무선 채널에서의 Selective Repeat ARQ 프로토콜의 Delay 성능 분석

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Delay Analysis of Selective Repeat ARQ for a Markovian Source Over a Wireless Channel

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요 약

이 논문에서는 시간에 따라 채널 상태가 변화는 무선 채널 상에서 Markov 소스의 딜레이 성능을 분석하였다. 무선 링크의 양단에서 Selective-repeat (SR) ARQ 프로토콜을 사용한다고 가정했다. 이 논문에서는 대기 시간과 전송 및 재전송 시간 그리고 재 정렬 시간으로 구성된 단대단 평균 패킷 딜레이에 대한 근사화된 분석 방식을 제안하였다. 수치적인 분석과 시뮬레이션 결과와의 분석을 통해서, 이 연구에서 제안한 분석 방식이 대부분의 경우 정확한 결과를 예측하고 있음을 증명하였다.

Key Words : Selective repeat ARQ, delay performance, Markov channel.

ABSTRACT

In this paper, we analyze the delay performance for a Markovian source transported over a wireless channel with time-varying error characteristics. To improve the reliability of the channel, the end points of the wireless link implement a selective-repeat (SR) ARQ error control protocol. We provide an approximate discrete-time analysis of the end-to-end mean packet delay, which consists of transport and resequencing delays. Numerical results and simulations indicate that our approximate analysis is sufficiently accurate for a wide range of parameter values.

Ⅰ. Introduction

In this study, we consider a wireless link that provides sequential delivery of packets and that uses Selective Repeat (SR) automatic repeat request (ARQ) for error control. There exist the various delay components that a packet undergoes when transported over a wireless link. The end-to-end delay consists of transport and resequencing delays. The transport delay is again subdivided into queueing and retransmission delays. The queueing delay is defined as the time taken by a packet from its arrival at the transmitter buffer until its first transmission attempt. The retransmission delay is defined as the time from a packet's first transmission until its successful arrival at the receiver. The resequencing delay is defined as the waiting time of the packet in the resequencing buffer.

In this study, we investigate the mean

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end-to-end delay for a general Markovian source that is transported over a wireless link with SR ARQ error control. To capture the time-varying and correlated nature of the radio channel, we model it using Gilbert-Elliot's model. We divide the end-to-end delay into queueing, retransmission, and resequencing delays. For the queueing delay, we simplify the analysis by eliminating the dependence of the queueing process on the past packet transmission process. We derive the exact probability generating function (PGF) for the ideal SR ARQ and obtain the mean delay using Little's law. The mean retransmission delay is easily obtained since it only depends on the channel parameters and the round-trip delay. Finally, we derive an expression for the mean resequencing delay under heavy-traffic conditions. The adequacy of our analytical results are verified by contrasting them against more realistic simulation results.

An extensive amount of literature exists on analyzing the performance of SR ARQ protocol in terms of throughput, mean queue length, and mean delay. In order to analyze other measures of performance such as buffer distribution and packet delay, Konheim used the system state vector considering a feedback delay [7]. Anagnostou and Protonotarios proposed an alternative approximate approach that reduces the computational complexity of the analytical results [1]. One problem with these approaches is that their computational complexity increases dramatically with the feedback delay. Fantacci used a 2-state Markovian radio channel, yet employing a Bernoulli process for packet arrivals [5]. Rosberg and Shacham analyzed the resequencing delay and the buffer occupancy at the resequencing buffer assuming heavy-traffic conditions and static radio channel [9]. Rosberg and Sidi analyzed the joint distribution of buffer occupancy at the transmitter and receiver [10]. In addition, they derived the mean transmission and resequencing delays. However, they assumed a renewal arrival process and independent packet errors.

Ⅱ. Queueing and Retransmisson Delays

Consider the queueing system at the transmitter side of a wireless link. Our queueing model is based on an Markov chain in which the number of packets in the queue is observed at the beginning of each time slot, just before the arrival of a new packet or of an ACK/NACK message. A time slot corresponds to a packet transmission time. We assume that ACK/NACK messages are always error free. The arrival process is N-state Markovian that is governed by a transition probability matrix P, where at each state i, $i=0, \cdots, N$, i packets are generated in one time slot. The wireless channel is modeled by Gilbert-Elliot's model, in which the channel alternates between Good and Bad states, with corresponding bit error probabilities P_{eg} and P_{eb}, respectively. The packet error probability when the channel state is in state j is denoted by e_j, $j=0,1$. The packet error probability in Good ($j=0$) and Bad ($j=1$) channel states are given by:

$$e_0 = 1-(1-P_{eg})^L \qquad (1)$$

$$e_1 = 1-(1-P_{eb})^L \qquad (2)$$

for a packet size of L bits.

Our analytical approach is based on the approximation in [1, 5], where the transport delay is divided into two parts: queueing and retransmission delays. In order to obtain the queueing delay, the authors in [1, 5] approximate the behavior of a real SR ARQ by ignoring the dependence of ACK/NACK arrivals on the system's past history. This simplification is referred to as the ideal SR ARQ case [5]. Note that this assumption does not mean the feedback delay is ignored, but that its impact on the queueing process is not incorporated. In the following, we derive the PGF for the queue length in the ideal SR ARQ case. We assume that packets are served on a FCFS basis and that the buffer capacity is infinite. Key notations are summarized as follows:

$a(k)$: Number of new arrivals during the kth slot.

$r(k)$: Channel state at the beginning of the kth slot.

$q(k|i,j)$: Queue length at the beginning of the kth slot when the source is in state i and the channel is in state j.

P:: Transition probability matrix for the arrival process at the transmitter buffer.

R:: Transition probability matrix for the process that describes the state of the radio channel.

The transition probabilities for the arrival process are defined as $P=[p_{i,j}]$, where

$$p_{i,j} \triangleq \Pr[a(k+1)=j|a(k)=i], \quad 0\le i,j\le N. \tag{3}$$

Also, the transition probabilities for the channel process are defined as $R=[r_{i,j}]$, where

$$r_{i,j} \triangleq \Pr[r(k+1)=j|r(k)=i], \quad i,j\in\{0,1\} \tag{4}$$

where states 0 and 1 denote Good and Bad channel states, respectively.

The size of the queue at the beginning of slot k is a function of its size in the previous slot, the number of packets that arrive during slot k, and the state of the feedback message. Thus, the queue size at the beginning of the (k+1)th slot is obtained as follows:

If $q(k|\cdot,\cdot)+a(k)>0$, then

$$q(k+1|l,j)=\begin{cases} q(k|i,j)+i-1 \\ \quad \textit{with probability } p_{i,l}\cdot(1-e_j)\cdot r_{j,j} \\ q(k|i,j)+i \\ \quad \textit{with probability } p_{i,l}\cdot e_j\cdot r_{j,j} \\ q(k|i,1-j)+i-1 \\ \quad \textit{with probability } p_{i,l}\cdot(1-e_{1-j})\cdot r_{1-j,j} \\ q(k|i,1-j)+i \\ \quad \textit{with probability } p_{i,l}\cdot e_{1-j}\cdot r_{1-j,j} \end{cases} \tag{5}$$

and if $q(k|\cdot,\cdot)+a(k)=0$, then

$$q(k+1|l,j)=0, \quad \text{with probability } p_{i,l}\cdot(r_{j,j}+r_{1-j,j}) \tag{6}$$

where $0\le i,\ l\le N$ and $0\le j\le 1$. In (5), the last two cases correspond to the state of the radio channel going from 1-j to j, whereas no transition occurs in the other two cases. Furthermore, the first and third cases correspond to a successful packet transmission, whereas in the other cases, the transmitted packet is in error. The steady state probability $q_{i,j}(n)$ is defined as:

$$q_{i,j}(n) \triangleq \lim_{k\to\infty} \Pr[q(k|i,j)=n]. \tag{7}$$

From (5) and (6), the state balance equation is obtained as follows:

If $n>0$,

$$\begin{aligned} q_{i,j}(n)= &\sum_{l=0}^{\min(N,n+1)} (r_{j,j}\overline{e_j}p_{l,i}q_{l,j}(n-l+1) \\ &+r_{\bar{j},j}\overline{e_{\bar{j}}}p_{l,i}q_{l,\bar{j}}(n-l+1)) \\ &+\sum_{l=0}^{\min(N,n)}(r_{j,j}e_jp_{l,i}q_{l,j}(n-l) \\ &+r_{\bar{j},j}e_{\bar{j}}p_{l,i}q_{l,\bar{j}}(n-l)) \end{aligned} \tag{8}$$

where $\overline{x}$ denotes $1-x$. And, if $n=0$

$$\begin{aligned} q_{i,j}(n)= &\sum_{l=0}^{\min(N,n+1)}(r_{j,j}\overline{e_j}p_{l,i}q_{l,j}(n-l+1)+r_{\bar{j},j}\overline{e_{\bar{j}}}p_{l,i} \\ &\cdot q_{l,\bar{j}}(n-l+1))+p_{0,i}(r_{j,j}q_{0,j}(0)+r_{\bar{j},j}q_{0,\bar{j}}(0)). \end{aligned} \tag{9}$$

Let $Q_{i,j}(z)$ denote the PGF of the queue length:

$$Q_{i,j}(z) \triangleq \sum_{n=0}^{\infty} q_{i,j}(n)z^n.$$

From (8) and (9), we can obtain $Q_{i,j}(z)$:

$$\begin{aligned} Q_{i,j}(z)= &\sum_{n=1}^{\infty}\sum_{l=0}^{\min(N,n+1)}(r_{j,j}\overline{e_j}p_{l,i}q_{l,j}(n-l+1) \\ &+r_{\bar{j},j}\overline{e_{\bar{j}}}p_{l,i}q_{l,\bar{j}}(n-l+1))z^n+\sum_{n=1}^{\infty}\sum_{l=0}^{\min(N,n)} \\ &(r_{j,j}e_jp_{l,i}q_{l,j}(n-l)+r_{\bar{j},j}e_{\bar{j}}p_{l,i}q_{l,\bar{j}}(n-l))z^n \\ &+\sum_{l=0}^{1}(r_{j,j}\overline{e_j}p_{1,i}q_{1,j}(1-1)+r_{\bar{j},j}\overline{e_{\bar{j}}}p_{1,i}q_{1,\bar{j}}(1-1)) \\ &+p_{0,i}(r_{j,j}q_{0,j}(0)+r_{\bar{j},j}q_{0,\bar{j}}(0)). \end{aligned} \tag{10}$$

After some algebraic manipulation, we obtain:

$$\begin{aligned} Q_{i,j}(z)= &r_{j,j}\overline{e_j}p_{0,i}q_{0,j}(0)+r_{\bar{j},j}\overline{e_{\bar{j}}}p_{0,i}q_{0,\bar{j}}(0) \\ &+r_{j,j}\overline{e_j}\sum_{l=2}^{N}p_{l,i}z^{l-1}Q_{l,j}(z)+r_{j,j}\overline{e_j}(z^{-1}p_{0,i}(Q_{0,j}(z) \\ &-q_{0,j}(0))+p_{1,i}Q_{1,j}(z))+r_{\bar{j},j}\overline{e_{\bar{j}}}\sum_{l=2}^{N}p_{l,i}z^{l-1}Q_{l,\bar{j}}(z) \\ &+r_{\bar{j},j}\overline{e_{\bar{j}}}(z^{-1}p_{0,i}(Q_{0,\bar{j}}(z)-q_{0,\bar{j}}(0))+p_{1,i}Q_{1,\bar{j}}(z)) \\ &+r_{j,j}e_j\sum_{l=0}^{N}p_{l,i}z^{l}Q_{l,j}(z)+r_{\bar{j},j}e_{\bar{j}}\sum_{l=0}^{N}p_{l,i}z^{l}Q_{l,\bar{j}}(z) \end{aligned} \tag{11}$$

Arranging the previous equation, we obtain:

$$Q(z)=\sum_{l=0}^{\infty}[P^T \mathrm{diag}[z^i]\otimes R^T E(z)]^{l+1}[I\otimes E(z)^{-1}-I]Q_0$$
$$=\sum_{l=0}^{\infty}\sum_{i=0}^{2N+1}\lambda_i^{l+1}(z)g_i(z)h_i(z)[I\otimes E(z)^{-1}-I]Q_0$$
$$=\sum_{i=0}^{2N+1}\frac{\lambda_{i(z)}}{1-\lambda_{i(z)}}g_i(z)h_i(z)[I\otimes E(z)^{-1}-I]Q_0. \quad (12)$$

where $[A]_{(i)}$ denotes the (i)th row of A and

$$Q_{l(z)} \triangleq [Q_{l,0}(z) \quad Q_{l,1}(z)]^T$$

$$E(z) \triangleq \mathrm{diag}[\eta_0(z), \eta_1(z)]$$

$$\mathrm{diag}[z^i] \triangleq \mathrm{diag}[1, z, z^2, \cdots, z^N]$$

$$Q(z) \triangleq [Q_{0,0}(z), Q_{0,1}(z), Q_{1,0}(z), Q_{1,1}(z), \cdots, Q_{N,0}(z), Q_{N,1}(z)]^T$$

In this step, detailed derivation is skipped for the sake of brevity, but will be available on request. Substituting Q_0 into the previous equation, we obtain:

$$Q(z)=\sum_{i=0}^{2N+1}\frac{\lambda_i(z)}{1-\lambda_i(z)}\sum_{l=0}^{2N+1}g_{li}(z)\left(h_{i0}(z)\frac{1-\eta_{0(z)}}{\eta_{0(z)}}q_{0,0}+h_{i1}(z)\frac{1-\eta_1(z)}{\eta_1(z)}q_{0,1}\right). \quad (13)$$

Let $\Delta(z)$ denote the characteristic function of the system:

$$\Delta(z) \triangleq \prod_{i=0}^{2N+1}(1-\lambda_i(z)). \quad (14)$$

The poles of (13) are equal to the roots of this characteristic function. We need to determine two unknown variables $q_{0,0}$ and $q_{0,1}$ using two conditions. First, since $Q(z)$ is analytic for each root z_i, $|z_i|<1$, we can set up the following boundary condition:

$$h_{i0}(z_i)\frac{1-\eta_0(z_i)}{\eta_0(z_i)}q_{0,0}+h_{i1}(z_i)\frac{1-\eta_1(z_i)}{\eta_1(z_i)}q_{0,1}=0 \quad (15)$$

Secondly, we use the relation:

$$\lim_{z\to 1}Q(z)=1. \quad (16)$$

Solving (15) and (16), we can determine the values of the unknown variables $q_{0,0}$ and $q_{0,1}$. Thus, the mean queue length $\overline{q}$ is given by

$$\overline{q}=Q'(1). \quad (17)$$

Also, using Little's law, we obtain the mean packet delay $\overline{d}$ given by

$$\overline{d}=\frac{\overline{q}}{\rho_s} \quad (18)$$

where ρ_s is the mean arrival rate. Recall that we approximate the queueing delay under SR ARQ error control by $\overline{d}$ in (18), which is the mean queueing delay under an ideal SR ARQ system with zero feedback delay.

To obtain the retransmission delay for a real SR ARQ, we use the results in [6], where the mean number of transmission attempts per correctly received packet $\overline{n}$ was given by

$$\overline{n}=1+U_r(I-S)^{-1}V \quad (19)$$

where $U_r=[1 \quad 1]$ and

$$S=\begin{bmatrix} r_{0,0}^{(s)}e_0 & r_{1,0}^{(s)}e_0 \\ r_{0,1}^{(s)}e_1 & r_{1,1}^{(s)}e_1 \end{bmatrix} \quad (20)$$

$$V=\begin{bmatrix} \pi_{r,0}e_0 \\ \pi_{r,1}e_1 \end{bmatrix} \quad (21)$$

where $r_{i,j}^{(s)}$ corresponds to the (i,j)th element of s-step transition matrix R, and $\pi_{r,0}$ and $\pi_{r,1}$ are the steady-state probabilities that the channel is in Good and Bad states, respectively.

Combining the queueing delay in (18) and the retransmission delay in (19), we obtain the normalized mean transmission delay T:

$$T=\overline{d}+s\overline{n}-\frac{s}{2}. \quad (22)$$

Ⅲ. Resequencing Delay

In this section, we derive an upper bound on the mean resequencing delay obtained under a heavy-traffic scenario, i.e., packets are always supplied. Given a feedback delay of s slots, the feedback message from the receiver is delivered to the transmitter s slots after the packet is transmitted.

Let $X(t) \triangleq (X_1(t), X_2(t), \cdots, X_s(t))$ denote the set of identifiers of the packets which are transmitted during window t. We assume that packet identifiers are numbered in an increasing order. This assumption affects the accuracy of this analytical approach since the packet error probability is dependent on the location of a slot. However, the error caused by this assumption is acceptable in most practical situations except when the sojourn time of a channel state is small relative to the window size (or the feedback delay).

The process $\{X(t), t=1,2,\cdots\}$ governs the evolution of the occupancy of the resequencing buffer. Let $D_i(t)$ and $W_k(t)$ be defined as follows:

$$D_{i(t)} \triangleq X_{i+1}(t)-X_i(t), \quad i=1,2,\cdots,s \qquad (23)$$

$$W_j(t) \triangleq \sum_{i=j}^{s} D_i(t), \quad j=1,2,\cdots,s \qquad (24)$$

with $D_s(t) \triangleq 1$. Rosberg and Shacham [9] observed that the buffer occupancy at window t, $B(t)$, is given by:

$$B(t)=W_1(t)-s. \qquad (25)$$

Furthermore, they observed that the system state $W_{s-i}(t)$, $t\geq 1$, $1\leq i< s-1$ is governed by the following:

- If there were fewer than $s-i$ NACK's during window t, then $W_{s-i}(t+1)=i+1$
- If there were $s-i+l$ NACK's, $0\leq l\leq i$, and if the $(s-i)$th NACK was for the packet $X_k(t)$, $s-i\leq k\leq s-l$, then $W_{s-i}(t+1)=W_k(t)+(i-l)$.

In the following, we extend the previous analysis to the case of Gilbert-Elliot's channel. First, let $W_i(t|g)$ and $W_i(t|b)$ denote the value defined in (24) given that the state of the radio channel before the beginning of window t-1 is Good (g) and Bad (b), respectively. The distribution of $W_{s-i}(t+1|g)$ is given by:

$$W_{s-i}(t+1|g)=\begin{cases} i+1, & \text{with probability } \sum_{m=0}^{s-i-1} p(s,m|g) \\ W_k(t)+(i-l), & \text{with probability } P_{t,g}(i,k,l) \end{cases} \qquad (26)$$

where

$$P_{t,g}=\sum_{k=s-i}^{s-l}(p(k-1,s-i-1,g|g)(r_{0,0}e_0p(s-k,l|g) + r_{0,1}e_1p(s-k,l|b))+p(k-1,s-i-1,b|g) (r_{1,0}e_0p(s-k,l|g)+r_{1,1}e_1p(s-k,l|b)).$$

In the previous equation, $p(n,k|r_1)$ denotes the probability of k unsuccessful transmissions in n consecutive slots given that the radio state at the beginning of a window is r_1. And $p(n,k,r_2|r_1)$ denotes the probability of k unsuccessful transmissions in n consecutive slots and the state of the radio channel of the last slot is r_2 given that a radio state before the beginning of a window is r_1. In a similar way, the distribution of $W_{s-i}(t+1|b)$ is given by:

$$W_{s-i}(t+1|b)=\begin{cases} i+1, & \text{with probability } \sum_{m=0}^{s-i-1} p(s,m|b) \\ W_{k(t)}+(i-l), & \textit{with probability } P_{t,b}(i,k,l) \end{cases} \qquad (27)$$

where

$$P_{t,b}(i,k,l)=\sum_{k=s-i}^{s-l}(p(k-1,s-i-1,g|b) (r_{0,0}e_0p(s-k,l|g)+r_{0,1}e_1p(s-k,l|b)) +p(k-1,s-i-1,b|b)(r_{1,0}e_0p(s-k,l|g) +r_{1,1}e_1p(s-k,l|b)).$$

Taking the z-transform and some manipulation, we have

$$W_{s-i}(z)=\sum_{m=0}^{s-i-1}\Pi P[s,m]Uz^{i+1}+\sum_{l=0}^{i}\sum_{k=s-i}^{s-l}\Pi \cdot P[k-1,s-i-1]REP[s-k,l]UW_k(z)z^{i-l}. \qquad (28)$$

where Π is the steady-state probability vector of the radio state, i.e., $\Pi=[\pi_{r,0},\pi_{r,1}]$, $E=$ diag$[e_0,e_1]$, and

$$P[n,k] \triangleq \begin{bmatrix} p(n,k,g|g) & p(n,k,b|g) \\ p(n,k,g|b) & p(n,k,b|b) \end{bmatrix}$$

Exploiting the recursive structure, we obtain the following difference equation:

$$P[n,k] = R\overline{E}P[n-1,k] + R\,E\,P[n-1,k-1] \quad (29)$$

with the boundary conditions

$P[0,0]=1$

$P[n,k]=0$, if $n<k$ or $n,k<0$.

where $\overline{E} = \mathrm{diag}[\overline{e_0}, \overline{e_1}]$. The solution to the above difference equation is obtained numerically. To obtain the mean buffer size, we differentiate (28) with respect to z and evaluate at z=1. Let μ_{s-i} be defined as:

$$\mu_{s-i} \triangleq \frac{dW_{s-i}(z)}{dz}\Big|_{z=1}. \quad (30)$$

Thus, we have

$$\mu_{s-i} = (i+1)f_1(i) + \sum_{l=0}^{i}\sum_{k=s-i}^{s-l}((i-l)f_2(i,k,l) + f_2(i,k,l)\mu_k) \quad (31)$$

where

$$f_1(i) = \sum_{m=0}^{s-i-1} \Pi P[s,m]\, U$$

$$f_2(i,k,l) = \Pi P[k-1, s-i-1] R\,E\,P[s-k, l]\, U.$$

Arranging the previous equation, we obtain for $1 \le i \le s-1$:

$$\mu_{s-i} = ((i+1)f_1(i) + \sum_{l=0}^{i}\sum_{k=s-i+1}^{s-l} f_2(i,k,l)(i-l+\mu_k) + \sum_{l=0}^{i} f_2(i,s-i,l)(i-l))(1-\sum_{l=0}^{i} f_2(i,s-i,l))^{-1} \quad (32)$$

and $\mu_s = 1$. The mean buffer occupancy is $\mu_1 - s$. Using Little's law, we obtain the mean resequencing delay T_r:

$$T_r = \frac{\mu_1 - s}{\pi_{r,0}\overline{e_0} + \pi_{r,1}\overline{e_1}}. \quad (33)$$

Ⅳ. Numerical Results

We now give numerical examples based on the previously presented analysis and contrast them against more realistic simulation results. We consider a single discrete-time on-off source in which one packet is generated in a time slot during the on periods. Transitions between on and off states are governed by the transition probability matrix $P=[p_{i,j}], 0 \le i, j \le 1$. The characteristics of the on-off source are represented by the mean arrival rate (ρ_s) and the mean length of the on periods (T_{on}). We also define three parameters for the Gilbert-Elliot's radio channel: the average packet error rate (ε). Table 1 gives the values of the various parameters used in our experiments.

Parameter	Symbol	Range of values (default value)
Mean arrival rate	ρ_s	0.3-0.7 (0.5)
Mean on period	T_{on}	10-300 (100)
Mean packet error rate	ε	0.01-0.3 (e_1=0.9, e_0=0.001)
Duty cycle of Bad period	ρ_r	0.05-0.2 (0.1)
Transition probability from Good to Bad	$r_{0,1}$	0.005-0.1 (0.03)

Table 1. Parameters used in the numerical results.

Figure 1 shows the mean transport delay as a function of ρ_s for s=10,50,100 (time is in slot units). As shown in the figure, the mean transport delay is less sensitive to the input load. Since one packet is generated per slot, no queueing delay is occurred unless a NACK is returned. Since we fix the average duration of the Bad period at 10% of the average duration of the

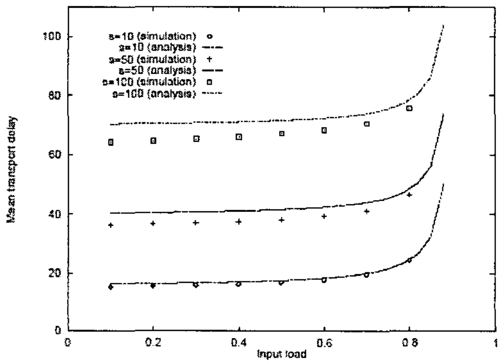

Figure 1. Mean transport delay versus input load.

Good period, it is hard to notice any significant queueing delay up to medium input load. As ρ_s increases, it is more likely that the on state and Bad state occur simultaneously which may cause a higher queueing delay. In this figure, the analytical results tend to overestimate the simulations by less than 10%.

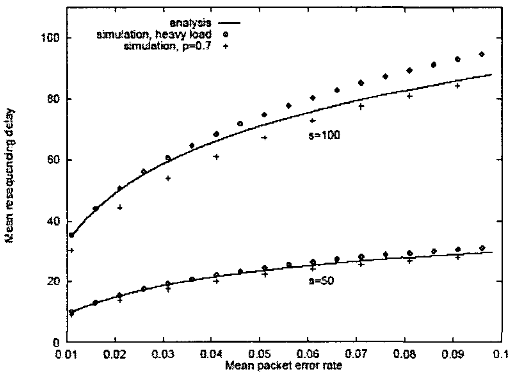

Figure 2. Mean resequencing delay versus ε.

Figure 2 shows the mean resequencing delay versus ε for s=50,100. With such large values of s, we can examine the worst-case inaccuracy of the analysis with respect to the second assumption. The analysis is contrasted with exact simulation results obtained under heavy load and under 70% load. If the resequencing analysis were to be conducted without the second assumption, then we would expect a match between the analytical results and the heavy-traffic simulations. But Fig. 2 shows that the heavy-traffic simulations upper bound the analytical results, indicating opposite effects for the above two assumptions. For s=50, the analytical results are sufficiently close to both types of simulations. In general, we observed that at small values of s the mean resequencing delay is somehow insensitive to the input load. For s=100, the analytical results lie between the two types of simulations, being closer to the heavy-traffic simulations when ε is small and to the 70%-load simulations when ε is large.

V. Conclusions

In this paper, we investigated the mean end-to-end delay for a general Markovian source transported over a wireless channel with time-varying error characteristics. An SR ARQ error control protocol was assumed between the transmitter and the receiver. We obtained an approximation for each component of the total mean delay, which consists of queueing, transmission/retransmission, propagation, and resequencing delays. Numerical examples based on the analysis indicate good agreement with simulation results obtained under less stringent assumptions. It was observed that the mean resequencing delay becomes a more significant portion of the total mean delay as the channel conditions deteriorate.

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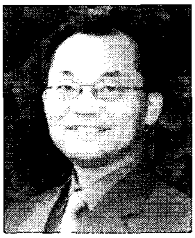

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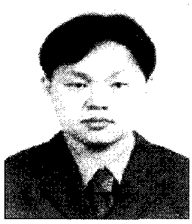

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