An End-to-End Support for Short-Lived TCP Flows in Heterogeneous Wired-cum-Wireless Networks: An Analytical Study

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Abstract: *Transmission control protocol has been adapted to various types of wireless networks (e.g., IEEE 802.11 WLAN, 3G cellular and ad hoc networks). However, wireless transmission control protocol flows are much shorter than wired flows due to the time varying characteristics of wireless networks. Hence, transmission control protocol performance in these networks is determined by the start up effects such as connection establishment. Several analytical models were proposed to describe the steady-state behaviour of short-lived transmission control protocol flows in wired networks, while few similar studies targeted wireless networks. Moreover, almost all of the previous models did not investigate the effect of heterogeneity (e.g., link speed and segment loss probability) of wireless networks on the end-to-end performance of transmission control protocol flows. In this paper, a recursive and analytical model is developed and used to determine the performance of short-lived transmission control protocol flows in heterogeneous wired-cum-wireless networks in terms of average completion time. Two different schemes are proposed to solve the wireless loss problems by the end hosts, namely, end-to-end scheme and connection division scheme. The proposed analytical model has been validated by means of simulations using NS-2 simulator. Performance results show that the proposed model is in close analogy with values obtained from the analytical model. As such, the proposed model can be used to accurately tune many parameters that affect the behaviour of transmission control protocol in wired-cum-wireless networks.*

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1. Introduction

Transmission Control Protocol (TCP) is the ubiquitous transport protocol used in the Internet world. The Transmission Control Protocol is a reliable, connection-oriented, full-duplex, byte-stream and end-to-end protocol that supports flow and congestion control [1]. Also, it is widely used to support applications like Telnet, and FTP [2]. TCP's performance influences Internet traffic behavior for different versions of TCP implementations, e.g., TCP Tahoe and TCP Reno [1]. Hence, many models of TCP latency and throughput have been proposed in order to capture its characteristics (e.g., [5, 13]). In most of these models, the TCP performance is evaluated based on the network parameters such as TCP round trip time and packet loss rate.

In today's world, more people are moving towards using mobile and wireless technology for communication. This technology allows flexible and convenient ways of communication. Indeed, different types of wireless networks can be found today, e.g., IEEE 802.11 WLAN, 3G cellular networks, wireless mesh networks, and ad hoc wireless networks. Since TCP was originally designed for wired networks, it fails to meet the requirements of wireless networks without degrading the performance of TCP. This is due to many reasons. First, these networks have different characteristics and different packet error behaviors. Second, many of the assumptions made in the wired-domain networks are not valid in the wireless-domain networks. From the shared, open-air media, to the characteristics of the physical channels, to the radio signal propagation challenges, to supporting mobile devices, TCP faces many challenges in responding to these emerging needs. Third, the standard TCP error recovery algorithms unnecessarily decrease the throughput in wireless links because TCP assumes all losses are caused by congestion, while in fact errors and packet losses in wireless networks can result from random bit errors, fading, shadowing, mobility, low bandwidth, handovers, channel losses, and link latency [14, 17]. Finally, TCP flows in wireless networks are much shorter than those in wired networks. Since short-lived flows do not reach the steady-state, their performance is dominated by startup effects such as three-way handshake connection establishment and slow start mechanisms. We will investigate and quantify these different behaviors in this paper in the general wired-cum-wireless networks.

In recent years, the modeling of the TCP behavior in wireless networks received considerable attention and many analytical models have been proposed to characterize TCP performance in wireless world (e.g., [6, 8, 13, 16]). These studies revealed that most TCP flows are short-lived flows with average sizes of around 10 KB [13, 77]. However, the results of many of these analytical models whether related to wired or wireless cannot be directly used for short-lived flows. Recently, some analytical models were proposed to study short-lived TCP flows in wired networks [5, 12, 16] . In [9], a recursive and analytical model for wired networks was proposed to determine the short-lived TCP performance in terms of connection setup time and completion time. The proposed model introduced good results when compared with simulation results. On the other hand, Pack et al. [12] extended the recursive and analytical model in [9] and introduced a new model for short-lived TCP flows in wireless networks. However, the model did not take into account the heterogeneity of wireless networks that is demonstrated by different loss packet probability, different link bandwidths, and different round trip times.

In this paper, we propose a recursive and analytical model for heterogeneous wired-cum-wireless networks that is based on the model in [12]. Although, our model adopts the criteria used in the model of [9, 12], our model is more general and more practical as it is closer to the real systems. The major differences are in the following aspects. First, the model did not investigate the heterogeneity of wireless networks and considered a constant packet loss probability. However, heterogeneity is an important issue in wireless networks and has a significant impact on TCP performance. Our model investigates the heterogeneity of wireless networks for various schemes. Second, our model uses multi-wireless networks each of which is connected to wired network, e.g. Internet, with non- homogeneous wired link, i.e., speed of that link.

We focus on the average completion time of the short-lived flow as TCP performance metric. The average completion time is defined as the time needed by the source to successfully transfer a given amount of data to a destination in addition to the connection establishment time. Two different schemes are proposed to solve the wireless loss problems by the end hosts. They are called End-to-End scheme and connection division scheme. The idea of End-to-End scheme is similar to [4, 10, 15] and is used to improve the performance of TCP over wireless links. This scheme solves the wireless loss problems at the transport layers of the sender. The connection division scheme breaks the TCP connection into two connections at the border of the wired and wireless domains (e.g., base station of WLAN). The purpose of this division is to distinguish between the characteristics of the different networks. It should be noted that the Connection The connection division scheme proposed here is different from the Split Connection scheme that appeared in [3] [4] [15], which was used to identify the source of packet corruption or losses in wireless networks from the congestion losses of wired networks. The Local Retransmission scheme that was proposed in [3] [4] [15] can also be adapted in our model to provide local reliability. However, we will not present the model of this scheme in this paper because of the complexity of the derived equations.

The NS-2 simulator [11] was used to validate our proposed model. The simulation values were compared to the model values for the two different schemes. Based on the obtained results we found that the proposed models reflect the behavior of TCP well. Moreover, simulation results show close analogy with those values obtained from the analytical model (the percentage difference for the average completion time is less than 3% and 6% for the two schemes). As such, the proposed model can be used to accurately tune many parameters that affect the behavior of TCP in wired-cum-wireless networks.

2. The System Model

In this section, the system model is discussed. The main goal of our proposed model is to estimate the average completion time for short-lived TCP flow in heterogeneous wired-cum-wireless networks, e.g., Internet. A transfer is considered successful when the source receives the acknowledgment ACK for the last segment from the destination. The average completion time consists of two parts: (i) the connection establishment time: the time it takes to successfully complete the three way handshake algorithm [15], and (ii) the time to actually complete transferring the data segment. We assume an average size of short-lived TCP flows of 10 KB (similar to [13, 77]).

Table 1. System parameters.

Variable Wired1	Its Meaning	Variable Wired2	Its Meaning	Variable Wireless	Its Meaning
R_1	Average round trip time	$R_2(i)$	Average round trip time	$R_3(i)$	Average round trip time
P_{s1}	Synchronization segment (SYN) dropping probability	$P_{s2}(i)$	Synchronization segment (SYN) dropping probability	$P_{s3}(i)$	Synchronization segment (SYN) dropping probability
T_{s1}	Retransmition Time Out (RTO) for SYN segment	$T_{s2}(i)$	Retransmition Time Out (RTO) for SYN segment	$T_{s3}(i)$	Retransmition Time Out (RTO) for SYN segment
P_1	Data segment dropping probability	$P_2(i)$	Data segment dropping probability	$P_3(i)$	Data segment dropping probability
q_1	Data segment success probability	$q_2(i)$	Data segment success probability	$q_3(i)$	Data segment success probability (q_3=1-p_3)
T_1	Estimated RTO for data segment	$T_2(i)$	Estimated RTO for data segment	$T_3(i)$	Estimated RTO for data segment

Assuming a unidirectional data transfer with Maximum Transfer Unit (MTU) of 1.5 KB, this will result in 10 KB/1.5 KB ≅ 8 segments, which covers most of short-lived TCP flows. We use the slow start algorithm implemented in [18] as all major TCP proposals such as Reno and New Reno implement this same slow start and the loss recovery algorithms. We also assume that the sender maintains only one timer for all in-flight segments [13, 15]. The timer is associated with the segment with the lowest sequence number that has not been acknowledged yet. When an ACK segment is received, the timer is reset and re-assigned to the subsequent segment. Because of the small size of TCP flows, many of these flows never exit the slow start phase and the probability that the loss packet will trigger the fast recovery algorithm is very low. This is because the window size will be very small and the sender will not be able to send enough segments that generate the three duplicate acknowledgments that will trigger the fast recovery algorithm. Therefore, most losses will trigger the Retransmission Time Out (RTO) that will cause the TCP to re-enter the slow start phase [12].

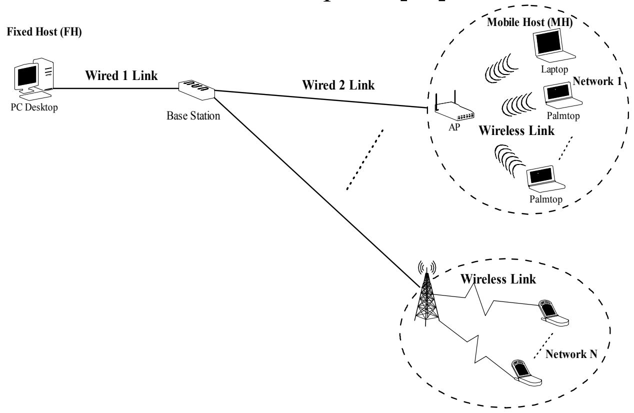

Figure 1. The network topology used in the model.

For ease of reference, Table 1 summarizes the variables that will be used in this paper. In particular, the variables used at various segments of the topology are listed. Figure 1 shows the network topology used in this paper. The model assumes two wired links as shown in Figure 1. These two links are used to connect a fixed host to a base-station that in turn connects the base-station to various types of wireless networks. The two wired links are needed to resolve the mismatch since the links are not homogeneous (i.e., determining the performance of TCP is not the purpose of this separation). Such selection will make the system more practical and achieve the simplicity and tractability when splitting the connection from a fixed host to a mobile host at the base station.

3. The Proposed TCP Model

In this section, both end-to-end and connection division schemes are detailed.

3.1. End-to-End Scheme

Phase 1: connection establishment time, C_{setup}, derivative and analysis: in End-to-End scheme, both wired and wireless losses are solved at the transport layer of the sender. In the connection establishment time as shown in Figure 2, the TCP sender transmits one SYN segment and waits for a SYN-ACK segment. When the sender receives this segment, the sender acknowledges the SYN-ACK segment and then starts the data transmission.

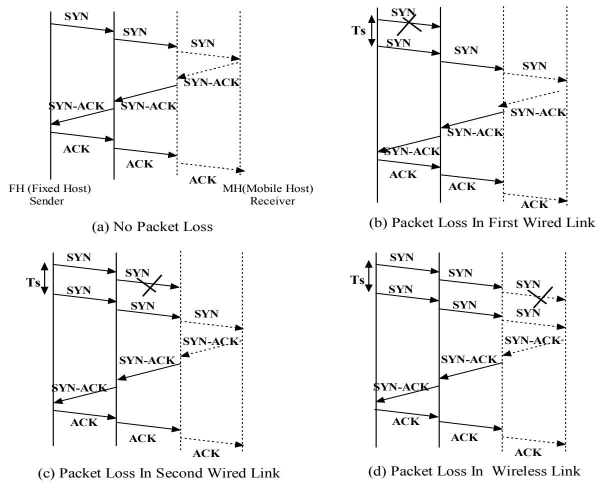

Figure 2. Connection establishment in End-to-End scheme.

Derivation of connection establishment time, C_{setup}: in this section, we will derive the connection establishment time depending on the variable distribution as shown in Figure 3 and using the geometric distribution.

$$C_{setup} = R_1 + R' + (1 - p_{s\text{-}total}) \Sigma_{(i=1 \text{ to } \infty)} p^i_{s\text{-}total} \Sigma_{(j=1 \text{ to } i)} 2^{j-1} T_{s1} = R_1 + R' + T_{s1} (p_{s\text{-}total} / (1-2\, p_{s\text{-}total})) \quad (1)$$

We derive $p_{s\text{-}total}$ according to the properties of probabilities, as shown in Figure 4.

$$p_{s\text{-}total} = p_{s1} + \prod_{(i=1 \text{ to } N)} (p_{s2}(i) + p_{s3}(i) - p_{s2}(i)\, p_{s3}(i)) - p_{s1} + \prod_{(i=1 \text{ to } N)} (p_{s2}(i) + p_{s3}(i) - p_{s2}(i)\, p_{s3}(i)) \quad (2)$$

R' = the average round trip time in wired-wireless links

$$= (1/N)\, \Sigma_{(i=1 \text{ to } N)} [R_2(i) + R_3(i)] \quad (3)$$

During the connection establishment time as shown in Figure 2, if the segment is lost in wired or wireless links, the sender will retransmit the SYN segment after retransmission timeout (T_{s1}) and double the SYN timeout value ($T_{s1} = 2* T_{s1}$). The term (R_1+R') is the average round trip time when there is no segment loss in the entire network, the index (i) refers to the number of SYN segments dropped, the index (j) refers to the number of back-offs of the retransmission timer (T_{s1}), ($p_{s\text{-}total}$) is the overall dropping probability for SYN segment in End-to-End scheme and (N) is the number of wireless networks.

Phase 2: data completion time C (m, w), derivation and analysis: in the following, we will derive the general form for average completion time by using a recursive manner. Let C (m, w) be the average completion time required to successfully send (m) data segments with an initial congestion window of size (w), let C (m, 1) be the average completion time of a flow of size (m) segments with an initial congestion window of size one, and let (N) be the number of wireless networks.

C (m, w) = C (m, m) for w ≥ m, because we need only a congestion window of size (m) to send the (m) segments, while C (m, 1) = C (1, 1) + C (m-1, 2), since after the TCP source receives the ACK for the first segment, it increases its congestion window and transmits the remaining (m-1) segments using an initial congestion window of size two. Using eight segments as a maximum data transfer, the average completion time C (m, w) is generally defined by

$$C(m,w)=\begin{cases} C(1,1)+C(m-1,2) & ,\ 8\geq m\geq 1,\ w=1 \\ C_{setup}=C(1,1) & ,\ m=1,\ w>0 \\ C(m,m) & ,\ w\geq m \\ q^2_{total}(R_1+R'+C(m-w,2w)) + q_{total}\,p_{total}(T_1+R_1+R'+C(m-1,2)) + p_{total}\,q_{total}(T_1+C(m-1,1)) + p^2_{total}(T_1+C(m,1)) & ,\ 8\geq m\geq 2,\ w=2 \\ q^3_{total}(R_1+R') + 2q^2_{total}\,p_{total}(T_1+R_1+R'+C(1,1)) + p_{total}\,q^2_{total}(T_1+C(1,1)) + q_{total}\,p^2_{total}(T_1+R_1+R'+C(2,1)) + 2p^2_{total}\,q_{total}(T_1+C(2,1)) + p^3_{total}(T_1+C(3,1)) & ,\ m=3,\ w=3 \\ q^4_{total}(R_1+R') + 3q^3_{total}\,p_{total}(T_1+R_1+R'+C(1,1)) + p_{total}\,q^3_{total}(R_1+R'+C(1,1)) + q_{total}\,p^3_{total}(T_1+R_1+R'+C(3,1)) + 3p^3_{total}\,q_{total}(T_1+C(3,1)) + 3q^2_{total}\,p^2_{total}(T_1+R_1+R'+C(2,1)) + 3p^2_{total}\,q^2_{total}(T_1+C(2,1)) + p^4_{total}(T_1+C(4,1)) & ,\ m=4,\ w=4 \\ q^4_{total}(R_1+R'+C(1,1)) + 2q^3_{total}\,p_{total}(T_1+R_1+R'+C(2,2)) + 2p_{total}\,q^3_{total}(R_1+R'+C(2,1)) + q_{total}\,p^3_{total}(T_1+R_1+R'+C(4,2)) + 3p^3_{total}\,q_{total}(T_1+C(4,1)) + 3q^2_{total}\,p^2_{total}(T_1+R_1+R'+C(3,2)) + 3p^2_{total}\,q^2_{total}(T_1+C(3,1)) + p^4_{total}(T_1+C(5,1)) & ,\ m=5,\ w=4 \end{cases} \quad (4)$$

where p_{total} = the overall dropping probability for the data segment in End-to-End scheme. $p_{total} = p_1 + \prod_{(i=1\ to\ N)} (p_2(i) + p_3(i) - p_2(i)\,p_3(i)) - p_1 \prod_{(i=1\ to\ N)} (p_2(i) + p_3(i) - p_2(i)\,p_3(i))$, $q_{total} = 1 - p_{total}$ = the overall success probability for the data segment in End-to-End scheme.

Analysis of C (2, 2), C (3, 2), C (4, 2), C (5, 2), C (6, 2), C (7, 2), C (3, 3), C (4, 4), and C (5, 4):

Case one: the following terms denote that there is no segment loss, q^2_{total} (R1 + R'), q^2_{total} (R_1 + R'+ C (1, 1)), q^2_{total} (R_1 + R'+ C(2,2)) ,q^2_{total} (R_1 + R'+ C (3, 3)), q^2_{total} (R_1 + R'+ C(4,4)), and q^2_{total} (R_1 + R'+ C(5,4)) in C(2, 2), C (3, 2), C (4, 2), C (5, 2), C (6, 2) and C (7, 2), respectively. Upon receiving the ACK (After R_1+R'), the sender doubles its congestion window and sends the remaining segments. The probability for this case is q^2_{total}.

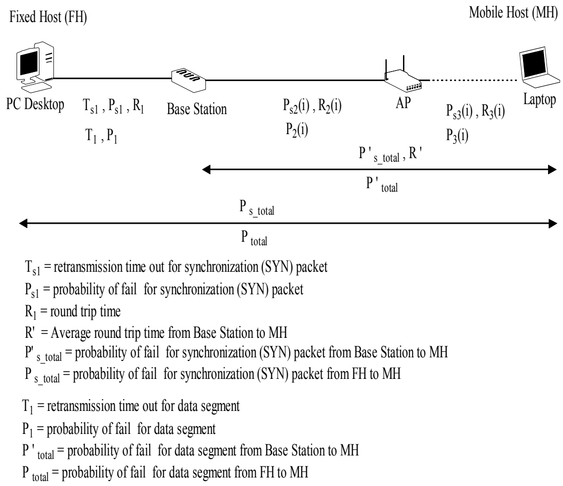

Figure 3. Variables distribution.

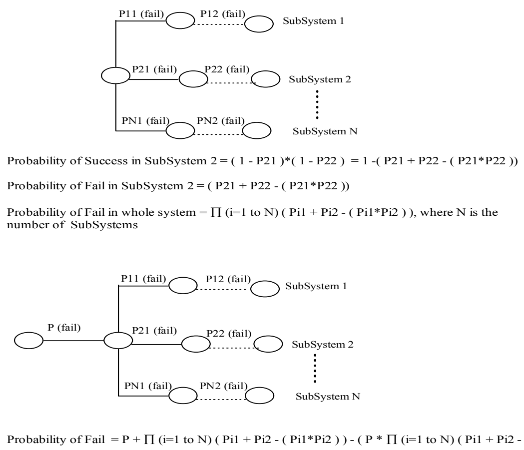

Figure 4. Derivation of fail probability.

Case two: the following terms denote that the first segment is successfully transmitted while the second segment is lost, $q_{total}\,p_{total}$ (T_1 + R_1 + R' + C (1, 1)) , $q_{total}\,p_{total}$ (T_1 + R_1 + R' + C (2, 2)), $q_{total}\,p_{total}$ (T_1 + R_1 + R' + C (3, 2)), $q_{total}\,p_{total}$ (T_1 + R_1 + R' + C (4, 2)), $q_{total}\,p_{total}$ (T_1+ R_1 + R' + C (5, 2)), and $q_{total}\,p_{total}$ (T_1+ R_1 + R' + C (6, 2)) in C(2, 2), C (3, 2), C (4, 2), C (5, 2), C (6, 2) and C (7, 2), respectively.

Upon receiving the ACK for the first segment (After R_1+R'), the sender increases its congestion window. At the same time, the retransmission timer is rescheduled (T_1). Upon expiration of the retransmission timer (T_1), the congestion window is reset to one segment. But, because TCP uses cumulative acknowledgments and uses only one retransmission timer, the sender retransmits the lost and the remaining segments at the same time as a burst of two segments. The probability for this case is $q_{total}\,p_{total}$.

Case three: the following terms denote that the first segment is lost while the second segment is successfully transmitted, $p_{total}\, q_{total}\, (T_1 + C\,(1, 1))$, $p_{total}\, q_{total}\, (T_1 + C\,(2, 1))$, $p_{total}\, q_{total}\, (T_1 + C\,(3, 1))$, $p_{total}\, q_{total}\, (T_1 + C\,(4, 1))$, $p_{total}\, q_{total}\, (T_1 + C\,(5, 1))$ and $p_{total}\, q_{total}\, (T_1 + C\,(6, 1))$ in C(2, 2), C (3, 2), C (4, 2), C (5, 2), C (6, 2) and C (7, 2), respectively.

After retransmission timeout (T_1) for the first segment, the congestion window is reset to one segment and the sender retransmits the lost and the remaining segments. The probability for this case is $p_{total}\, q_{total}$.

Case four: the following terms denote that the two segments are lost, $p^2_{total}\, (T_1 + C\,(2, 1))$, $p^2_{total}\, (T_1 + C\,(3, 1))$, $p^2_{total}\, (T_1 + C\,(4, 1))$, $p^2_{total}\, (T_1 + C\,(5, 1))$, $p^2_{total}\, (T_1 + C\,(6, 1))$ and $p^2_{total}\, (T_1 + C\,(7, 1))$ in C(2, 2), C (3, 2), C (4, 2), C (5, 2), C (6, 2) and C (7, 2), respectively.

After the retransmission timer expires (T_1), the congestion window is reset to one and the sender resends all segments again .The probability for this case is p^2_{total}. Similarly to the previous cases, we can derive equations C (3, 3), C (4, 4) and C (5, 4) that have $2^x.2^x$ combinations, where x is the minimum (m, w).

In case three in C (4, 4) and C (5, 4), we found that after *three duplicate acknowledgements*, the fast recovery algorithm will be triggered, and the sender will retransmit the segment immediately without waiting for an RTO.

3.2. Connection Division Scheme

Phase 1: connection establishment time, C_{setup}, derivation and analysis: in connection division scheme we divide a TCP connection at the base station into two separate TCP connections: wired and wired-wireless TCP connections as shown in Figure 5. The main goal of connection division scheme is to distinguish between different characteristics of networks. Whereas, the Split connection scheme is used to discriminate the congestion losses in wired networks from the corruption losses in wireless networks by splitting the connection at base station in to two connections: wired and wireless connections. We deal with wired-wireless link as End-to-End scheme.

Derivation of connection establishment time, C_{setup}: we derive the connection establishment time depending on the variable distribution as shown in Figure 3 and using the geometric distribution.

$$C_{setup} = C_{setup\text{-}wired} + C_{setup\text{-}wired\text{-}wireless} = [R_1 + (1 - p_{s1}) \Sigma_{(i=1\ to\ \infty)} p^i_{s1} \Sigma_{(j=1\ to\ i)} 2^{j-1} T_{s1} + R_1/2] + [R' + (1 - p'_{s\text{-}total}) \Sigma_{(i=1\ to\ \infty)} (p'_{s\text{-}total})^i \Sigma_{(j=1\ to\ i)} 2^{j-1} T_{s2}] = 3R_1/2 + T_{s1} (p_{s1} / (1 - 2p_{s1})) + R' + T_{s2} (p'_{s\text{-}total} / (1 - 2p'_{s\text{-}total})) \quad (5)$$

We derive $p'_{s\text{-}total}$ according to the properties of probabilities as shown in Figure 4.

$$p'_{s\text{-}total} = \prod_{(i=1\ to\ N)} (p_{s2\,(i)} + p_{s3\,(i)} - p_{s2\,(i)}\, p_{s3\,(i)}) \quad (6)$$

$$T_{s2} = Maximum\ \{T_{s2}\,(i),\ worst\ case\} \quad (7)$$

The base station sends the data to the destination node only after receiving all the data from the fixed host. The connection is started in wired-wireless links only after it is completed in the wired link, so an additional time ($R_1/2$), which is equal to half of the round trip time in the wired link is required. During the connection establishment time as shown in Figure 5, if the segment is lost in wired link, the sender will retransmit the SYN segment after retransmission timeout (T_{s1}) and double the SYN timeout value ($T_{s1} = 2 * T_{s1}$). The terms R_1, R' is the average round trip time when there is no segment loss in the wired and wired-wireless links, the index (i) refers to the number of SYN segments dropped, the index (j) refers to the number of back-offs of the retransmission timer (T_{s1}), (p_{s1}) is the dropping probability for the SYN segment in wired link ,($p'_{s\text{-}total}$) is the overall dropping probability for SYN segment in wired-wireless links and (T_{s2}) is the retransmission timer for the wired-wireless link.

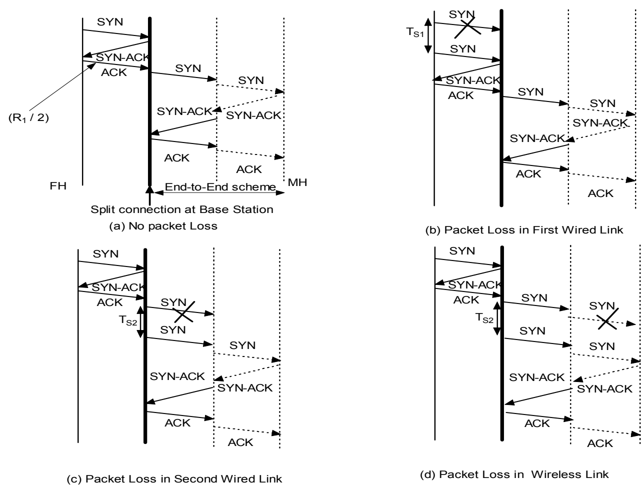

Figure 5. Connection establishment in connection division scheme.

Phase 2: Data completion Time C (m, w), derivation and analysis: in the following, we will derive the general form for average completion time by using a recursive manner. Let C (m, w) = C_{wired}(m, w) + $C_{wired\text{-}wireless}$ (m, w) be the average completion time required to successfully send (m) data segments with an initial congestion window of size (w) in wired and wired-wireless links, respectively. We compute the average completion time for wired-wireless links exactly as it was computed in End-to-End scheme. Let C (m, 1) is the average completion time of a flow of size (m) segments with an initial congestion window of size one. C (m, 1) = C (1, 1) + C (m-1, 2) as discussed in End-to-End scheme. We will use up to eight segments as a maximum data transfer as before to derive the average completion time C (m, w) which is defined for this scheme by a general form as follows:

$$
C(m,w)=\begin{cases}
C_{wired}(1,1)+C_{wired}(m-1,2)+C_{wired\text{-}wireless}(1,1)+C_{wired\text{-}wireless}(m-1,2) & ,\ 8\ge m\ge 1,\ w=1\\
C_{setup}=C_{wired}(1,1)+C_{wired\text{-}wireless}(1,1) & ,\ m=1,\ w>0\\
C_{wired}(m,m)+C_{wired\text{-}wireless}(m,m) & ,\ w\ge m\\
C_{wired}(m,w)+C_{wired\text{-}wireless}(m,w)\\
q_1^2(R_1+C_{wired}(m-w,2w))+q_1p_1(T_1+R_1+C_{wired}(m-1,2))+p_1q_1(T_1+C_{wired}(m-1,1))+p_1^2(T_1+C_{wired}(m,1))+\\
q'^2_{total}(R'+C_{wired\text{-}wireless}(m-w,2w))+q'_{total}p'_{total}(T_2+R'+C_{wired\text{-}wireless}(m-1,2))+p'_{total}q'_{total}(T_2+C_{wired\text{-}wireless}(m-1,1))+p'^2_{total}(T_2+C_{wired\text{-}wireless}(m,1)) & ,\ 8\ge m\ge 2,\ w=2\\
q_1^3R_1+2q_1^2p_1(T_1+R_1+C_{wired}(1,1))+p_1q_1^2(T_1+C_{wired}(1,1))+q_1p_1^2(T_1+R_1+C_{wired}(2,1))+2p_1^2q_1(T_1+C_{wired}(2,1))+p_1^3(T_1+C_{wired}(3,1))+\\
q'^3_{total}R'+2q'^2_{total}p'_{total}(T_2+R'+C_{wired\text{-}wireless}(1,1))+p'_{total}q'^2_{total}(T_2+C_{wired\text{-}wireless}(1,1))+q'_{total}p'^2_{total}(T_2+R'+C_{wired\text{-}wireless}(2,1))+\\
2p'^2_{total}q'_{total}(T_2+C_{wired\text{-}wireless}(2,1))+p'^3_{total}(T_2+C_{wired\text{-}wireless}(3,1)) & ,\ m=3,\ w=3\\
q_1^4R_1+3q_1^3p_1(T_1+R_1+C_{wired}(1,1))+p_1q_1^3(R_1+C_{wired}(1,1))+q_1p_1^3(T_1+R_1+C_{wired}(3,1))+3p_1^3q_1(T_1+C_{wired}(3,1))+\\
3q_1^2p_12(T_1+R_1+C_{wired}(2,1))+3p_1^2q_12(T_1+C_{wired}(2,1))+p_1^4(T_1+C_{wired}(4,1))+q'^4_{total}R'+\\
3q'^3_{total}p'_{total}(T_2+R'+C_{wired\text{-}wireless}(1,1))+p'_{total}q'^3_{total}(R'+C_{wired\text{-}wireless}(1,1))+q'_{total}p'^3_{total}(T_2+R'+C_{wired\text{-}wireless}(3,1))+\\
3p'^3_{total}q'_{total}(T_2+C_{wired\text{-}wireless}(3,1))+3q'^2_{total}p'2_{total}(T_2+R'+C_{wired\text{-}wireless}(2,1))+3p'^2_{total}q'^2_{total}(T_2+C_{wired\text{-}wireless}(2,1))+\\
p'^4_{total}(T_2+C_{wired\text{-}wireless}(4,1)) & ,\ m=4,\ w=4\\
q_1^4(R_1+C_{wired}(1,1))+2q_1^3p_1(T_1+R_1+C_{wired}(2,2))+2p_1q_1^3(R_1+C_{wired}(2,1))+q_1p_1^3(T_1+R_1+C_{wired}(4,2))+\\
3p_1^3q_1(T_1+C_{wired}(4,1))+3q_1^2p_1^2(T_1+R_1+C_{wired}(3,2))+3p_1^2q_1^2(T_1+C_{wired}(3,1))+p_1^4(T_1+C_{wired}(5,1))+\\
q'^4_{total}(R'+C_{wired\text{-}wireless}(1,1))+2q'^3_{total}p'_{total}(T_2+R'+C_{wired\text{-}wireless}(2,2))+2p'_{total}q'^3_{total}(R'+C_{wired\text{-}wireless}(2,1))+\\
q'_{total}p'^3_{total}(T_2+R'+C_{wired\text{-}wireless}(4,2))+3p'^3_{total}q'_{total}(T_2+C_{wired\text{-}wireless}(4,1))+3q'^2_{total}p'^2_{total}(T_2+R'+C_{wired\text{-}wireless}(3,2))+\\
3p'^2_{total}q'^2_{total}(T_2+C_{wired\text{-}wireless}(3,1))+p'^4_{total}(T_2+C_{wired\text{-}wireless}(5,1)) & ,\ m=5,\ w=4
\end{cases}
\quad (8)
$$

where p'_{total} = the overall dropping probability for the data segment in wired-wireless link.

$p'_{total}=\prod_{(i=1\ to\ N)}(\,p_2(i)+p_3(i)-p_2(i)\,p_3(i)\,)$

q'_{total} = the overall success probability for the data segment in wired-wireless link.

$q'_{total}=1-p'_{total}$

The average completion time for data transmission in the connection division scheme is the sum of the completion times in the wired link and wired-wireless links. Each completion time is calculated separately using the same recursive model as in End-to-End scheme. The analysis of these equations is the same as discussed before for the End- to- End scheme, the main difference is in the using of variables in wired link and wired-wireless links.

4. Performance Evaluation

Network Simulator (NS) [11] was used as a simulation tool to validate our proposed model and to evaluate its performance in terms of average completion time for short-lived TCP flow. For simulations we used the network topology shown in Figure 6. All values used in our simulations are the same as those used previously in other analytical models in [9, 12]. The number of wireless networks (N) is a simulation parameter that was varied to reflect the network TCP performance. The bandwidth and round-trip delay of the wired links are 10 Mbps and 20 ms, respectively. On the other hand, the wireless link is assumed to follow the specification of IEEE 802.11 with omni antenna, the bandwidth, round-trip delay are 1 Mbps and 20 ms, respectively. Initial retransmission timers (RTO) in wired and wireless links are set to 1500 and 500 ms, respectively. The dropping probabilities in all wired links are 0.1 %. The dropping probabilities in wireless links are different from one wireless network to another in order to achieve the heterogeneity. Packet dropping follows the uniform distribution. All simulations are based on the TCP-Reno, which is the most popular implementation in the Internet world.

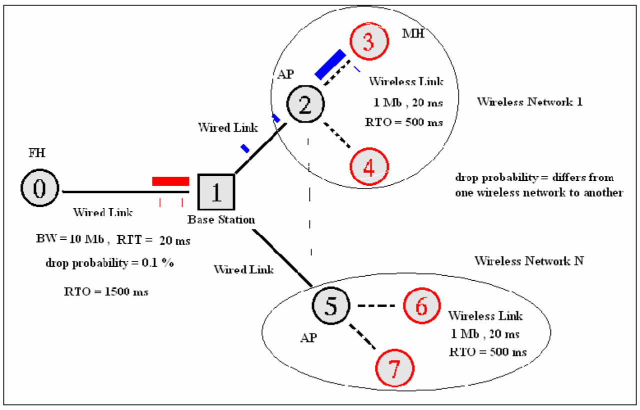

Figure 6. Network topology and simulation scenario.

4.1. End-to-End Scheme

In this section, we run the simulations using the same simulation methodology mentioned in section 4.1. We used two, three and six wireless networks in these simulations. The dropping probabilities for these wireless networks are 1%, 2%, 6%, 4%, 6% and 2% respectively. Figures 7, 8, and 9 show that the average completion time increases as the session size (i.e., the number of data segments in the flow) increases. From these figures, it is observed that the NS-2 simulation and the model result obtained from equations for the End-to End scheme is relatively close to each other as shown in Table 2. Also in these figures, the behaviour of TCP in computing the average completion time for N≥6 seems to be slightly increasing line which holds for all values of the parameters of the model.

Table 2. Difference between simulation values and model values.

Number of Wireless Networks (N)	Average Differences for the Average Completion Time (ms)	
	End-to End scheme	Connection Division Scheme
2	10.073	20.702
3	6.327	23.750
6	7.553	25.360

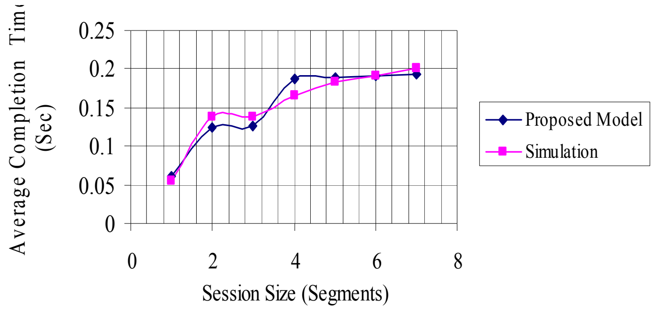

Figure 7. Average completion time in end-to-end scheme with N = 2 (N: number of wireless networks).

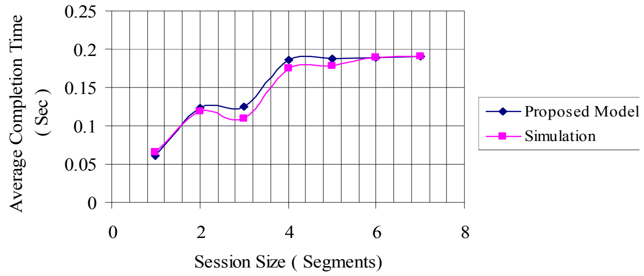

Figure 8. Average completion time in end-to-end scheme with N =3.

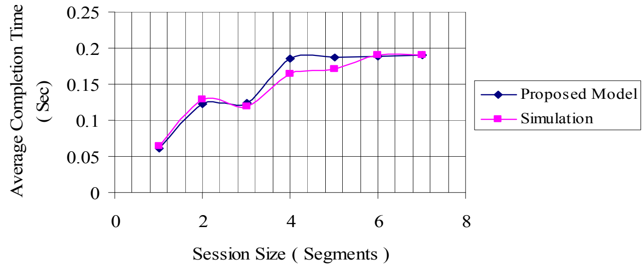

Figure 9. Average completion time in end-to-end scheme with N =6.

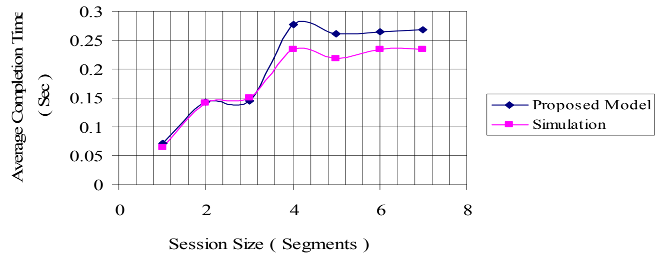

Figure 10. Average completion time in connection division scheme with N = 2.

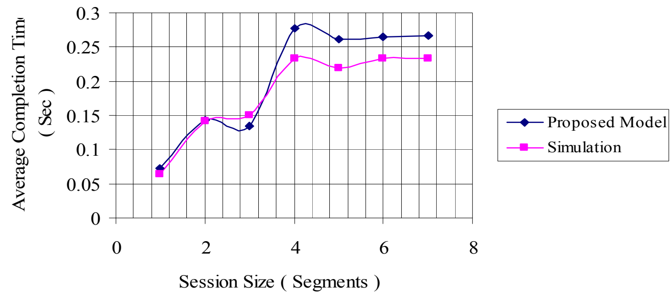

Figure 11. Average completion time in connection division scheme with N =3.

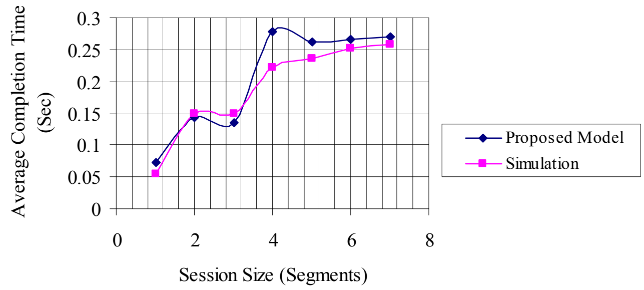

Figure 12. Average completion time in connection division Scheme with N = 6.

These plots give a conclusion that the percentage of difference between simulation and model value for average completion time (in sec) is less than 3%.

4.2. Connection Division Scheme

In this section we run the simulations using the same simulation methodology mentioned in section 4.1.The difference here is that we have two different connections; one from fixed host to the base station and the other from base station to the mobile host. We used two, three and six wireless networks in these simulations. The dropping probabilities for these wireless networks are 1%, 2%, 6%, 4%, 6% and 2% respectively.

Figures 10, 11, and 12, show that the average completion time increases as the session size (in segment) increases. From these Figures, it is observed that the NS-2 simulation and the model result obtained from equations for the connection division scheme is relatively close to each other as shown in Table 2. This indicates that the proposed analytical model is accurate. As such, the proposed model can be used to accurately tune many parameters that affect the behaviour of TCP in wired-cum-wireless networks. The plots give a conclusion that the percentage of difference between simulation and model value for average completion time (in sec) is less than 6%. Also, the difference between the simulation and the model values of the connection division scheme is larger than that of the End-to-End scheme. This is because the proposed model for connection division scheme calculates the total average completion time as a simple sum of the average completion times in wired and wired-wireless links. Also, the purpose of connection division scheme is different from the split connection scheme. This will result in addition time ($R_1/2$) as shown in Figure 5. Whereas, the split connection scheme is used to discriminate the congestion losses in wired networks from the corruption losses in wireless networks.

5. Conclusions

We proposed a recursive and analytical model for short-lived TCP flows for heterogeneous wired-cum-wireless networks was proposed. The heterogeneity of the networks was represented with various parameters, e.g., different packet dropping probability. Two schemes within this model were proposed, namely, End-to-End scheme, and connection division scheme. The average completion time was calculated to determine the TCP performance using the average round trip time, retransmission timeout, flow size and the segment dropping probability. Using NS-2 simulator, the accuracy of our model were validated and compared to the simulated result for heterogeneous wireless topology. Based on the obtained results, we found that the proposed model for the two wireless schemes reflects TCP behaviour well, specifically the session completion time at the initial stage (i.e., slow start).

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