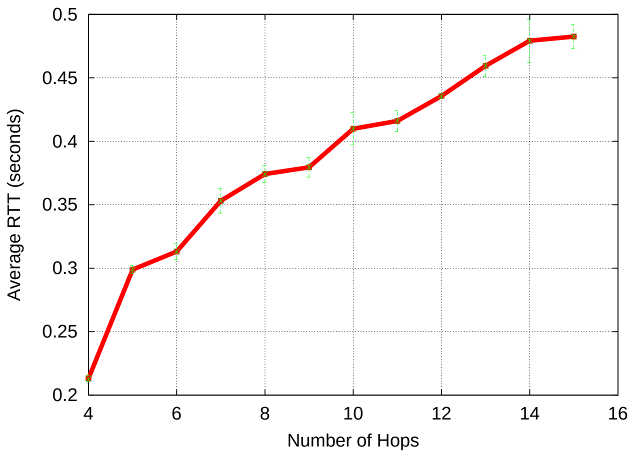

Fig. 5. TFRC round-trip time over ad hoc network

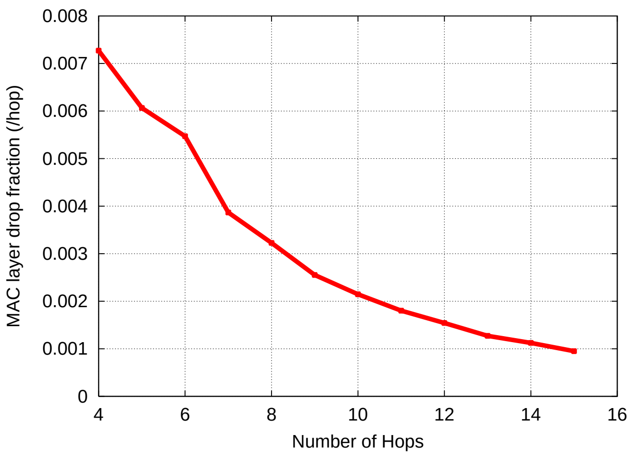

Fig. 4. MAC layer drop fraction over ad hoc network

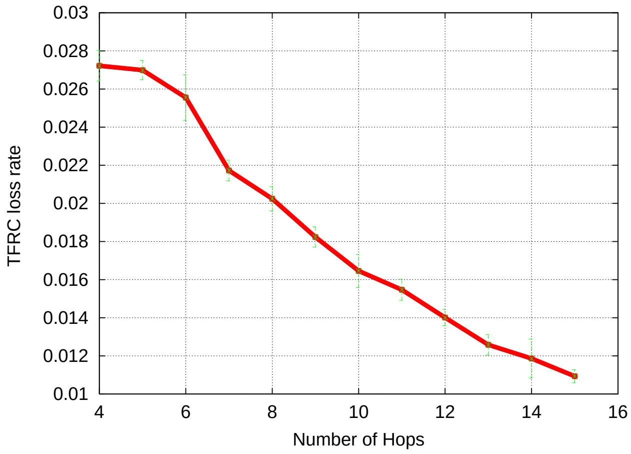

Fig. 6. TFRC loss event rate over ad hoc network

between offered load and throughput reduces and TFRC sends closer to the optimal or saturated rate.

In order to understand the 802.11 MAC layer behavior, we measured MAC layer RTS packet drops for different numbers of hops. The 802.11 standard specifies a maximum number of permitted RTS packet retransmissions, which was set to 7 in NS-2. We counted the number of RTS packets which were dropped after 7 unsuccessful retransmission attempts, normalizing it on a per-hop and per-packet basis. Figure 4 illustrates that the ratio of MAC layer drops decreases as the number of hops increases. RTS collisions also cause an increase in MAC contention time and TFRC round-trip time (RTT), as offered load is increased. Figure 5 shows the increase in TFRC RTT as the number of hops is increased.

Finally, we observed the loss event rate reported by the TFRC receiver. The loss event rate reported by TFRC is lower than the data link layer loss rate since MAC layer retransmissions hide some packet losses from the TFRC protocol. Therefore, even when the MAC layer is congested, the upper layer is unable to detect and respond to it. The loss event rates estimates in the TFRC receiver are shown in Figure 6.

B. *Rate Constrained Simulation*

As discussed in the previous section, the unmodified TFRC protocol will reach a stable status with a higher sending rate than the MAC layer saturation throughput, resulting in a higher RTT, higher loss event ratio and lower throughput at the transport layer. To clarify the behavior of TFRC overloading of the 802.11 MAC layer in a multihop environment, we constrained the TFRC sending rate in NS-2. The following results are for a 7-hop 802.11 network.

Figure 7 depicts the TFRC offered load and throughput under constrained sending rates. As the constrained rate increases, the offered load and throughput increase linearly until a divergence occurs at approximately 300 Kbps. Subsequent increase in the constrained TFRC rate leads to decrease in throughput as offered load increases.

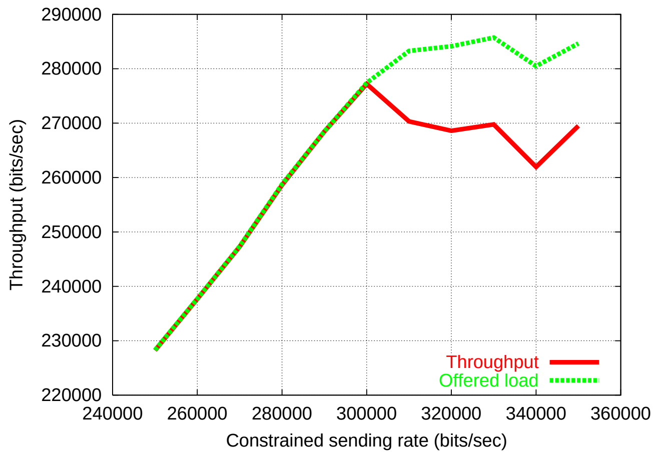

Fig. 7. Offered load and Throughput versus the constrained rate

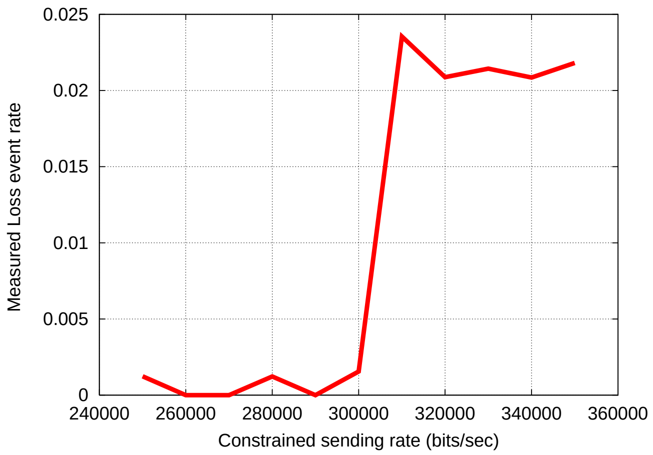

Fig. 9. TFRC loss event rate versus the constrained rate

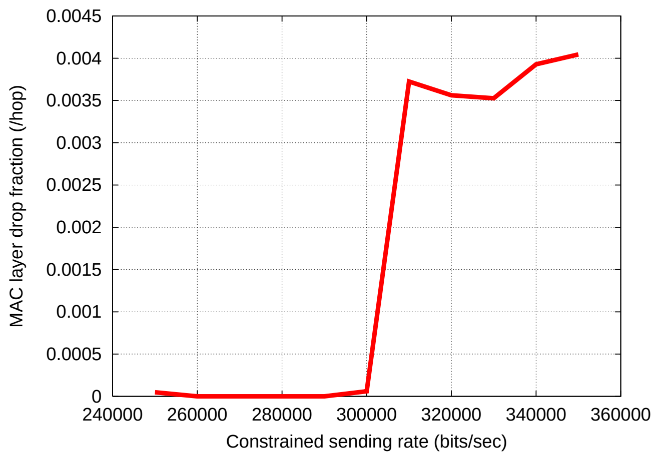

Fig. 8. MAC layer drop fraction versus the constrained rate

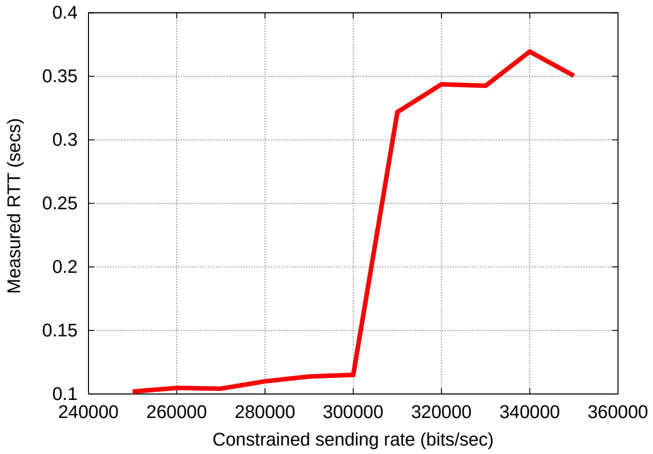

Fig. 10. Round-trip time versus the constrained rate

Beyond the turning point of 300 Kbps, the difference between the offered load and throughput is due to lost packets. Figure 8 shows a sharp increase in MAC layer losses starting at about 300 Kbps, as the constrained sending rate increases. Other related experiments showed that the TFRC RTT and loss event ratio also increased sharply at about 300 Kbps. Figure 9 and 10 show the dramatic increase just after the turning point of 300 Kbps.

The average sending rate, which TFRC used to control the interval between transmitted packets, was retrieved from the TFRC debug information in NS-2. The TFRC protocol computed a TCP friendly rate using the current RTT and loss event rate. In our rate-constrained mode, TFRC uses the minimum of the constrained rate and the computed TCP friendly rate to control the sending rate. However, the retrieved average sending rate is slightly different from the offered load, which is measured from the trace output of the simulation.

Figure 11 depicts the relationship between the average sending rate, constrained sending rate and TCP friendly rate. Above 300 Kbps, TFRC uses the TCP-Friendly rate to control the sending rate. This implies that TFRC does not keep the sending rate below the MAC saturation point on wireless LANs. Namely, TFRC will select a sub-optimal transmission rate on wireless LANs when the MAC layer is saturated.

Thus, in Section IV, we present a new algorithm to constrain the TFRC sending rate and avoid saturating the MAC layer on 802.11 wireless network to archive a lower RTT, lower loss rate and higher throughput.

C. Bit Error Rate

Another major concern in wireless networks is the Bit Error Rate (BER). In a wireless network, the BER is higher than typical values for a wired network, causing more performance degradation than in a wired network. Figure 12 shows that with rate constraints, even in a higher bit error rate, the throughput is better than with regular TFRC. However, when the BER is higher than 5×10^{-4}, both the regular TFRC and rate constrained TFRC get a very low

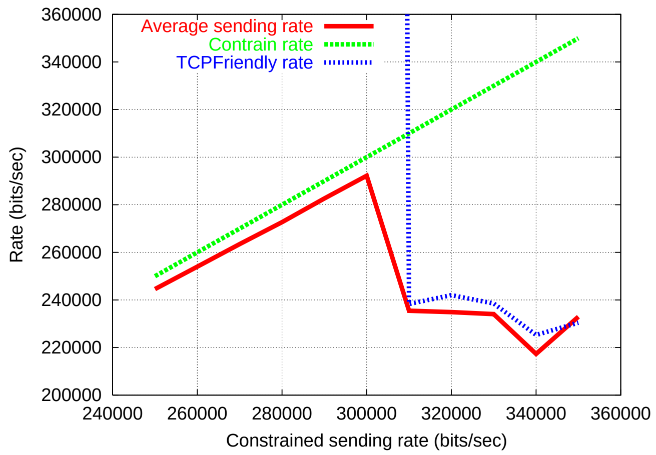

Fig. 11. TCP-friendly rate and constrained sending rate

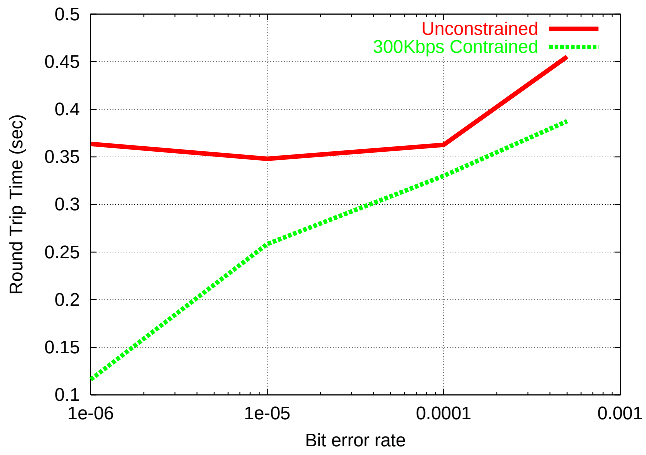

Fig. 13. RTT of different bit error rate

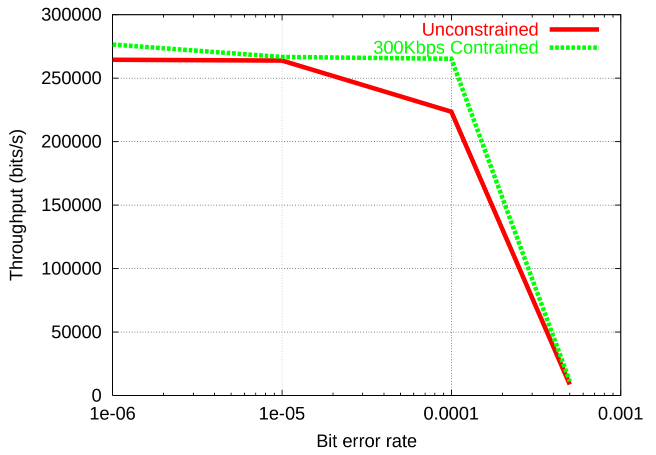

Fig. 12. Throughput of different bit error rate

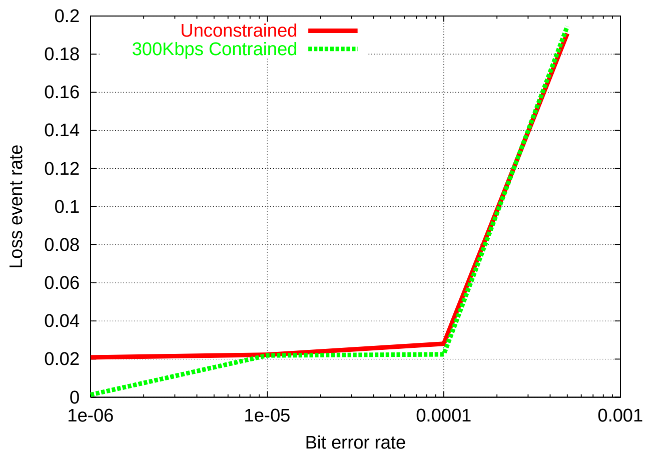

Fig. 14. Loss event rate of different bit error rate

throughput since they respond to the data link bit errors as congestion.

Figure 13 and 14 depict the RTT and loss event rates of regular and rate constrained TFRC. The rate constrained TFRC achieves a lower RTT and loss event rate in both cases.

IV. Enhancing TFRC Performance

A. Rate Estimation

From the results in Section III, when unconstrained, TFRC produces an offered load that is above the rate sustainable by the multi-hop 802.11 MAC layer. The MAC layer then suffers from multiple frame retransmissions which increases the round-trip time. Although TFRC eventually receives some packet loss notification because of the frame retransmissions, these packet losses arrive too late for TFRC to curtail its offered load below the saturation point of the MAC layer. In order to adjust its sending rate to below the MAC layer saturation point, TFRC needs to determine the loss event rate (p) that corresponds to the MAC layer congestion.

We propose to enhance the performance of TFRC based on aspects of TCP Westwood [15], a TCP variant designed to perform well over wireless links. TCP Westwood uses a bitrate estimation algorithm based on the minimum observed round-trip time and acknowledgment rate to compute a window threshold for TCP. Whenever there is congestion, the TCP congestion window is set equal to the window capable of producing the bitrate estimate (B) assuming no queuing delay (i.e. $window = B \times r_{min}$). We propose a similar algorithm to estimate the MAC layer saturation bitrate. However, instead using r_{min}, we use what we call r_{opt}, which represents the minimum round-trip time during MAC layer saturation. We use r_{opt} instead of r_{min} because when the maximum sustainable throughput in the MAC layer is achieved, there is a small queue at individual nodes of a multihop flow. TFRC has a built-in function for estimating the receiving rate, R, which we use as a basis for our modifications.

As described in Section II, TFRC's sending rate is not

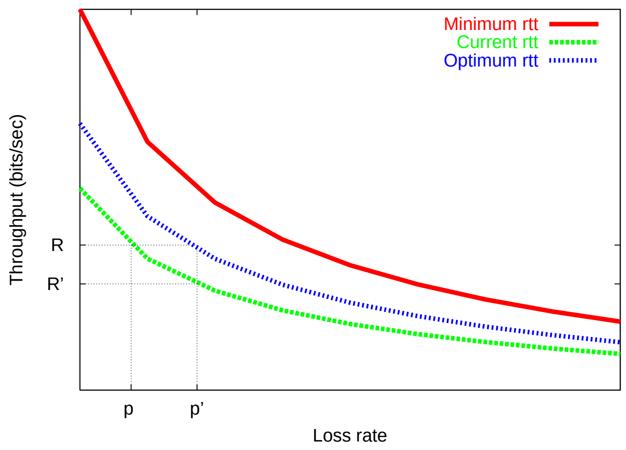

Fig. 15. Throughput versus loss event rate (p) for different round-trip times

constrained by a window size but rather by the computed TCP-Friendly rate directly. TFRC uses an equation based on TCP throughput to compute an estimated TCP-Friendly sending rate, which is a function of the round-trip time (r), loss event rate (p), packet size and time out value (rto). Assuming a fixed packet size (typically around the network MTU) and the default value of $rto = 4 \times r$, we simplify the TCP-Friendly bitrate equation in Equation 1 and derive a function for p:

$$X = f(r, p) \tag{2}$$

$$p = \overline{f}(r, X) \tag{3}$$

Therefore, we can estimate the equivalent TFRC loss event rate (p') using the inverse function $\overline{f}(r, X)$, and then use p' and the current round-trip time measured by TFRC (r_{cur}) to estimate the optimum sending rate (R') that will just saturate the MAC layer:

$$\begin{aligned} p' &= \overline{f}(r_{opt}, R) \\ R' &= f(r_{cur}, p') \end{aligned}$$

Figure 15 depicts the relationship between TCP-Friendly bitrate and loss event rate, where each curve is the TCP-Friendly bitrate for a particular round-trip time.

B. Round-Trip Time Modeling

In order to realize the benefits of our proposed TFRC enhancements, we must compute r_{opt}, the minimum round-trip time during MAC layer saturation. Previous research on delay modeling of 802.11 networks [16] shows that the average delay (the service time) of a single hop ad hoc network at saturation can be modeled by:

TABLE II
PHYSICAL LAYER PARAMETERS

	DSSS	FHSS
W_{min}	32	16
W_{max}	1024	1024
MAC header	34 bytes	34 bytes
Phy header	24 bytes	16 bytes
ACK	38 bytes	30 bytes
CTS	38 bytes	30 bytes
RTS	44 bytes	36 bytes
Slot time	20 μsec	50 μsec
SIFS	10 μsec	28 μsec
DIFS	50 μsec	128 μsec

$$\overline{T} = \overline{T}_B + t_s \tag{4}$$

where t_s is the time required to to successfully transmit a packet and $\overline{T}_B$ is the average MAC layer back-off time:

$$\overline{T}_B = \frac{\alpha(W_{min} - 1)}{2q} + \frac{(1-q)}{q} t_c \tag{5}$$

Here, α is the average back-off step size, W_{min} is the initial contention window size, q is the probability of successful transmission, and t_c is the time wasted during a single collision. W_{min} is a physical layer parameter (with a default of 32 for Direct-Sequence Spread Spectrum (DSSS)), while [16] assumes α and q are computable as functions of the number of nodes (n) in the network. t_s and t_c are constants for fixed size packets and can be computed using:

$$\begin{aligned} t_s = rts + sifs + \delta + cts + sifs + \delta + \\ H + E\{P\} + sifs + \delta + ack + difs + \delta \end{aligned} \tag{6}$$

and

$$t_c = rts + difs + \delta \tag{7}$$

Here, rts, cts, ack, $sifs$ and $difs$ are listed in Table II, δ is the propagation delay, H being the packet header (physical layer plus MAC layer), and $E\{P\} = P$ for a fixed packet size.

Therefore, given the physical network type and the number of nodes in the network, we can use Equation 6 as a model for estimating the average service time to obtain the delay under saturation conditions.

To extend this this model in multi-hop wireless networks, we first assume that under saturation conditions, the traffic at each hop is independent, which allows a multi-hop ad hoc network to be divided conceptually into

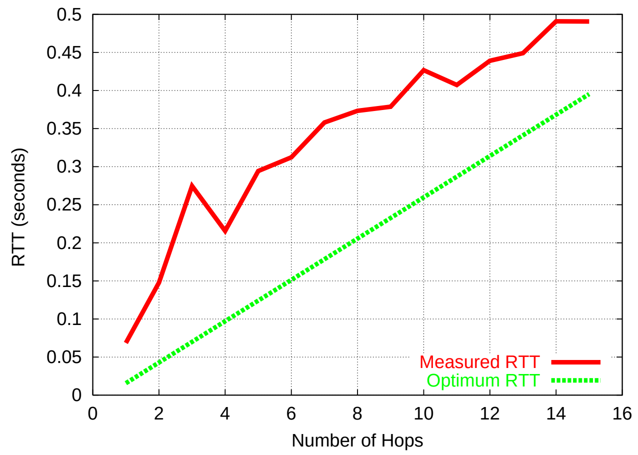

Fig. 16. Estimating the optimum round-trip time

multiple independent, single-hop networks. By using the model on each of the single hops, we get a cumulative delay for the multi-hop network. We next assume using RTS/CTS solves the hidden terminal problem so in applying the single-hop analysis we do not need to consider the interference from other nodes outside the transmission range. We can then divide an N-hop chain network into $N-2$ single-hop networks with four nodes and 2 single-hop networks with three nodes at the source and destination. The round-trip time at the transport layer (such as in TFRC) is estimated by measuring the time elapsed between sending a data packet and receiving the acknowledgment. Therefore, we can compute the round-trip time as:

$$\begin{aligned} \overline{r}(N) &= \Sigma_{i=0}^{N} T_{data_i} + \Sigma_{i=0}^{N} T_{ack_i} \\ &\approx 2 \times \overline{T}_{data}(3) + (N-2)\overline{T}_{data}(4) \\ &\quad +2 \times \overline{T}_{ack}(3) + (N-2)\overline{T}_{ack}(4) \end{aligned} \quad (8)$$

Based on the model, the round-trip time ($r(N)$) from Equation 8 assumes saturation of the MAC layer and can therefore be used for r_{opt} for an N hop ad hoc wireless network.

Figure 16 depicts the round-trip time estimate from our model and the round-trip time obtained by TFRC during simulation. TFRC provides an offered load past the MAC saturation level which causes the round-trip time to increase beyond r_{opt}.

C. Algorithm Summary and Implementation

By combining the loss event rate estimation algorithm from TFRC and our extended round-trip time model, we provide a complete rate estimation algorithm for TFRC, shown in Figure 17.

on receiving ack
1. if (not $slowstart$)
2. // compute original TCP-Friendly rate
   $X = f(r_{cur}, ack.p)$
3. // choose modeled RTT or smallest measured RTT
   $r_{opt} = max(r(N), min([Sliding\ Window]))$
4. // compute new loss event rate given RTT
   $p' = \overline{f}(r_{opt}, R)$
5. // compute new TCP-Friendly
   $R' = f(r_{cur}, p')$
6. // use original rate if new rate is larger
   $R' = min(X, R')$
7. // if there is a rate change, do so incrementally
   $if\ (rate_{cur} > R')$
   $decrease\_rate()$
   $else$
   $increase\_rate(p')$
8. $end\,if$

Fig. 17. The rate estimation algorithm for TFRC (RE TFRC)

In implementing the RE TFRC algorithm in Figure 17, we added a few enhancements to make it more stable and adaptive. First, at line 2 and 6 of the algorithm, we keep the TCP-Friendly sending rate computation that is fundamental to TFRC in order to ensure appropriate response to transport layer congestion. Second, as we mentioned in Section III, as the number of hops or flows increases, the round-trip time curve of r_{cur} shifts up over the r_{opt} curve in Figure 15. In this case, the r_{opt} curve will no longer represent the saturation status, so we instead use the alternate r_{min} in place of r_{opt}. Therefore, in line 3, we find the minimum round-trip time in a sliding window and use the larger of the computed rount-trip time ($r(N)$) or the window value to estimate the p' for these particular cases.

V. Performance Evaluation

The goals of Rate Estimation TFRC (RE TFRC) are to reduce MAC layer congestion, reduce TFRC loss event rate and average round-trip time, and improve throughput, all without changing the MAC layer protocol. This section evaluates RE TFRC using NS-2 simulations with the same wireless chain topology used in Section III. The first step is a detailed analysis of RE TFRC performance in a seven hop simulation. Second are simulation experiments that vary the the number of hops from 4 to 15. Next are simulations that with offered load from an aggregate of multiple flows. The section concludes with a study of the behavior of the RE TFRC in typical Bit Error Rate (BER) network environment.

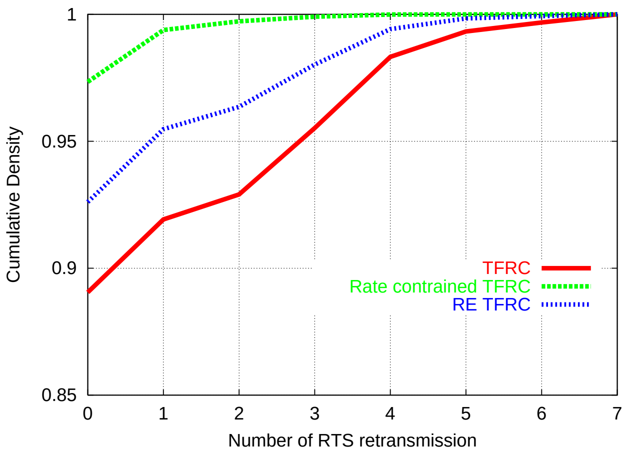

Fig. 18. Distribution of RTS retransmissions

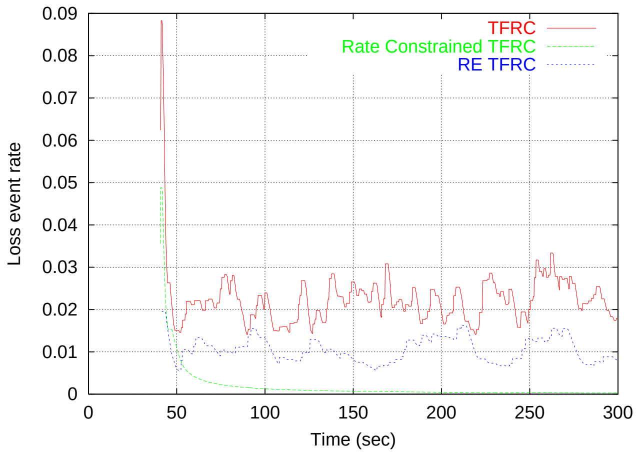

Fig. 19. Comparison of Loss event rate

A. *Performance Improvement*

Using a seven hop chain topology, three distinct simulations were run to compare the performance of a standard TFRC implementation, Rate Estimated TFRC (RE TFRC), and a Rate Constrained strategy. From the previous chained seven-hop, wireless network results, the throughput of a single flow is optimized when the throughput rate is constrained at 300 Kbps. Thus, the Rate Constrained simulation provides the best basis for comparison.

Since the RTS backoff mechanism drops an RTS frame after seven consecutive collisions occur, this event represents a packet loss as seen by TFRC. Thus Figure 18 presents the Cumulative Density Function (CDF) for RTS retransmissions for the three simulations. The x-axis is the number of RTS contention backoffs from value 0 to 7 where 0 implies no collision and 7 means TFRC will see this as a packet loss. Figure 18 shows that TFRC has a 89% chance of not having to retransmit an RTS while for the rate constrained TFRC, this probability is more than 97%. At 93retransmit than TFRC and will experience less backoff delay. Since the backoff algorithm causes exponential growth in backoff delay with an increased number of retransmissions, a small difference in the CDF curves represents a significant change in the contention delay.

Figure 19, 20 and 21 compare the loss event rate, RTT and sending rate of the three algorithms. RE has a smoother sending rate, a lower loss event rate and lower RTTs than TFRC. However, as we can see from the figures, there is still room between the RE algorithm and the theoretic optimum for further improvement.

B. *Multihop Performance Evaluation*

We next evaluate RE TFRC by varying the number of wireless hops from 4 to 15. Figure 22 shows the improvement of MAC layer loss rate for RE TFRC. The MAC layer

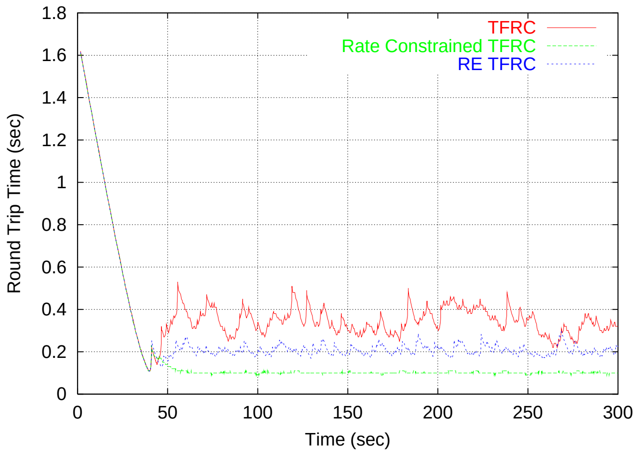

Fig. 20. Comparison of round-trip time

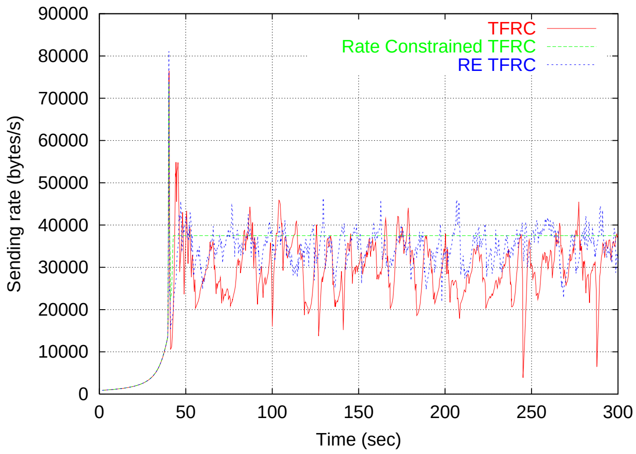

Fig. 21. Comparison of sending rate

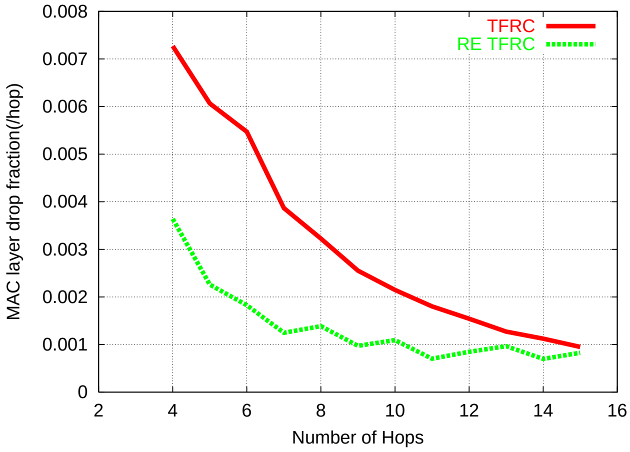

Fig. 22. MAC layer drops fraction versus number of hops

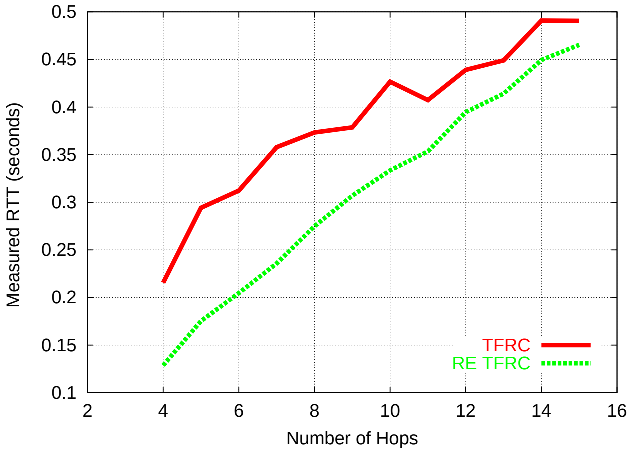

Fig. 23. Average round-trip time versus number of hops

drop ratio is reduced by between 13% to 66% compared to TFRC.

Figure 23 demonstrates that the round-trip time of RE TFRC is 5% to 40% lower than that of TFRC, and Figure 24 shows that the RE TFRC loss event rate is 8% to 55% less than that of TFRC.

Figure 25 compares the throughput of TFRC and RE TFRC. RE TFRC shows upto 5% throughput improvement over TFRC when the number of hops is from 5 to 15.

C. Multi-Flow Performance Evaluation

This section considers the situation when more than a single flow is providing the offered load. Figure 26 shows that using RE TFRC can reduce the MAC layer drop rate by 71% over regular TFRC.

Figure 27 and 28 indicates that in a three flow scenario, the average RTT for RE is up to to 41% lower than TFRC, while the loss event rate is reduced by up to 80% over TFRC in multi-flow cases. Figure 29 shows that RE has little effect on throughput in the four simulations shown.

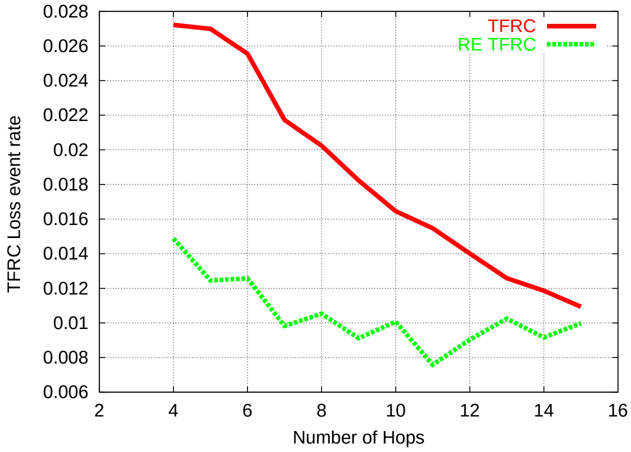

Fig. 24. Average loss event rate versus number of hops

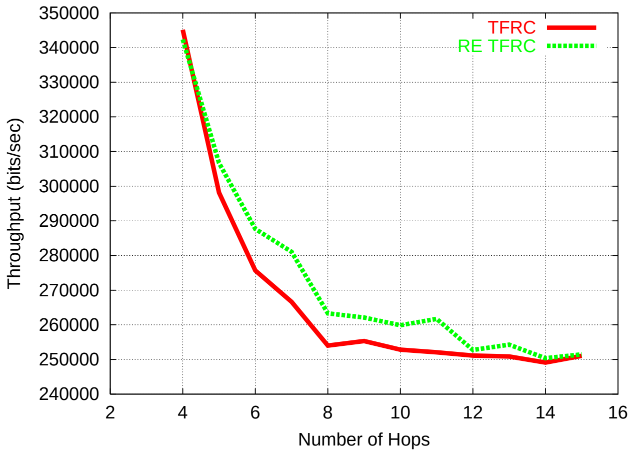

Fig. 25. Average throughput versus number of hops

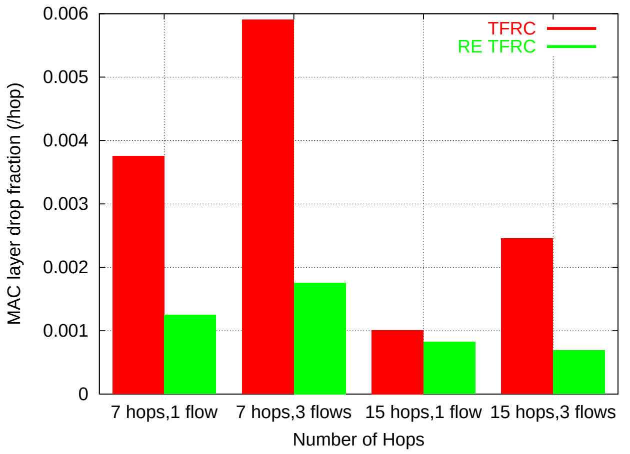

Fig. 26. MAC drop fraction for various flow scenarios

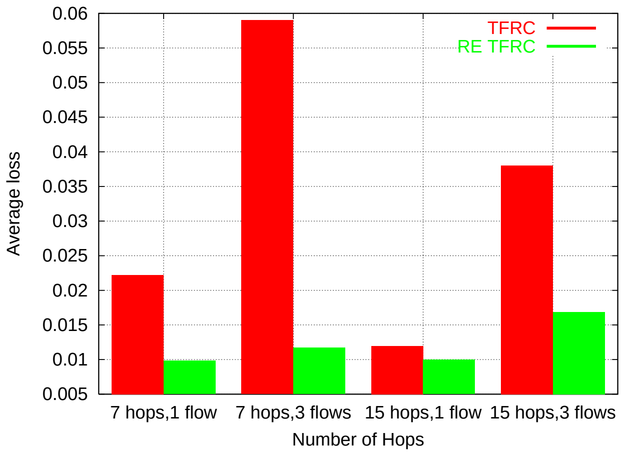

Fig. 27. Loss event rate for various flow scenarios

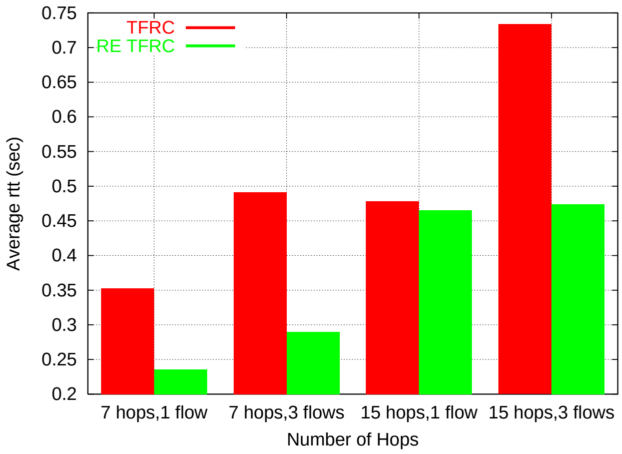

Fig. 28. Round-trip times for various flow scenarios

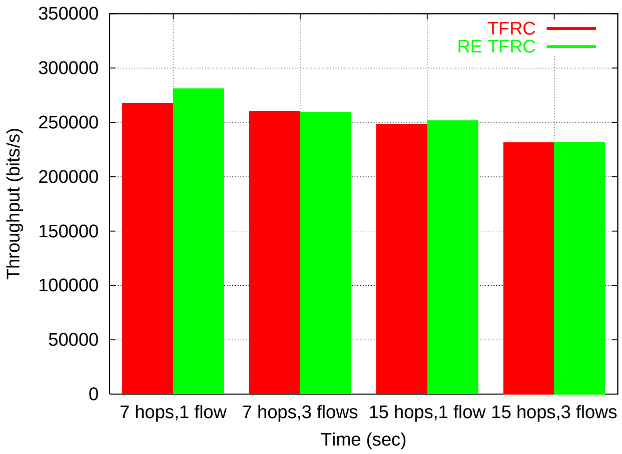

Fig. 29. Throughput for various flow scenarios

TABLE III
RE TFRC IMPROVEMENT FOR VARIOUS BER

BER	10^{-6}	10^{-5}	10^{-4}
RTT Reduction	39%	32%	14%
Loss Rate Reduction	55%	45%	29%
Throughput Improvement	6.5%	4.2%	0.5%

D. Bit Error Rate

The Bit Error Rate (BER) in wireless networks is usually higher than in wired networks. Typical BER range is from 10^{-6} to 10^{-4}, which is what we use to evaluate RE TFRC. A 7-hop wireless network topology with single flow simulation is used to demonstrate the effects of various BER on RE TFRC performance. As described in Table III, RE TFRC performs considerably better over most of metrics over a wide range of BER.

VI. CONCLUSIONS

The RTS/CTS mechanism in IEEE 802.11 was designed to mitigate the hidden terminal problem in wireless networks. It can reduce packet loss due to collisions in the MAC layer and works well for infrastructure wireless networks. However, in wireless ad hoc networks, the side effects of RTS/CTS mechanism include congestion and jamming in the MAC layer, which are hidden from higher layer protocols, such as TFRC. Consequently, rate-based transport protocols which do not account for MAC layer delays, such as TFRC, will overestimate optimal sending rates. This, in turn, will further congest the MAC layer, leading to an increase in packet loss and round-trip time and ultimately a decrease in throughput.

By characterizing TFRC over a multihop chain topology wireless ad hoc network, we found that by constraining sending rates to values which do not trigger MAC layer saturation rate, TFRC performance is greatly improved, lowering the loss event rate and average round-trip time and increasing throughput. Based on our findings, we proposed a Rate Estimation enhancement for TFRC which models the effects of MAC layer saturation, and controls TFRC such that the MAC layer is not overloaded.

RE TFRC estimates a sending rate using an optimal round-trip time based on the network topology and equivalent loss event rate. The optimal round-trip time was estimated by modeling multi-hop contention delay and service time, while the equivalent loss event rate was estimated using the inverse TCP Friendly rate equation with the optimal round-trip time. The basic idea is infer the lower-layer MAC layer jamming in the upper layer TFRC to make it aware of lower layer congestion and reduce the jamming effects.

RE TRFC is estimated by simulating multiple hops and flows and confirmed that the RE algorithm significantly enhanced TFRC performance, with about a 50% improvement in some metrics, in many network scenarios.

VII. Future Work

Our ongoing RE TFRC research is currently focused on refining the sending rate, loss event rate and round-trip time estimation algorithm. The goal is a more robust RE algorithm that will adapt and remain stable even when the wireless nodes become mobile and the topologies are more complex. Other potential RE enhancements include incorporating particular characteristics of TFRC applications, such as streaming multimedia, in further optimizing performance. Ultimately, the objective is to implement TFRC with wireless extensions on an operational ad hoc wireless network testbed and empirically evaluate its performance.

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