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# Modelling of wireless TCP for short-lived flows§

Sangheon Pack*,† and Yanghee Choi‡

*301-518, Multimedia and Mobile Communication Lab., School of Computer Science and Engineering, Seoul National University, Seoul, Korea*

## SUMMARY

The transmission control protocol (TCP) is one of the 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 researches have 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 an unified all-IP network that includes both wireless and wired networks integrated together. In short, modelling short-lived TCP flows in wireless networks constitutes an important axis of research. In this paper, we propose simple wireless TCP models for short-lived flows that extend the existing analytical model proposed in [*IEEE Commun. Lett.* 2002; **6**(2):85–88]. In terms of wireless TCP, we categorized wireless TCP schemes into three types: end-to-end scheme, split connection scheme, and local retransmission scheme, which is similar to the classification proposed in [*IEEE/ACM Trans. Networking* 1997; 756–769]. To validate the proposed models, we performed ns-2 simulations. The average differences between the session completion time calculated using the proposed model and the simulation result for three schemes are less than 9, 16, and 7 ms, respectively. Consequently, the proposed model provides a satisfactory means of modelling the TCP performance of short-lived wireless TCP flows. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: wireless TCP; short-lived flow; TCP modelling; simulation

## 1. INTRODUCTION

The 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 WWW, E-mail, FTP services, etc. To date, many analytic models have been published with the purpose of characterizing TCP performance. In Reference [1], a simple analytical model of the steady-state

*Correspondence to: Sangheon Pack, 301-518, Multimedia and Mobile Communication Lab., School of Computer Science and Engineering, Seoul National University, Seoul, Korea.
† E-mail: shpack@mmlab.snu.ac.kr
‡ E-mail: yhchoi@snu.ac.kr
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throughput, which is a function of loss rate and round trip time, was proposed. The proposed model shows not only the behaviour of TCP's fast retransmission mechanism but also the effect of TCP's timeout mechanism on throughput. The analytical model presented in Reference [1] is based on the TCP Reno, which is the most popular implementation in the current Internet [2]. In Reference [3], a TCP model based on Markovian model of a single TCP source was proposed. In this model, several performance indices such as throughput, queuing delay, and packet loss of TCP flows were presented and validated by means of simulations. On the other hand, Sikdar *et al.* proposed analytical models to estimate the latency and steady-state throughput in TCP Tahoe, Reno, and SACK [4]. The proposed models were validated using both simulations and TCP traces collected from the Internet.

These models mainly focused on the throughput of bulk transfer services using TCP, especially throughput in the steady state. However, recent researches show that most TCP flows are very short with mean sizes of around 10 kB, and that their median sizes are less than 10 kB [1, 5]. The performance of short-lived flows is dependent on the initial phase, specifically the slow-start phase, because short-lived flows do not reach the steady state. Therefore, the previous analytical models cannot be directly employed for short-lived flows. Consequently, alternative analytical models for short TCP flows have been proposed in References [6, 7].

Also, previous TCP models focused on the issue of TCP performance over wired networks. However, TCP will be widely used as a transport protocol for wireless networks [8]. Wireless Internet services such as web browsing and mail services are good examples. Furthermore, the advent of wireless/mobile network technologies has 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 high service charges and the fact that the available services are still immature. Therefore, modelling analytically short TCP flows over wireless networks provides a good method of characterizing TCP performance.

In this paper, we propose simple analytical TCP models for wireless networks that extend the existing wired TCP model proposed in Reference [7]. Among the various performance factors, we focus on the completion time of short-lived TCP flows. Although many different schemes have been proposed to improve wireless TCP performance, for simplicity of modelling, we categorized these schemes into three types: end-to-end scheme, split connection scheme, and local retransmission scheme, which is similar to the classification proposed in Reference [9].

The remainder of this paper is organized as follows. Section 2 introduces related works, namely several TCP schemes for wireless networks and a few TCP models for short-lived flows in wired networks. Section 3 describes the basic models and Section 4 proposes analytical models for three wireless TCP schemes. In Section 5, the proposed model is validated by simulations. Finally, Section 6 concludes this paper.

## 2. RELATED WORK

### 2.1. TCP models for short-lived flows

Cardwell *et al.* extended the steady-state model proposed in Reference [1] to capture startup effects [6]. 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. The 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. Using simulation and measurement, they showed that the proposed connection establishment model seems promising, and that the extended data transfer model characterizes flows of varying lengths under different loss conditions.

Mellia *et al*. proposed a recursive and analytical model to predict TCP performance in terms of completion time for short-lived flows [7]. 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 compared with simulation results. This model is quite simple and can be easily extended for wireless TCP. Therefore, in this paper, we used this model as a basic model for short-lived TCP flows.

### 2.2. *Wireless TCP*

Since TCP was 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 [10–13].

To improve the TCP performance over wireless networks, a large number of schemes have been proposed in the literature. More recently, three wireless TCP versions have been proposed in References [14–16].

Although a number of TCP variants have been proposed, the classification method used in Reference [9] is widely used. Balakrishnan *et al*. [9] classified various wireless TCP schemes into three broad categories: *end-to-end scheme*, where loss recovery is performed by the sender; *local retransmission scheme*, that provide local reliability; and *split-connection scheme*, that break the end-to-end connection into two parts at the base station. Since it is impossible to consider all the characteristics of each wireless TCP variant, we limited our model to consider the main behaviour of each scheme, based on the classification of Reference [9].

## 3. BASIC MODEL DESCRIPTION

In this paper, we propose three different wireless TCP models based on the classification of Reference [9]. In terms of the analytical model, we extend the short-lived TCP model proposed in Reference [7]. Table I shows the variables that are used for wired links, along with their meanings. Although the notation and the basic model are cited from Reference [7], we introduce them briefly in this section for the sake of clarity.

Table I. Notation of variables.

| Variable | Meaning |
|---|---|
| $R$ | Average round trip time |
| $p_s$ | SYN segment dropping probability |
| $T_s$ | Retransmission timeout (RTO) for SYN segment |
| $p$ | Data segment dropping probability |
| $q$ | Data segment success probability |
| $T$ | Estimated RTO for data segment |

 

### 3.1. Connection establishment time

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 our 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 (i.e. $T_s \leftarrow 2 \times T_s$). Therefore, the average connection setup time ($C_{\text{setup}}$) can be calculated as follows. The first term of Equation (1) is the round trip time when there is no packet dropping. Index $i$ in the second term refers to the number of SYN packet droppings, whereas index $j$ is the number of backoffs of the retransmission timer.

$$C_{\text{setup}} = R + (1 - p_s) \sum_{i=1}^{\infty} p_s^i \sum_{j=1}^{i} 2^{j-1} T_s = R + T_s \frac{p_s}{1 - 2p_s} \tag{1}$$

### 3.2. Data transmission time

Let $C(m, w)$ be the average time required to successfully send $m$ segments with an initial congestion window size of $w$. Then, $C(m, 1)$ is the average completion time of a flow of size $m$. Obviously, $C(m, w) = C(m, m)$ for $w \geqslant m$. 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 $C(m, 1) = C(1, 1) + C(m - 1, 2)$, since after the TCP source receives the ACK for the first segment, it transmits the remaining $m - 1$ segments using a congestion window size of two (i.e. slow start [17]). If $m = 1$, the completion time for data transmission is similar to that of connection establishment:

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

With a burst of two segments, one of the following cases occurs:

1. No packet loss: The completion time is equal to the average round trip time ($R$).
2. The first packet is lost: After retransmission timeout for the first packet ($T$), the lost packet is retransmitted ($C(1, 1)$). The RTO triggers the packet retransmission and the congestion window is reset to one segment.
3. The first packet is successfully transmitted while the second packet is lost: After receiving the ACK for the first packet ($R$), the sender reschedules the retransmission timer for the second packet. Upon expiration of the retransmission timer for the second packet ($T$), the congestion window is reset and the sender retransmits the lost second packet ($C(1, 1)$).
4. Two packets are lost: If two packets are lost, the congestion window is reset after RTO and the lost packets are retransmitted ($C(2, 1)$).

The probabilities for cases 1, 2, 3, and 4 are $q^2$, $pq$, $qp$, and $p^2$, respectively. Therefore, $C(2, 2)$ can be expressed as Equation (2)

$$C(2, 2) = q^2 R + pq(T + C(1, 1)) + qp(R + T + C(1, 1)) + p^2(T + C(2, 1)) \tag{2}$$

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

## 4. THE PROPOSED WIRELESS TCP MODEL

To extend the basic model of Reference [7], several additional variables are needed, especially the parameters used in the wireless link. To distinguish them from the variables used in the wired link, we used an apostrophe in the name of the variable. For example, $R'$ means the average round trip time in the wireless link. These notations are shown in Table II.

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

### 4.1. End-to-end scheme

In the end-to-end scheme, since loss recovery is handled only by end hosts (i.e. the senders), data transmission is transparent to intermediate nodes such as base stations. Figure 1 shows the

Table II. Notation of additional variables.

| Variable | Meaning |
|---|---|
| $R'$ | Average round trip time in wireless link |
| $p'_s$ | SYN segment dropping probability in wireless link |
| $T'_s$ | RTO for SYN segment in wireless link ($T'_s < T_s$) |
| $p'$ | Data segment dropping probability in wireless link |
| $q'$ | Data segment success probability in wireless link ($q' = 1 - p'$) |
| $T'$ | Estimated RTO for data segment in wireless link ($T' < T$) |

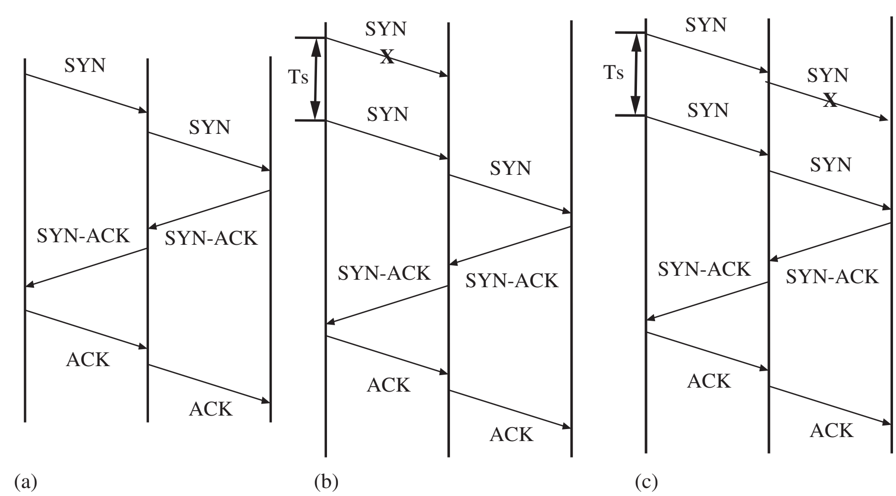


Figure 1. Connection establishment in the end-to-end scheme: (a) No packet loss; (b) packet loss in wired link; and (c) packet loss in wireless data.

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 retransmission timeout. Therefore, in the model of the end-to-end 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, $p_{s\_\text{total}}$ denotes the overall dropping probability.

$$p_{s\_\text{total}} = p_s \quad \text{OR} \quad p'_s$$

Using the overall dropping probability, we can calculate the average time required for connection establishment as Equation (3). $R + R'$ is the average round trip time in a wired–wireless link. The third term in Equation (3) represents the average latency due to retransmission timeouts in the end-to-end scheme.

$$\begin{aligned} C_{\text{setup}} &= R + R' + (1 - p_{s\_\text{total}}) \sum_{i=1}^{\infty} p_{s\_\text{total}}^{i} \sum_{j=1}^{i} 2^{j-1} T_s \\ &= R + R' + T_s \frac{p_{s\_\text{total}}}{1 - 2p_{s\_\text{total}}} \end{aligned} \quad (3)$$

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 (i.e. $p_{\text{total}} = p$ OR $p'$). For example, $C_{\text{total}}(2,2)$ can be described by the following equation:

$$\begin{aligned} C_{\text{total}}(2,2) &= q_{\text{total}}^2 (R + R') + q_{\text{total}} p_{\text{total}} (T + R + R' + C(1,1)) \\ &\quad + p_{\text{total}} q_{\text{total}} (T + C(1,1)) + p_{\text{total}}^2 (T + C(2,1)) \end{aligned}$$

### *4.2. Split connection scheme*

Split connection scheme uses an intermediate node (e.g. base station) to divide a TCP connection into two separate TCP connections: wired and wireless TCP connections. The implementations of these schemes avoid 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 assume that the intermediate node sends data to a destination node only after receiving all the data from the source node. Namely, in the case of data communication from a fixed host to a mobile host, the connection setup procedure in the wireless link is started only after the completion of the connection setup in the wired link. Therefore, unlike other schemes, an additional time ($R/2$), which is equal to half of the round trip time in the wired link, is required.[¶] Then, the average time spent in the connection establishment is given by Equation (4). In Equation (4), the first and fourth terms denote the average round trip times without packet droppings in wired and wireless links, respectively. The second and fifth terms represent the latencies incurred by retransmission

[¶] Note that we considered the connection establishment time required for a uni-directional connection setup in this paper.

 

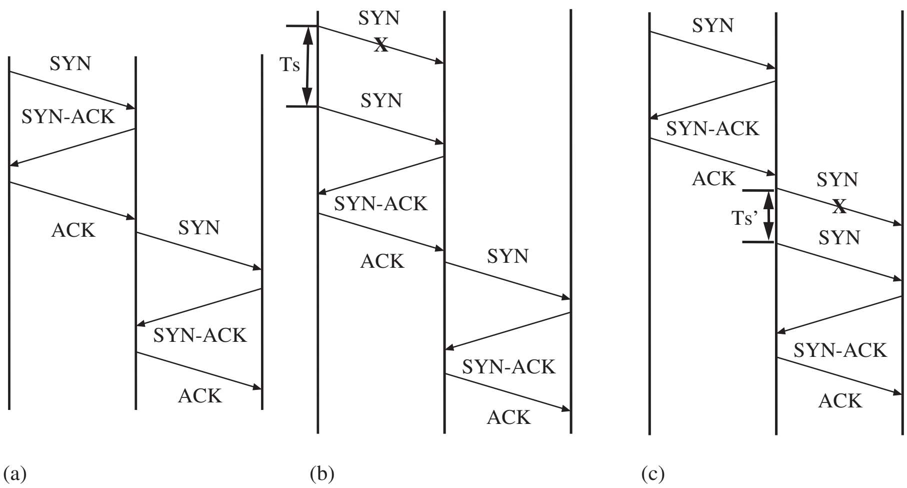


Figure 2. Connection establishment in the split connection scheme: (a) No packet loss; (b) packet loss in wired link; and (c) packet loss in wireless link.

timeouts based on the exponential backoff. The third term is the additional latency in the split connection scheme.

$$C_{\text{setup}} = R + (1-p_s)\sum_{i=1}^{\infty} p_s^i \sum_{j=1}^{i} 2^{j-1} T_s + \frac{R}{2} + R' + (1-p'_s)\sum_{i=1}^{\infty} p_s'^i \sum_{j=1}^{i} 2^{j-1} T'_s$$
$$= \frac{3R}{2} + T_s \frac{p_s}{1-2p_s} + R' + T'_s \frac{p'_s}{1-2p'_s} \quad (4)$$

The completion time for data transmission in the split connection 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 ($C_{\text{total}}(m,w)$), is given by Equation (5). In Equation (5), $C(m,w)$ 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.

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

### *4.3. Local retransmission scheme*

In the local retransmission scheme, local retransmission between the base station and the mobile host is supported. Figure 3 shows the connection setup procedure used in the local retransmission scheme. When a SYN segment is lost in a wired link, the sender retransmits the lost segment after a predefined retransmission timeout for the wired link. However, if a segment is lost in a wireless link, since the base station keeps a timer ($T'_s$) for data retransmission over the wireless link, it retransmits the lost segment before the expiration of the retransmission timeout ($T_s$) of the wired link. Generally, since the timer of the base station is set to a smaller value than that of the sender (i.e. $T_s > T'_s$), it is possible to avoid unnecessary end-to-end

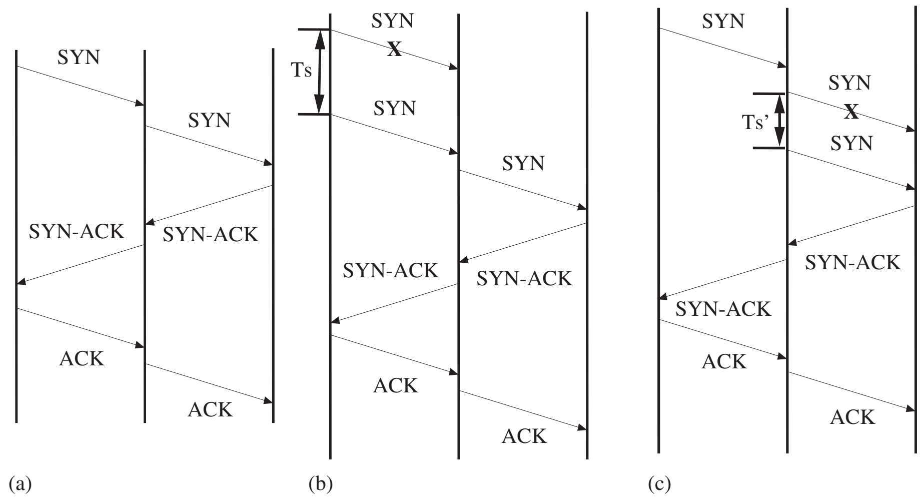


Figure 3. Connection establishment in the local retransmission scheme: (a) No packet loss; (b) packet loss in wired link; and (c) packet loss in wireless link.

retransmissions. Namely, several local retransmissions can occur before the expiration of the sender's timeout. In this paper, we assume that all packet losses in a wireless link can be handled by local retransmissions, without any end-to-end retransmissions being necessary. Equation (6) shows the connection setup time based on this assumption.

$$C_{\text{setup}} = \frac{R}{2} + (1-p_s)\sum_{i=1}^{\infty} p_s^i \sum_{j=1}^{i} 2^{j-1} T_s + \frac{R'}{2} + (1-p'_s)\sum_{i=1}^{\infty} p_s'^i \sum_{j=1}^{i} 2^{j-1} T'_s + \frac{R}{2} + \frac{R'}{2}$$

$$= R + T_s \frac{p_s}{1-2p_s} + R' + T'_s \frac{p'_s}{1-2p'_s} \qquad (6)$$

Compared with Equation (4), the completion time of the local retransmission scheme is less than that of the split connection scheme, with the difference being equal to $R/2$. In the case of the split connection scheme, an additional time equal to $R/2$ is needed for the connection setup process in the wired link, before starting the connection establishment procedure 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 the connection setup time between the split connection scheme and the local retransmission scheme.

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

 

For example, $C_{\text{total}}(2,2)$ can be expressed as follows:

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

In the transmission of $C_{\text{total}}(2,2)$, 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 short, in the case of $C_{\text{total}}(2,2)$, there are sixteen ($= 4 \times 4$) combinations that need to be considered to obtain the transmission time. Of course, some combinations can be handled by the same term. Also, certain 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 do not 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, $C_{\text{total}}(m,w)$.

## 5. MODEL VALIDATION AND RESULT

To verify the correctness of the proposed wireless TCP models, we performed comprehensive simulations using the ns-2 simulator [18]. In these simulations, we validated the calculated completion time using the proposed model with the simulation results. Figure 4 shows the network topology used for the simulations. The bandwidth and round-trip delay of the wired link are 10 Mbps and 20 ms, respectively. On the other hand, the wireless link is assumed to follow the specification of IEEE 802.11 and its round-trip delay is 20 ms. Initial retransmission timers in wired and wireless links are set to 1.5 and 0.5 s, respectively. The dropping probabilities are 0.1 and 1.0% in the wired and wireless links, respectively. In terms of packet dropping, the uniform distribution is used. To obtain more precise results, we repeated the same simulations more than 1000 times.

Figure 5 shows the simulation result for the end-to-end scheme. The maximum and minimum differences between the simulation results and the model values are 25 and 1 ms, respectively. The average difference is about 9 ms. The percentage of 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.

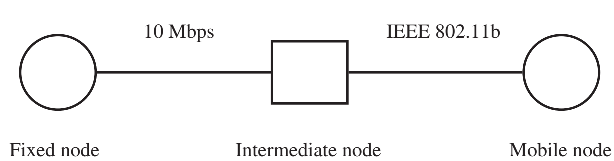


Figure 4. Simulation topology.

 

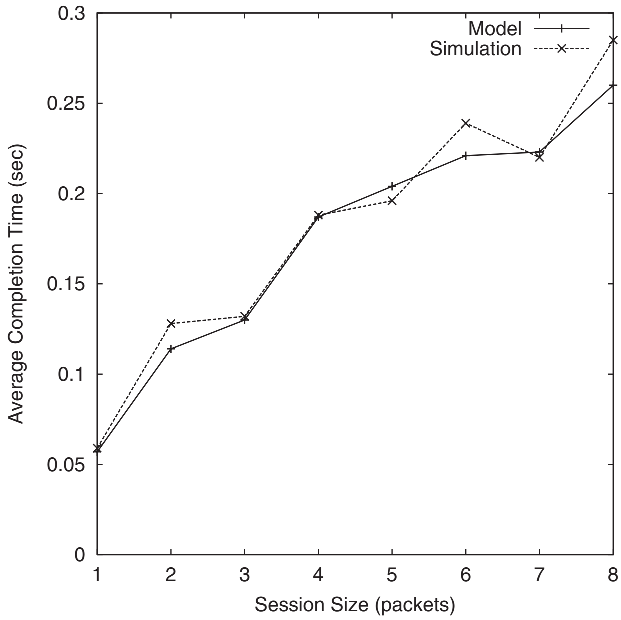


Figure 5. Simulation results vs model values for the end-to-end scheme.

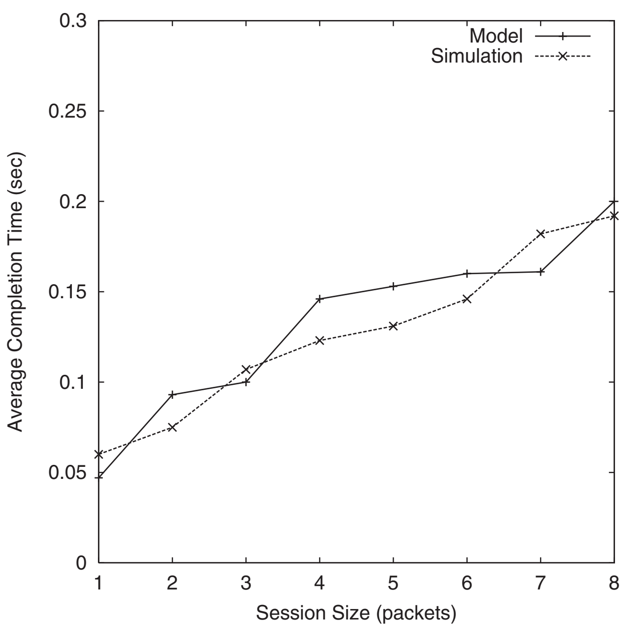


Figure 6. Simulation results vs model values for the split connection scheme.

 

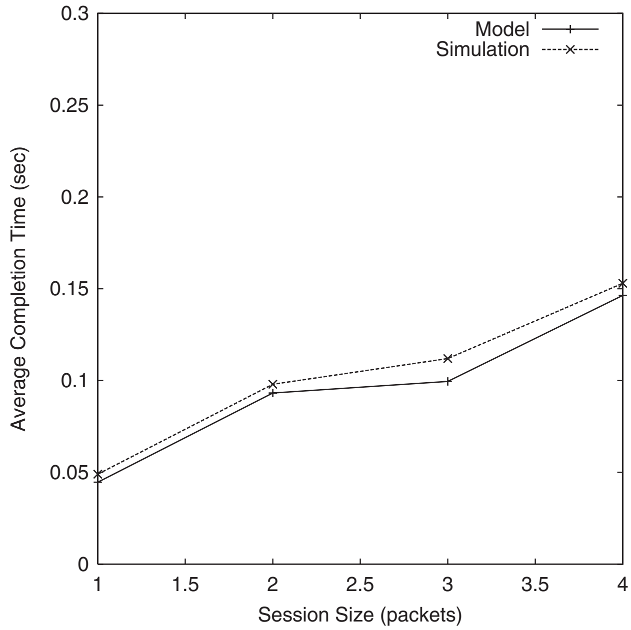


Figure 7. Simulation results vs model values for the local retransmission scheme.

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

Finally, Figure 7 shows the simulation result for the local retransmission scheme. For the simulation of the local retransmission scheme, we used the Snoop protocol [19], which is a representative local retransmission scheme. Unlike the previous simulations, this simulation was performed for sessions involving four or less packets being transmitted, because the computation complexity is so high for sessions with five or more packets. The maximum and minimum differences are 12.5 and 4.4 ms, respectively. The average difference is about 7 ms. Namely, the average difference obtained from the local retransmission scheme is smaller than those of the end-to-end scheme and the split connection scheme. However, it is inappropriate to compare this result with the other results, because the simulations performed for the local retransmission scheme were performed for sessions with a much smaller size.

In short, although there are small differences between the calculated completion time using the proposed model and the simulation results, the percentage of difference in total transmission time is less than 10% for all schemes: the end-to-end scheme, split connection scheme, and local retransmission scheme.

 

## 6. CONCLUSION

In this paper, we proposed simple analytical wireless TCP models for short-lived flows. The proposed models are based on the previous model of Reference [7]. To consider various wireless TCP schemes, we followed the widely used classification defined in Reference [9], which divides wireless TCP schemes into three different types: end-to-end scheme, split connection scheme, and local retransmission scheme. The session completion time in the proposed wireless TCP model is calculated using the average round trip time, the retransmission timeout, and the segment dropping probability in the wired and wireless links. In terms of performance evaluation, we performed ns-2 simulations and compared the simulation results with the calculated values obtained from the proposed models. Based on our results, we found that the proposed models reflect TCP behaviour well, specifically the session completion time at the initial stage in wireless TCP schemes. Therefore, the proposed models are well adapted to the study of TCP performance in wireless networks. Based on this work, we will extend the proposed model for the heterogeneous wireless network.

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## AUTHORS' BIOGRAPHIES

**Sangheon Pack** received his BS (2000, magna cum laude) and PhD (2005) degrees from Seoul National University, both in computer engineering. He is Post-doctoral Fellow in the School of Computer Science and Engineering at the Seoul National University, Korea. He is a member of the IEEE and ACM. Since 2002, he has been a recipient of the Korea Foundation for Advanced Studies (KFAS) Computer Science and Information Technology Scholarship. He has also been a member of Samsung Frontier Membership (SFM) from 1999. He received a student travel grant award for the IFIP Personal Wireless Conference (PWC) 2003. He was a visiting researcher to Fraunhofer FOKUS, German in 2003. His research interests include mobility management, QoS provision, and scalability issues in the next-generation wireless/mobile networks.

**Yanghee Choi** received his BS in electronics engineering from Seoul National University, MS in electrical engineering from Korea Advanced Institute of Science, and Doctor of Engineering in Computer Science from Ecole Nationale Superieure des Telecommunications (ENST) in Paris, in 1975, 1977 and 1984, respectively. Before joining the School of Computer Engineering, Seoul National University in 1991, he has been with Electronics and Telecommunications Research Institute (ETRI) during 1977–1991, where he served as director of Data Communication Section, and Protocol Engineering Center. He was research student at Centre National d'Etude des Telecommunications (CNET), Issy-Ies-Moulineaux, during 1981–1984. He was also Visiting Scientist to IBM T. J. Watson Research Center for the year 1988–1989. He is now leading the Multimedia Communications Laboratory in Seoul National University. He is also director of Computer Network Research Center in Institute of Computer Technology (ICT). He was editor-in-chief of Korea Information Science Society journals. He was chairman of the Special Interest Group on Information Networking. He has been associate dean of research affairs at Seoul National University. He was president of Open Systems and Internet Association of Korea. His research interest lies in the filed of multimedia systems and high-speed networking.

 