Performance Evaluation of TCP Throughput on Wireless Cellular Networks

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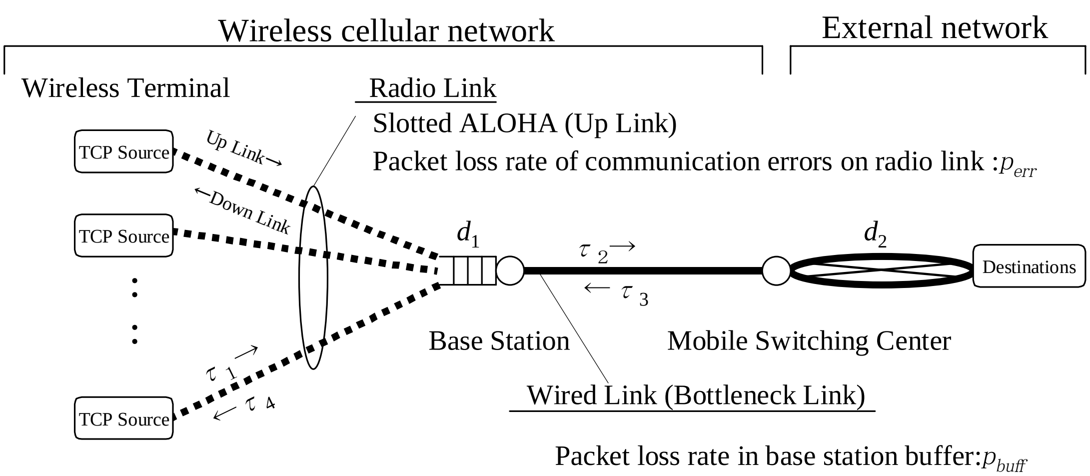
Abstract: We propose an analytical method for evaluating the TCP throughput performance in a wireless cellular network environment, where the slotted ALOHA protocol is adopted as a data link layer. By using our method, we show that improving throughput at the data link layer level does not necessarily lead to the TCP throughput improvement. Furthermore, we evaluate TCP throughput by considering transmission errors on the radio link. It is shown that when we introduce FEC as an error correcting method, we show that TCP throughput can be improved by selecting an appropriate error correction code with careful consideration on the overhead and the error correction capability according to the quality of the wireless channel.

I. Introduction

Mobile Internet technology on wireless cellular networks has been developed rapidly in these several years. It is necessary to consider the following issues for the wireless cellular networks when the users communicate using TCP. First, communication errors frequently occur on the radio link. Second, we should take account of the characteristics of the underlying data link protocol, which is used for communication between the base station and wireless terminals.

The performance of only the data link protocols is studied in [1-3], where the data packet transmission is considered on the CDMA channels. The TCP performance on the wireless cellular networks is studied in [4,5], but the authors in those papers do not consider the influence of the lower layer protocols. When we evaluate TCP throughput performance on wireless cellular networks, it is necessary to consider the effect of packet losses and transmission errors on the radio link on the TCP performance, which is our main subject of this paper. We evaluate the TCP performance by explicitly modeling the performance characteristics of the underlying data link layer protocol. For IMT-2000 [6], we adopt the slotted ALOHA for the data link layer protocol. In our modeling, the TCP throughput is characterized by *RTT* (Round Trip Time), *To* (Time out), and *p* (Packet loss). Then, we consider the



τ_1, τ_2, τ_3, τ_4: propagation delay
d_1: delay in bottleneck buffer, d_2: delay on external network

Figure 1: Wireless cellular network model

influence of the slotted ALOHA on those parameters. Our performance model clearly show that improving the throughput of the data link layer level does not necessarily lead to the TCP throughput improvement. It is also shown that reliability enhancements for the data transmission in the lower layer protocols (such as ARQ and FEC) can improve the TCP performance. And we show that FEC is more effective than ARQ to prevent TCP performance degradation. It is especially important to adequately change the FEC parameters for an error correction capability according to the noise level.

The rest of this paper is organized as follows. In Section 2, we show the analytical model. In Section 3, we evaluate the TCP performance. Finally, we describe the concluding remarks in Section 4.

II. Analytical Model of TCP Throughput

We explain the analytical model on wireless cellular network for the TCP throughput evaluation. The network model for our analysis is shown in Figure 1. TCP throughput, S_{TCP}, in our analysis is characterized by three parameters *RTT*, *To*, *p*, and is given as [7].

$$S_{TCP} = \frac{1}{RTT\sqrt{\frac{2bp}{3}} + To\min(1,3\sqrt{\frac{3bp}{8}})\,p(1+32p^2)} \tag{1}$$

$$W = \frac{2+b}{3b} + \sqrt{\frac{8(1-p)}{3bp} + \left(\frac{2+b}{3b}\right)^2} \tag{2}$$

where *W* is the average window size of the TCP connection, and *b* is a delayed ACK parameter. Normally, *b*=2.

In the wireless cellular network environment, values of *RTT* and *To* must be influenced by the packet loss characteristics of slotted ALOHA because of frame retransmissions at the data link layer. The TCP segment loss probability *p* is also affected by the transmission error on a radio link. In what follows, we will show *RTT* and *To* values encountered by TCP when the slotted ALOHA is used as the data link layer protocol. To clearly investigate the error characteristics of the wireless networks, we consider that the packet loss probability *p* is given by the sum of p_{err} (the packet error probability of the wireless network) and p_{buff} (the packet loss probability at the buffer of the base station). See Figure 1.

For the slotted ALOHA, we first determine an expected value of *RTT* as follows:

$$E[RTT] = \tau_1 + \tau_2 + \tau_3 + \tau_4 + d_1 + d_2 \tag{3}$$

Due to the link contention, the packet transmission delay experienced in the slotted ALOHA network, τ_1, is likely to be much larger than the propagation delays τ_2 through τ_4. Eq. (3) thus may be simply rewritten as

$$E[RTT] \approx \tau_1 + d_2 \tag{4}$$

We next want to determine the packet transmission delay, τ_1. It is well known that the throughput of the slotted ALOHA can be determined by

$$S_{ALOHA} = \frac{G}{L}\exp(-G) \tag{5}$$

where *G* is offer load, *N* is packet transmission interval and *L* is packet length. The underlying assumption for the above equation is that the number of terminals is large and the Poisson arrivals can be assumed for the traffic generation. Apparently, it is not true in our case: nevertheless we introduce it for the following derivation, and will validate its accuracy by comparing with simulation results. In our analysis, the traffic load, *G*, is given by

$$G = \frac{nW}{N} \tag{6}$$

where *n* shows the number of terminals and *N* is the packet transmission interval.

An expected value of the up-link delay, τ_1, is then represented the following equation by S_{ALOHA} when packet collision happens *i* times in the slotted ALOHA.

$$E[\tau_1] = \sum_{i=0}^{\infty}(i+1)NL(1-S_{ALOHA})^i S_{ALOHA} \tag{7}$$

Then we can derive *E*[*RTT*] by adding the external network delay d_2 as:

$$E[RTT] = \sum_{i=0}^{\infty}(i+1)NL(1-S_{ALOHA})^i S_{ALOHA} + d_2 \tag{8}$$

An expected value of the timeout time is given in [8] as:

$$To = rtt\_old + 4rtt\_var \tag{9}$$

In our case, it is written by:

$$E[To] = E[RTT] + 4\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\left|E[\tau_1]_i - E[\tau_1]_j\right| \tag{10}$$

We finally derive the packet loss rate *p*. By assuming that the transmission error on the radio link and buffer overflow occur independently, *p* is given by p_{err} and p_{buff} as follows:

$$p = p_{err} + p_{buff} - p_{err}\,p_{buff} \tag{11}$$

We can now determine the TCP throughput on the wireless channels using Eqs. (1), (2), (8), (10), and (11), based on Eqs. (1) and (2).

We validated the accuracy of our analysis by comparing with simulation using ns2 [9], with the library of the slotted ALOHA. The parameters are summarized in Table 1, and the results of simulation and analysis are shown in Figs. 2 and 3. The analysis results are in a good agreement with simulation results.

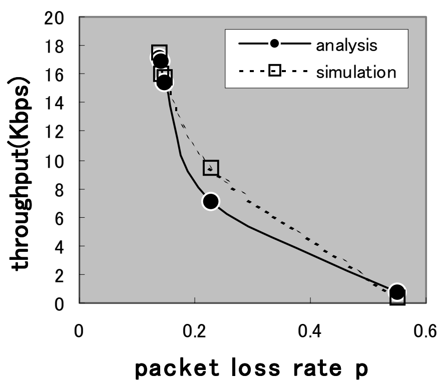


Figure 2: Comparisons of TCP throughput
(The number of wireless terminals is 5)

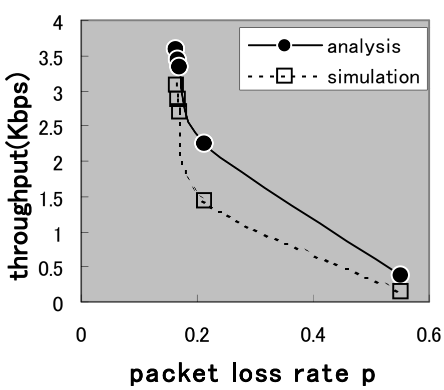


Figure 3: Comparisons of TCP throughput
(The number of wireless terminals is 30)

Table 1: Parameter sets

Bandwidth of radio link	2 Mbps
Bandwidth of wired link	125 Kbps
TCP segment size	100 bytes
Packet transmission interval *N*	70 packets (5 nodes) 35 packets (30 nodes)
TCP throughput External network delay *d*2	100 ms

III. Performance Evaluation

III-I. Influence of slotted ALOHA protocol

In this subsection, the influence of slotted ALOHA on TCP throughput performance is evaluated using our analysis method. Table 2 shows parameters set that we used in evaluation. We show the throughput values of slotted ALOHA and TCP in Figs. 4, and 5, respectively. In these figures, the horizontal axis represents the packet retransmission interval. As shown in the figure, as N is increased, slotted ALOHA throughput reaches at its maximum (around N = 80 in the current case), and then decreases. However, TCP throughput exhibits different results. It is because at N = 80, packet loss occurs frequently as shown in Figure 6. Thus, it is clear that improving throughput on the data link layer level does not necessarily lead to the TCP throughput improvement.

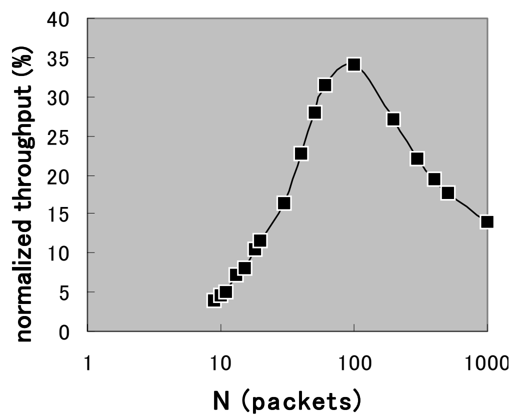


Figure 4: slotted ALOHA throughput

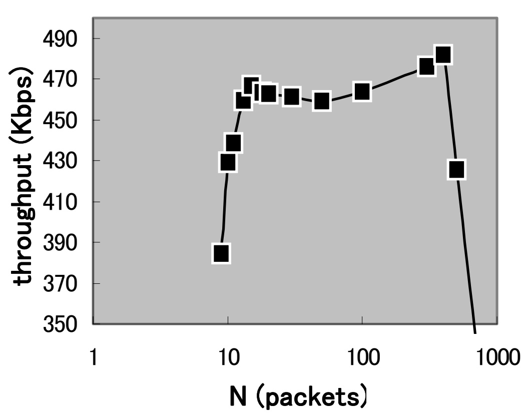


Figure 5: TCP throughput

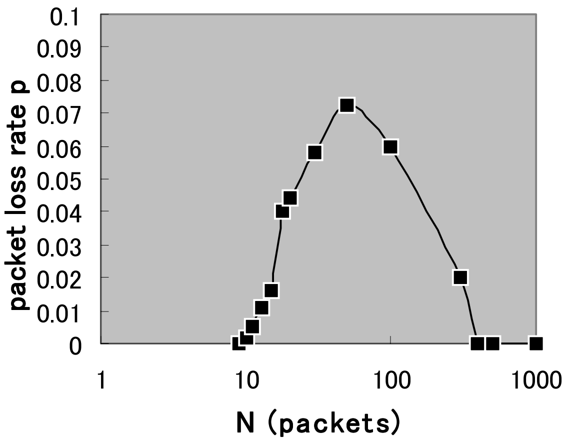


Figure 6: Packet loss rate in BS buffer

Table 2: Evaluation parameters
(Comparison of S_{ALOHA} and S_{TCP})

Bandwidth of radio link	2 Mbps
Bandwidth of wired link	125 Kbps
Number of Terminal	30 node
TCP segment size	100 bytes
BS buffer Size	50 packets
External network staying delay *d*2	0 ms

III-II. Influences of transmission errors on radio link channel

We next evaluate the influence of the transmission errors on the radio link on TCP performance. The cases of using ARQ and FEC are considered as a data link layer protocol with improving the reliable packet transmission. We adopt Reed Solomon (127.117) or (127.87) as the FEC code. We assume the ARQ overhead to be 5% [10]. To choose the number of packet retransmissions by ARQ, we change it and compare the TCP performance. It is shown in Figure 7, where the horizontal axis *Eb/E0* is a noise level which affects communication errors on the radio link. See appendix for its determination. As shown in the figure, increasing the number of packet retransmissions at ARQ is very limited. Figure 8 shows the comparative results for ARQ and FEC. In the case of ARQ, the number of packet retransmissions is set to be one. As shown in the figure, FEC is more effective than ARQ to prevent TCP throughput degradation. It can also be observed that there exists the optimal FEC parameter to achieve the best performance dependent on the noise level. The last result shown in Figure 9 investigates the effect of packet transmission interval *N*. As indicated in the figure, the points that the TCP throughput is suddenly degraded are almost unchanged. Its reason is that the TCP timeout algorithm does not work correctly because RTT changes are small in the current case.

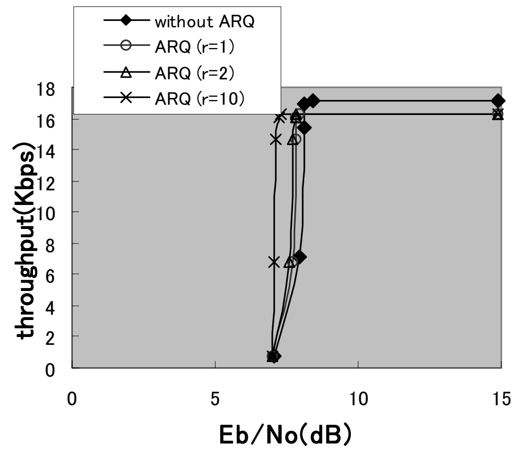


Figure 7: Influences of the number of packet retransmissions on TCP throughput

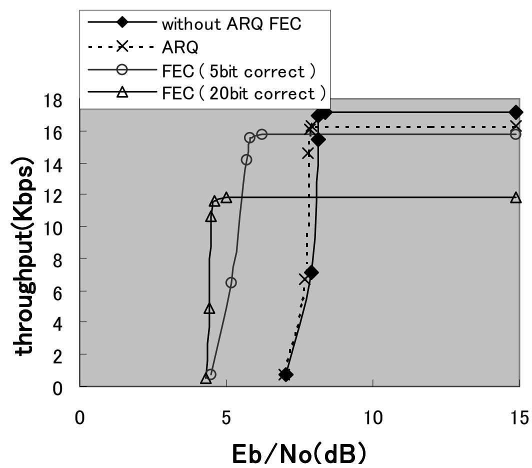


Figure 8: TCP throughput using ARQ, FEC

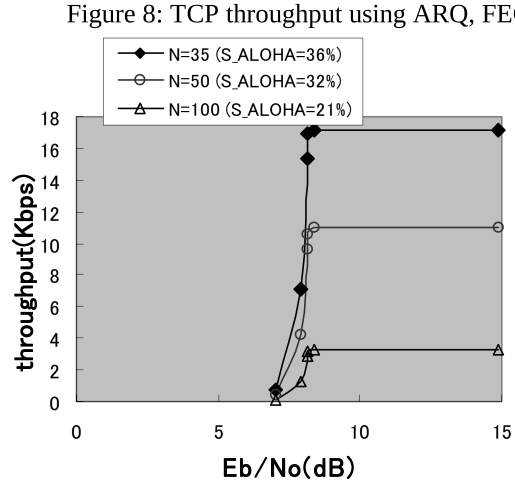


Figure 9: Influences of data link layer throughput on TCP throughput

Table 3: Evaluation parameters
(Communication errors on the radio link)

Bandwidth of radio link	2 Mbps
Bandwidth of wired link	125 Kbps
Terminals number	5 node
TCP segment size	100 bytes
Packet transmission interval *N*	70 packets
BS buffer Size	50 packets
External network staying delay *d*2	0 ms

IV. Conclusion

We have constructed an analytical model for TCP throughput in wireless cellular network. In our analytic model, the influence of data link layer and communication errors on the radio link has been explicitly modeled. An accuracy of our analysis model is examined by comparing with simulation results. Using our method, we next evaluated TCP throughput through the wireless cellular network. We have shown that improving throughput at the data link layer level does not necessarily lead to the TCP throughput improvement. It is also shown that TCP throughput performance is much degraded by communication errors on the radio link. The use of FEC is effective to prevent TCP throughput degradation, but it is necessary to appropriately choose an error correction code with careful consideration on its overhead and the quality level of the wireless channel.

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Appendix

In this appendix, we will show the relation between Eb/N_0 with p_{err}. We assume that the physical layer uses QPSK modulation, which should be using CDMA method of IMT-2000. In the case of QPSK modulation, it is known that p_{err} is given by the following expression.

$$p_b = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \qquad \text{(a-1)}$$

Without ARQ or FEC, p_{err} is represented by using bit error rate p_b and packet length l as:

$$p_{err} = 1-(1-p_b)^l \qquad \text{(a-2)}$$

When we use ARQ, p_{err} is represented by using bit error rate p_b, packet length l and retransmission number r as:

$$p_{err} = \{1-(1-p_b)^l\}^{r+1} \qquad \text{(a-3)}$$

In the case of using FEC, p_{err} is represented by the following binomial distributed expression by using bit error rate p_b, packet length l and error correct ability c.

$$p_{err} = 1-\sum_{i=0}^{c}\binom{l}{i} p_b^i (1-p_b)^{l-i} \qquad \text{(a-4)}$$

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