TCP-controlled Long File Transfer Throughput in Multirate WLANs with Nonzero Round Trip Propagation Delays

Pradeepa BK and Joy Kuri
Centre for Electronics Design and Technology,
Indian Institute of Science, Bangalore. India.
bpradeep, kuri@cedt.iisc.ernet.in

***Abstract*—In a multirate WLAN with a single access point (AP) and several stations (STAs), we obtain analytical expressions for TCP-controlled long file transfer throughputs *allowing nonzero propagation delays between the file server and STAs*. We extend our earlier work in [3] to obtain AP and STA throughputs in a multirate WLAN, and use these in a closed BCMP queueing network model to obtain TCP throughputs. Simulation show that our approach is able to predict observed throughputs with a high degree of accuracy.**

***Index Terms*—WLAN, Access Points, Infrastructure Mode, Uploading and Downloading, TCP, Closed Queueing Network, BCMP Network.**

I. Introduction

This paper is concerned with infrastructure mode WLANs that use IEEE 802.11 DCF mechanism. We are interested in analytical models for evaluating the performance of TCP-controlled downloads where each link experiences propagation delay. A detailed analysis of the aggregate throughput of TCP flows in WLANs for a single rate Access Point (AP) (where all stations (STAs) are associated with the AP at a single rate) is given in [1] by assuming negligible or zero round trip time (RTT). Similarly, the performance of the AP is evaluated in the multi rate case in [2], [3] and [4]. However these works also ignore the RTT. Here in our work we model the AP by considering round trip propagation delay (RTPD) and hence RTT.

In this paper, we are interested in obtaining analytical expressions for TCP-controlled long file transfer throughputs in case nonzero RTTs. Clearly, this is the case that is most relevant in practice. In addition, we allow STAs to be associated with the AP at one of a number of possible rates; for example, in 892.11g, the rate association belongs to the set { 54, 48, 36, 24, 18, 12, 6 } Mbps. Again this is common in practice, because STAs can be at varying distances from the AP.

We obtain the closed-form expressions and numerical evaluations apply them in other contexts of practical relevance. One such application, which we are working on now, is to utilize the results reported here in devising an improved AP-STA association scheme.

Our approach is divide the problem into two parts. The first part is to get the model to represent the number of STAs with ACKs in MAC queues as an embedded Discrete Time Markov Chain (DTMC), embedded at the instants of successful transmission events. We consider a successful transmission from the AP as a reward. This leads to viewing the aggregate TCP throughput in the framework of Renewal Reward theory as given for example in [16]. We obtain expressions for network state probabilities, as well as the service rates of the AP and STAs. The second part is to model the complete network, with nonzero RTT, as a closed BCMP queueing network [15].

The main contribution of this paper is the analytical model for TCP-controlled long file transfer throughput in a WLAN with nonzero RTPD, using a BCMP queueing network. Simulations indicate that download traffic scenario with RTPDs, our numerical evaluation of analytical expression matches with error less than 3% .

This paper is organized as follows: Section II outlines related work. In Section III we state the system model and we discuss the assumptions in the modelling. In Section IV we obtain throughput analysis. In Section V, we present performance evaluation results. In Section VI we present some key observations on the model, and the results and we conclude the paper.

II. Related Work

Numerous models and analyses have been proposed for wireless networks with TCP-controlled traffic, but very few consider propagation delays. In [5], RTT is considered in modelling the TCP traffic in a WLAN. However, the authors' interest was in showing that 802.11e supports features that can be exploited to overcome certain TCP performance anomalies.

[1] and [8] provide a model for single rate AP-STA WLAN assuming zero RTT and consider file transfers from a server located in the LAN. An extension of this model in [2] considers two rates of association with long file uploads from STAs to a local server. The multirate case, with k rates, is analysed in [3]. [4] considers the single rate case, but allows simultaneous TCP uploads and downloads with arbitrary maximum window sizes. [9] and [10] analyze TCP-controlled uploads and downloads in the presence of UDP traffic. However, the effect of RTT on the network performance is ignored. The letter [11] gives the average value analysis of TCP performance with upload and

download traffic without considering RTT. In [12], finite buffer AP with TCP traffic in both upload and download direction is analysed with delayed and undelayed ACK cases. They consider server system located on the Ethernet to which the AP is connected and hence number of packets "in flight" outside the WLAN is ignored.

[13] provides an analysis for a given number of STAs and maximum TCP receive window size by using the well known p persistent model proposed in [7]. However both [13] and [7] do not consider the effect of RTT on the performance. In [14], a queueing model is proposed to compute the mean session delay of HTTP sessions in the presence of short-lived TCP flows and the impact of TCP maximum congestion window size on this delay is studied.

III. System Model

We consider a WLAN with M STAs are associated to an AP as shown in Figure 1.The STAs are downloading long files from a server which is far away from the local wireless network. Hence there is a propagation delay between the AP and the server. Every packet experiences this delay. The AP sends TCP data packets to these STAs. The arrows in Figure 1 show the direction of the data packets in the network. Since these are TCP links, there is also feedback traffic composed of TCP-ACK packets.

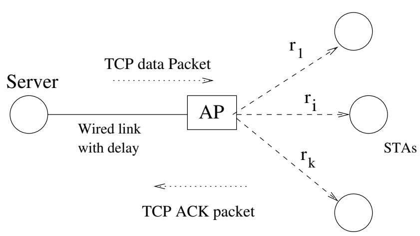

Fig. 1. The network and traffic configurations. STAs are downloading long files from a server through an AP.

Every STA has a single TCP connection.Further, because of long file transfer scenario, we can assume that TCP sources are operating in Congestion Avoidance mode. Hence TCP startup transients can be ignored. TCP windows grow to the maximum value possible, i.e., the maximum receive window advertised by the receiver. Also, TCP timeouts do not occur.

Both AP and STA contend for the channel using the DCF mechanism. We assume that there are no link errors. Packets in the medium are lost only due to collisions. When the AP wins the channel, it delivers TCP data packets towards the STA and the STA returns TCP-ACK packets again by contending and winning the channel. Further, we assume that the AP uses the RTS-CTS mechanism while sending data packets, while the STAs use basic access to send ACK packets, which is more realistic and efficient as TCP-ACK packets are much shorted than TCP data packets. As soon as the STA receives a data packet, it generates an ACK packet without any delay and it is enqueued at the MAC layer for transmission. We assume that all the nodes have sufficiently large buffers, so that packets are not lost due to buffer overflow. These ACK packets travel through wired network and reach the server. Again server generates next window of TCP data packets. All packets from server experience the propagation delay, reach the WLAN and are enqueued at the AP to reach STAs.

IV. Analysis

A. AP and STA throughputs

Let m_i be the number of STAs associated with the AP at the PHY rate r_i, where $i \in \{1, 2, \ldots k\}$ with $r_1 > r_2 > ...r_k$ as discussed in [2] and [3]. The probability that the AP sends a TCP data packet to an STA at rate r_i is p_i. Part of the development (till Equation (5)) is along the lines of [3]; this is included here for completeness and readability. Consider

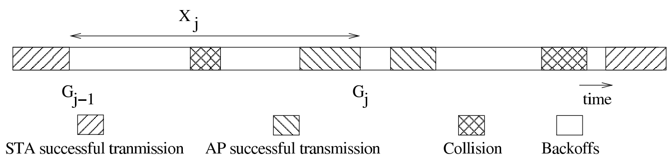

Fig. 2. Channel activity: G_j are the random epochs at which successful transmissions end. Random variable X_k denotes the duration of the j^{th} contention cycle $[G_{j-1}, G_j)$. Each contention cycle consists of one or more back off and collisions slots but ends with a successful transmission.

Figure 2, where a possible sample path of the events on the WLAN channel is shown. The random epochs G_j indicate the end of the j^{th} successful transmission from either the AP or one of the STAs. We begin by assuming that each m_i is large. We observe that most STAs have empty MAC queues, because, in order for many STAs to have TCP-ACK packets, the AP must have had a long run of successes – and this is unlikely because no special priority is given to the AP. So, when the AP succeeds in transmitting, the packet is likely to be for an STA with an empty MAC queue.

Let $S_{i,j}$ be the number of STAs at rate r_i, ready with an ACK. Let $\sum_{i=1}^{k} S_{i,j} = N$ be the number of nonempty STAs. Since there are N nonempty STAs and a nonempty AP, each nonempty WLAN entity attempts to transmit with probability $\beta_{(N+1)}$ as in [6]. So $(S_{1,j}, S_{2,j}, ..., S_{k,j})$ evolves as a Discrete Time Markov Chain (DTMC) over the epochs G_j. This allows us to consider $((S_{1,j}, S_{2,j}, ..., S_{k,j}), G_j)$ as a Markov Renewal Sequence, and $(S_1(t), S_2(t), ..., S_k(t))$ as a semi-Markov process. We have a multidimensional DTMC which is shown in Figure 3; transition probabilities are indicated as well (we used in n_i as running index). By inspection, we can say that the DTMC is irreducible. The Detailed Balance Equation holds for a properly chosen set of equilibrium probabilities. The DBE is

$$\pi(n_1, ...n_i, ...n_k) \frac{p_i}{(N+1)} = \pi(n_1, ...(n_i+1), ...n_k) \frac{(n_i+1)}{(N+2)} \quad (1)$$

Here $\pi(n_1, ..., n_k)$, $n_1, n_2, ...n_k \in \{0, 1, 2, ...k\}$ is the stationary distribution of the DTMC. From the set of equations given in (1) and $\sum_{n_1=0}^{\infty} \sum_{n_2=0}^{\infty} ... \sum_{n_k=0}^{\infty} \pi(n_1, ..., n_k) = 1$, the stationary distribution is

$$\pi(n_1, n_2, ...n_i, ...n_k) = (N+1) \Pi_{i=1}^{k} \frac{(p_i)^{n_i}}{(n_i!)} * \frac{1}{(2e)} \quad (2)$$

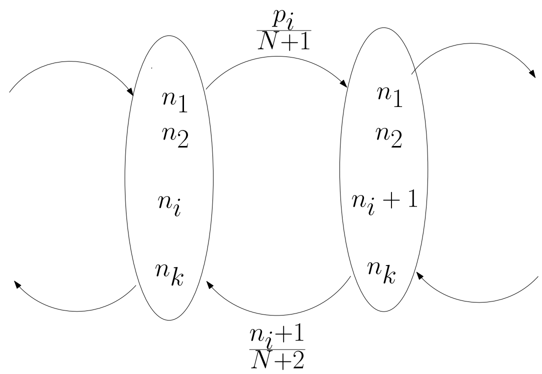

Fig. 3. Embedded Markov chain formed by the AP and $n_1+n_2+...+n_k = N$ stations associated with the AP at k different data rates

Let X be the sojourn time in a state $(S_{i,j}, ...S_{k,j})$. Conditioning on various events (idle slot, collision or successful transmission) that can happen in the next time slot, the following expression for the mean cycle length can be written down:

$$\begin{aligned} E_{n_1..n_k}X = {} & P_{idle}(\delta + E_{n_1..n_k}X) + \Sigma_i(P^{r_i}_{sAP}T^{r_i}_{sAP}) \\ & + \Sigma_i(P^{r_i}_{c}(T^{r_i}_{c} + E_{n_1..n_k}X) \\ & + \Sigma_i(P^{r_i}_{sSTA}T^{r_i}_{sSTA}) \\ & + \Sigma_i\left(P^{r_i}_{cSTA}(T^{r_i}_{cSTA} + E_{n_1..n_k}X)\right) \end{aligned} \quad (3)$$

In the above expression (3), P_{idle} is the probability of the slot being idle. $P^{r_i}_{sAP}$ is the probability that the AP wins the contention and transmits the data packet with rate r_i. $P^{r_i}_{sSTA}$ is the probability that the STA wins the contention and transmits the data packet with rate r_i. Detailed expressions are tabulated in [3]. In the above expression, collisions correspond to different cases are as follows. First, the third term in (3) arises when the AP transmits a TCP data packet to an STA at rate r_i and some other STAs are involved in a collision. The second case (fifth term in (3)) corresponds to an STA transmitting a TCP ACK packet to the AP at rate r_i and some other node transmitting simultaneously. In the above expression, various probabilities have been obtained by considering the events and using channel access probability β_{N+1},when there are $(N+1)$ contending nodes.

From Equation (3) we have $E_{n_1..n_k}X =$

$$\frac{P_{idle} + \sum P^{r_i}_{sAP}T^{r_i}_{sAP} + \sum P_c^{r_i}T_c^{r_i} + \sum P^{r_i}_{sSTA}T^{r_i}_{sSTA} + \sum P^{r_i}_{cSTA}T^{r_i}_{cSTA}}{1 - P_{idle} - \sum P^{r_i}_{sAP} - \sum P^{r_i}_{c} - \sum P^{r_i}_{sSTA} - \sum P^{r_i}_{cSTA}} \quad (4)$$

In Equation 4, calculations of probabilities and times are shown in [3]. We are interested in finding long run time average of successful transmissions from the AP. This leads to Markov regenerative analysis or the renewal reward theorem approach. To get mean renewal cycle length, we can use the mean sojourn time given in Equation (4). The mean reward in a cycle can be obtained as follows. A reward of 1 is earned when the AP transmits a TCP data packet successfully by winning the channel. The probability of the AP winning the channel is $\frac{1}{(n_1+n_2+...n_k+1)}$. Hence, the semi Markov process exits the state $(n_1, n_2, ...n_k)$ with probability $\frac{1}{(n_1+n_2+...n_k+1)}$. A reward of 0 is earned with the probability $(1 - \frac{1}{(n_1+n_2+...n_k+1)})$. Therefore, the expected reward is $\frac{1}{(n_1+n_2+...n_k+1)}$.

Hence, the aggregate TCP throughput for the AP in this case can be calculated as

$$\Phi_{AP-TCP} = \frac{\Sigma^{\infty}_{n_1=0}\Sigma^{\infty}_{n_2=0}...\Sigma^{\infty}_{n_k=0}\pi(n_1...n_k)\frac{1}{n_1+...+n_k}}{\Sigma^{\infty}_{n_1=0}\Sigma^{\infty}_{n_2=0}...\Sigma^{\infty}_{n_k=0}\pi(n_1...n_k)E_{n_1,..n_k}X} \quad (5)$$

We are also interested in finding the mean TCP throughput for the STAs. A reward of 1 is counted when any STA transmits a TCP-ACK packet successfully by winning the contention. The probability of STA at rate r_i winning the contention is $\frac{n_i}{(n_1+n_2+...n_k+1)}$. A reward of 0 is counted with probability $(1 - \frac{n_i}{(n_1+n_2+...n_k+1)})$. Hence the TCP throughput for the STA at rate r_i is

$$\Phi_{STA-TCP-(r_i)} = \frac{\Sigma^{\infty}_{n_1=0}\Sigma^{\infty}_{n_2=0}...\Sigma^{\infty}_{n_k=0}\pi(n_1...n_k)\frac{n_i}{n_1+...+n_k}}{\Sigma^{\infty}_{n_1=0}\Sigma^{\infty}_{n_2=0}...\Sigma^{\infty}_{n_k=0}\pi(n_1...n_k)E_{n_1,..n_k}X} \quad (6)$$

B. BCMP model

We can model the scenario shown in Figure 1 as a BCMP closed queueing network [15] with service centers as shown in Figure 4. We consider RTPD as a delay center. Once wireless specific aspects are captured in Φ_{AP-TCP} and Φ_{STA}, we consider the BCMP network service centres as if they were linked by regular wired links. This is a modelling assumption for tractability.

Let us consider W packets in this network. The queues in this network representing the AP and STA are first come first served queues (FCFS) which are "Type 1" service centres in the terminology of [15]. Similarly, the queue representing round trip propagation delay (RTPD) is an infinite server queue with deterministic service time, which is a "Type 3" service center.

Let the service rate of the AP be τ. Let us consider w_0 packets to be at center 0. That is, w_0 among W packets are in the AP. Also, let w_1 out of W packets be in center 1, which is an STA at rate r_1 . Similarly, w_i packets in center correspond to STA i. The remaining packets we say w_d are in the delay center. The state of the network can be represented by $S = (x_0, x_1, x_2, x_3, ..., x_M, x_d)$, as in [15]. The definitions of $x_0, x_1, x_2...$ depend on the type of the service center i and are given in [15].

Let there be m_j STAs at rate r_j. STAs at a particular rate constitute customers of a particular class in the BCMP network. We have $m_1 + m_2 + m_k = M$.

Every transition is both a departure from one center and an arrival at another center. For every i, let $e_{i,j}$ be the fraction of transitions that are arrivals at (departures from) center i. Let $v_{i',j',i,j}$ be the probability that a customer of class j' at center i' goes to center i and becomes a class j customer. From [16], $e_{i,j}$ is the unique solution (that sums to 1) of the following system of equations: $e_{i,j} = \sum_{i',j'}(e_{i',j'})v_{i',j',i,j}$. From Figure 4, all the packets from the RTPD delay center go to the AP:

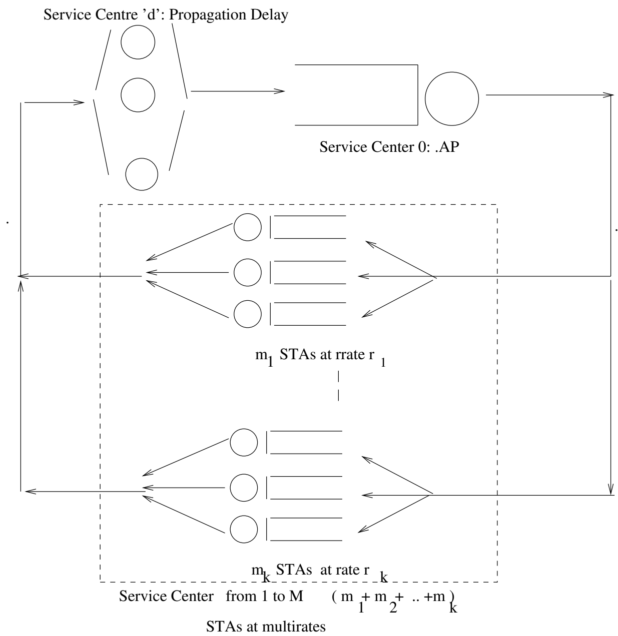

Fig. 4. An equivalent queueing network model for the scenario shown in Figure 1, considering packets as customers. Total number of customers is the sum of maximum receive windows advertised by each receiver.

$v_{d,j,0,j} = 1$. The probability that a j class customer from the AP arrives to the i^{th} service center is $v_{0,j,i,j} = 1/(m_i)$ when $j - i$, and is 0 otherwise. The probability that a j^{th} class customer from the i^{th} center arrives to the delay center is $v_{i,j,d,j} = 1$. The remaining probabilities are zero. It can be shown easily that for k different possible rates, $e_{0,j} = \frac{m_j}{3M}$ and $e_{d,j} = \frac{m_j}{3M}$ for each j and the arrival rate into a class j is $\frac{e_{0,j}}{m_j} = \frac{1}{3M}$.

By the BCMP theorem [15], the equilibrium probabilities are given by

$$\begin{aligned} &P(S = x_0, x_1, x_2, ..., x_M, x_d) \\ &= Cd(S) f_0(x_0) f_1(x_1) f_2(x_2) ... f(x_M) f_d(x_d) \end{aligned} \tag{7}$$

where C is the normalizing constant chosen to make the equilibrium state probabilities sum to 1, $d(S)$ is a function of the number of customers in the system, and f_i is a function that depends on the type of service center i. The exact form of the states $x_0, x_1, ...$ is shown in [15].

Let us take n_i as the total population at service center i, From [15], for the FCFS server, AP (center 0),

$$f_0(x_0) = \left(\frac{1}{\tau}\right)^{n_0} \Pi_{j=1}^{n_0} e_{0,x_{0,j}} \tag{8}$$

where $x_{0,j}$ represents the class of the j^{th} customer in FCFS order at service center 0, for the FCFS servers at STAs, for all $i \in \{1, .., M\}$

$$f_i(x_i) = \left(\frac{1}{\mu_i}\right)^{n_i} \Pi_{j=1}^{n_0} e_{i,x_{i,j}} \tag{9}$$

where $x_{i,j}$ indicates the class of the j^{th} customer in FCFS order at service center i, and for the infinite server, delay model, center 'd', is represented by cascading of c number of exponential servers in c stages with service rate $\frac{1}{c \times t_{RTPD}}$ method (by considering large value of c) gives

$$f_d(x_d) = \Pi_{j=1}^{k} \Pi_{l=1}^{c} \left(\frac{e_{d,j}}{c \times \tau_{RTPD}}\right)^{n_{d,j,l}} (1/n_{d,j,l}!) \tag{10}$$

where $n_{d,j,l}$ represents the number of class j customers in stage l of service at center d. For a closed network, $d(S) = 1$. The average number of packets in the AP, n_{AP}, the average number of packets in STA i, n_{STA-i}, and the average number of packets in propagation n_{RTPD} can be obtained by finding the marginal distributions from (7).

From Figure 4, it is clear that

$$n_{AP} + \sum_{i=1}^{M} n_{STA-i} + n_{RTPD} = W$$

Let the throughput in the closed network of Figure 4 be t_H. Then, applying Little's Theorem to service center 'd', we have

$$n_{RTPD} = t_H \times t_{RTPD} \tag{11}$$

V. Evaluation

To verify the accuracy of the model, we performed experiments using the Qualnet 4.5 network simulator [17], with the IEEE 802.11b standard. We take 2 STAs associated at rate 5.5 Mbps and 3 STAs at rate 11 Mbps with control packets transmission rate at 2 Mbps. RTPD is varied from 10ms to 90ms in steps of 10ms. TCP Receive window is taken as 60 packets per link. In Table I, results are given with 95 % confidence interval over 30 runs. In Tables I to IV and Figure 5 comparisons between analytical and simulation values are given for selected data rates to illustrate the accuracy of the analytical model.

	Analysis	Simulation		
RTPD(ms)	Packets	Mean	Max	Min
10	297.9	296.862	299.115	294.608
20	295.2	294.181	296.385	291.977
30	292.5	291.425	293.615	289.235
40	289.8	288.716	290.899	286.532
50	287.0	286.034	288.23	283.837
60	284.3	283.277	285.389	281.165
70	281.5	280.077	282.383	277.771
80	278.7	277.645	279.74	275.551
90	276.6	275.484	277.528	273.441

TABLE I
Number of packets in AP buffer for different values of RTPD.

	Analysis	Simulation		
RTPD(ms)	Packets	Mean	Max	Min
10	2.58	2.718	2.765	2.672
20	4.27	5.374	5.517	5.231
30	7.16	7.862	8.061	7.663
40	10.72	10.782	11.078	10.485
50	13.18	13.778	14.05	13.505
60	16.15	16.467	16.724	16.211
70	18.26	19.083	19.475	18.691
80	20.13	21.459	21.799	21.119
90	23.59	24.768	25.252	24.285

TABLE II
Number of packets in "in flight" for different values of RTT.

	Analysis	Simulation		
RTPD(ms)	Packets	Mean	Max	Min
10	0.12	0.128	0.132	0.124
20	0.125	0.131	0.136	0.125
30	0.121	0.127	0.131	0.123
40	0.121	0.127	0.13	0.124
50	0.122	0.129	0.134	0.124
60	0.121	0.126	0.132	0.121
70	0.12	0.125	0.129	0.121
80	0.121	0.127	0.13	0.123
90	0.128	0.13	0.134	0.127

TABLE III
NUMBER OF PACKETS IN STAS BUFFER AT RATE 11 MBPS AND 5.5 MBPS FOR DIFFERENT VALUES OF RTT.

	AP Throughput (packets/s)		STA Throughput (packets/s)	
RTPD(ms)	Analysis	Simulation	Analysis	Simulation
10	274.8	276.831	69.6	68.968
20	271.5	273.513	69.4	68.407
30	271.1	273.058	69.3	68.32
40	269.5	271.01	69.9	69.229
50	268.1	270.615	68.2	67.862
60	270.8	270.577	68.7	67.767
70	268.5	270.457	67.4	68.049
80	267.2	268.099	66.1	68.817
90	263.4	264.357	66.3	67.323

TABLE IV
AVERAGE THROUGHPUT OF THE AP AND THE STAS AT DIFFERENT RTPD VALUES OBTAINED BY ANALYSIS AND SIMULATION

VI. CONCLUSION

In this work, we presented an analytical model to obtain the aggregate throughput for several TCP-controlled long file downloads in a network with positive RTPD. We consider that TCP window sizes are the same for all connections to make the model simpler and to restrict our analysis to study the effect of RTPD and RTT on throughput. Our earlier work in [4] gives the effect of arbitrary TCP windows when RTPD is zero.

In our simulation and numerical evaluation, we used the 802.11b standards. However, our mathematical analysis is independent of the parameters in these standards. We can obtain similar analysis for other standards as well. We assumed no packet losses; this is a topic for future work.

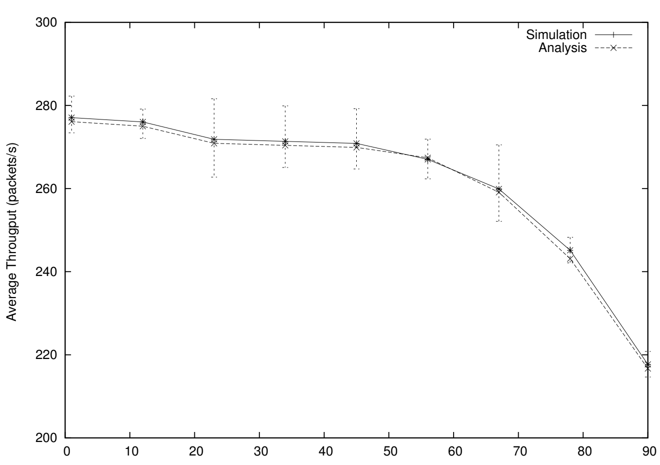

Fig. 5. TCP throughput vs RTPD for TCP window of size 40 packets per link

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