Performance Enhancement of TFRC in Wireless Ad Hoc Networks

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Abstract—**The TCP-Friendly Rate Control (TFRC) is a rate-based transport protocol designed for streaming multimedia applications to provide smooth, low delay and TCP-Friendly packet transmission. However, as TFRC was designed for wired networks, it does not perform well in multihop ad hoc wireless networks. Specifically, MAC layer contention effects, such as retransmission and exponential backoff mislead TFRC's congestion control mechanism, resulting in an inaccurate sending rate adjustment. 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 the desirable TCP-Friendly characteristics. RE TFRC requires minimal changes to TFRC and no changes to the MAC layer and evaluation of RE TFRC shows substantial improvements over TFRC for some wireless scenarios.**

Keywords—**Wireless, Multimedia, IEEE 802.11, TFRC, Ad Hoc**

I. Introduction

The Transmission Control Protocol (TCP) is the de facto transport layer protocol used in wireless ad hoc networks. Recent research [1], [2], [3], [4], [5], [6], [7] has shown that TCP can perform poorly in 802.11 wireless networks because many of the TCP mechanisms assume a wired network infrastructure.

Designed to support rate-based streaming multimedia and telephony applications over wired networks, the TCP-Friendly Rate Control (TFRC) protocol [8],[1] faces challenges similar to that of TCP on wireless ad hoc networks. However, to the best of our knowledge, there has been very little TFRC-related performance research 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 the Request-to-Send/Clear-to-Send (RTS/CTS) mechanism to reduce hidden terminal collisions. However, as the 802.11 MAC layer approaches saturation, contention delays and retransmissions caused by the RTS/CTS mechanism become the major cause of TCP/TFRC performance degradation. This behavior is referred to as RTS/CTS jamming [9] or RTS/CTS-induced congestion [10]. Moreover, 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, the wireless network reaches a sub-optimal stable state with respect to throughput and round-trip time.

Previous research in TCP performance improvements over wireless ad hoc network includes 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 that reduces MAC layer collisions by limiting TCP's sending window, while Cali *et al* [5] limit TCP window sizes directly. While these previous efforts share a common goal with this research, as window-based approaches they are not applicable to the rate-based TFRC protocol. Furthermore, none of these studies attempt to minimize round-trip times which are of critical concern for interactive multimedia applications.

This investigation focuses on the problem of the mis-interaction between TFRC and the 802.11 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 major contribution of this paper is the introduction of a new Rate Estimation (RE) algorithm in TFRC 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 43% reduction in round-trip times, a 8% to 75% reduction in the loss event rate, and up to 7% improvement in overall throughput. Given that TFRC is intended for multimedia applications, large delay reductions with slight throughput improvements with 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 analyzes TFRC behavior in wireless ad hoc networks and investigates the relationship between performance and a constrained sending rate; Section III details the RE TFRC algorithm; Section IV evaluates the RE TFRC algorithm in several wireless ad hoc network scenarios; Section V summarizes our conclusions and presents possible future work.

II. TFRC Performance Analysis

While the RTS/CTS collision avoidance mechanism reduces hidden terminal collisions in the 802.11 MAC layer, repeated

[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.

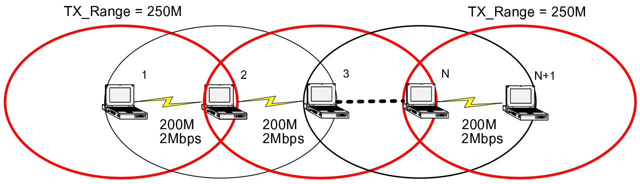

Fig. 1. Simulation topology

MAC layer backoffs and retransmissions can lead 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 and round-trip time information gathered from the network. However, since these metrics also include the effects of the RTS/CTS mechanism, MAC layer backoffs and retransmissions when operating on a wireless network, they cannot be used effectively as congestion indicators.

This section shows simulations (via NS-2 [11]) of the TFRC protocol 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. The goal is a meaningful characterization of the effects of 802.11 on TFRC and to gain insight into adapting TFRC's sending rate when transmitting streaming flows over wireless LANs.

A. Simulation Environment

To simplify the analysis of TFRC performance, the chain topology shown in Figure 1 with the default NS-2 802.11 parameter settings is used in a series of simulations. For the simulation results presented, all nodes are immobile, the distance between nodes is set to 200 meters, the transmission range is 250 meters, and the wireless channel capacity is 2 Mbps (the NS-2 default setting).

The throughput equation used for TFRC [8] is a version of the throughput equation for a conformant TCP Reno flow:

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

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 which is the number of loss events as a fraction of the number of packets transmitted ($0 \leq p \leq 1$), t_{rto} is the TCP retransmission timeout value in seconds, and b is the number of packets acknowledged by a single TCP acknowledgment.

Research in [12] establishes the maximum throughput for an ad hoc network to be approximately $\frac{1}{5}$ to $\frac{1}{7}$ of the link capacity. Our simulations show the maximum achievable throughput for TFRC over a multihop wireless network to be significantly lower than the line capacity. Since Bianchi [13] showed that 802.11 MAC layer throughput decreases when offered load exceeds the saturation threshold, this lower-than-expected throughput can be attributed to the RTS/CTS congestion [10] that occurs when the MAC layer becomes saturated.

As expected, all transport layer packet loss in our simulations are caused by MAC layer contention and frame drops when no transport layer congestion is induced. While TFRC is supposed to react to transport layer losses, it is not tuned to respond to MAC layer congestion, and hence does not reduce its sending rate appropriately. The MAC layer congestion also causes an increase in MAC contention time and end-to-end round-trip time. The details of this performance are not given here due to lack of space, but the complete analysis can be found in [14].

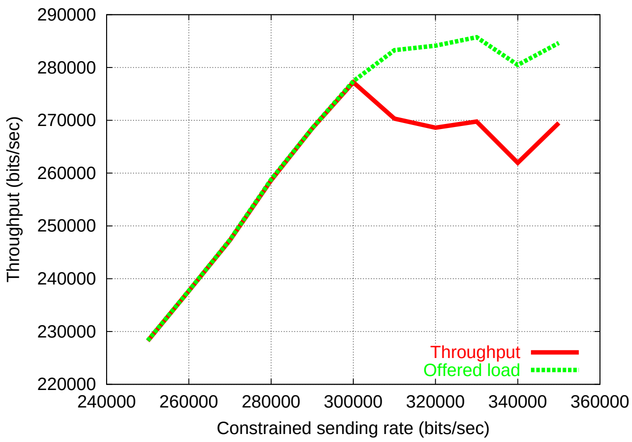

Fig. 2. Offered load and throughput versus the constrained sending rate

B. Rate Constrained Simulations

To clarify the behavior of TFRC in overloading the 802.11 MAC layer in a multihop environment, we modified NS-2 to provide a version of TFRC that had a *manually constrained* sending rate. Figure 2 shows the TFRC offered load and throughput as the constrained sending rate is varied for a seven hop network. As the constrained rate increases, offered load and throughput increase linearly until a divergence occurs at approximately 300 Kbps. Beyond this point, increasing the constrained TFRC rate yields reduced throughput. The observed gap between offered load and throughput at high TFRC rates is due to lost packets.

Figure 3 shows a sharp increase in MAC layer losses starting at about 300 Kbps, as the constrained sending rate increases. Graphs of TFRC's round-trip time and loss event rate (available in [14]) also show a sharp increase at about 300 Kbps. Additional simulations run with typical wireless bit error rates still show constraining the rate of TFRC under 300 Kbps achieves a round-trip time lower than that of unconstrained TFRC.

In rate-constrained mode, TFRC uses the minimum of the constrained rate and the TCP-Friendly rate to control the sending rate. Figure 4 depicts the relationship between the average sending rate, the constrained sending rate and the computed 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, the next section presents a new algorithm designed to constrain TFRC and avoid saturating the MAC layer on 802.11 wireless networks.

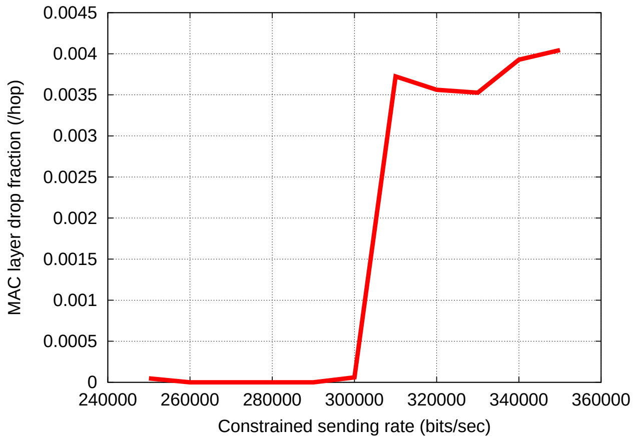

Fig. 3. MAC layer drop fraction versus constrained sending rate

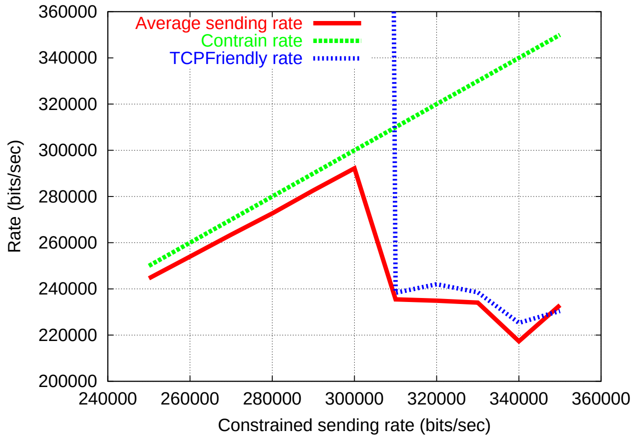

Fig. 4. Average sending rate and TCP-Friendly rate versus constrained sending rate

III. Enhancing TFRC Performance

A. Rate Estimation

From the results in Section II, 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 that increase 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. To be able 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 point.

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 of using r_{min}, we use r_{opt}, which represents the minimum round-trip time during MAC layer saturation. r_{opt} is used 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 is used as a basis for our modifications.

As described in Section II, TFRC's sending rate is not constrained by a window size but rather by the computed TCP-Friendly rate. 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 $rto = 4 \times r$ (as set in [8]), 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, the equivalent TFRC loss event rate (p') can be estimated using the inverse function $\overline{f}(r, X)$, and then p' and the current round-trip time measured by TFRC (r_{cur}) can be used 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 5 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.

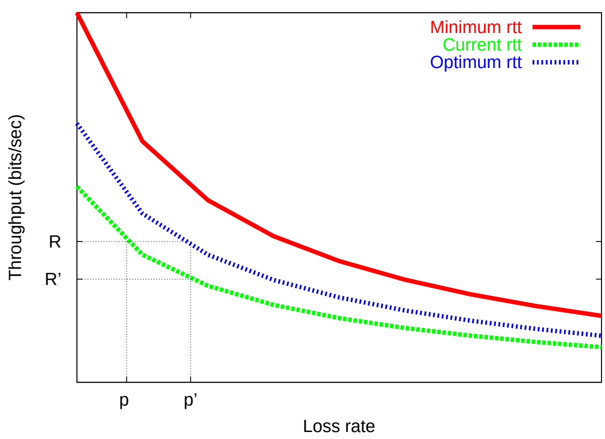

Fig. 5. Throughput versus loss event rate (p) for different round-trip times

B. Round-Trip Time Modeling

Realizing the benefits of the proposed TFRC enhancements requires a mechanism to 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:

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

TABLE I

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

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:

$$\begin{aligned} t_s = \; & rts + sifs + \delta + cts + sifs + \delta + H \\ & + E\{P\} + sifs + \delta + ack + difs + \delta \qquad (6) \\ & t_c = rts + difs + \delta \qquad (7) \end{aligned}$$

where rts, cts, ack, H and $E\{P\}$ are the transmission times of RTS, CTS, ACK, packet header (physical layer plus MAC layer) and data packets, respectively, and $E\{P\} = P$ for a fixed packet size. δ is the propagation delay. $sifs$ (Short Interframe Space), $difs$ (Distributed Interframe Space) and other specific values for DSSS and FHSS are listed in Table I.

Therefore, given the physical network type and the number of nodes in the network, Equation 6 can be used to estimate the average service time to obtain the delay under MAC saturation conditions.

To extend this model in multi-hop wireless networks, we 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 multiple independent, single-hop networks. By using the model on each of the single hops, a cumulative delay for the multi-hop network can be estimated. By assuming RTS/CTS solves the hidden terminal problem in applying the single-hop analysis, we do not need to consider the interference from other nodes outside the transmission range. The N-hop chain network can then be divided into $N-2$ single-hop networks with four nodes and two 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, the round-trip can be computed as:

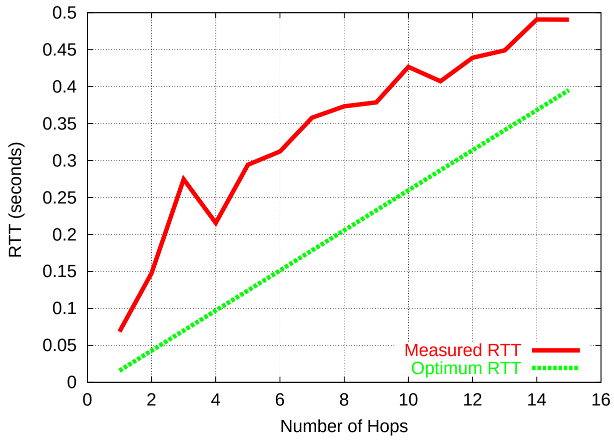

Fig. 6. Estimating the optimum round-trip time

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

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 6 depicts the round-trip time estimate from this model and the round-trip time obtained by TFRC during simulation. TFRC provides an offered load above 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 the extended round-trip time model, we provide a complete rate estimation algorithm for TFRC, shown in Figure 7.

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. 7. The rate estimation algorithm for TFRC (RE TFRC)

To make the implementation of the RE TFRC algorithm in Figure 7 more stable and adaptive, a few enhancements were needed. First, at line 2 and 6 of the algorithm, the TCP-Friendly sending rate computation that is fundamental to TFRC is used to ensure appropriate response to transport layer congestion. Second, note as the number of hops or flows increases, the round-

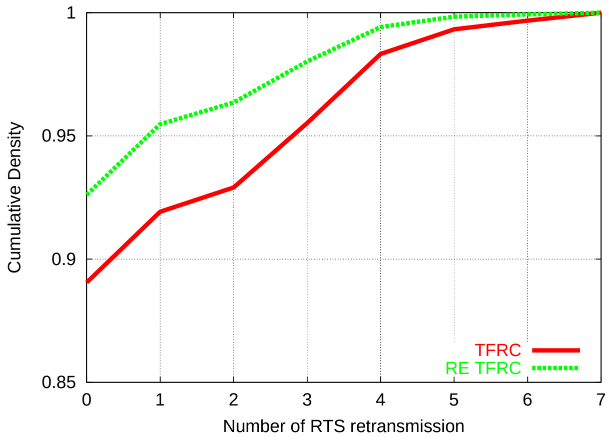

Fig. 8. Distribution of RTS retransmissions

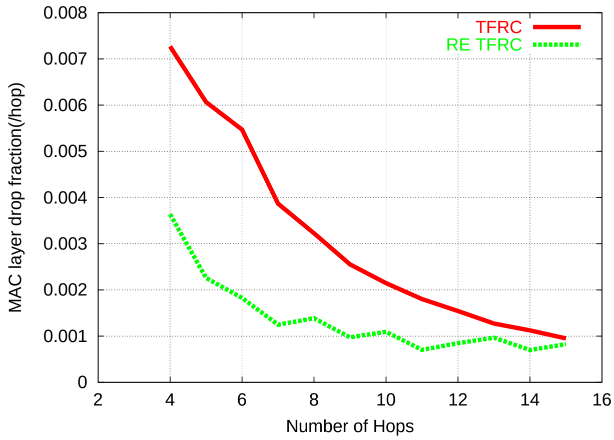

Fig. 9. MAC layer drop fraction versus number of hops

trip time curve of r_{cur} will shift up and go above the r_{opt} curve in Figure 5. In this case, the r_{opt} curve no longer represents saturation. Hence, r_{min} should be used in place of r_{opt}. Therefore, line 3, determines the minimum round-trip time in a sliding window interval and uses the larger of the computed round-trip time ($r(N)$) and the window value to estimate p' in these situations.

IV. 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 without changing the MAC layer protocol. This section evaluates RE TFRC using NS-2 simulations with the same wireless chain topology used in Section II. The first step is a detailed analysis of RE TFRC performance in a seven hop simulation. This is followed by simulation experiment results where the the number of hops is varied from 4 to 15 and other simulations where three flows generate the offered load. The section concludes with a study of the behavior of the RE TFRC in typical Bit Error Rate (BER) network environment.

A. *Performance Improvement*

A seven hop chain topology was used to compare a standard TFRC implementation against the Rate Estimation TFRC (RE TFRC) algorithm. Since the RTS backoff mechanism drops an RTS frame after seven consecutive collisions, this event represents a packet loss as seen by TFRC. Figure 8 presents the Cumulative Density Function (CDF) for RTS retransmissions for the two simulations. The x-axis is the number of RTS contention backoffs from 0 to 7 where 0 implies no collisions and 7 means TFRC will see this as a loss event. Figure 8 shows that TFRC has a 89% chance of not having to retransmit an RTS while RE TFRC, has a 93% chance of not having to retransmit an RTS, so RE TFRC will experience less backoff delay. Since the backoff algorithm causes exponential growth in backoff delay with an increase in the number of retransmissions, the seemingly small differences in the CDF curves represent significant changes in the contention delay. The reduced collisions result in a lower loss event rate and round-trip time and a smoother sending rate for RE TFRC (see [14]).

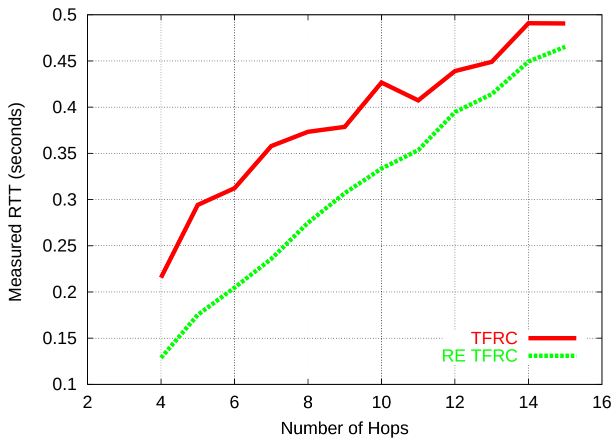

Fig. 10. Average round-trip time versus number of hops

B. *Multi-hop Performance Evaluation*

The next evaluation of RE TFRC involves varying the number of wireless hops from 4 to 15. Figure 9 shows the improvement of MAC layer loss rate for RE TFRC. The MAC layer drop ratio is reduced by between 13% to 66% compared to TFRC.

Figure 10 demonstrates that the round-trip time of RE TFRC is 5% to 40% lower than that of TFRC, and Figure 11 shows that the RE TFRC loss event rate is 8% to 55% less than that of TFRC.

From the results of multi-hop simulations, RE TFRC also shows up to 5% throughput improvement over TFRC when the number of hops is increased from 5 to 15. (see [14]).

C. *Multi-flow Performance Evaluation*

This section considers situations where three flows are providing the offered load. Table II shows RE TFRC reduces the MAC layer drop rate, TFRC loss event rate and average round-trip times significantly. However, RE TFRC has little effect on throughput in the multi-flows scenarios (see [14]). The “-” in the table means the difference is less than 1%.

D. *Bit Error Rate Evaluation*

The Bit Error Rate (BER) in wireless networks is usually higher than in wired networks. Typical BER ranges from 10^{-6}

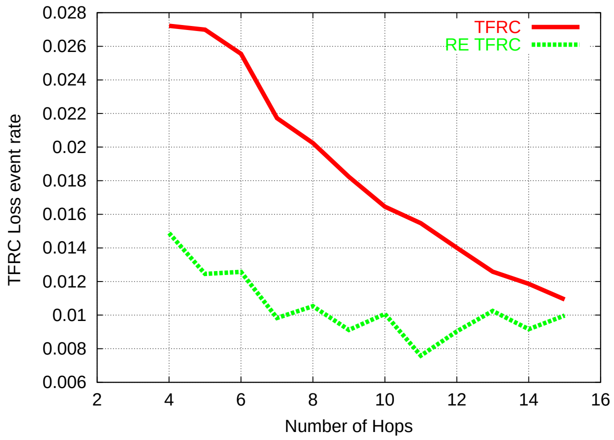

Fig. 11. Average loss event rate versus number of hops

TABLE II
RE TFRC IMPROVEMENT FOR MULTI-FLOW ENVIRONMENT

Hops	7-hop	15-hop
MAC drop fraction reduction	50%	85%
RTT reduction	29%	43%
Loss rate reduction	53%	75%
Throughput improvement	-	-

to 10^{-4} were used 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 shown in Table III, RE TFRC performs considerably better over most of metrics over a wide range of BER.

V. Conclusions

This paper presents a new algorithm, Rate Estimation (RE) TFRC, designed to enhance TFRC performance in wireless Ad Hoc network environment. 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 is estimated by modeling multi-hop contention delay and service time and the equivalent loss event rate is estimated using the inverse TCP Friendly rate equation with the optimal round-trip time. The basic idea is to 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.

Our simulations confirm that the RE algorithm can significantly enhance TFRC performance with a reduced round trip time and loss event rate while still providing the same or better throughput than regular TFRC. As TFRC was designed for streaming multimedia and telephony applications, large delay and loss rate reductions with slight throughput improvements implies this scheme can improve performance for streaming flows in wireless networks.

TABLE III
RE TFRC IMPROVEMENT FOR VARIOUS BER

BER	10^{-6}	10^{-5}	10^{-4}
MAC drop fraction reduction	77%	25%	12%
RTT reduction	39%	32%	14%
Loss rate reduction	55%	45%	29%
Throughput improvement	7%	4%	-

Our current ongoing RE TFRC research is 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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