

# Bulk File Download Throughput in a Single Station WLAN with Nonzero Propagation Delay

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**Abstract**—We analyze TCP-controlled bulk file transfers in a single station WLAN with nonzero propagation delay between the file server and the WLAN. Our approach is to model the flow of packets as a closed queueing network (BCMP network) with 3 service centres, one each for the Access Point and the STA, and the third for the propagation delay. The service rates of the first two are obtained by analyzing the WLAN MAC. Simulations show a very close match with the theory.

**Index Terms**—WLAN, Access Points, TCP, RTT, RTPD, Propagation Delay, Closed Queueing Network, BCMP Network.

## I. INTRODUCTION

We consider an infrastructure wireless network employing the IEEE 802.11 DCF mechanism and carrying TCP-controlled file downloads. In this paper, we study analytical models for evaluating the performance of TCP-controlled downloads with non zero round trip propagation delays. In the literature, many works address the analysis of TCP flows in wireless networks. However very few consider non negligible round trip propagation delays in their models.

Our approach can be summarized as follows. First, we consider only two nodes in the network -an Access Point (AP) and an station (STA). We obtain expressions for AP and STA throughput in the absence of propagation delays. We consider that all the wireless medium specific proprieties of the system are encapsulated in these expressions. Next, we include the effect of round trip propagation delay (RTPD) by using a closed queueing network. We validate our model by comparison with various simulated quantities, such as mean number of packets in the AP, STA and in flight. Our numerical results of model matches with maximum error of 1.87 % error.

Outline of the paper: Section II outlines related work. In Section III we summarize out the modelling assumption with the system model. In Section IV we provide analysis for throughputs in case of two contending nodes. In Section V, we validate the model by comparing with the results obtained from the Qualnet network simulator. In Section VI we discuss the results and 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 for

modelling the TCP traffic in WLAN, but the authors' interest was in providing analysis supporting the service differentiation feature in 802.11e. The authors ensured fairness among TCP data packets and TCP ACKs by utilizing the different Access Categories in 802.11e, and their analysis exploited this fairness to show that service differentiation is possible.

A detailed analysis and modelling of the aggregate throughput of TCP flows in WLANs for a single rate access point is given in [1] and [8] 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.

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 is considered in [3], and arbitrary TCP windows are allowed in [4]. [9] and [10] present another analysis of a scenario of TCP-controlled upload and download file transfers, with UDP traffic. They ignored the RTT effect on the behaviour of the network. The letter [11] gives the average value analysis of TCP performance with upload and download traffic with out considering RTT. In [12], a finite buffer AP with TCP traffic in both upload and download directions 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] and [14] provide models in finite load conditions by approximating the packet arrival process at the STAs as a Poisson process. [13] extended saturated model proposed in [15] to non saturated model by introducing a term for probability of queue being empty. [14] models every STA with M/G/1 queue considers the propagation delay as the delay in transmission of packet in wireless medium, and not the time spent in reaching the WLAN from the server.

[16] 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 [16] and [7] consider no RTT effect in the traffic.

[17] considers HTTP traffic. A queueing model is proposed to compute the mean session delay in the presence of short-lived TCP flows and the impact of TCP maximum congestion window size on this delay is studied. The analysis is extended

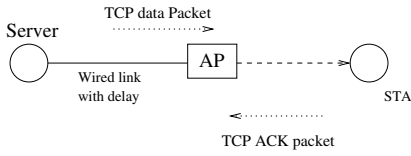


Fig. 1. The network and traffic configurations. An STA is downloading a long file from a server through an AP.

to consider delayed ACKs as well.

### III. SYSTEM MODEL

We consider a WLAN in which an STA is associated with an AP as shown in Figure 1. We consider long-lived TCP connections having bulk data to send. That is, we focus on large file transfers. The server is far away from the LAN. Hence, there is propagation delay between the AP and the server. Every packet experiences this delay. Figure 1 shows the direction of TCP flow. The STA has a single TCP connection to download long files from the server. Further, because of bulk transfer scenario, we can assume that the TCP flow is in the steady state. We assume that the application at the receiver reads data from the socket receive buffer at the rate at which it is received from the network. Hence, the TCP ACK packets always advertise the maximal TCP receive window size. Therefore, TCP startup transients can be ignored. Also, TCP timeouts do not occur.

The AP and the 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 between transmission attempts of AP and STA. Further, we assume that all the nodes use the RTS-CTS mechanism while sending packets, and use basic access to send ACK packets. As soon as the station 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.

### IV. ANALYSIS

Because two entities, i.e., the AP and the STA, are contending for the channel, we can consider probability of attempt as  $\beta_2$ , as in [6]. This amounts to assuming that both AP and STA are backlogged permanently, i.e., that saturation conditions apply. Current TCP implementations use very large windows (window scaling option), and with these, our assumption is justifiable.

Figure 3 shows one possible sample path of events on the wireless channel in the WLAN with an AP and an STA. The random epochs  $G_j$  indicate the end of the  $j^{\text{th}}$  successful transmission from either the AP or the STA.

Let  $T_{sAP}$  be the time taken by the AP to transmit one packet TCP packet including MAC and PHY headers. This can be

Parameter	Symbol	Value
PHY data rate	$r_d$	11 Mbps
Control rate	$r_c$	2 Mbps
PLCP preamble time	$T_p$	144 $\mu\text{s}$
PHY Header time	$T_{PHY}$	48 $\mu\text{s}$
MAC Header size	$L_{MAC}$	34 bytes
RTS Header size	$L_{RTS}$	20 bytes
CTS Header size	$L_{CTS}$	14 bytes
MAC ACK Header size	$L_{ACK}$	14 bytes
IP Header size	$L_{IPH}$	20 bytes
TCP Header size	$L_{TCPH}$	20 bytes
TCP ACK Packet size	$L_{TCP-ACK}$	20 bytes
TCP data payload size	$L_{TCP}$	1460 bytes
System slot time	$\delta$	20 $\mu\text{s}$
DIFS time	$T_{DIFS}$	50 $\mu\text{s}$
SIFS time	$T_{SIFS}$	10 $\mu\text{s}$
EIFS time	$T_{EIFS}$	364 $\mu\text{s}$
Min. Contention Window	$CW_{min}$	31
Max. Contention Window	$CW_{max}$	1023

TABLE I  
VALUES OF PARAMETERS USED IN ANALYSIS AND SIMULATION

obtained by using parameter shown in Table I. We have

$$\begin{aligned}
 T_{sAP} = & T_p + T_{PHY} + \frac{L_{RTS}}{r_c} + T_{SIFS} \\
 & + T_p + T_{PHY} + \frac{L_{CTS}}{r_c} + T_{SIFS} + T_p + T_{PHY} \\
 & + \frac{L_{MAC} + L_{IPH} + L_{TCPH} + L_{TCP}}{r_d} + T_{SIFS} \\
 & + T_p + T_{PHY} + \frac{L_{ACK}}{r_c} + T_{DIFS}
 \end{aligned} \quad (1)$$

As data transmission follows an RTS-CTS exchange, the lengths of the RTS and CTS packets, as well as  $T_{SIFS}$ , are used in (1). We note that whenever there is a collision between RTS packet from the AP and a TCP-ACK packet from the STA, the channel time wasted is that due to the TCP-ACK packet. This is because the RTS packet is smaller than a TCP-ACK packet as given in Table I. Let  $T_c$  be the time spent in collision.

$$\begin{aligned}
 T_c = & T_p + T_{PHY} + \frac{L_{MAC} + L_{IPH} + L_{TCP-ACK}}{r_d} \\
 & + T_{EIFS}
 \end{aligned} \quad (2)$$

In the above expressions, we have considered that TCP data packets are larger than the RTS threshold and hence the AP uses the RTS-CTS access mechanism. Since TCP-ACKs are smaller, the STA uses the basic access mechanism. Let  $T_{sSTA}$  be the time taken by the STA to transmit one TCP ACK packet, including MAC and PHY overhead. We have

$$\begin{aligned}
 T_{sSTA} = & T_p + T_{PHY} \\
 & + \frac{L_{MAC} + L_{IPH} + L_{TCP-ACK}}{r_d} \\
 & + T_{SIFS} + T_p + T_{PHY} + \frac{L_{ACK}}{r_c} + T_{DIFS}
 \end{aligned} \quad (3)$$

The probability that the AP wins the contention in the first attempt is  $\beta_2(1 - \beta_2)$ ; let this be denoted as  $\alpha_2$ .

Let the mean back-off length at  $i^{th}$  attempt be

$$EB^i = \frac{2^i CW_{min} + 1}{2}$$

Let  $s_{sAP}^k$  be the mean time taken by AP to transmit a TCP data packet after  $k$  collisions. This can be obtained as

$$s_{sAP}^k = \sum_{i=1}^{k+1} EB^i + kT_c + T_{sAP} \quad (4)$$

which is mean weighted sum of conditional means. In the above Equation, if the back-off window reaches  $CW_{max}$ , it stays fixed at  $CW_{max}$ .

Also the probability of  $k$  times collisions and the success at  $(k+1)^{th}$  is  $(1 - \alpha_2)^k \alpha_2$ .

Hence the mean service time at the AP, with the STA is also contending for the channel is given by

$$s_{AP} = \sum_{i=1}^{\infty} s_{sAP}^k (1 - \alpha_2)^k \alpha_2 \quad (5)$$

Similarly, the time taken by the STA to transmit a TCP-ACK packet after  $k$  collision is

$$s_{sSTA}^k = \sum_{i=1}^{k+1} EB^i + kT_c + T_{sSTA} \quad (6)$$

and the mean service time at the STA is

$$s_{STA} = \sum_{i=1}^{\infty} s_{sSTA}^k (1 - \alpha_2)^k \alpha_2 \quad (7)$$

#### A. BCMP network

Having obtained the service rate of the AP and STA, we can model the scenario shown in Figure 1 as a BCMP (Baskett, Chandy, Muntz and Palacios) closed queueing network with three service centers [18]. 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 [18]. 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 us consider  $W$  packets in this network. Let  $w_1$  packets to be at center 1; that is,  $w_1$  among  $W$  packets are at the AP. Also, let  $w_2$  out of  $W$  packets be at center 2, which is an STA. Similarly, the remaining packets, say  $w_3$ , are in the delay center. The state of the network can be represented by  $S = (x_1, x_2, x_3)$ , as in [18]. The definitions of  $x_1, x_2$  and  $x_3$  depend on the type of the service center and are given in [18].

Every transition is both a departure from one center and an arrival at another center. For every  $i$ , let  $e_i$  be the fraction of transitions that are arrivals at (departures from) center  $i$ . Let  $v_{i',i}$  be the probability that a customer at center  $i'$  goes to center  $i$ . We have  $v_{1,2} = v_{2,1} = v_{1,1} = v_{2,2} = 1$ . From [19],  $e_i$  unique solution (that sums to 1) of the following system of equation

$$e_i = \sum_{i'} (e_{i'}) v_{i',i} \quad (8)$$

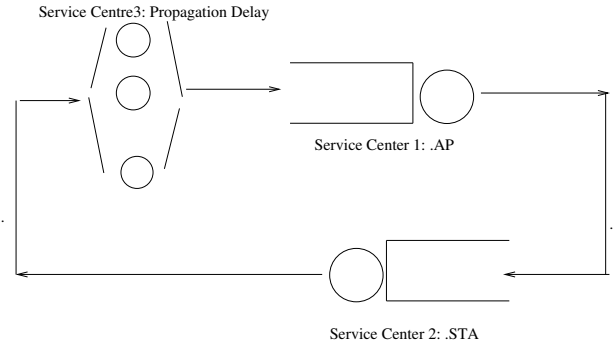


Fig. 2. An equivalent BCMP closed queueing network model for the scenario given in Figure 1 considering packets as customers. Total number of customers is equal to the maximum receive window advertised by TCP receiver

Hence,  $e_i = \frac{1}{3}$ . Every packet moves from one service center to another.

By the BCMP theorem [18], the equilibrium probabilities are given by

$$P(S = x_1, x_2, x_3) = Cd(S) f_1(x_1) f_2(x_2) f_3(x_3) \quad (9)$$

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  $i$ .

From [18], for the FCFS server, i.e., AP, center 1,

$$f_1(x_1) = (s_{AP})^{n_1} e_1 \quad (10)$$

for the FCFS server STA, center 2,

$$f_2(x_2) = (s_{STA})^{n_2} e_2 \quad (11)$$

and for the infinite server, delay model, center 3, is represented by cascading of  $c$  number of exponential servers in  $c$  stages with service rate  $\frac{1}{c \times t_{RTPD}}$  method in [20] (by considering large value of  $c$ ) gives

$$f_3(x_3) = \prod_{l=1}^c \left( \frac{e_3}{c \times \tau_{RTPD}} \right)^{n_{3,l}} (1/n_{3,l}!) \quad (12)$$

For a closed network,  $d(S) = 1$ .

The average number of packets at the AP,  $n_{AP}$ , the average number of packets at the STA,  $n_{STA}$ , and the average number of packets in propagation,  $n_{RTPD}$  can be obtained by finding the marginal distributions from (9).

From Figure 2 the total number of packets is distributed among the three service centers.

$$n_{AP} + n_{STA} + n_{RTPD} = W$$

Let the throughput in the closed network of Figure 2 be  $t_H$ . Then, applying Little's Theorem to service center 3, we have

$$n_{RTPD} = t_H \times t_{RTPD} \quad (13)$$

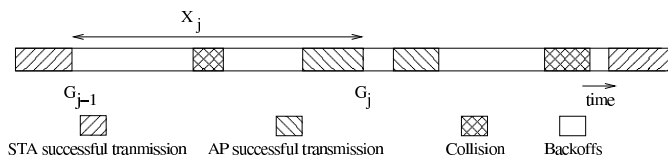


Fig. 3. An example of activities in a channel. Here,  $G_j$  are random time instants at which successful transmissions complete for a packet. Random duration  $X_k$  denotes the  $j^{th}$  contention cycle  $[G_{j-1}, G_j)$ . Each contention cycle consists of one or more back off periods and collisions but ends with a successful transmission.

## V. EVALUATION

In this section, we compare the numerical results obtained from our analysis with those obtained from simulation using the the Qualnet 4.5 network simulator [21]. The parameters used were taken from the IEEE 802.11b standard and are given in Table I. The error bars in the simulation curves denote 95% confidence intervals. We have taken the STA to be associated at rate 11 Mbps, with control packet transmission rate at 2 Mbps. RTPD is varied from 10ms to 90ms in step of 10ms. TCP Receive window is taken as 70 packets.

In Table II, the average number of packets in the AP obtained from analysis and simulations are shown. Further, to verify the accuracy of the model we compared number of packets ‘in flight’ (Table III) and in STAs buffer (Table IV).

RTPD(ms)	Analysis	Simulation		
	Packets	Mean	Max	Min
10	34.75	34.77	37.40	32.14
20	29.89	29.93	33.05	26.81
30	31.52	31.58	33.47	29.66
40	28.85	28.90	30.68	27.12
50	26.92	26.97	28.79	25.14
60	26.78	26.84	28.22	25.46
70	23.84	23.89	25.19	22.59
80	22.34	22.40	23.46	21.33
90	20.51	20.56	21.45	19.67
100	19.27	19.32	19.94	18.71

TABLE II  
NUMBER OF PACKETS IN AP BUFFER AT RATE 11Mbps FOR DIFFERENT VALUES OF RTPD.

RTPD(ms)	Analysis	Simulation		
	Packets	Mean	Max	Min
10	3.19	3.19	3.21	3.18
20	6.37	6.361	6.39	6.33
30	9.55	9.536	9.59	9.48
40	12.74	12.723	12.78	12.66
50	15.92	15.89	15.96	15.82
60	19.06	19.02	19.12	18.92
70	22.22	22.168	22.31	22.03
80	25.44	25.381	25.52	25.25
90	28.57	28.492	28.61	28.37
100	31.65	31.557	31.71	31.4

TABLE III  
NUMBER OF PACKETS IN “IN FLIGHT” FOR DIFFERENT VALUES OF RTPD.

In Tables V and Figures 4, 5, 6 and 7 comparisons between analytical and simulation values are given for 11Mbps to

RTPD(ms)	Analysis	Simulation		
	Packets	Mean	Max	Min
10	32.07	33.40	36.8	30.00
20	33.74	33.14	35.46	30.82
30	28.93	27.95	29.88	26.03
40	28.40	28.55	30.17	26.94
50	27.16	27.99	29.99	25.98
60	24.16	24.12	25.44	22.79
70	23.94	23.36	24.69	22.03
80	22.22	22.59	23.69	21.47
90	20.93	20.21	21.42	18.99
100	19.09	19.41	20.04	18.78

TABLE IV  
NUMBER OF PACKETS IN STAs BUFFER AT RATE 11 Mbps FOR DIFFERENT VALUES OF RTPD.

RTPD(ms)	Analysis	Simulation		
	packets/s	Mean	Max	Min
10	320.26	320.34	321.47	319.21
20	319.54	319.75	320.97	318.54
30	319.45	319.64	321	318.29
40	319.38	319.57	321.2	317.95
50	319.07	319.15	320.46	317.86
60	318.85	319.11	320.55	317.68
70	318.49	318.75	320.34	317.17
80	318.41	318.56	319.81	317.33
90	318.32	318.45	319.71	317.21
100	318.3	318.53	320.01	317.06

TABLE V  
THROUGHPUT OF THE AP WITH A SINGLE STA AT RATE 11 MBPS FOR DIFFERENT VALUES OF RTPD. TCP WINDOW = 100 PACKETS

illustrate the accuracy of the analytical model. We can notice from the Figures 4 for both simulation and analysis that average throughput decreases faster with window size 40 compare to window size 70 as RTPD increases.

## VI. CONCLUSION

In this paper we developed a simple analytical framework to obtain accurate closed-form expressions for the performance of the AP and STAs with persistent TCP connections in the presence of round trip propagation delay. We verified the accuracy of the analytical model with the simulation results. We consider that TCP in its steady state, the TCP advertised window is smaller than the TCP congestion window.

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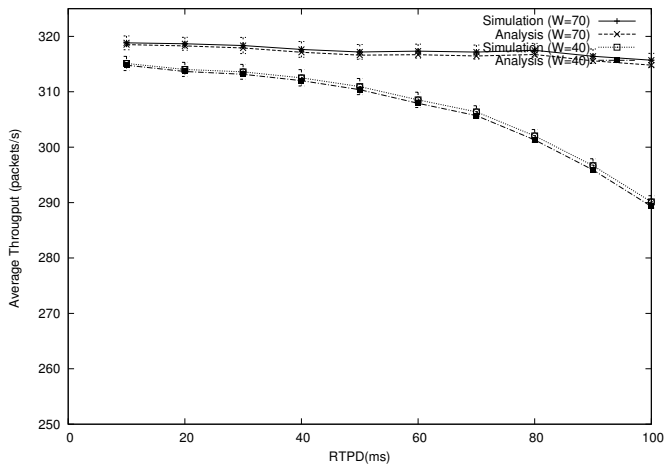


Fig. 4. TCP throughput vs RTPD for TCP window 40 and 70 packets

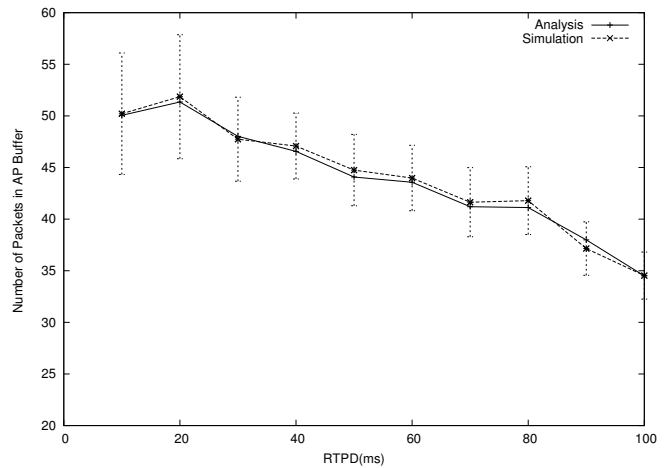


Fig. 6. Number of Packets in AP buffer. TCP window = 100 packets.

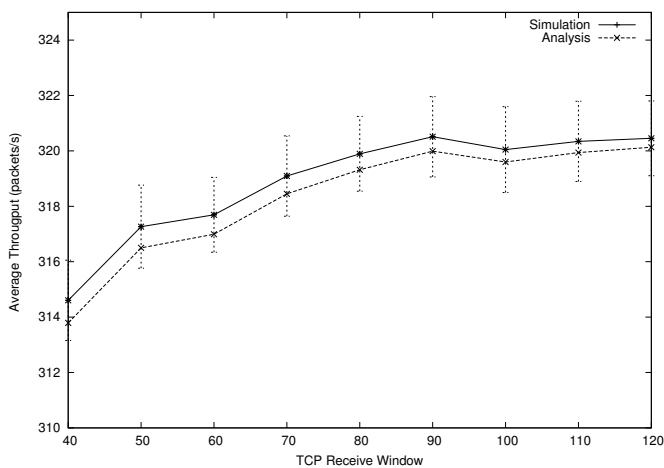


Fig. 5. TCP throughput vs TCP window for RTPD of 10 ms

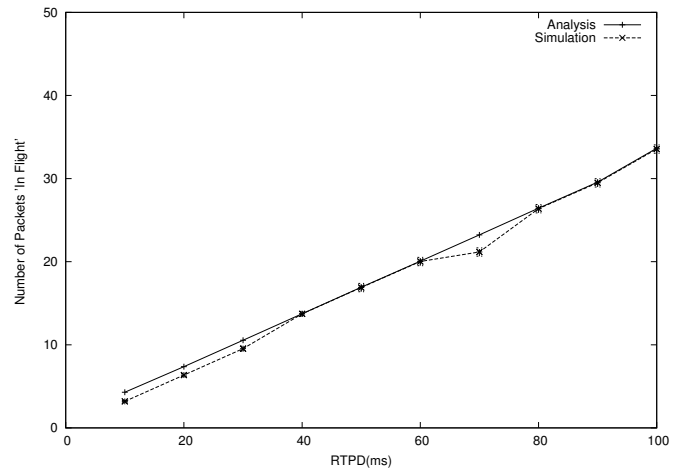


Fig. 7. Number of Packets In Flight. TCP window = 100 packets.

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