A Delayed Multiple Copy Retransmission Scheme for Data Communication in Wireless Networks

Zhisheng Niu, Yi Wu, and Jing Zhu

Abstract: **In this paper, we propose a delayed multiple copy retransmission (DMCR) scheme for data communication in wireless networks, by which multiple copies of a lost link layer frame are retransmitted one-by-one with a retransmission delay in between. The number of the copies gradually increases with the number of retransmissions. Furthermore, for implementation of the DMCR scheme in practical mobile communication system, we also propose a dynamic retransmission scheme by interleaving and a new round-robin scheduling algorithm. We compare our scheme with the previous non-delayed retransmission schemes on the performance of frame loss probability, channel capacity and total transmission time. Numerical results show that the DMCR scheme can achieve higher performance. The effect of the delay time on end-to-end TCP throughput is investigated as well.**

Index Terms: **Mobile communication, Fading channels, Internet, ARQ.**

I. INTRODUCTION

With fast development of TCP/IP-based Internet and mobile communications, there is a growing trend toward the convergence of these two systems, i.e., wireless/mobile Internet. Traditional mobile communication systems were designed to mainly provide voice services and therefore facing many challenges in the coming wireless data networks. Among them, frame (more generally speaking, link layer packet) loss due to lossy wireless channels is one of the key issues. To solve this problem, reliable link layer protocols such as ARQ have been widely used.

ARQ schemes can be roughly classified into Stop-and-Wait, Go-back-N, and Selective Repeat (SR). Among them, SR-ARQ is most efficient and has been widely used in practical mobile systems (e.g., 3GPP2 [1], [2]). Since the retransmission number is generally limited (say 3 in 3GPP2) in order to avoid long persistence time, SR-ARQ is not reliable enough for wireless data communication [3]. Therefore, to further improve the performance of SR-ARQ, the success probability of each retransmission must be improved. One effective way is to retransmit multiple copies at each retransmission, i.e., multiple copy retransmission (MCR) scheme by sacrificing the transmission efficiency of the radio channel. Specifically, two MCR schemes have been proposed: Linear-MCR scheme [2] and Exp-MCR scheme [4], where $i+1$ and x^i (usually, x is equal to 2) copies of a lost frame are retransmitted at the ith retransmission respectively.

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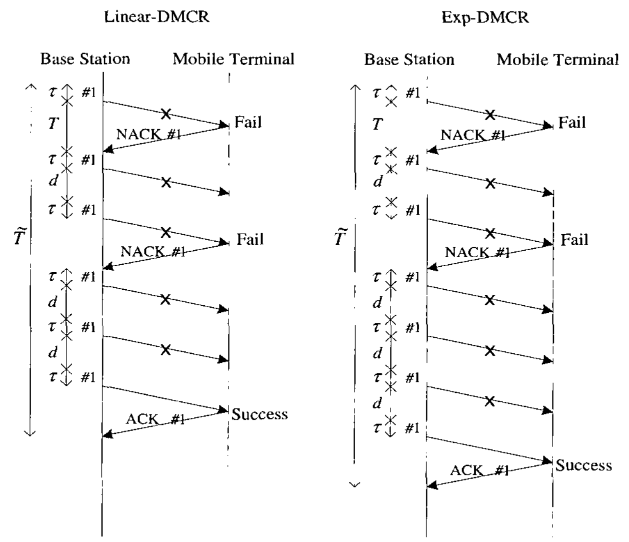

Fig. 1. A typical frame retransmission sequence of delayed multiple copy retransmission schemes.

However, the burst nature of the errors in a correlated fading channel [5], [6] may result in successive frame losses so that the retransmitted copies may be lost again, which will significantly degrade channel capacity accordingly. To solve this problem, we propose a delayed multiple copy retransmission (DMCR) scheme, by which a retransmi:ssion delay is inserted between successive copies of the lost frame. If we set the retransmission delay to be zero, our scheme comes to the previous MCR scheme.

Our paper is organized as follows. In Section II, a brief introduction to the DMCR scheme and its performance analysis are given. In Section III we study the performance of TCP-over-DMCR system by simulation. In Section IV we propose an interleaving retransmission scheme and a new round-robin scheduling algorithm for easy practical implementation. Finally we conclude the whole paper in Section V.

II. DELAYED MULTIPLE COPY RETRANSMISSION: SCHEME AND PERFORMANCE ANALYSIS

A. Scheme Description and Modeling

Fig. 1 shows a typical frame retransmission sequence of the delayed multiple copy retransmission schemes, where T denotes the round trip time of a wireless link, τ denotes the duration of each frame, d denotes the retransmission delay inserted between the adjacent retransmitted copies, and $\widetilde{T}$ denotes the total transmission time. Data flow direction is assumed to be from base station to mobile terminal, which is the usual case in practice.

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As illustrated in the diagram, the copies of a lost frame are sent out one-by-one with the retransmission delay d in between to prevent the retransmitted copies from falling into the same error burst of the fading channel. Moreover, two specific DMCR schemes are proposed: Linear-DMCR and Exp-DMCR, where $i+1$ and x^i (usually, x equals 2) copies of a lost frame are retransmitted at the ith retransmission respectively. Note that the Exp-MCR scheme in this paper is a bit different from that in [4], where multiple retransmission is executed for both the NACK frames and data frames due to backward error prone channel. In this paper we assume the multiple retransmission is only for data frames. Generally, the backward channel is error prone. However, the length of a control frame over the backward channel is much shorter so that the loss probability is much lower compared with the data frame. Also, some strong forward error correction methods are adopted by control frames to improve their ability to resist corruption. Therefore, we assume that the backward channel is error-free.

Obviously, the longer the retransmission delay, the smaller the probability of successive frames falling in the same error burst. But an excessively long delay time definitely increases the total transmission time of a frame and as a result degrades the performance. Therefore, an appropriate value of the delay time should be chosen, which depends on the fading characteristics of wireless channel. Since the error burst length is stochastic, the delay time should be a random variable accordingly. However, in order to simplify the theoretical analysis, a fixed value is assumed in the sequel.

It has been well investigated that since the wireless channel has the correlated nature caused by fading, the power of the received signal fluctuates as time varying [6]. By setting appropriate thresholds of the fading amplitude, the channel can be divided into m states, in which the probability of error is significantly different. Thus the correlated fading channel is assumed to be a first-order discrete-time Markov chain with m states [7], [8].

In our analysis, all time-related parameters are normalized by the duration of one frame transmission, which is also the interval for channel state transition. The notation used in our analysis is shown as follows:

- T: Round trip time of a wireless link;
- d: The retransmission delay inserted between the retransmitted link layer frames;
- m: Number of channel states;
- D: One-step transition matrix of channel state of order $m \times m$, whose (i,j)th element p_{ij} represents the transition probability from state i to state j in one step $(i,j = 1,2,\ldots,m)$;
- π: Row vector of stationary probabilities whose ith element π_i represents the stationary probability of state i;
- e_i: Bit error rate (BER) of the channel when it is in state i $(i = 1,2,\ldots,m)$;
- l: Length of the information frame in bits;
- τ: Duration of each frame transmission;
- N: Number of transmission times until the information frame is successfully received (including the first transmission);
- N_m: Number of maximum retransmission times for each information frame (including the first transmission);
- P_c: Probability matrix, whose (i,j)th element $P_c(ij)$ denotes the probability of successful transmission of the link-layer frame in one-step transition of the channel state from i to j.
- P_e: Probability matrix, whose (i,j)th element $P_e(ij)$ denotes the probability of failed transmission of the link-layer frame in one-step transition of the channel state from i to j.
- Q_n: Probability matrix, whose (i,j)th element $q_n(ij)$ denotes the probability that a frame is correctly received at the nth retransmission when the channel is in state j, given that the channel is in state i when the frame transmission starts.

When the channel is in state i, the success probability of a l-bit frame transmission is $(1-e_i)^l$. Therefore, given that the channel is in state i when frame transmission begins, the probability of a successful frame transmission ending in state j is $(1-e_i)^l p_{ij}$, which constructs the probability matrix P_c. Similarly, $(1-(1-e_i)^l)p_{ij}$ constructs the probability matrix P_e. Noting that the matrix D represents the channel state transition probabilities in one-step no matter the frame transmission is successful or failed, it is easy to know that $D = P_c + P_e$.

First, let us derive the frame loss probability. If the number of copies at the nth retransmission is v_n and all copies in this retransmission are lost, the probability matrix related to this event is $(P_e D^d)^{v_n-1} P_e D^T$, where D^d characterizes the channel state transition during the retransmission delay d inserted between adjacent retransmitted frames and D^T characterizes the channel state transition during the round trip time T. From the first to the nth retransmission, the transition probability matrix $F_L^{(n)}$ is $\prod_{k=1}^{n}[(P_e D^d)^{v_k-1} P_e D^T]$. So the frame loss probability after the maximum times of retransmissions is given by $\pi F_L^{(N_m)} \mathbf{e}$, where $\mathbf{e}$ is a column vector of all 1's.

Then, we focus on the success probability after the nth retransmission. Note that any copy at the nth retransmission has the possibility to be received correctly. Suppose that the νth copy is received correctly and all copies sent before that copy are lost, then the transition probability matrix is $(P_e D^d)^{\nu-1} P_c$. From the first to the last copy, the transition probability matrix $F_S^{(n)}$ is $\sum_{\nu=1}^{v_n}(P_e D^d)^{\nu-1} P_c$. Consequently, we obtain the probability matrix Q_n:

$$\begin{aligned} Q_n &= F_L^{(n-1)} F_S^{(n)} \\ &= \Big(\prod_{k=1}^{n-1}(P_e D^d)^{v_k-1} P_e D^T\Big)\Big(\sum_{\nu=1}^{v_n}(P_e D^d)^{\nu-1} P_c\Big). \quad (1) \end{aligned}$$

Therefore, the success probability after the nth retransmission is $\pi Q_n \mathbf{e}$.

We define channel capacity η as the mean number of frames that are received correctly during each frame time, which is given by

$$\eta = \sum_{n=1}^{N_m} (\pi Q_n \mathbf{e}) \frac{\mathbf{1}}{\mathbf{M_n}}, \quad (2)$$

where M_n denotes the total number of copies after the nth retransmission, which equals $\frac{n(n+1)}{2}$ or $2^n - 1$ for Linear-DMCR and Exp-DMCR respectively.

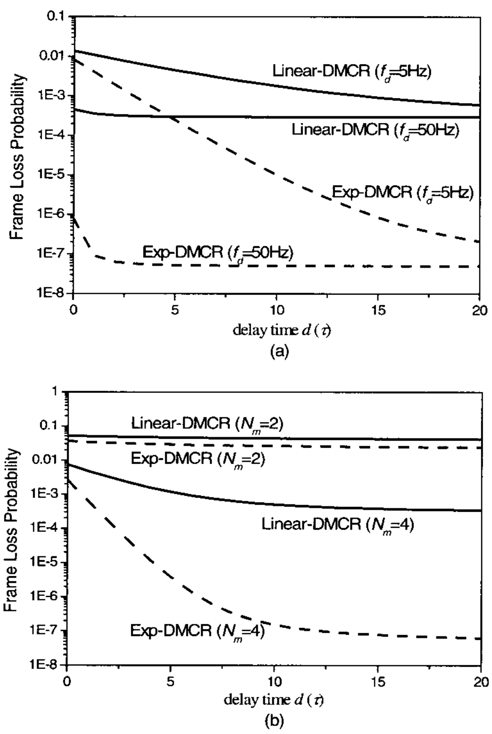

Fig. 2. Effect of delay time on frame loss probability: (a) Frame loss probability against delay time, (b) frame loss probability against delay time.

Also, after nth retransmission we have total transmission time $\tilde{T}$ for the DMCR schemes as

$$\tilde{T}=\sum_{n=1}^{N_m}\pi\Big(\Big(\prod_{k=1}^{n-1}(P_eD^d)^{v_k-1}P_eD^T\Big)\Big(\sum_{\nu=1}^{v_n}(P_eD^d)^{\nu-1}P_c t_\nu^{(n)}\Big)\Big)\mathbf{e}, \quad (3)$$

where

$$t_\nu^{(n)}=\sum_{i=1}^{n-1}v_i+\nu+\Big[\sum_{j=1}^{n-1}(v_j-1)+(\nu-1)\Big]d+nT. \quad (4)$$

B. Numerical Results and Discussions

With the analytical model proposed above, we study in depth on frame loss probability, channel capacity, and total transmission time at link layer. In the numerical examples, we have assumed that the frame length l is 768 bits, the round trip time of a wireless channel is 3τ, the modulation is BPSK, the information symbol rate R_s is 2Mbps, and the average SNR value of the channel is 20dB. Without loss of generality, the number of channel states m is set to be 2 which means that we adopt the Gilbert-Elliott (GE) model [9] in characterizing the dynamics of the correlated fading channel.

Recall that the GE channel is a first-order discrete-time stationary Markov chain with two states: one GOOD state and one BAD state where $e_1 \ll e_2$. To match the GE model to the terrestrial mobile channel, we choose a threshold γ_t for the signal-to-noise ratio (SNR), where the channel is supposed to change state, and then match the average duration the fading altitude is below this threshold to the average number of time units the GE channel is in BAD state. In doing this, we arrive at [10] and obtain the parameters of state transition matrix D as

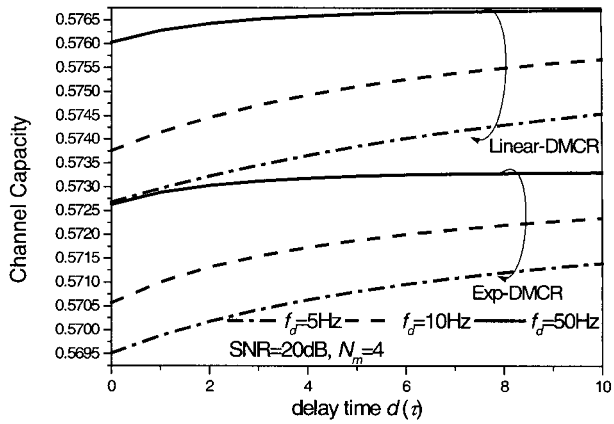

Fig. 3. Effect of the delay time on channel capacity.

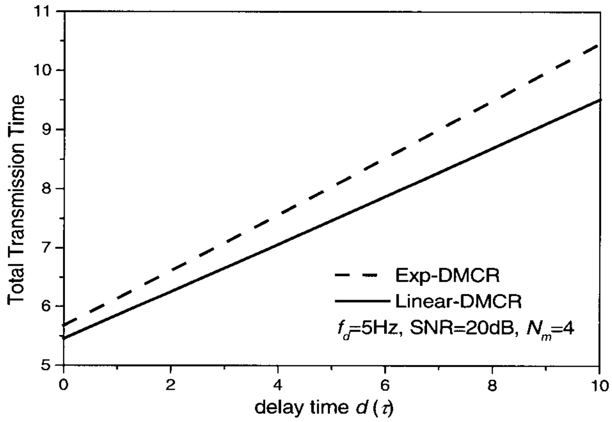

Fig. 4. Effect of the delay time on total transmission time.

$$D(1,2)=\frac{l\rho f_d\sqrt{2\pi}}{R_s(e^{\rho^2}-1)}, \quad (5)$$

$$D(2,1)=\frac{l\rho f_d\sqrt{2\pi}}{R_s}, \quad (6)$$

where f_d is the so-called Doppler frequency shift and ρ^2 is the ratio of the SNR threshold γ_t to the average SNR value $\overline{\gamma}$ of the received signal. Then the bit error rate in the respective states of the GE channel are obtained as:

$$e_1=\frac{1}{1-e^{-\rho^2}}\int_0^{\gamma_t}\frac{1}{\overline{\gamma}}e^{-\gamma/\overline{\gamma}}P_e(\gamma)d\gamma, \quad (7)$$

$$e_2=\frac{1}{e^{-\rho^2}}\int_{\gamma_t}^{\infty}\frac{1}{\overline{\gamma}}e^{-\gamma/\overline{\gamma}}P_e(\gamma)d\gamma, \quad (8)$$

where $P_e(\gamma)$ is the bit error rate for a given value of γ, which depends on the modulation format used. The detailed derivation of (7) and (8) could be found in [10], which will not be presented in this paper.

The numerical results of the theoretical analysis are shown in Figs. 2–4, and we have the following conclusions:

1) Compared with Linear-DMCR scheme, Exp-DMCR scheme achieves the great improvement on reliability with the cost of little channel capacity loss.

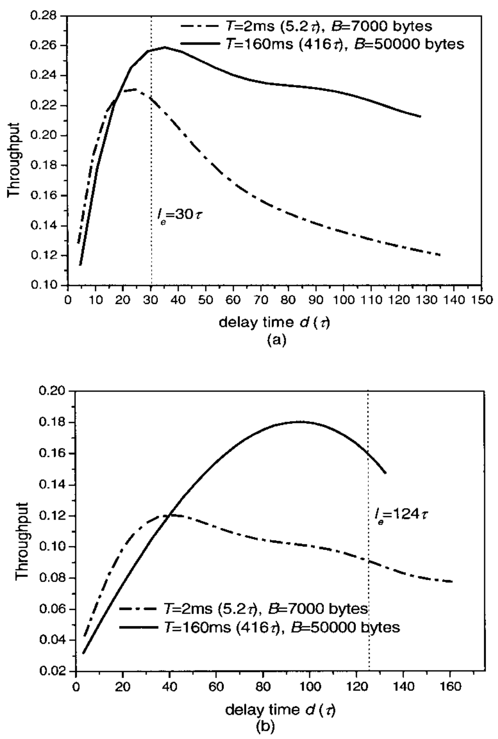

Fig. 5. Effect of wireless round trip time on the optimal delay time: (a) f_d =20Hz, SNR=10dB, N_m =4, Exp-DMCR, (b)f_d =5Hz, SNR=10dB, N_m =4, Exp-DMCR.

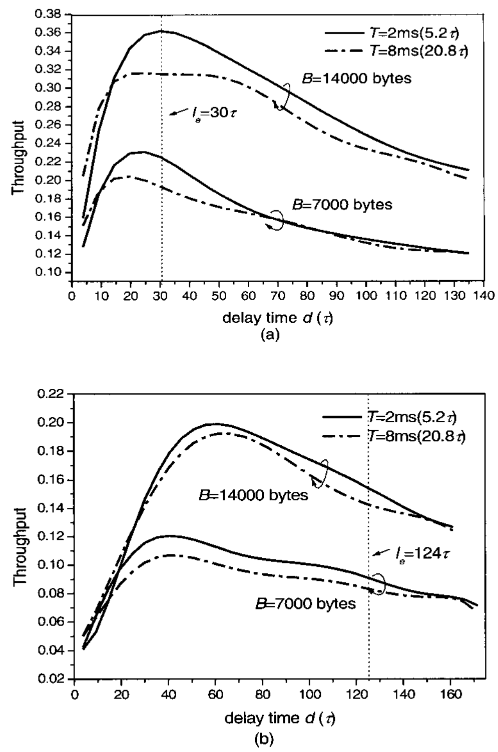

Fig. 6. Effect of TCP buffer size on the optimal delay time: (a) f_d =20Hz, SNR=10dB, N_m =4, Exp-DMCR, (b)f_d =5Hz, SNR=10dB, N_m =4, Exp-DMCR.

Table 1. Parameters of two-state continuous time Markovian channel model.

f_d	SNR	λ	μ	l_e	e_1	e_2
5(Hz)	10 (dB)	6.28145	21.99753	124	0.00304	0.20200
20(Hz)	10 (dB)	25.1258	87.99011	30	0.00304	0.20200

2) In contrast to MCR schemes where d is zero, introducing delay can improve performance in terms of frame loss probability and channel capacity, whereas, leading to longer total transmission time.
3) For a fixed N_m (e.g., $N_m = 4$), the smaller the fading speed, the greater the performance improvement of the DMCR schemes. This is because that in slower fading channels the error burst is longer and the probability of successive frame losses is larger. DMCR schemes can effectively avoid whole copy losses by introducing delay, thus the frame loss probability decreases.
4) For a fixed f_d (e.g., $f_d = 10$Hz), increasing the number of maximum retransmission times will improve the performance of DMCR schemes. Furthermore, the scheme with larger maximum retransmission number is more sensitive to the delay time (see Fig. 2(b)). This is because DMCR schemes benefit more from the delay time with more retransmitted copies.

III. SIMULATION STUDY OF TCP-OVER-DMCR SYSTEMS

However, the enhancement achieved above is independent of the higher-level protocol such as TCP which implements its own end-to-end retransmission protocol. Studies have shown that independent retransmission protocols can lead to degraded performance, especially as error rates become significant [11], [12]. Specifically, considering the interaction of link layer and TCP layer, the determination of the optimal value to the delay time is very important. It depends on buffer size, fading speed, wireless delay and so on. Since no accurate analytical model for TCP over DMCR scheme exists now, we study this problem by simulation.

For our simulations we use *ns-2* (version *2.1b6*) [13] incorporating several additions we develop, on a set of Pentium III class workstations running the Linux OS. We consider a typical mobile communication system, where we take the capacity of the wired network as 100 Mbps, the capacity of the wireless link as 2Mbps, the propagation delay of the wired network as 50 ms, the link layer frame size as 768 bits (i.e. 96 bytes), and the TCP packet length as 4608 bits (i.e. 576 bytes). Additionally, the retransmission delay d is normalized by the transmitting duration of each link layer frame τ, which equals 0.384ms. The buffer size of base station is denoted by B.

In our simulation, the two-state continuous-time Markovian channel model [10], [14] is used, where the bit error rate of GOOD state and BAD state are e_1 and e_2, respectively. The durations of these two states have the exponential distribution with parameter λ and μ. Then the mean time of the BAD state can be obtained as $1/\mu$, which is called the error burst length, denoted by l_e. Given by the conditions such as SNR, bandwidth and fading speed, we can derive the values for all parameters in the channel model. In Table 1, we enumerate the channel parameters set in simulation.

For saving the space, we show the results for the Exp-DMCR

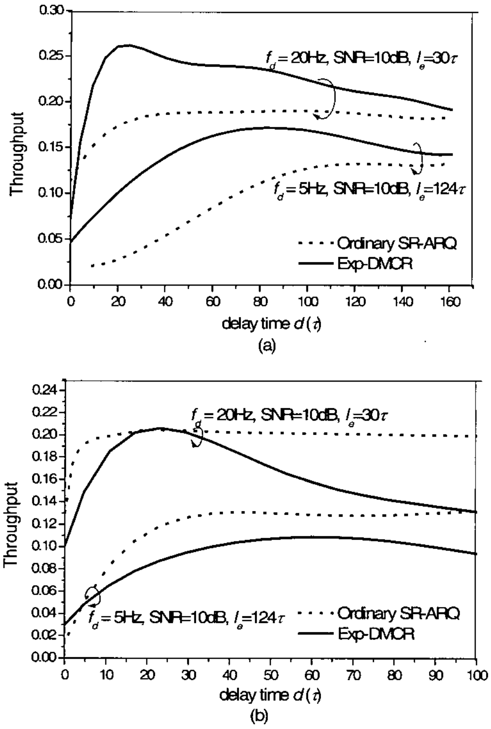

Fig. 7. Performance comparison of TCP over DMCR with TCP over ordinary SR-ARQ: (a)T'=160ms(416 tau), N_m=4, B=30000bytes, (b)T'=8ms(20.8 tau), N_m=4, B=7000bytes.

scheme only in the sequel and the same conclusions can be applied to the Linear-MCR case too. Figs. 5 and 6 illustrate TCP throughput over Exp-DMCR scheme at link layer with different retransmission delay d. Note that when d approaches 0 in x-axis, the DMCR scheme turns back to the MCR scheme. Thus the performance improvement brought by the inserted retransmission delay is demonstrated by the simulation results. Furthermore, these figures indicate that the optimal value of the delay time is limited by the error burst length l_e and is proportionate to the wireless round trip time. On the other hand, when the round trip time of wireless link is fixed, the larger buffer size gives TCP more robust capability to tolerate the longer delay introduced by the DMCR scheme. Thus larger optimal value for the delay time can be chosen as a result (see Fig. 6).

Next we make the performance comparison between TCP over DMCR scheme and that over the ordinary SR-ARQ scheme by simulations. For the purpose of fairness, first we introduce a new parameter D_{max} defined as the maximum tolerable delay time, which has the relationship with parameter N_m as follows:

a) For ordinary SR-ARQ:

$$D_{max} = N_m(T + \tau), \tag{9}$$

b) For Exp-DMCR:

$$D_{max} = (2^{N_m} - 1)\tau + N_m T + (2^{N_m} - N_m - 1)d. \tag{10}$$

Apparently, the same number of maximum retransmission times N_m results in different maximum tolerable delay time D_{max} in each case. Therefore, the parameter D_{max} needs to be fixed for all the schemes in order to guarantee the fairness of

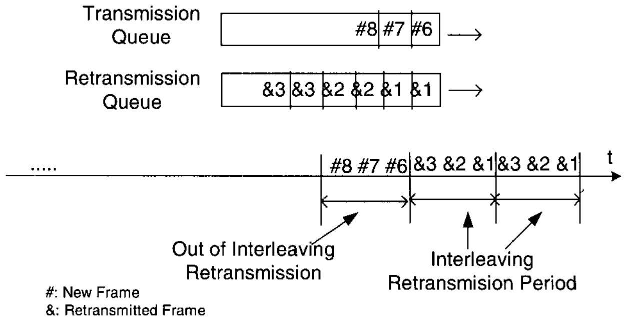

Fig. 8. A typical frame transmission example for interleaving retransmission.

comparison. In our simulations, we set the value of N_m for Exp-DMCR scheme as 4, and then from joint equations (9) and (10), the value of N_m of the ordinary SR-ARQ scheme is determined by

$$\begin{aligned} N_m &= \frac{\{(2^{N_m} - 1)\tau + N_m T + (2^{N_m} - N_m - 1)d\}|_{N_m=4}}{T + \tau} \\ &= \frac{15\tau + 4T + 11d}{T + \tau}. \end{aligned} \tag{11}$$

In this way we keep the same value of D_{max} for the two comparing schemes in simulations and maintain the fairness in comparison.

We focus on the performance of throughput, which is defined as TCP end-to-end throughput normalized by the wireless bandwidth. In our simulation two cases are concerned: One with the shorter wireless round trip time ($T = 20.8\tau = 8ms$) compared with the error burst length of wireless channel ($l_e = 124\tau, 30\tau$), and the other with the longer wireless round trip time ($T = 416\tau = 160ms$).

Fig. 7 shows that the improvement achieved by DMCR scheme is significant in the wireless network with a large value of round trip time. This implies that the long delay wireless network, such as satellite systems, can benefit more from our DMCR scheme. Essentially, DMCR scheme proposes the time diversity effect, which is obtained by retransmitting multiple copies with the interval of delay time d. However, in the wireless network with a small value of round trip time, the optimal value of the delay time may be much longer compared with the wireless round trip time (Fig. 6(b)). In this case, the cost of long transmission delay due to the delay time should be considered.

IV. IMPLEMENTATION ISSUE

The results of analysis above show that it is difficult to determine the optimal value of the delay time. Furthermore, fixing the delay time is not an effective solution especially when the characteristic of a channel is time-varying. As a refinement of the DMCR approach in implementation, we propose a dynamic scheme of retransmission interleaving, where the retransmission delay is randomized to account for stochastic variations of the channel conditions.

In order to give a more detailed explanation, we consider a scenario as shown in Fig. 8, in which there are three frames lost in transmission: #1, #2, #3, and then two copies for each lost

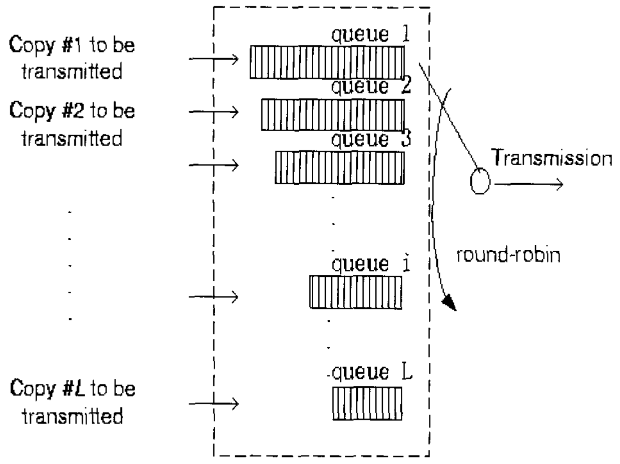

Fig. 9. A round-robin scheme for interleaving retransmission.

frame are generated in the retransmission queue (i.e., &1, &2, &3 as seen in Fig. 8). These copies should be interleaved before retransmission. Consequently, between two copies of the same lost frame there are two copies of other lost frames. In other words, the delay time d is two when measured by the duration of a frame time. From above, we can easily find that the delay time realized by interleaving depends on the number of different lost frames in the retransmission queue. Furthermore, increasing number of lost frames leads to the larger value of the delay time.

Generally, two queues are required in base station. One denoted by transmission queue is for new frames, the other denoted by retransmission queue is for retransmitted frames. The retransmission queue has higher priority than the transmission queue, which means that frames in the transmission queue can not be sent out unless the retransmission queue is exhausted. Specifically, the interleaving retransmission scheme works as follows:

- Step 1: If there are frames in the retransmission queue, interleaving process starts. After interleaving, all the copies in the retransmission queue are sent out one-by-one;
- Step 2: If the retransmission queue is empty, it means interleaving retransmission is over and frames in the transmission queue are sent out. Otherwise, go to step 1 and the interleaving retransmission scheme continues.

To implement the interleaving process, we suggest a round-robin scheduling algorithm as shown in Fig. 9. It uses L queues for retransmission, where L is given by the maximum number of retransmitted copies for a lost frame. For example, L is N_m for the Linear-DMCR scheme and 2^{N_m-1} for the Exp-DMCR scheme respectively. It works as follows:

- Upon the arrival of retransmitted copies, the ith copy is directed to the ith queue;
- Retransmission must begin with the first retransmission queue, and the copies in the $(i+1)$th queue can be sent out only after the ith queue becomes empty. After all the retransmission queues are exhausted, the transmission queue start to send new frames with lower priority.

As seen in Fig. 9, all the retransmission queues used by the round-robin scheme follow the FIFO (First-In-First-Out) rule. Furthermore, since the probability of the retransmission failure is proportional to the inverse of the number of retransmission

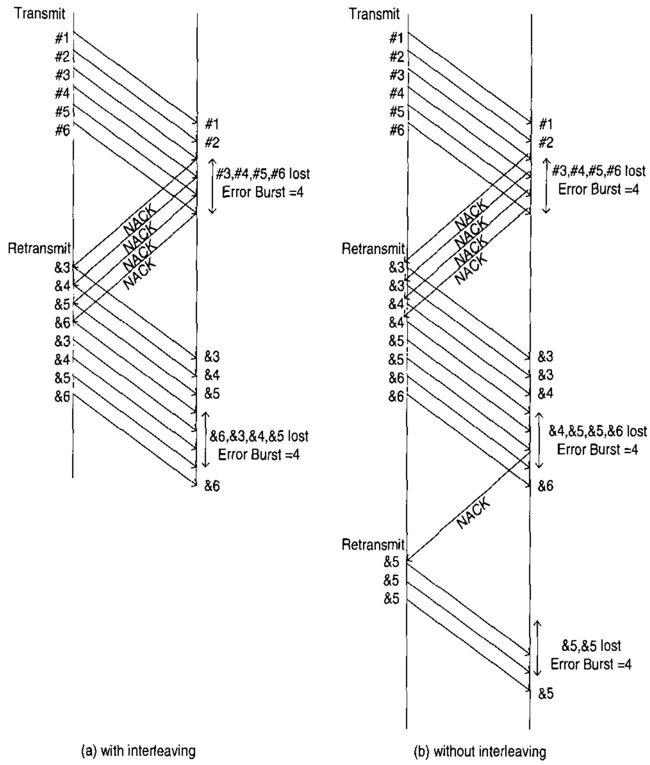

Fig. 10. Multiple copy retransmission scheme with interleaving and without interleaving.

times, the length of the queue decreases with serial number of the queue as shown in Fig. 9.

Fig. 10 explains how the interleaving retransmission scheme improves the performance by avoiding the case that multiple retransmitted copies of the same frame fall in the period of error burst. For simplicity of illustration, we assume a specific scenario that the error burst happens with fixed length as 4. Accordingly, we assume the number of successive lost frames is 4. Therefore, for each lost frame, there are at least three copies of other frames inserted between its two retransmitted copies after interleaving. As a result, one copy of each lost frame (&3, &4, &5, &6) is successfully received as shown in Fig. 10(a). Actually, in practical system the length of bad state is stochastic, and the round-robin scheme can dynamically execute the interleaving process with efficient diversity. Fig. 10(b) also shows the disadvantage of the previous MCR scheme (without interleaving) indicating the necessity of interleaving process.

Fig. 11 shows TCP end-to-end performance improvement caused by Exp-DMCR scheme, where interleaving retransmission is used for implementation. In our simulation, the maximum number of retransmissions is 3, TCP packet length is 500 bytes, and link layer packet length is 50 bytes. The underlying fading channel is assumed to be same with the foregoing model described in Section 3 and the average SNR is assumed as 10dB. The bandwidth of the wired network and the wireless network is 10Mbps and 1Mbps respectively. The wireless round trip time (RTT) is 100ms, and we ignore the propagation delay in the wired network. It shows that with different fading speeds, the Exp-DMCR scheme with retransmission interleaving always improves the performance greatly.

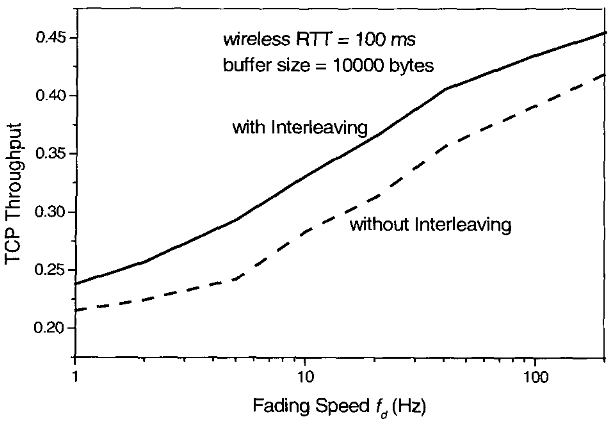

Fig. 11. TCP end-to-end performance improvement with the refinement of DMCR scheme.

V. CONCLUSION

By introducing the retransmission delay d between retransmitted copies, we proposed a delayed multiple copy retransmission scheme (DMCR) for wireless data communication in correlated fading channels. The number of copies increases linearly (Linear-DMCR) or exponentially (Exp-DMCR) as the number of retransmissions increases. It is shown that the proposed DMCR scheme is particularly well suited in the presence of a correlated fading channel. In particular, the Exp-DMCR technique achieves the lower frame loss probability, but the higher total transmission time and the lower capacity compared with the Linear-DMCR scheme. The performance of these different schemes is analytically derived by means of a matrix approach to account for the different states of the channel. Analytical results show that our proposal obtains higher performance in terms of both frame loss probability and channel capacity than the previous MCR schemes. The impact of the DMCR scheme on the TCP performance is investigated through computer simulations in the presence of a two-state continuous time channel model and with different round trip time (RTT). Through simulation, we find out that for a special DMCR scheme (Linear-DMCR or Exp-DMCR), when fixing the ratio of the wireless delay to the error burst length, the optimal value of the delay time linearly depends on the error burst length. However, their exact relationship is left for future work. Finally, for the issue of implementation, a refinement of the DMCR approach is proposed, where multiple copies of different frames are interleaved before retransmissions. Furthermore, when the maximum number of retransmission times is limited, a practical scheduling algorithm called round-robin is suggested. Simulation results show that the DMCR scheme acquires higher TCP end-to-end throughput than the previous MCR scheme does.

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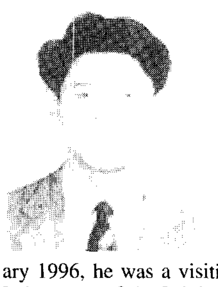

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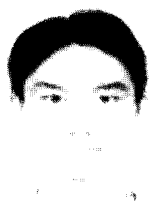

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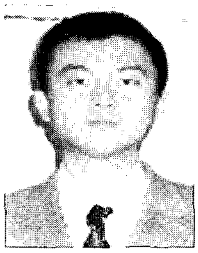

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