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

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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 802.11g, 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.

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 \( r_1 > r_2 > \ldots r_k \) 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 (until Equation 5) is along the lines of [3]; this is included here for completeness and readability. Consider 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.

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

![Diagram of network and traffic configurations](image)

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 shorter 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 are not lost due to buffer overflow. These ACK packets move through the 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.

Fig. 2. Channel activity: G\(_i\) are the random epochs at which successful transmissions end. Random variable \( X_j \) 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.

![Diagram of channel activity](image)

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 \((S_{1,j}, S_{2,j}, \ldots, S_{k,j})\) evolves as a Discrete Time Markov Chain (DTMC) over the epochs \( G_j \). This allows us to consider \((S_{1,j}, S_{2,j}, \ldots, S_{k,j}, G_j)\) as a Markov Renewal Sequence, and \((S_1(t), S_2(t), \ldots, S_k(t))\) 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

\[
\pi(n_1, \ldots, n_k) \frac{p_k}{N+1} = \pi(n_1, \ldots, (n_i + 1), \ldots, n_k) \frac{n_k + 1}{N+2}
\]  

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

\[
\pi(n_1, n_2, \ldots, n_k) = (N+1) \prod_{i=1}^{k} \frac{(p_i)^{n_i}}{(n_i)!} \frac{1}{(2^e)}
\]  

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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:

$$E_{n_1, ..., n_k} = P_{idle}(\delta + E_{n_1, ..., n_k}) + \sum_i (P'_{sAP} r'_{sAP} + P'_{sSTA} T_{sSTA})$$

$$+ \sum_i (P'_{cSTA} T_{cSTA} + E_{n_1, ..., n_k})$$  

$$+ \sum_i (P'_{eSTA} T_{eSTA} + E_{n_1, ..., n_k})$$  

(3)

In the above expression, $P_{idle}$ is the probability of the slot being idle. $P'_{sAP}$ is the probability that the AP wins the contention and transmits the data packet with rate $r_i$. $P'_{sSTA}$ 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 as are 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 successfully by winning the contention.

From Equation (3) we have 

$$E_{n_1, ..., n_k} = \frac{P_{idle} + \sum P'_{sAP} r'_{sAP} + \sum P'_{sSTA} T_{sSTA} + \sum P'_{cSTA} T_{cSTA} + \sum P'_{eSTA} T_{eSTA}}{1 - P_{idle}}$$  

(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 cycle length, we can use the mean sojourn time given in Equation 3. 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 $(n_1, n_2, ..., n_{k+1})$. 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

$$\Phi_{AP-TCP} = \frac{\sum_{n_1=0}^{\infty} \sum_{n_2=0}^{\infty} \ldots \sum_{n_k=0}^{\infty} \pi(n_1, ..., n_k) \frac{1}{n_1+n_2+...n_k}}{\sum_{n_1=0}^{\infty} \sum_{n_2=0}^{\infty} \ldots \sum_{n_k=0}^{\infty} \pi(n_1, ..., n_k) E_{n_1, ..., n_k}}$$  

(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 $(\frac{1}{n_1+n_2+...n_{k+1}}$). A reward of 0 is counted with probability $(1 - \frac{1}{n_1+n_2+...n_{k+1}}$. Hence the TCP throughput for the STA at rate $r_i$ is

$$\Phi_{STA-TCP} = \frac{\sum_{n_1=0}^{\infty} \sum_{n_2=0}^{\infty} \ldots \sum_{n_k=0}^{\infty} \pi(n_1, ..., n_k) \frac{n_i}{n_1+n_2+...n_k}}{\sum_{n_1=0}^{\infty} \sum_{n_2=0}^{\infty} \ldots \sum_{n_k=0}^{\infty} \pi(n_1, ..., n_k) E_{n_1, ..., n_k}}$$  

(6)

B. BCMP model

We can model the scenario shown in Figure 4 as a BCMP closed queueing network [15] with service centers as shown in Figure 3. We consider RTDP as a delay center. Once wireless specific aspects are captured in $\Phi_{AP-TCP}$ and $\Phi_{STA}$, 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 (RTDP) is an infinite server queue with deterministic service time, which is a “Type 3” service center.

Let the service rate of the AP be $r$. 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, $w_1$ 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 $v_{i,j}$ 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:

$$e_{i,j} = \sum_{i'} v_{i',j} e_{i',j}$$  

From Figure 4 all the packets from the RTDP delay center go to the AP.
Simulation

8.061
2.765
293.615
11.078
275.484
21.799
5.374
19.083
280.077
24.768
284.3
294.608
19.475
275.551
Max
276.6
297.9
299.115
16.467
13.778
283.837
287.0
Mean
294.181
278.7
16.724
289.8
289.235
295.2
18.691
288.716
Min
277.771
281.5
7.862
13.18
292.5
20.13
2.718
281.165
10.72
13.505
14.05
286.532
273.441
16.15
296.385
Packets
5.231
7.663
296.862
Mean
16.211
291.425
7.16
2.672
279.74
10.782

Service Centre ‘d’: Propagation Delay

e
and
are given by

Figure 1, considering packets as customers. Total number of customers is the

e
x

where

x

i

∈ {1, 2, ..., M}

From [15], for the FCFS server, AP (center 0),

d
depends on the type of service center

i

that depends on the type of service center

i

for

v_0, x_i \in [0, 1]

and

v_0 = \frac{e_j}{1 - \sum_{j=1}^{M} e_j}

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

\[ P(S = x_0, x_1, \ldots, x_M, x_d) = C d(S) f_0(x_0) f_1(x_1) f_2(x_2) \ldots f_M(x_M) f_d(x_d) \]  (7)

where

C

is the normalizing constant chosen to make the
e
marginal distributions from (7).

Let us take

n_i

to be the marginal distribution from (7).

From [15], for the FCFS server, AP (center 0),

\[ f_0(x_0) = \left( \frac{1}{T} \right)^{n_0} \prod_{j=1}^{M} e_{0,x_0,j} \]  (8)

where

x_0,j

covers 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, 2, ..., M\}

\[ f_i(x_i) = \left( \frac{1}{\mu_i} \right)^{n_i} \prod_{j=1}^{M} e_{i,x_i,j} \]  (9)

where

x_i,j

covers the class of the

j

th customer in FCFS order at service center

i

, and for the infinite server, delay

delay

model, center ‘d’, is represented by cascading of

c
number of exponential servers in

c
stages with service rate

\[ \frac{1}{c \times RTPD} \]

method (by considering large value of

c
) gives

\[ f_d(x_d) = \prod_{j=1}^{k} \prod_{c=1}^{c} \left( \frac{e_{d,j}}{c \times RTPD} \right)^{n_{d,j,l}} \left( 1/n_{d,j,l}! \right) \]  (10)

where

n_{d,j,l}

covers the number of class

j

customers in stage

l

of service at center

d
.d.

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

\[ n_{RTPD} = t_H \times RTPD \]  (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 II, results are given with 95% confidence interval over 30 runs. Table I presents comparisons between analytical and simulation values are given for selected data rates to illustrate the accuracy of the analytical model.
TABLE III
NUMBER OF PACKETS IN STAS BUFFER AT RATE 11 MBPS AND 5.5 MBPS FOR DIFFERENT VALUES OF RTTP.

| RTPD(ms) | Analysis | Simulation |
|---------|----------|------------|
| 10      | 0.12     | 0.128      |
| 20      | 0.125    | 0.131      |
| 30      | 0.121    | 0.127      |
| 40      | 0.122    | 0.129      |
| 50      | 0.121    | 0.134      |
| 60      | 0.121    | 0.132      |
| 70      | 0.12     | 0.125      |
| 80      | 0.121    | 0.127      |
| 90      | 0.128    | 0.134      |

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

| RTPD(ms) | AP Throughput (packets/s) | STA Throughput (packets/s) |
|---------|---------------------------|----------------------------|
|         | Analysis                  | Simulation                 |
| 10      | 274.8                     | 268.98                    |
| 20      | 271.5                     | 273.513                   |
| 30      | 271.1                     | 273.058                   |
| 40      | 269.5                     | 270.011                   |
| 50      | 268.1                     | 270.615                   |
| 60      | 270.8                     | 270.577                   |
| 70      | 268.5                     | 270.457                   |
| 80      | 267.2                     | 268.099                   |
| 90      | 263.4                     | 264.357                   |

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.

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