Performance Evaluation of TCP over Selective Repeat ARQ in Correlated Fading Channel

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Abstract: In this paper, we evaluate the performance of TCP-over-Selective Repeat (SR) ARQ in wireless fading channels. We show that fading speed has great impact on buffer requirement in order to acquire high end-to-end throughput. In addition, TCP end-to-end throughput will degrade due to ARQ's transmission window stalling if wireless propagation delay is so large as not to be ignored. Two advanced SR-ARQ schemes derived from normal SR-ARQ, called Linear-SR and Expo-SR, are studied. Simulation results show that they can greatly improve TCP performance.

Key Words: Mobile Internet, ARQ, fading channel

1. Introduction

Rapid development in the areas of wireless communications and Internet makes it more and more necessary to provide data services such as email, web browsing, telnet in wireless environments. All these applications depend on TCP. But much research has shown that TCP can not work properly in networks with high bit error [3]. Using link layer protocol to hide TCP from wireless losses has been considered a feasible way [4]. Currently, SR-ARQ is widely used at link layer in most mobile communication systems. This is why we study the performance of TCP over SR-ARQ.

Our paper is organized as follows. In Section 2, we will first investigate channel model and give out our analysis about average packet error rate in a correlated fading channel. We show our simulation results in Section 3. Finally conclusion is given in Section 4.

2. Correlated Fading Channel Model

We consider a DS-CDMA forward link (base station to mobile link) where the slowly varying shadow and distance losses are perfectly compensated, and rapid variation due to multi-path fading remain uncompensated. In our simulation two-state channel model [1] is used (fig.1).

Let $S(t)$ denote the state of the wireless channel at time $t$. When the signal power is below a given threshold, the channel is said to be in the "bad" state ($S(t) = 0$), otherwise it is in the "good" state($S(t) = 1$). The good and the bad states are assumed to last for duration, which are exponentially distributed with parameter $\lambda$ and $\mu$ respectively. Thus $\{ S(t); t \in R \}$ is modeled as a continuous time Markov process on the state-space{$0, 1$}. Given the power threshold and the Doppler frequency, the mean duration of the good $(1/\lambda)$ and the bad $(1/\mu)$ states can be
estimated by using the level crossing analysis [1] of the fading process. Also we use $P_E^{(G)}$ and $P_E^{(B)}$ respectively to denote the bit error probability of the good and the bad states, then we can easily get the average bit error rate as

$$P_E = P_E^{(G)} \frac{1}{1 + \frac{\lambda}{\mu}} + P_E^{(B)} \frac{\lambda/\mu}{1 + \frac{\lambda}{\mu}}.$$  

Assuming that the value of $\frac{\lambda}{\mu}$ is independent of fading speed $f_d$, from the above equation we can see that average bit error rate is independent of the fading speed. But when packet transfer is concerned, we find out that, although average bit error rate is not changed with changing fading speed, average packet error rate denoted by $F_E$ will be changed accordingly. Accurate analysis for $F_E$ needs complex computation, thus we give some assumptions to ease the procedure.

We assume that the correlation of a fading channel will be hidden and i.i.d model can be used instead when the sum of duration times of succeeded good and bad state is smaller than the transmission time of a packet that is denoted by $T_F$. We also assume that the start time ($t$) of packet transfer is uniformly distributed over 0 to $t_G + t_B$, where both $t_G$ and $t_B$ are exponentially distributed with parameters $\lambda$ and $\mu$ respectively (fig.2).

Other terms used are shown as follows,

$L$: Length of link layer data packet,
$\hat{\delta}$: Transmission rate.

Then we have $T_F = L\hat{\delta}$,

and $F_E(t_G, t_B)$ is equal to

if $T_F \leq t_B$ and $T_F \leq t_G$, then

$$\{(t_B - T_F)[1 - (1 - P_E^{(B)})^L]$$

$$+ 2 \int_0^{T_F} \left[1 - (1 - P_E^{(B)})^{x \frac{T_F}{T_B}} (1 - P_E^{(G)})^{\frac{x}{T_B}} \right] dx$$

$$+ (t_G - T_F)[1 - (1 - P_E^{(G)})^L] \right) \times \frac{1}{t_G + t_B}.$$  

if $T_F > t_B$ and $T_F \leq t_G$, then

$$\{(T_F - t_B)\left[1 - (1 - P_E^{(B)})^{\frac{t_B}{T_B}} \right]$$

$$+ 2 \int_0^{t_B} \left[1 - (1 - P_E^{(B)})^{x \frac{T_F}{T_B}} (1 - P_E^{(G)})^{\frac{x}{T_B}} \right] dx$$

$$+ (t_G - T_F)[1 - (1 - P_E^{(G)})^L] \} \times \frac{1}{t_G + t_B}.$$  

if $T_F \leq t_B$ and $T_F > t_G$, then

$$\{(t_B - T_F)[1 - (1 - P_E^{(B)})^L]$$

$$+ 2 \int_0^{t_B} \left[1 - (1 - P_E^{(B)})^{x \frac{T_F}{T_B}} (1 - P_E^{(G)})^{\frac{x}{T_B}} \right] dx$$

$$+ (T_F - t_G)[1 - (1 - P_E^{(G)})^{\frac{t_G}{T_B}} (1 - P_E^{(B)})^{\frac{T_F - t_G}{T_B}}] \} \times \frac{1}{t_G + t_B}.$$  

if $T_F > t_B$, $T_F > t_G$, and $T_F \leq t_B + t_G$, then

$$\{(T_F - t_B)[1 - (1 - P_E^{(B)})^L]$$

$$+ 2 \int_0^{t_B} \left[1 - (1 - P_E^{(B)})^{x \frac{T_F}{T_B}} (1 - P_E^{(G)})^{\frac{x}{T_B}} \right] dx$$

$$+ (T_F - t_G)[1 - (1 - P_E^{(G)})^{\frac{t_G}{T_B}} (1 - P_E^{(B)})^{\frac{T_F - t_G}{T_B}}] \} \times \frac{1}{t_G + t_B}.$$  

Fig.2 Illustration for Analysis
if \( T_F > t_B + t_G \), then

\[
1 - (1 - P_E^{(B)}) \left( \frac{t_B}{T_B} \right) \left( 1 - P_E^{(G)} \right) \left( \frac{t_G}{T_G} \right).
\]

Therefore we get the mean value of \( F_E \) as follows

\[
E(F_E) = \int_{t_B=0}^{t_B} \int_{t_G=0}^{t_G} F_E(t_B, t_G) \lambda dt_B dt_G.
\]

For example, as shown in [1] the mean duration of the bad state for a Raleigh fading channel with a fading margin 10 dB can be approximately \( 0.1/ f_d \), where \( f_d \) is the Doppler frequency. And, the sum of the mean durations of successive good and bad states is \( 1/ f_d \). Thus, the mean duration of the good state can therefore be closely approximated by \( (1-0.1)/ f_d \approx 1/ f_d \). Then we can easily get that average bit error rate:

\[
P_E = (P_E^{(G)} 0.1 + P_E^{(B)}) / 1.1.
\]

From the above analysis, we can give some results shown in Table 1.

<table>
<thead>
<tr>
<th>Doppler (Hz)</th>
<th>Average Packet Error Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.084</td>
</tr>
<tr>
<td>30</td>
<td>0.128</td>
</tr>
<tr>
<td>100</td>
<td>0.163</td>
</tr>
</tbody>
</table>

Table 1. \( E(F_E) \) against Doppler Frequency

3. Simulation Results

Fig.3 is our simulation scenario. We use TCP-Reno, and the length of TCP data packet is 576 bytes. At link layer, a full reliable SR-ARQ is adopted.

First we study the effect of fading speed on TCP performance. We consider three values of Doppler frequency (10Hz, 30Hz, and 100Hz). Both Fig.4 (LL = 576 bytes) and Fig.5 (LL=100 bytes) show that throughput is improved with increasing buffer size of the bottleneck. The reason is obviously that retransmission delay in link layer will accumulate packets in the bottleneck. The large buffer size leads to small probability of buffer overflow. Additionally, if buffer size is so large that probability of packet loss due to overflow is small enough to be neglected, fast fading results in low throughput. We can explain as follows. The large buffer hides the correlated characteristic of fading channel so that the average packet error rate will play the key role in TCP end-to-end performance. Although increasing fading speed does not change average bit error rate, the average packet error rate increases accordingly as shown in Table 1, which degrades the performance.

From fig.4 and fig.5 we find that fast fading speed achieves higher throughput when buffer size is small. It is because that the slow fading leads to long persistent time of a packet in the buffer and increases the probability of overflow. In addition, fragmentation at link layer is necessary for good performance.

In the above analysis, propagation delay of the wireless link is ignored (\( D = 150ms\) \( d = 1ms\)). In follows, we take it considered. Fig.6 shows that when end-to-end propagation delay
is fixed (D+d=151ms), throughput degrades with increasing wireless propagation delay due to window stalling of SR ARQ. Increasing its up-bound can make it work better (fig.6), but requires the receiver of a larger buffer for re-sequencing. Another solution is increasing the speed of error recovery. Two advanced SR-ARQ schemes, called Linear-SR and Expo-SR, can improve performance greatly by sending multiple copies for each lost packet during the retransmission period (fig.8). When fixing the maximum window size of ARQ, these two schemes can improve the end-to-end throughput greatly as shown in Fig.7.

4. Conclusion

Through our simulation and analysis, we get the following conclusions,

(1) Reliable SR-ARQ can effectively hide TCP from wireless losses. However, the long persistence time of ARQ scheme will require large buffer at base station.

(2) If packet loss rate is high, fragmentation at link layer is indispensable.

(3) If buffer size is small, slow fading leads to poor performance due to buffer overflow. On the other hand, fast fading increases the average packet error rate, it is why better performance can be acquired in slow fading channel when buffer size is large enough and not the bottleneck for achieving high performance.

(4) If wireless propagation delay is ignored, a normal SR ARQ is enough. While in a network with long wireless propagation delay, the performance degrades greatly especially when buffer is small. To speed up error recovery of SR-ARQ, multiple copy retransmission schemes such as Linear-SR and Expo-SR should be used. Simulation results show that both of them can effectively improve throughput.

(5) Transmission window of SR-ARQ is important to performance especially when wireless propagation delay can not be ignored. It directly impacts the transmission rate as shown in follows.

\[ \bar{R}(t) = \min(R, W / D(t)) \]

- \( \bar{R}(t) \): An effective bandwidth seen by upper layer.
- \( R \): raw bandwidth of wireless link
- \( D(t) \): A random variable to characterize the delay from sending a packet to successful received by receiver
- \( W \): Window size of ARQ

In future work, we will investigate the details of \( \bar{R}(t) \). Based on it, a queuing model for wireless transmission can be constructed, which is very helpful for deep understanding the performance of wireless data networks.

Reference:


Analysis of ARQ Schemes for Wireless Networks, 0-7803-3925-8/97, 1997, IEEE.


Fig.3 Network Scenario

Fig.4 Throughput comparison for different fading speed 
(D=150ms d=1ms LL PDU =576B)

Buffersize(B)

Throughput Percentage

LL PDU Size = 576B
Fig. 5 Throughput comparison for different fading speed (D=150ms d=1ms LL PDU =100B)

Fig. 6 Throughput against normalized window size of SR ARQ

(Normalized Value = Window Size / (RTT*BandWidth) )
**Fig. 7** Throughput comparison for different SR ARQ schemes

**Fig. 8** Procedure Details of Cons-SR, Linear-SR and Expo-SR