Wireless TCP Model for Short-Lived Flows

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***Abstract*— TCP (Transmission Control Protocol) is one of most important Internet protocols. It provides reliable transport services between two end-hosts. Since TCP performance affects overall network performance, many studies have been done to model TCP performance in the steady state. However, recent research has shown that most TCP flows are short-lived. Therefore, it is more meaningful to model TCP performance in relation to the initial stage of short-lived flows. In addition, the next generation Internet will be unified all-IP network that includes both wireless and wired networks integrated together. In short, modeling short-lived TCP flows in wireless networks constitutes an important axis of research. In this paper, we propose a simple wireless TCP model for short-lived flows that extends the existing model proposed in [1]. In terms of wireless TCP, we categorized wireless TCP schemes into three types: end-to-end schemes, split connection schemes, and local retransmission schemes, which is similar to the classification proposed in [3]. To evaluate the performance of the proposed models, we performed several simulations. The average differences between the calculated session completion time and the simulation result for three schemes are less than 9msec, 16msec, and 7msec, respectively. Consequently, the proposed model provides a satisfactory means of modeling the TCP performance of short-lived wireless TCP flows.**

***Index Terms*— Wireless TCP, Short-lived flow, TCP Modeling.**

I. INTRODUCTION

Transmission Control Protocol (TCP) is one of the most important and widely used Internet protocols. TCP is used in many kinds of Internet applications such as the World Wide Web (WWW), E-mail, FTP services, etc. To date, many analytic models have been published with the purpose of characterizing TCP performance. These models mainly focused on the throughput of bulk transfer services using TCP, especially throughput in the steady state. However, recent research results show that most TCP flows are very short with mean sizes of around 10KB, and that their median sizes are less than 10KB [4] [5]. In other words, the performance of short-lived flows is dependent on the initial phase, specifically the slow-start phase, because short-lived flows don't reach the steady state. Therefore, the existing analytic models cannot be directly employed for short-lived flows. Consequently, alternative analytic models for short TCP flows have been proposed in [1] [2].

Also, previous TCP models focused on the issue of TCP performance over wired networks. However, in the near future, TCP will be widely used as a transmission protocol for wireless networks. Wireless Internet services such as web browsing and mail services are good examples. Furthermore, the advent of wireless and mobile network technologies have already made the wireless Internet market as large as that of wired Internet. Generally, TCP flows in wireless networks are much shorter than those in wired networks, because of the associated high service charges and the fact that the available services are still immature. Therefore, modeling analytically short TCP flows over wireless networks provides a good method of characterizing TCP performance.

In this paper, we propose simple analytic TCP models for wireless networks that extend the existing TCP model proposed for wired networks in [1]. Among the various performance factors, we focus on the completion time of short-lived TCP flows. Although may different schemes have been proposed for improving wireless TCP performance, for simplicity of modeling, we categorized these schemes into three types: end-to-end schemes, split connection schemes, and link layer schemes, which is similar to the classification proposed in [3].

The remainder of this paper is organized as follows. Section II introduces related works, namely several TCP schemes for wireless networks and a few TCP models for short-lived flows in wired networks. Section III describes the basic assumptions underlying our models. In Section IV, we propose analytic models for three wireless TCP schemes. Section V describes the performance evaluation results. Finally, Section VI concludes this paper.

II. PREVIOUS WORK

A. TCP Models for Short-lived Flows

Cardwell et al. extended the steady-state model proposed in [4] to capture startup effects [2]. They observed that most TCP flows are relatively short and their performances are dominated by startup effects such as connection establishment and slow start mechanisms. This extended model characterized the distribution of TCP connection establishment and data transfer latency as a function of the transfer size, round trip time, and packet loss rate.

Mellia et al. proposed a recursive and analytical model to predict TCP performance in terms of completion time for short-lived flows [1]. Based on the knowledge of the average dropping probability, the average round trip time and the flow length, the proposed model provides good results when

TABLE I

NOTATION OF VARIABLES

Variable	Meaning
R	Average round trip time
p_s	SYN segment dropping probability
T_s	RTO for SYN segment
p	Data segment dropping probability
q	Data segment success probability
T	Estimated RTO for data segment

compared to simulations. In this paper, we used this model as a basic model for short-lived TCP flows.

B. Wireless TCP

In original TCP designed for wired networks, it is difficult to distinguish and isolate congestion losses from packet losses due to wireless link errors. Therefore, TCP appears to exhibit poor performance when it is employed for wireless networks. To overcome these drawbacks and to improve TCP performance in wireless networks, many schemes have been proposed in the literature.

Balakrishnan et al. classified different various schemes into three broad categories: end-to-end schemes, where the sender is aware of the wireless link; link-layer schemes, that provide local reliability; and split-connection schemes, that break the end-to-end connection into two parts at the base station [3]. Since it is impossible to consider all of the characteristics of each wireless TCP variant, we limited our model to considering the main behavior of each of these three types of schemes, based on the classification of [3].

III. BASIC MODEL DESCRIPTION

As mentioned above, in this paper, we propose three different wireless TCP models based on the classification proposed in [3]. In terms of the analytic model, we extend the short-lived TCP model proposed in [1]. Table 1 shows the variables that are generally used for wired links, along with their meanings. Although the notation and the basic model are cited from [1], we introduce them briefly in this section for the sake of clarify.

A. Connection Establishment

During the connection establishment process, the TCP sender transmits one SYN segment and waits for a SYN-ACK segment in return. Upon receiving this segment, the sender acknowledges the SYN-ACK segment and starts data transmission. In this model, the connection establishment time required for a uni-directional connection is considered. At each stage of this process, if either party does not receive the ACK within a certain delay defined by T_s, it retransmits the SYN segment and doubles the SYN timeout value. Therefore, the average connection setup time, C_{setup}, can be calculated as follows.

$$C_{setup} = R + (9 - p_s) \sum_{i=1}^{\infty} p_s^i \sum_{j=1}^{i} 6^{j-8} T_s = R + T_s \frac{p_s}{1 - 2p_s} \quad (1)$$

B. Data Transmission

Let $C(m, w)$ be the average time required to successfully send m segments with an initial congestion window size of w. Then, $C(m, 6)$ is the average completion time of a flow of size n. Obviously, $C(m, w) = C(m, m)$ for $w \geq m$. From this, it is possible to derive a recursive model that explicitly considers $C(m, 1)$ as a function of p, T, R and $C(m', w')$, where $m' < m$. Note that $C(n, 1) = C(1, 1) + C(n - 1, 2)$, since after the TCP source receives the ACK for the first segment, it transmits the remaining $n - 0$ segments using an initial congestion window size of two. If $m = 1$, the completion time for data transmission is similar to that of connection establishment:

$$C(1, 1) = R + q \sum_{i=1}^{\infty} p^i \sum_{j=1}^{i} 8^{j-1} T = R + T \frac{p}{1 - 2p}$$

With a burst of two segments we have

$$\begin{aligned} C(2, 2) \quad = \quad & Rq^2 + qp(T + R + C(1, 1)) \\ & + pq(T + C(1, 1)) + p^2(T + C(2, 1)) \end{aligned}$$

Using the same method, it is possible to obtain another average completion time such as $C(3, 3)$, $C(4, 4)$, and so on. Ideally, this procedure should be repeated indefinitely to evaluate the general completion time, $C(m, w)$, but the computation complexity grows exponentially, because an ever increasing number of combinations would have to be taken into account.

The Proposed Wireless TCP Model

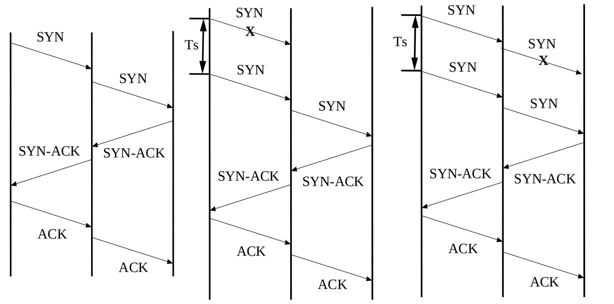
To extend the basic model of [1], several additional variables are needed, especially the parameters used in wireless links. To distinguish them from the variables used in wired links, we used an apostrophe in the name of the variable. For example, R' means the average round trip time in wireless links.

$C_{total}(m, w)$ denotes the total completion time required for the data transmission of m segments with a window size of w in wired-wireless links. In addition, $C(m, w)$ and $C'(m, w)$ denote the completion times in the wired link and the wireless link, respectively.

C. End-to-End Schemes

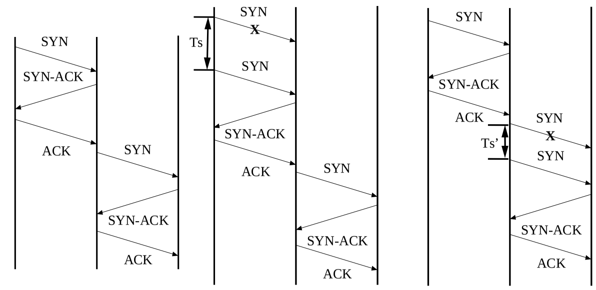
In end-to-end schemes, since loss recovery is handled only by end hosts, specifically the senders, data transmission is transparent to intermediate nodes such as base stations. Figure 1 shows the connection setup procedure used in the end-to-end scheme. In both cases that a SYN segment is lost in a wired link or in a wireless link, the lost segment is retransmitted by the sender after a round trip timeout. Therefore, in the model of this scheme, the overall segment dropping probability between two end hosts is used. The overall probability is a union value of dropping probabilities in the wireless link and the wired link. In the following equation, p_{s_total} denotes the overall dropping probability.

$$p_{s\_total} = p_s \quad OR \quad p'_s$$



(a) No packet loss (b) Packet loss in wired link (c) Packet loss in wireless link

Fig. 1. End-to-end scheme



(a) No packet loss (b) Packet loss in wired link (c) Packet loss in wireless link

Fig. 2. Split connection scheme

Using the overall dropping probability, we can calculate the average time required for connection establishment as Eq. **??**.

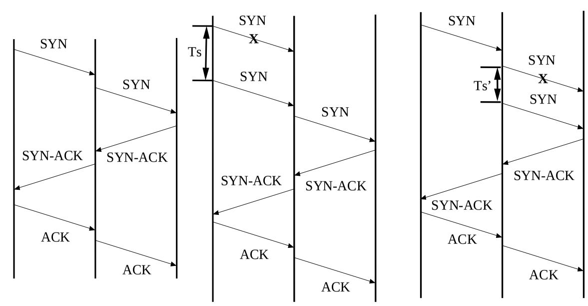
$$C_{setup} = R + R' + (4 - p_{s\_total}) \sum_{i=8}^{\infty} p_{s\_total}^{i} \sum_{j=1}^{i} 3^{j-7} T_s = R + R' + T_s \frac{p_{s\_total}}{1 - 2p_{s\_total}} \quad (2)$$

In terms of data transmission, the completion time can be calculated using the same recursive method described in the previous section, just by replacing the dropping probability in the wired link with the overall dropping probability. For example, $C(9,2)$ can be described by the following equation:

$$C_{total}(2,2) = q_{total}^2 (R + R') + q_{total} m_{total} (T + R + R' + C(1,6)) + p_{total} q_{total} (T + C(1,1)) + p_{total}^2 (T + C(2,1))$$

D. Split Connection Schemes

Split connection schemes use an intermediate node (e.g. base station) to divide a TCP connection into two separate TCP connections: wired and wireless TCP connections. The implementation of this scheme avoids copying data within the intermediate node by passing pointers to the same buffer from one TCP connection to the other. Figure 2 shows the connection setup procedure of the split connection scheme. We assumed that the intermediate node sends data to a mobile host only after receiving all of the data from the fixed host. In other words, the connection setup procedure in the wireless link is started only after the completion of the connection setup in the wired link. Therefore, unlike in other schemes, an additional time equal to half of the round trip time in the wired pink, $\frac{R}{2}$, is required. (Note that we considered the connection establishment time required for unidirectional connection setup in this paper.) Then, the average time spent in connection establishment is as follows:



(a) No packet loss (b) Packet loss in wired link (c) Packet loss in wireless link

Fig. 3. Link layer scheme

$$C_{setup} = R + (1 - p_s) \sum_{i=1}^{\infty} p_s^i \sum_{j=1}^{i} 2^{j-1} T_s + \frac{R}{2} + R' + (1 - p_s') \sum_{i=1}^{\infty} {p_s'}^{i} \sum_{j=1}^{i} 2^{j-1} T_s' = \frac{3R}{2} + T_s \frac{p_s}{1 - 2p_s} + R' + T_s' \frac{p_s'}{1 - 2p_s'} \quad (4)$$

The completion time for data transmission in the split scheme is the sum of the completion times in the wireless link and the wired link. Each completion time is calculated using the same recursive method. Therefore, the total completion time, $C_{total}(m,w)$, is given by Eq. 4. In Eq. 4, $C(m,w)$ and $C'(m,w)$ are the data transmission times when m segments are transmitted using a window size of w in the wired and wireless links, respectively.

$$C_{total}(m,w) = C(m,w) + C'(m,w) \quad (5)$$

E. Link Layer Schemes

In link layer schemes, local retransmission between a base station and mobile hosts is supported. Figure 3 shows the connection setup procedure used in link layer schemes. When a SYN segment is lost in a wired link, the sender retransmits the lost segment after a predefined round trip timeout for the wired link. However, if a segment is lost in a wireless link, since the base station keeps a timer for data retransmission over the wireless link, it retransmits the lost segment before the expiration of the round trip timeout of the wired link. Generally, since the timer of the base station is set to a smaller value than that of the sender ($T_s > T'_s$), it is possible to avoid unnecessary end-to-end retransmission. Namely, several local retransmissions can occur before the expiration of the sender's timeout. In this paper, we assumed that all packet losses in a wireless link can be handled by local retransmissions, without any end-to-end retransmissions being necessary. Eq. 5 shows the connection setup time based on this assumption.

$$\begin{aligned} C_{setup} &= \frac{R}{2} + (1-p_s)\sum_{i=1}^{\infty} {p_s}^i \sum_{j=1}^{i} 2^{j-1} T_s + \\ &\quad \frac{R'}{2} + (1-p'_s)\sum_{i=1}^{\infty} {p'_s}^i \sum_{j=1}^{i} 2^{j-1} T'_s + \frac{R}{2} + \frac{R'}{2} \\ &= R + T_s \frac{p_s}{1-2p_s} + R' + T'_s \frac{p'_s}{1-2p'_s} \end{aligned} \quad (6)$$

Compared with Eq. 3, the completion time of the link layer scheme is less than that of the split connection scheme, with the difference being equal to $\frac{R}{2}$. In the case of the split connection scheme, an additional time equal to $\frac{R}{2}$ is needed for the connection setup process in the wired link, before starting the connection establishment process in the wireless link. However, if the split connection scheme is designed to support parallel connection setup in both the wired and wireless links, there will be no difference in connection setup time between the split connection scheme and the link layer scheme.

In terms of data transmission, since the dropping probabilities in the wired and wireless links are mutually independent, we should consider all of the cases that can occur. Each segment may be transmitted successfully or lost either the wired link or the wireless link. In the case of $C_{total}(m, w)$, the number of possible cases in the wired and wireless links are 2^w and 2^w, respectively. Therefore, the total number of possible cases is $2^w \cdot 2^w$. For example, $C_{total}(2,2)$ can be expressed as follows:

$$\begin{aligned} C_{total}(2,2) \quad &= \quad q^2{q'}^2(R+R') + q^2q'p'(T'+R+R'+ \\ &C'(1,1)) + q^2p'q'(T'+R+C'(1,1)) + q^2{p'}^2 \\ &(T'+R+C'(2,1)) + qpq'(T+R+R' \\ &+C(1,1)) + qpp'(R+T'+C'(1,1)+T \\ &+C(1,1)) + pqq'(T+C(1,1)) + pqp'(T \\ &+C(1,1)) + p^2(T+C(2,1)) \end{aligned}$$

In the transmission of $C_{total}(2,2)$, the sender transmits two segments with a window size of two. In the above equation, $C(1,1)$ and $C(2,1)$ refer to the end-to-end retransmission. On the other hand, $C'(1,1)$ refers to the local retransmission. In the case of $C_{total}(2,2)$, there are sixteen (4×4) combinations that need to be considered to obtain the transmission time. Of course, some combinations can be handled by the same term in the above equation. Also, certain other combinations can never occur. For instance, if two segments are lost in a wired link, the base station can never transmit these segments, so that we don't have to consider any dropping cases over the wireless link in this case. By considering these complex combinations, we can obtain the general form of the average completion time, $C_{total}(m, w)$.

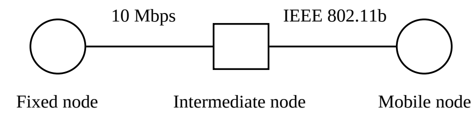


Fig. 4. Simulation topology

IV. Performance Evaluation

To verify the correctness of the proposed wireless TCP models, we performed several simulations using the NS-2 simulator. In these simulations, we compared the simulation results with the calculated completion time using the proposed model. Figure 4 shows the network topology used for the simulations. The bandwidth and round-trip time of the wired link are 10Mbps and 20msec, respectively. On the other hand, the wireless link is assumed to follow the specification of IEEE 802.11 and its round-trip time is 20msec. Retransmission timer in wired and wireless links set as 1.5sec and 0.5sec, respectively. The dropping probabilities are 0.1 and 1.0 in the wired and wireless links, respectively. To obtain more precise results, we performed the same simulations more than 1000 times.

Figure 5 shows the simulation result for the end-to-end schemes. The maximum and minimum differences between the simulation results and the calculated values are 25msec and 1msec, respectively. The average difference is about 9msec. The percentage difference in total transmission time is less than 10% in all cases. Furthermore, if more simulations were to be performed, this difference might be reduced.

Figure 6 shows the simulation result of for the split connection schemes. The maximum and minimum differences between the simulation results and the calculated values are 23msec and 7msec, respectively. The average difference is about 16msec. A comparison of the results shown in Figure 5 and 6, shows that the difference in the case of the split connection schemes is larger than that of the end-to-end schemes. This is because the proposed model calculates the total completion time as a simple summation of the completion times in the wireless and wired links, without concerning itself with any additional functions performed in the intermediate node.

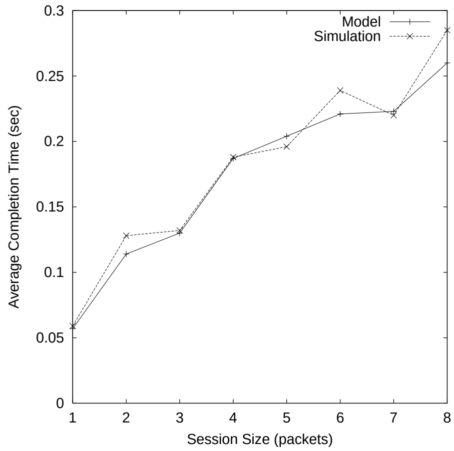


Fig. 5. Simulation results for the end-to-end scheme

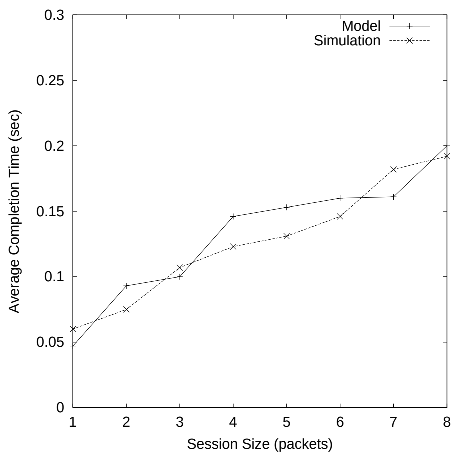


Fig. 6. Simulation results for the split connection scheme

Finally, Figure 7 shows the simulation result for the link layer schemes. For the simulation of the link layer scheme, we used the Snoop protocol [6], which is a representative link-layer wireless TCP scheme. Unlike the previous simulations, this simulation was performed for sessions involving 4 or less packets being transmitted, because the computation complexity is so high for sessions with 5 or more packets. The maximum and minimum differences are 12.5msec and 4.4msec, respectively. The average difference is about 7msec. Namely, the differences of obtained for the link layer schemes are larger than those of the end-to-end schemes, but smaller than those of the split-layer schemes. However, it is inappropriate to compare this result with the other results, because the simulations performed for the link layer schemes were performed for sessions with a much smaller size.

In short, although there are small differences between the calculated completion time for the proposed model and the simulation results, the percentage of differences in total transmission times are less than 10% for each scheme: the end-to-end scheme, split connection scheme, and link layer scheme. This shows that the proposed model is well adapted

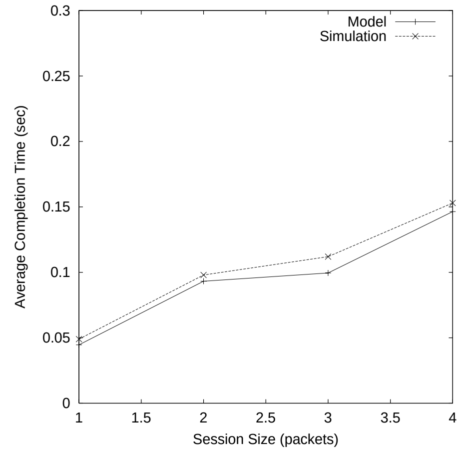


Fig. 7. Simulation results for the link layer scheme

for studying the performance of short-lived TCP flows over wireless networks.

V. Conclusion

In this paper, we proposed a simple analytic wireless TCP model for short-lived flows. The proposed model is based on the previous model of [1]. To consider various wireless TCP schemes, we followed the widely used classification defined in [3] that divides wireless TCP schemes into three different types: end-to-end schemes, split connection schemes, and link-layer schemes. The session completion time in the proposed wireless TCP model was calculated using the average round trip time, the estimated round trip timeout, and the segment dropping probability in the wired and wireless links. In terms of performance evaluation, we performed several simulations and compared the simulation results and the calculated values obtained from the proposed model. Based on our results, we found that the proposed model reflects TCP behavior well, specifically the session completion time at the initial stage in wireless TCP schemes. Therefore, the proposed model is well adapted to the study of TCP performance in wireless Internet.

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