

Performance of TCP over wireless links with hybrid ARQ*

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Abstract: This paper studies TCP performance over a wireless link where hybrid Automatic Repeat reQuest (ARQ) schemes are adopted for combating packet loss due to wireless channel errors. A Markov chain is developed to analytically evaluate the TCP throughput over an arbitrary hybrid ARQ scheme. Base on this model, we can learn how the underlying coding scheme, the link layer retransmission method and the TCP packet buffer size at the access point affect the TCP performance. We demonstrate by analysis and verify by simulation that the CT-TCM hybrid ARQ scheme provides more efficient spectrum utilization and higher TCP throughput than other existing hybrid ARQs.

Keywords: Wireless TCP, hybrid ARQ, TCM code.

1 Introduction

The increasing demand for high data rate services in wireless networks promotes Transmission Control Protocol (TCP) to be extensively used in the Third Generation (3G) systems. The congestion control mechanism of TCP dominates the wired networks under the assumption that packet losses are mainly due to network congestion. However, previous studies have demonstrated that TCP will suffer serious performance degradation, e.g., spurious end-to-end retransmission and timeouts, when it is directly used over wireless links [1, 4]. The reason is that the above assumption is not suitable for wireless networks, where packet losses are mainly incurred by wireless channel errors instead of congestion. Various solutions have been proposed to improve the TCP performance over wireless networks [2]-[6]. Among these solutions, error control schemes, e.g., local retransmission by ARQ, forward error recovery (FEC) or their hybrid (hybrid ARQ), are proposed to enhance the reliability of wireless links [4]-[6]. These error control schemes have demonstrated the following benefits to wireless TCP applications: 1) They can cooperate with

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TCP without requiring any changes to the current congestion control mechanism. 2) If the cross-layer configuration is considered between the link layer and TCP, they can provide useful physical or link layer information to TCP for optimization, or they can cooperate with some existing wireless TCP solutions, e.g., snoop TCP [4], explicit-loss-notification based TCP [4], to maximize the throughput over wireless links.

With new error control schemes used in the link layer, one would naturally be interested in what are their impacts on the TCP level throughput, because these impacts have implications for performance perceived by end users. In [4]-[6], simulations or analyzes based on a simple channel model with two states (good and bad) are used to evaluate the TCP level throughput. However, when hybrid ARQ schemes are used in wireless links, the channel condition is characterized by the symbol error rate (SER) or frame error rate (FER) achieved by the hybrid ARQ under a given signal-to-noise ratio (SNR). It is therefore desirable to know the resulting TCP level throughput for a given SNR. In this paper, we develop an analytical model to study the performance of TCP over a wireless link, where hybrid ARQ schemes are deployed to combat wireless channel errors.

The remainder of this paper is organized as follows. A Markov chain is developed to evaluate the TCP throughput over an arbitrary hybrid ARQ in Section 2, which is followed by a survey of recently proposed hybrid ARQ schemes in Section 3. Analytical and simulation results of TCP performance over these hybrid ARQs are presented in Section 4. The conclusions are presented in Section 5.

2 An analytical model for TCP over hybrid ARQ

We consider the TCP performance in a common scenario in practice, as shown in Fig. 1, where a mobile user downloads information from a server. A hybrid ARQ scheme is used for local error control in the wireless link from the access point (AP) to the receiver. In Fig. 1, d and D are round trip propagation delays over the wireless link and the wired path from the sender to the AP, respectively; B is the TCP buffer size at the AP for queueing TCP packets from the sender; T and T_w are random variables representing service time and queueing delay of a TCP packet at the AP, respectively; t_a is the transmission delay of a link layer acknowledgement (ACK) or negative acknowledgement (NAK) packet over the wireless link; C is the wireless link capacity in bits/s; p is FER over the wireless link.

To simplify our analysis on TCP performance in the considered scenario, the wired path is assumed error-free, the wireless link is assumed to be an additive white Gaussian noise (AWGN) channel, where the packet errors are independently and identically distributed (i.i.d.). With i.i.d. packet errors, the TCP sender is not likely to experience two or more consecutive packet losses. Hence, it is reasonable to assume that the probability of TCP timeouts due to consecutive packet losses is small enough to be negligible. It is also reasonable to assume that most of the traffic from the sender to the receiver is made of aggressive large flows. Under these circumstances, we ignore the slow-start phase and only consider the congestion avoidance phase of TCP.

The TCP packets from the sender are queued in the buffer at the AP. Each TCP packet is fragmented into N smaller link layer frames with fixed length L_f and transmitted in the wireless link. Since the link layer ACKs and NAKs usually have fairly smaller size than TCP packets, t_a can be ignored. For the same reason, we also ignore any delay that

$\{p_{ss'} : 1 \leq s, s' \leq NM_r\}$ according to Fig. 2 are given by

$$p_{ss'} = \begin{cases} e_{M_r}, & \text{for } s = nM_r, s' = 1 \\ g_j, & \text{for } s = (N-1)M_r + j, s' = 1 \cup s = (n-1)M_r + j, s' = nM_r + 1 \\ e_s, & \text{for } s = (n-1)M_r + j, s' = s + 1 \\ 0, & \text{for } s = s'. \end{cases}$$

From $p_{ss'}$, we can form the transition probability matrix $\mathbf{P}_{NM_r \times NM_r} = [p_{ss'}]$. Let π_s be the probability of the system being in state s . Define $\Pi = [\pi_s]$ a row vector representing the state probabilities of the DTMC. We now have the set of steady state equations $\pi_s = \sum_{s' \in \Omega} \pi_{s'} p_{s's}$ for all $s \in \Omega$ and the normalizing equation $\sum_{s \in \Omega} \pi_s = 1$. By solving these equations, we obtain the set of stationary state probabilities Π . However, on calculating \bar{T} and $E[T^2]$, we are also interested in the transient state probabilities of the model.

Define $\Pi^{(0)}$ as a row vector representing the initial probabilities for state $s \in \Omega$ with elements $\pi_1^{(0)} = 1$ and $\pi_s^{(0)} = 0$ for $s \in \Omega - \{1\}$, because the state transition always starts from state $(1, 1)$ ($s = 1$) for every TCP packet. Let Φ be a NM_r -by- NM_r matrix, representing the state transition probabilities of our Markov chain, excluding the transitions to state $(1, 1)$ ($s = 1$). Let $\phi_{ss'}$, $s, s' \in \Omega$, be the element of Φ . Its values are given by $\phi_{ss'} = p_{ss'}$ for $s \neq s', s' \neq 1$ and $\phi_{ss'} = 0$ for other $s, s' \in \Omega$. Define $X = [x_s]$ and $Y = [y_s]$ as two column vectors representing the transition probabilities from state $s \in \Omega$ to state $(1, 1)$ due to success and failure in a TCP packet transmission, respectively. From Fig. 2, we have $x_s = g_j$ for $\{s = (N-1)M_r + j : 1 \leq j \leq M_r\}$ and $x_s = 0$ for all other s ; $y_s = e_{M_r}$ for $\{s = nM_r : 1 \leq n \leq N\}$ and $y_s = 0$ for all other s . Let l be the number of state time slots experienced in one TCP packet transmission (including success and failure). Based on the property of Markov chains [8], the transient state probabilities for state $s \in \Omega$ at discrete time l is given by $\Pi^{(l)} = \Pi^{(0)} \Phi^{l-1} (X + Y)$. From Fig. 2, l is given from $\min(M_r, N)$ to $N \times M_r$. Thus, the average service time of a TCP packet over the wireless link and its second moment can be calculated by

$$\bar{T} = \sum_{l=\min(M_r, N)}^{NM_r} \Pi^{(0)} \Phi^{(l-1)} (X + Y) l T_f, \quad (3)$$

$$E[T^2] = \sum_{l=\min(M_r, N)}^{NM_r} \Pi^{(0)} \Phi^{(l-1)} (X + Y) (l T_f)^2. \quad (4)$$

Substituting Eq. (3) and Eq. (4) into Eq. (2), we can obtain the average RTT $\bar{\tau}$ of a TCP packet through the wireless link deploying a general hybrid ARQ scheme.

In order to obtain the average arrival rate λ of TCP packets at the AP, we need estimate the average size of congestion window (*cwnd*) of a TCP connection. There are following two cases related to the variations of the *cwnd* of a TCP connection over wireless links.

Firstly, if the detected packet losses related to wireless channel errors are very small, i.e., the wireless channel errors have been mostly or thoroughly combated by the link layer hybrid ARQ schemes, the size of *cwnd* can additively increase every RTT (since we have already assumed no congestion-related losses) till the maximum buffer size B at the AP is reached. Then, the subsequently arrived TCP packets will be dropped due to buffer overflow and the size of *cwnd* will be halved (e.g. for TCP Reno [9]) due to packet losses. Let w_p denote the maximum size of *cwnd* of a TCP connection. In such cases, we have

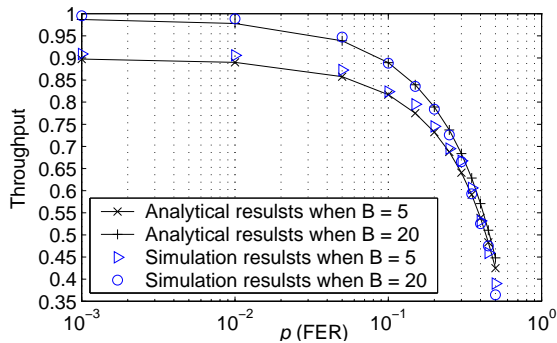


Fig. 3. TCP throughput by analysis and simulation.

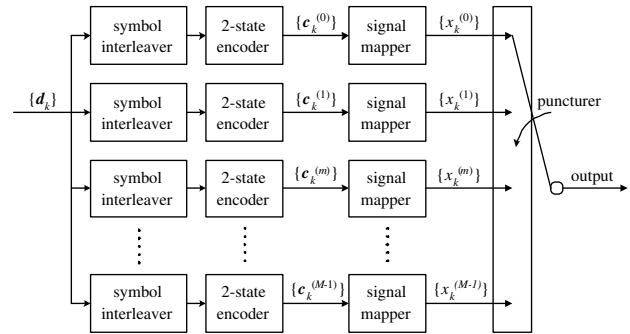


Fig. 4. The global structure of CT-TCM encoder.

3 Hybrid ARQ schemes

Using the model from the last section, we can compare the TCP throughputs over different hybrid ARQ schemes. Before we evaluate these performances, we first present several recently proposed hybrid ARQ schemes that adopt different coding algorithms to improve the spectrum utilization for possible applications in broadband wireless networks.

In hybrid ARQ schemes, type-II hybrid ARQ [11] can achieve efficient bandwidth utilization by sending parity-check bits in retransmission instead of repeating the same packet in all retransmissions as type-I hybrid ARQs do. However, it is difficult to combine a type-II hybrid ARQ with a bandwidth efficient trellis-coded modulation (TCM) scheme, because the information bits and redundancy bits of a TCM code cannot be separated. This nature of TCM codes confines their applications in hybrid ARQ schemes employing repetition method like type-I ARQs, e.g., the TCM-based schemes proposed in [12] and [13]. The scheme of [13] suggests to repeat the same TCM codeword in each retransmission but combine the multiple received versions of the original data packet for decoding at the receiver for better throughput performance. The scheme of [12] involves two different TCM codes that are alternatively used in retransmission. For the first transmission, the message is encoded by one TCM code. If the received copy contains uncorrectable errors, the message is encoded by the other TCM code for retransmission. After two transmissions, the scheme of [12] switches to the repetition mode like a type-I ARQ. Such a repetition method is not an optimized solution regarding transmission efficiency.

We proposed a new TCM-based hybrid ARQ for TCP applications over wireless in [14]. Our proposed scheme uses the concatenated two-state TCM (CT-TCM) algorithm [15] as the underlying coding algorithm to improve the bandwidth utilization over the wireless link. It overcomes the aforementioned limitation in the traditional TCM-based hybrid ARQ schemes by using different punctured parts of a CT-TCM code in retransmission, instead of repeating the same TCM code in all retransmissions as the schemes of [12] and [13] do. How to obtain the different punctured parts used in retransmissions is one key issue of our hybrid ARQ scheme in [14]. To answer this question, we first give an outline of the CT-TCM algorithm before we introduce the mechanism of our proposed hybrid ARQ. For more details of the CT-TCM algorithm, readers are referred to [15].

The CT-TCM algorithm comprises multiple component encoders concatenated in parallel by symbol interleavers. Fig. 4 shows the structure of a CT-TCM encoder which com-

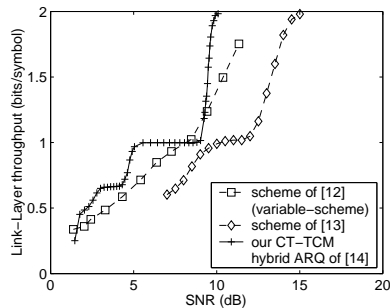


Fig. 5. Link layer throughput comparison.

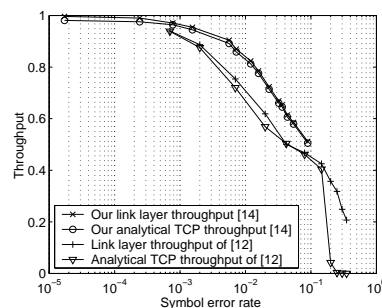
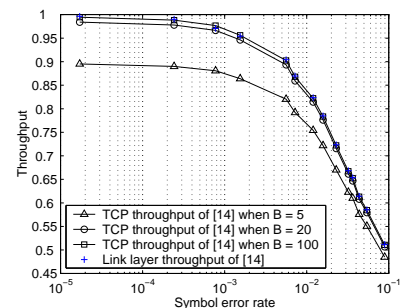


Fig. 6. TCP performance comparison.



(b) Under different buffer size B .

4 Comparisons of TCP performance over hybrid ARQs

Realizing that the link layer throughput provides the capacity limit of TCP over the wireless link, we plot in Fig. 5 the simulation results of the link layer throughput of our hybrid ARQ scheme as a function of the average SNR in an AWGN channel. The puncture pattern used for the i th transmission of a link layer data frame is given by $\gamma_i = \Gamma_{(i-1) \bmod M}$, where $i \geq 1$, $M = 4$ and $\Gamma_{(i-1) \bmod M}$ is given by Table 1. The link layer throughput is measured by the number of information-bits-per-symbol (bits/symbol) transmitted over the channel. For a 8PSK-based TCM scheme, the maximum information-bits-per-symbol is 2. For comparison, we also plot in Fig. 5 the link layer throughput provided by the TCM-based ARQ schemes in [12] and [13]³ over an AWGN channel. We can observe from Fig. 5 that significantly improved link layer throughput is achieved by our scheme over the other two schemes, except for the small SNR range (8.2 dB \sim 9.2 dB) where the performance of our scheme is worse than that of [12]. However, such stair-like phenomenon of our throughput can be eliminated and the link layer throughput can be further improved by the modified method presented in [14].

Now, we compare the performances of TCP over the wireless link using the above-mentioned hybrid ARQ schemes based on the following parameters. One FTP application over TCP Reno [9] is running in the system shown in Fig. 1, with the wireless link capacity $C = 2.048$ M bits/s. Each TCP packet contains 8192 bits. RTT over the wired link D is 100 ms. B is set to 20 TCP packets unless it is specified otherwise. $M_r = 4$. Fig. 6(a) presents the analytical results of the TCP throughput obtained by our hybrid ARQ scheme as a function of SER over the wireless link with SNR ranging from 1 dB to 10 dB. For comparison, we include in Fig. 6(a) the TCP throughput obtained by the scheme of [12], derived from the SER results provided in [12]. Since the results in Fig. 5 have shown that the link layer performance of [12] significantly outperforms that of [13], the TCP performance of [13] is not considered here. From Fig. 6(a), we observe that higher TCP throughput is achieved by our scheme than by that of [12]. For reference, we also include the link layer throughput of both schemes in Fig. 6(a). It demonstrates that the difference between the TCP throughput of the scheme of [12] and its link layer counterpart is higher

³ The results from [12], [13] are cited by converting their E_b/N_0 and E_s/N_0 coordinates into corresponding SNR coordinates.

by using different punctured parts of a CT-TCM code in retransmission. We demonstrated by both analysis and simulation that significantly improved end-to-end TCP throughput can be achieved by adopting the CT-TCM hybrid ARQ in a wireless link. In addition, we have observed that an optimal buffer size exists above which no significant improvement on TCP throughput can be achieved.

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