The Throughput of TCP Over Wireless Local Area Networks

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Abstract. The TCP protocol performance over Wireless Local Area Networks with 802.11b is analysed in this paper. Based on the communication system consisting of a large number of source-destination TCP pairs, a model for a TCP connection is proposed. According to the principles of TCP and RTS/CTS Access mechanism, the normalized throughput and the utilization of time slots are conducted. Based on the relevant parameters at TCP and MAC layers, TCP performance are analysed, and factors which determine TCP performance are explicitly obtained.

1. Introduction

In Wireless Local Area Networks (WLAN’s), the medium access control (MAC) protocol is the main element that determines the efficiency of sharing the communication bandwidth of the wireless channel. The distributed coordination function (DCF), based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol, was declared as the fundamental mechanism in 802.11 protocol [1]. A four-way handshaking technique called request-to-send/clear-to-send (RTS/CTS) mechanism was described as an optional scheme in DCF.

Since then, much effort has been devoted to the performance and the improvement on the MAC layer. The IEEE 802.11 protocol was explained in [2], and the medium access control sublayer was investigated. In [3], an analytical model for RTS/CTS Access mechanism was proposed, and the throughput performance of DCF was evaluated. The performance of IEEE 802.11 with RTC/CTS access mechanism was analysed under stationary traffic and network configurations in [4]. In order to support quality-of-service, a protocol at MAC layer was proposed in [5]. In [6], a physical layer methodology and a corresponding MAC protocol were proposed for multipacket reception at a given time. The framework of game theory for access points selection was adopted in [7] to achieve overall system throughput. In [8], a wireless IP forwarding architecture that uses MPLS with modifications to 802.11 MAC layer was proposed, which improves packet forwarding efficiency and system throughput in multihop 802.11 based IP networks. A frame aggregation scheme, which aggregates small-size frames into a large frame, is proposed in [9], and overheads of physical layer and MAC layer can be reduced to improve throughput performance. A MAC layer handoff algorithm which implements make-before-break mechanisms was proposed in [10], and made the handoff more efficiently. In [11], a parallel space-time Markov chain was adopted to evaluate the DCF in WLAN’s. In [12], the performance of IEEE 802.11 was analysed, and throughput upper limit and delay lower limit were theoretical proposed. Based on simulations, three services were evaluated with TCP and UDP flows over WLAN’s in [13]. A DCF model using the parallel space-time Markov chain was proposed in [14], and the contention phase, the backoff procedure, the post-backoff procedure, and the transmission queue
status were analysed. In [15], an analytical model was proposed for DCF with hidden terminals over WLAN’s, and the throughput in saturated situation was analysed. The problem of buffer sizing of TCP stream based on 802.11 was analysed [16]. The TCP protocol and random access mechanism was also introduced into hadoop distributed file system to solve the random queries problem of large-scale data [17]. The Machine-to-Machine/Internet of Things services has been experiencing a continuous growth in the last few years, with the random access schemes commonly used. In [18], the comparison between TCP Tahoe, TCP Reno and TCP New Reno over various routing protocols was analysed with simulation. The comparison of TCP Old Tahoe and Tahoe in wireless mesh networks was conducted in [19], and the performance such as throughput, propagation delay and packets retransmitted, was analysed.

In this paper, The DCF based on RTS/CTS scheme is concentrated on the performance of TCP in WLAN’s with 802.11b. Firstly, the slow start phase and the congestion avoidance phase are considered for the condition that a lot of same SD pairs are competing over a free channel. Secondly, the normalized throughput and the utilization of time slots are obtained. With theoretical analysis and simulations, which factors playing role for the performance of TCP over DCF in WLANs are clearly deduced.

The rest of this paper is organized as follows: In Section 2, the system architecture for TCP terminals over WLANs is provided. Then transmission time for a pair of TCP data segment and TCP ACK segment is analysed. In Section 3, the normalized throughput and the utilization of a TCP connection are theoretical analysed. Finally, in Section 5, the main findings and the conclusion are represented in this paper.

2. The Model of TCP Connection in WLANs with 802.11b

In 1970s, TCP was proposed for reliable, end-to-end and flow control over wire networks [20]. Since then, many algorithms have been made [21-24]. Due to that TCP is one of the popular protocol in global networks, the performance of TCP in WLANs is analyzed in this paper, and a typical communication system consists of a large number of identical SD pairs over a common DCF based on RTS/CTS scheme is shown in Figure 1. For every SD pair, the length of all TCP segments is the same, they are encapsulated into a packet at the MAC layer, and transmitted in one time slot. As shown in Figure 2, TCP is a complex protocol that many data congestion control themes are composed together, such as the window flow control scheme, timeout-based retransmission scheme, slow start scheme, congestion avoidance scheme, fast re-transmit/recovery scheme, and so on. Between a pair
of SD, since a TCP connection is established, data segments begin to be sent in the slow start phase. Based on the acknowledgments (ACK) which conform data segments are received successfully at receiver, CWND increases in exponential way, and TCP sends following data segments. As soon as CWND reaches to the threshold ($W_0$), the TCP connection transforms to the congestion avoidance phase, and CWND increases in linear way. When three more duplicated acknowledgments (ACK) reach to the TCP receiver, more than one TCP data segment may be lost during transmission, the fast retransmit/recovery scheme is invoked, and lost data segments are retransmitted from the source node. The ACK which confirms that lost data segments are successfully retransmitted, $W_0$ is set to $CWND/2$, CWND is also halved, and TCP transforms to the congestion avoidance phase. Considering not to slow down data traffic too much, CWND is halved only once in the congestion avoidance for each round-trip. If timeout (RTO) of a TCP connection expires, TCP data continues to be transmitted as a new connection from the slow start phase as the CWND is 1. As assumed in [3] [25], the probability of a collision of each packet $p$ is independent and constant. The assumption is more accurate as long as CWND and the number of SD pairs becomes larger.

![Figure 2. The Protocol of TCP.](image)

![Figure 3. System with a large number of SD pairs in WLANs.](image)

Every TCP data segment must be encapsulated as a packet at MAC layer. In order to avoid packet collisions, packets are processed as shown in Figure 3 by means of the RTS/CTS Access mechanism. If a station needs to send data packet, it transforms to data sending stage, and waits for a period of time equal to a distributed interframe space (DIFS). If the wireless channel is still idle, a RTS packet is sent. As a CTS packet is received after a period of time called short interframe space (SIFS), which indicating that the channel is clear, the station waits for another SIFS, and send a data packet. When an ACK packet reaches at the sender after a SIFS, this data packet is successfully transmitted. Then, all wireless
stations that need to send data packets transform to backoff stage. The Backoff time, \( n_{bf} \), which is the number of time slots, is uniformly set in the range \((0, W_{MAC} - 1)\), where \( W_{MAC} \in [W_{MAC}^{\min}, W_{MAC}^{\max}] \) is contention window. \( n_{bf} \) is reduced by 1 after each time slot. If wireless channel is idle at the time that \( n_{bf} = 0 \), the station transforms to data sending stage, and a new data packet is processed to send. Otherwise, \( W_{MAC} \) is doubled until reaches \( W_{MAC}^{\max} \) and \( n_{bf} \) is uniformly reset as before.

Figure 4. a TCP data segment and its corresponding TCP ACK segment processed at MAC layer.

Due to that every TCP ACK segment is processed as same as the procession of TCP data segment at MAC layer, a TCP data segment and its corresponding TCP ACK segment are processed at MAC layer as shown in Figure 4. So the transmission time for a pair of TCP data segment and TCP ACK segment is deduced as follows:

\[
\begin{align*}
T_{\text{data}} &= n_{bf}^{\text{data}} < \sigma + \text{DIFS} + \delta + \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + \text{TCP}_{\text{data}} + \text{SIFS} + \delta + \text{ACK}_{MAC} = n_{bf}^{\text{data}} < \sigma + \text{DIFS} + \text{RTS} + 3 < \text{SIFS} \\
T_{\text{ACK}} &= n_{bf}^{\text{ACK}} < \sigma + \text{DIFS} + \delta + \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + \text{TCP}_{\text{ACK}} + 3 \cdot \text{SIFS} + \text{TCP}_{\text{ACK}} + \text{ACK}_{MAC} + 4\delta
\end{align*}
\]

(1)

\( n_{bf}^{\text{data}} \) and \( n_{bf}^{\text{ACK}} \) indicate the number of time slots in the stages of TCP data processing and TCP ACK processing individually, \( \sigma \) is the length of a slot time, \( \delta \) is propagation delay, \( T_{\text{data}} \) is propagation time of a packet encapsulating a TCP data segment, \( T_{\text{ACK}} \) is propagation time of a packet encapsulating a TCP ACK segment.

3. Throughput and utilization of TCP connection in WLANs

For the analysing of TCP performance, the normalized throughput for every SD pair is considered in this paper. According to [3], the normalized throughput is the number of packets (also the number of TCP segments) successfully sent per time slot. During the entire data transmission of the TCP connection, \( M \) is set the number of packets successfully sent, and \( L \) is the length of the TCP connection. The normalized throughput, \( T \) is expressed as

\[
T = \frac{E[M]}{E[L]}.
\]

(2)

In order to analysis the utilization of time slots which is occupied for the data transmission of a TCP connection, we let

\[
U = T \cdot N_s.
\]

(3)

\( N_s \) is the number of time slots for transmitting a TCP data segment.

According to RTS/CTS Access mechanism, packets will be transmitted in the condition that
wireless channel is clear. The concept of cycle is derived from [25]: the interval between two successive RTOs, Therefore, the TCP fast retransmit/recovery scheme is almost not be invoked for retransmitting data segments, and CWND is in the increase status until reach to the maximum value, \( W_m \). We let \( R_{top} \) be the round that CWND reaches to \( W_m \) at the first time, \( R_{total} \) be the total round of the whole TCP connection, \( W_j \) be the size of CWND in the last round, and \( W \) be the number of rounds in slow start phase. According to that CWND is doubled every round, \( 2^W = W_0 \). Then in Slow Start and Congestion Avoidance phases, the number of TCP segments sent in the whole TCP connection is deduced a

\[
\begin{align*}
M^0 &= \sum_{k=1}^{W+1} 2^{k-1}, \\
M^{1,1} &= \sum_{k=W+1}^{R_{top}} (W_0 + k - W) = \sum_{k=W+1}^{R_{top}} (2^W + k - W), \\
M^{1,2} &= \sum_{k=R_{top}}^{W_m + W_j} 1.
\end{align*}
\]

(4a) indicates the number of packets sent in the slow start phase. (4b) means the number of packets sent before CWND reaches to \( W_m \) in the congestion avoidance phase, and (4c) indicates the number of packets sent after CWND reaches to \( W_m \). Therefore, \( M \) is derived as

\[
M = M^0 + M^{1,1} + M^{1,2} = 2^W - 1 + \frac{1}{2} (R_{top} - W) (2^W + R_{top} - W) + W_m (R_{total} - R_{top}) + W_j.
\]

And \( M_b \) is

\[
M_b = M \cdot N_b.
\]

\( N_b \) is the length of a TCP segment.

As assumed in [3,25], the probability that the wireless channel is occupied of each time slot \( p \) in independent and constant. Let \( m = W_{MAC}^{min} \cdot 2^n \), \( m = W_{MAC}^{max} \), then \( E[n_{data}^{bf}] \) and \( E[n_{ACK}^{bf}] \) are derived as (7).

\[
E[n_{data}^{bf}] = E[n_{ACK}^{bf}]
\]

\[
= \frac{1-p}{m} \sum_{k=0}^{2^n-1} k + \frac{p^n(1-p)}{2^m} \sum_{k=0}^{2^n-1} \frac{(k + \frac{2m-1}{2} + \frac{2^{n-1}m-1}{2})}{2} + \eta
\]

\[
= \frac{(1-p)}{2} \sum_{k=0}^{n} ((2^{k+1}-1)m - (k+1))p^k + \eta. \tag{7}
\]

\( \eta \) is the value that after \( W_{MAC}^{MAC} \) reaches \( W_{MAC}^{max} \), the expression is (8).

\[
\eta = \sum_{k=0}^{n} p^k \left( \frac{2^n m^2 (2^n + 2^{n+1} + 2^{n+1} - 1)}{2} - \frac{2^n (2 + n + k)}{2} \right). \tag{8}
\]
Table 1. Parameters for performance analysis of a TCP connection over WLANs access links.

| Parameter          | Value                        |
|--------------------|------------------------------|
| Standard           | IEEE 802.11b                 |
| Channel Bit Rate   | 10 Mbit/s                   |
| TCP data segment   | \( Nb = 1460 \) bits         |
| SIFS               | 10us                        |
| slot time          | \( \sigma = 20 \) us        |
| DIFS               | SIFS + 2 \( \cdot \sigma \)  |
| \( W_{\text{MAC}}^{\min} \) | 16                          |
| \( W_{\text{MAC}}^{\max} \) | 16, 32, 64, 128, 256         |
| \( p \)            | 0, 0.01, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1 |

Hence, \( E[L] \) is derived as (9).

\[
E[L] = E[M]E[(T_{\text{data}} + T_{\text{ACK}})] \\
= E[M]E[H_{\text{bf}} + \sigma + TCP_{\text{data}} + n_{\text{bf}}^{ACK} + \sigma + TCP_{ACK}] \\
+ 2(DIFS + RTS + CTS + ACK_{MAC}) + 6 \cdot SIFS + 8\delta. \tag{9}
\]

As analysis in Section 2, the time for a round between a SD pair includes two parts: the time for TCP data segments transmitted from sender to receiver and the time for the TCP ACK segments transmitted back. According to (1) and (9), \( T_S \) is expressed as (10).

\[
T = \frac{E[M]}{E[L]} = \frac{1}{E[T_{\text{data}} + T_{\text{ACK}}]} \\
= \frac{1}{E[H_{\text{bf}} + n_{\text{bf}}^{ACK}] \sigma + TCP_{ACK} + 2(DIFS + RTS + CTS + ACK) + 6SIFS + 8\delta}. \tag{10}
\]

4. Performance Analysis

According IEEE 802.11b and TCP, the parameters of the MAC and transport layer, which are relevant to the performance analysis of a TCP connection over WLANs links, are proposed in Table 1.

Channel data transmitting rate is set 10Mbit/s, SIFS is set 10us, slot time, \( \delta \), is set 20us, and DIFS is SIFS + 2\( \delta \). We let \( W_{\text{MAC}}^{\min} = 16 \), and \( W_{\text{MAC}}^{\max} \) as 16, 32, 64, 128 and 256. The packet collision probability, \( p \), is set from 0 to 1.

Based on that the packets of RTS, CTS, ACKMAC are very small, each packet is transmitted in one time slot. Under normal conditions, the range of WLANs is not larger than 100 meters, and \( \delta \) can be ignored. The length of a TCP data segment is not larger than 1500 Bytes, and the length of a TCP ACK segment is not larger than 50 Bytes. Therefore, A TCP data packet needs almost \( N_s = 82 \) time slots for transmitting over 10Mb/s wireless links, and a TCP ACK packet needs only 3 time slots for transmitting. Therefore, \( T \) is expressed as

\[
T \approx \frac{1}{(E[H_{\text{bf}} + n_{\text{bf}}^{ACK}] + 100) \cdot \sigma}. \tag{11}
\]
Figure 5. The throughput of a TCP connection in case of $W_{\text{MAC}}^{\text{max}}$.

Figure 6. The utilization of a TCP connection in case of $W_{\text{MAC}}^{\text{max}}$.

Then $U$ is

$$U = T \cdot N_s = \frac{82}{E[n_{\text{data}}^{\text{bf}} + n_{\text{ACK}}^{\text{bf}}]} + 100.$$  \hspace{1cm} (12)

We set $p$ from 0 to 1, the throughput of a TCP connection in case of five $W_{\text{MAC}}^{\text{max}}$ values is shown as Figure 5. Obviously, it is very small and decreases as $p$ increases. After $p > 0.5$, the throughput decreases rapidly. It is also concluded among all the cases of $W_{\text{MAC}}^{\text{max}}$ values, the throughput in case of $W_{\text{MAC}}^{\text{max}} = 16$ is the largest, and the throughput in case of $W_{\text{MAC}}^{\text{max}} = 256$ is the smallest.

Figure 6 indicates the utilization of time slots for data transmission of a TCP connection. If $p = 0$, that means no packet collision over wireless links, the utilization ratio is almost 70%, and it decreases as $p$ increases. And the smaller the $W_{\text{MAC}}^{\text{max}}$, the higher the utilization ratio than 60% if $p > 0.3$. And if $p > 0.5$, the utilization ratio is less than 50% in any case of $W_{\text{MAC}}^{\text{max}}$. 
In Figure 7, we can get that the throughput of a TCP connection is not high in all cases of $p$. However, as Figure 8 shows, in cases of different $W_{\text{MAC}}^{\text{max}}$ values, the utilization is much higher than 60% if $p \leq 0.3$. And if $p > 0.5$, the utilization ratio is less than 50% in any case of $W_{\text{MAC}}^{\text{max}}$.

5. Conclusion
The following researches are deduced for analyzing the performance of TCP over WLANs: firstly, the model of TCP connection in WLANs with 802.11b is established; secondly, the normalized throughput and the utilization of time slots are theoretical analyzed; finally, simulations are processed to get the factors affecting TCP performance. According to our analysis, the performance of a TCP connection over WLANs is little affected by data congestion control themes (such as slow start scheme, congestion avoidance scheme, and fast re-transmit/recovery scheme, etc), but greatly affected by $W_{\text{MAC}}^{\text{max}}$ and $p$. Regardless of $W_{\text{MAC}}^{\text{max}}$ in case of that no packet collision, although the normalized throughput is not
high, the utilization of a TCP connection is almost 70%. However, if $p < 0.5$, the utilization is less than 50% in any case of $W_{\text{MAC}}^{\text{max}}$.

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References
[1] IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Nov. 1997, P802.11.
[2] Crow B P, Widjaja I, Kim J G and Sakai P T 1997 IEEE 802.11 Wireless Local Area Networks IEEE Communications Magazine 35(9) 116-126
[3] Bianchi G 2000 Performance analysis of the IEEE 802.11 distributed coordination function IEEE Journal on Selected Areas in Communications 18(3) 535-547
[4] Cali F, Conti M and Gregori E 2000 IEEE 802.11 protocol: design and performance evaluation of an adaptive backoff mechanism IEEE Journal on Selected Areas in Communications 18(9) 1774-1786
[5] Carlson E, Prehofer C, Bettstetter C, Karl H and Wolisz A 2006 A Distributed End-to-End Reservation Protocol for IEEE 802.11-Based Wireless Mesh Networks IEEE Journal on Selected Areas in Communications 24(11) 2018-2027
[6] Zheng P X, Zhang X J and Liew S C 2006 Multipacket Reception in Wireless Local Area Networks 2006 IEEE International Conference on Communications (Istanbul, Turkey, Dec. 2006)
[7] Yen L, Li J and Lin C 2011 Stability and Fairness of AP Selection Games in IEEE 802.11 Access Networks IEEE Transactions on Vehicular Technology 60(3) 1150-1160
[8] Acharya A, Misra A and Bansal S 2003 High-performance architectures for IP-based multihop 802.11 networks IEEE Wireless Communications 10(5) 22-28
[9] Kim Y, Choi S, Jang K and Hwang H 2004 Throughput enhancement of IEEE 802.11 WLAN via frame aggregation IEEE 60th Vehicular Technology Conference (Los Angeles, CA, Sep. 2004)
[10] Ramachandran K, Rangarajan S and Lin J C 2006 Make-Before-Break MAC Layer Handoff in IEEE 802.11 Wireless Networks 2006 IEEE International Conference on Communications, (Istanbul, Turkey, Jun. 2006)
[11] Ghaboosi K, Khalaj B H, Xiao Y and Latva-aho M 2008 Modeling IEEE 802.11 DCF Using Parallel Space-Time Markov Chain IEEE Transactions on Vehicular Technology, 57(4) 2404-2413
[12] Xiao Y and Rosdahl J 2002 Throughput and delay limits of IEEE 802.11 IEEE Communications Letters 6(8) 355-357
[13] Aad I and Castelluccia C 2001 Differentiation mechanisms for IEEE 802.11 Proceedings IEEE INFOCOM 2001 (Anchorage, Anchorage, AK, USA, Apr. 2001)
[14] Senthilkumar T D, Krishnan A and Kumar P 2008 Nonsaturation throughput analysis of IEEE 802.11 distributed coordination function 2008 International Conference on Electrical and Computer Engineering (Dhaka, 2008)
[15] Wu H, Zhu F, Zhang Q and Niu Z 2006 WSN02-1: Analysis of IEEE 802.11 DCF with Hidden Terminals IEEE Globecom 2006 (San Francisco, CA, 2006)
[16] Jamshaid K, Shihada B, Xia L, et al. 2011 Buffer Sizing in 802.11 Wireless Mesh Networks Eighth IEEE International Conference on Mobile Ad-Hoc and Sensor Systems (Vlencia, Spain, Oct. 2011)
[17] Zhou W, Han J, Zhang Z, et al 2012 Dynamic Random Access for Hadoop Distributed File System IEEE 32nd International Conference on Distributed Computing Systems Workshops (Macau, China, Jun. 2012)
[18] Shenoy, Sharada U, et al 2017 Performance analysis of different TCP variants in wireless ad hoc networks 2017 International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC) (Tamilnadu, India, Feb. 2017)
[19] Unnikrishnan R, Devi S R, Ramesh R, Rajesh A, Varma A 2017 A comprehensive analysis of TCP congestion control schemes in wireless mesh networks International Conference on Intelligent
Computing, Instrumentation and Control Technologies (ICICIICT) (Vimal Jyothi Engineering College, India, 2017)

[20] Cerf V, and Kahn R 1974 A protocol for packet network intercommunication IEEE Transactions on Communications 22(5) 637-648
[21] Jacobson V and Karels M 1988 Congestion avoidance and control ACM Sigcomm Computer Communication Review 18(4) 314-329
[22] Jacobson V 1990 Modified TCP congestion avoidance algorithm Technical Report, Apr. 1990.
[23] Brakmo L and Peterson L 1995 TCP Vegas: End to end congestion avoidance on a global internet IEEE Journal on Selected Areas in Communications 13(8) 1465-1480
[24] Henderson T, Floyd S, and Gurtov A 2012 The New Reno modification to TCP’s fast recovery algorithm IETF RFC 6582, Apr. 2012
[25] Liu J, Han Z, Li W 2020 Performance Analysis of TCP New Reno Over Satellite DVB-RCS2 Random Access Links IEEE Transactions on Wireless Communications 19(1) 435-446