TCP and IEEE 802.11b Protocol Performance in Indoor Wireless Channels

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ABSTRACT

Measurements of TCP flows in indoor wireless channels are analyzed to evaluate the response of TCP and IEEE 802.11b protocols in time-varying multipath channels. For the same position of the mobile terminal and access point, throughputs range from 2 - 5.5 Mbps under diverse channel conditions. Throughput limiting effects are found to result from both channel and protocol related events. Signal fade durations typically range from 1-4 seconds and the wireless channel induces multiple losses of the same TCP segment during these events. As a result, TCP backs off transmission for large time periods. During good channel conditions, a periodic loss behavior is observed at time intervals on the order of two seconds. These events are triggered by the growth of TCP congestion window to the maximum allowed by the receiver, causing an instantaneous increase in segment arrival rate at the access point. This results in overflows in the access point buffer. The lack of synchronization between the time scales involved in congestion window growth and channel access result in the pseudo-periodic TCP loss behavior on wireless channels.

1. INTRODUCTION

The IEEE 802-11b standard defines the medium access control (MAC) and physical (PHY) layer protocols for radio transmission in the unlicensed 2.4-2.485 Ghz frequency band. The performance of IEEE 802.11b systems has been investigated in many recent studies[1–4] . When the overhead generated by TCP, MAC and PHY layers are accounted for TCP throughput is expected to be on the order of 5.0 Mbps when operating at the 11 Mbps specification[1] . The positioning of the mobile terminal in non-LOS positions from the access point has also been found to significantly reduce throughput[3] . In this work TCP transmission experiments are carried out in indoor channels under non-LOS conditions and causes for throughput degradation is examined. By making simultaneous measurements of TCP headers, signal levels and MAC layer losses, the impact of channel and protocol related performance issues may be addressed. Section 2 presents a discussion of the measurement setup. The characterization of measurments is presented in Section 3. Section 4 presents some conclusions.

2. TCP AND CHANNEL MEASUREMENTS IN WIRELESS LANS

The performance of TCP and 802.11b protocols was measured using commercially available base stations and wireless cards. The network was configured in infrastructure mode with an Apple Airport base station functioning as the access point (AP). The AP was connected to a server on the wired Ethernet through a 100 Mbps hub. The mobile terminal (MT) was a Red Hat 8.0 (Linux) system equipped with the Lucent Orinoco wireless network interface card. The measurements were performed inside a research laboratory that consists of office cubicles, computer equipment, a conference area and people. TCP and channel performance are investigated for the case where the MT is placed behind a row of steel cabinets, thus forming a non-LOS transmission path. This position yields a number of time-dependent performance profiles that highlight the influence of an interference prone multipath channel.

The experiments involve the generation of TCP flows from the server to the MT. The application forwards data to the TCP layer at a specified rate which ranges from $0.5 - 4.5$ Mbps. The server opens a TCP connection to the MT and transmits data on the wired connection to the AP. During the course of the experiment, the packet headers are monitored at both the server and the client using the *tcpdump* utility. The measurement traces include the timestamp at microsecond resolution, TCP sequence (SEQ) and acknowledgement (ACK) numbers, and receiver window size. In addition to TCP packet monitoring, a MAC layer monitoring utility, available in the wireless extension tools was executed during the measurements. The MT is kept stationary for the duration of the experiment. The TCP performance for the wireless connection was examined in single user mode in order to isolate the channel effects on throughput from multiple user effects.

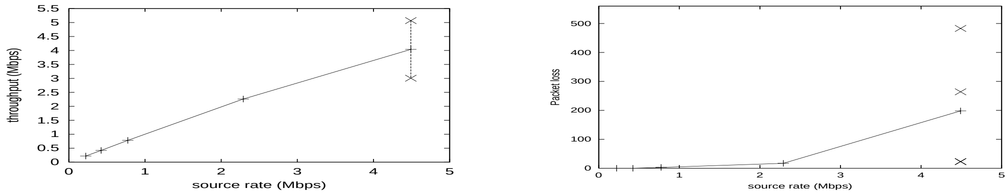
3. CHARACTERIZATION OF TCP FLOWS

The MT implements the Reno version of TCP congestion control[5] . The key features of this version are fast retransmit and fast recovery under segment losses. TCP maintains a congestion window (cwnd) parameter that evolves in time, the size of which determines the number of segments that may be transmitted at that time. The receiver responds with an acknowledgement (ACK) for every two segments that it has received and advertises a window (rwnd) available with each ACK. The number of segments transmitted is the minimum of cwnd and rwnd. Upon loss of a TCP segment, the receiver sends a duplicate ACK, for every out of order segment arriving at the receiver. After three duplicate ACKs are received, the source retransmits the segment assumed to be lost. For each additional duplicate ACK received, the cwnd is increased by one segment and a segment is transmitted. The retransmision and recovery phases are typically completed within a RTT, if the retransmitted segment was received. When multiple losses of the same segment occurs in two successive windows, retransmission backoff is set in place.

The average TCP throughput measured at the mobile client is plotted as a function of application source rate in Fig. 1 (a). For source rates in the 1-2.5 Mbps range, the link utilization is less than 50% and the throughput follows the application rate. For source rates that result in higher utilizations, TCP performance was limited by channel conditions. For transmission attempts at 4.5 Mbps and greater, a significant variability was observed in the throughput and loss performance metrics. As shown in Fig. 1 (a), over different measurement ensembles at these rates, throughputs at the receiver ranged from $3-5$ Mbps. A variable loss and throughput rate was observed during repeated experiments made for the same position of the MT. In Fig. 1 (b), the average number of packet losses observed is shown for each of the source data rates. At the bottleneck rates, the packet losses range from $0.05-0.6$ % and these variations reflect the sensitivity of the protocols to channel features. This result shows the effect of time-varying channels on TCP loss performance. The effective throughput at the receiver ranges from nearly 5 Mbps down to about 2.2 Mbps over the six experimental traces obtained for the same position.

The rest of the paper analyzes TCP performance for the limiting case of source rates greater than 4.5 Mbps. To evaluate the cause of the performance degradation three measurement traces were analyzed. These traces are representative of poor, moderate and good channels, represented as Set-I, Set-II and Set-III respectively. Fig. 2 (a-c) depicts the TCP sequence number growth in time for these cases. Indicated on these plots are vertical bars that depict the position in time where TCP segment losses were observed. The length of the bars depict the number of times the same segment was lost. Multiple losses have been found to range from 2-4. The panels in Fig. 3 (a-c) show the variation in signal level at the receiver during the course of the experiment. Also shown in these figures are time positions where the MAC layer of the receiver dropped a packet. These events were obtained from the iwevent utility of the wireless tools package. The signal levels show variations in the range of 6 decibels and the durations spent in the fade regions range from 1-4 seconds. The Set-I data exhibits faster transitions between the low and high signal levels and renders increased uncertainty in the channel sensing and access procedures carried out at the MAC layers of the wireless nodes. As a result one sees an increased number of drops at the MAC layer along with multiple losses of a retransmitted TCP segment. When multiple losses occur, TCP executes an exponential retransmission backoff using timeout values that increase as $3, 6$ and 12 seconds with each segment loss[6] . As a result, the channel can remain idle for durations upto 12 seconds. This feature has been found to be one of the primary causes of TCP throughput reduction in the measurements.

It is also observed that single losses of TCP segments are a characteristic feature across all three of the experiments. These losses are uniformly distributed in time and often independent of channel conditions. The comple-



(a) TCP throughput vs source rate (bps) (b) TCP losses vs source rate

Figure 1. TCP throughput and loss performance as a function of source rate.

mentary distribution function of the time between losses is shown in Fig.4 (a) for the three experiments. The horizontal axis represents the time between losses τ and the vertical axis depicts the $Pr[time\ between\ losses > \tau]$. The mean time between losses decreases from 4.5 to 1.2 seconds as the channel progresses from good to poor conditions. A distinctive feature observed in the loss pattern for all three cases and more predominantly for the good channel Set-III, is a deterministic trend, where the time between losses fluctuates around a 2 second time period. This feature can be visualized in the scatter plot of Fig. 4 (b) which shows the number of packets that were transmitted between the loss events as a function of the time between losses. Several distinct clusters are observed that may be attributed to channel and protocol related events. The instances of $12, 6, 3$ and 1.5 seconds between losses result from exponential backoff of TCP during multiple loss of the same segment. The linear trend between these two variables is expected behavior of the wireless link during good channel conditions. The dense cluster that occurs around the 2 second and 1000 packets region represents losses that occur due to buffer overflows at the AP. In this regime, the effective throughput is on the order of 5.8 Mbps and close to 100% of the channel capacity. This regime is visited periodically in the transmission process. The second cluster of events highlighted in the figure represents the channel losses during slow throughput conditions, which take place during the channel fade durations.

4. CONCLUSIONS

An experimental analysis of TCP performance on IEEE 802.11b wireless systems in non-LOS conditions and time-varying channels has been presented. For the same position of the mobile terminal, relative to the access point, a range of performance profiles that result in throughput reductions from 4.5-2.0 Mbps have been observed. A common feature across all of these experiments is the presence of pseudo-periodic loss patterns, occurring at time periods of approximately two seconds. These are attributed to the growth of TCP windows in error-free conditions beyond a size that can be supported by access point buffers. During channel fades, multiple losses of the same TCP segment have been observed causing TCP to execute exponential backoff for upto 12 seconds. These observations support the need for evaluating approaches for better synchronization of the TCP, MAC and PHY layer time-scales that characterize the TCP transmission rate and channel access rates.

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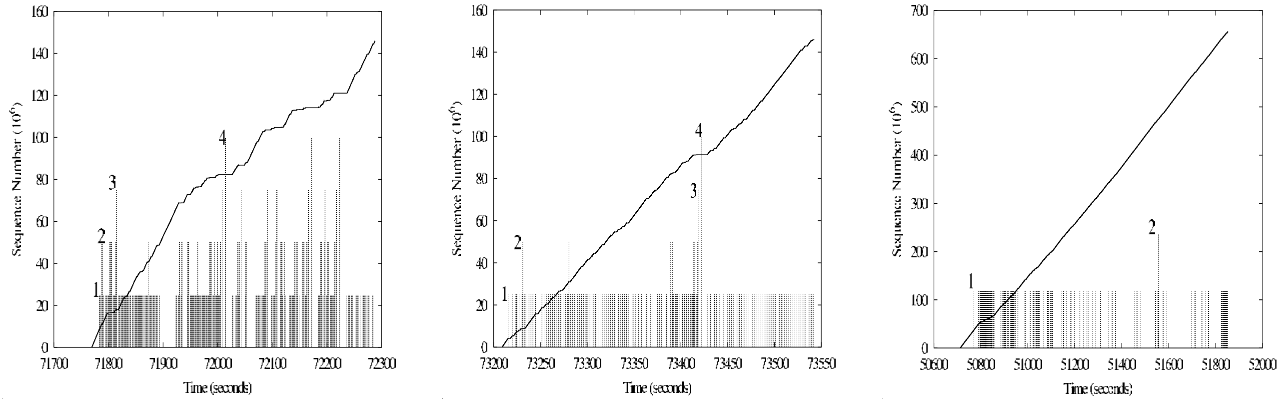
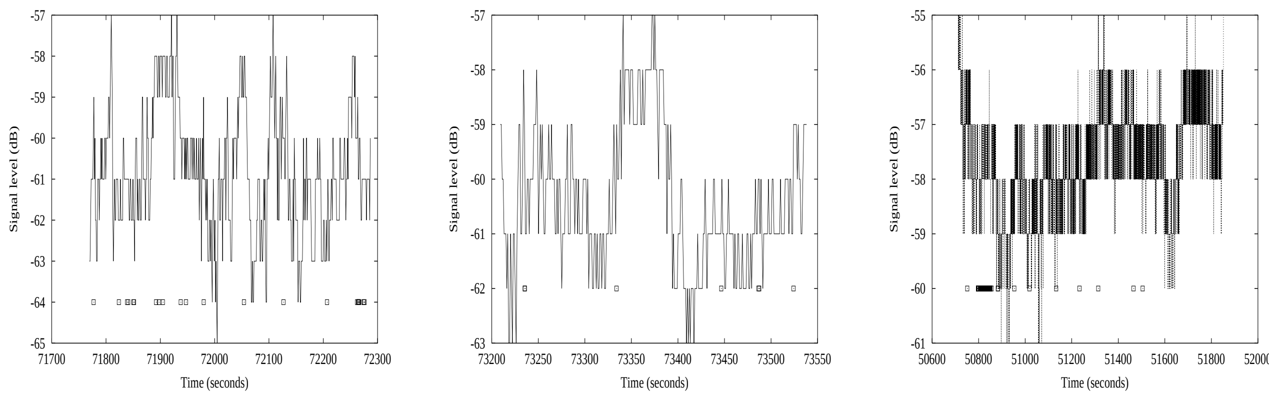


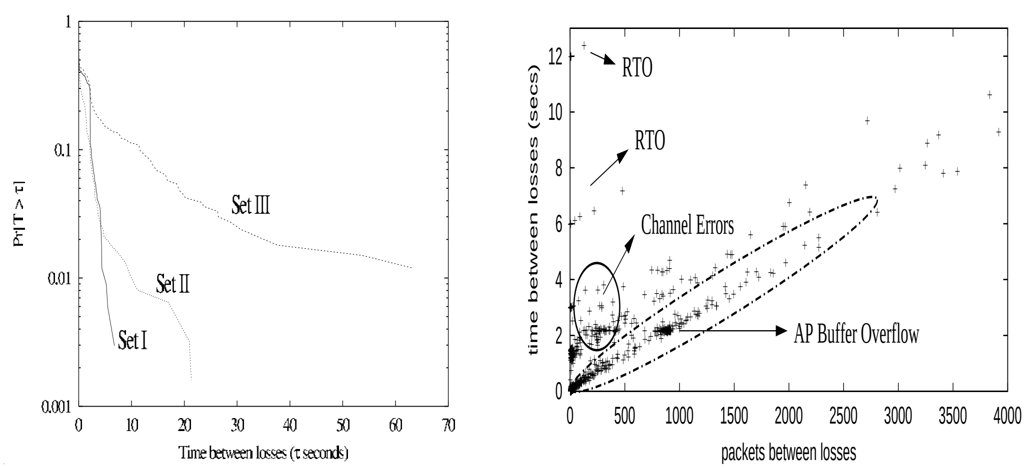
(a)Set I: Poor Channel (b)Set II: Moderate Channel (c) Set III: Good Channel

Figure 2. TCP sequence number growth in time and position of losses. Length of vertical bars indicate number of losses of same segment (1-4).



(a) Set I (b)Set II (c) Set III

Figure 3. Signal level variations in time at receiver. The symbols denote times where MAC layer dropped a packet.



(a) Distribution of time between losses (b) Dependence of packets transmitted and time between losses

Figure 4. Statistics of time between losses and its relation to packets transmitted between losses.