Delay Performance Analysis of the NAK-based SR-ARQ Protocol with the Reverse Acknowledgment (RA) Scheme

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ABSTRACT

The reverse acknowledgment (RA) scheme supports a fast loss recovery for negative acknowledgment (NAK)-based selective repeat automatic repeat request (SR-ARQ) by detecting a retransmission failure quickly before a retransmission timer expires. In this paper, we evaluate the performance of a NAK-based SR-ARQ protocol with the RA scheme and compare it with the conventional NAK-based SR-ARQ protocol. Particularly, we propose a simple analysis model for the transport delay of the NAK-based SR-ARQ protocol considering the traffic condition, the retransmission persistence, the timer-based retransmissions and the RA scheme's behavior. Both NAK-based SR-ARQ protocols with and without the RA scheme are implemented by using the OPNET simulator. We verified the analysis model's accuracy through the simulation results. Also, we evaluate the performance of the NAK-based SR-ARQ protocol with the RA scheme based on analysis and simulation results.

Key Words : RA scheme, Negative Acknowledgment, SR-ARQ, retransmission, transport delay

Ⅰ. 서 론

To ensure high reliability for data communications over a wireless link, many wireless access networks employ link level error control schemes, such as selective repeat automatic repeat request (SR-ARQ), forward error control (FEC) and Hybrid-ARQ. SR-ARQ protocols are widely used for a fast loss recovery. However, in the literature, it has been shown that retransmissions by the SR-ARQ protocol cause variable and sometimes very high packet delay that may degrade the performance of higher layer protocols such as transmission control protocol (TCP). RFC 3366[1] concretely describes the problems arising from the high and highly variable delay of ARQ. TCP can suffer performance degradation due to interaction problems between TCP and ARQ and spurious timeouts caused by excessive retransmissions of ARQ[1],[2].

The problem with the high packet delay variations may become severer with a negative acknowledgement (NAK)-based SR-ARQ protocol such as radio link protocol (RLP)[3]. Usually, NAK-based SR-ARQ receivers send no acknowledgement (ACK) messages for the packets received successfully but send only NAK messages to request the retransmission of the packets that are supposed to be lost. Therefore, the NAK-based scheme may bring a considerable reduction in the traffic load for feedback while it compromises the capability of detecting retransmission failures. That is, if a retransmitted packet is lost again, the receiver cannot detect it until a retransmission timer is expired. Typically, the period of the retransmission timer is longer than a round-trip time (RTT)[3],[5] so that the timer-based detection of a retransmission failure and retransmission may increase the overall packet transmission delay of the NAK-based SR-ARQ protocol.

In order to cover the problem, we proposed a simple modification called reverse acknowledgement (RA) scheme in [6]. The RA scheme enables a NAK-

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based SR-ARQ receiver to detect retransmission failures before a retransmission timer expires. In this paper, we evaluate the performance of the NAK-based SR-ARQ with the RA scheme through both analysis and simulation results. The proposed analysis model derives the mean transport delay by considering the traffic amount and the retransmission persistence as well as packet losses over a wireless link. Particularly, we compare the performance of the conventional NAK-based SR-ARQ and the NAK-based SR-ARQ with the RA scheme.

The remainder of this paper is organized as follows. In Section II, we briefly explain the RA scheme for the NAK-based SR-ARQ protocol. Section III presents an analysis model for the transport delay of the NAK-based SR-ARQ protocol with and without the RA scheme. In Section IV, the accuracy of the analysis model is verified by simulation results and we evaluate the performance of the NAK-based SR-ARQ protocol with the RA scheme. Section V concludes this paper.

Ⅱ. The RA Scheme[6]

Fig. 1 shows the loss recovery behaviors of a NAK-based SR-ARQ protocol. The left-hand figure shows an example in which an original packet is lost. As shown, the receiver detects the original packet loss by receiving the next well-transmitted packet. Thus, a NAK message is sent to request the retransmission of the lost packet and a retransmission timer starts to run at the moment. In the case of a retransmitted packet loss shown in the right-hand figure, however, the receiver cannot detect the retransmitted packet loss until the retransmission timer expires because it is not known when the retransmitted packet is exactly to be received after the delivery of the NAK message. Since the retransmitted packet is already out of order, the next packets received carry no information about the retransmitted packet loss[6].

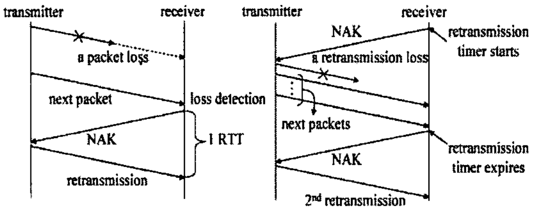

Fig. 1. The behaviors of a NAK-based SR-ARQ protocol for an original packet loss and retransmission loss

The RA scheme uses two additional parameters: the NAK identifier (nak_id) and NAK acknowledgement (nak_ack). Every NAK message includes nak_id as well as the lost packet's sequence number (seq). Unlike seq that identifies the lost packet that should be retransmitted, nak_id is used for identification of retransmission processes. The other parameter, nak_ack, is included in every data packet and retransmission, and its value is the same as nak_id associated with the most recent retransmission process. By using the additional information about a retransmission, the NAK-based SR-ARQ protocol with the RA scheme is able to detect and recover a retransmission failure before a retransmission timer expires[6].

Fig. 2 describes the key concept of the RA scheme. When a packet is corrupted or lost in transit and detected by the receiver, the receiver requests a retransmission of the lost packet by sending the NAK message with a nak_id. Then, the transmitter gets two types of information from a NAK message: the sequence number of lost packets and the identifier of the retransmission request (nak_id). On receiving the NAK message, the transmitter retransmits all the requested packets, and then, the transmitter sets nak_ack to the value of nak_id. Hereafter, the packets sent by the transmitter

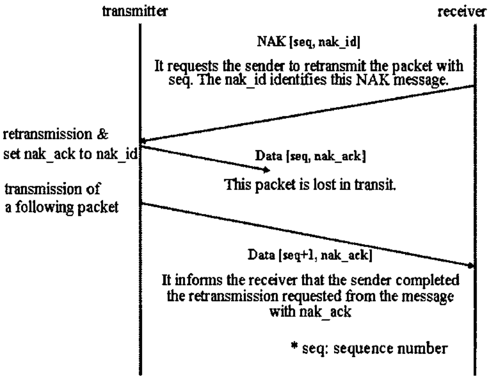

Fig. 2. The concept of the RA scheme

deliver the updated nak_ack to the receiver. Then, the nak_ack informs the receiver of retransmission requests processed by the transmitter up to now. Therefore, on receiving a packet with the nak_ack, the receiver is able to know whether the transmitter had already retransmitted the requested packets, or not. At that time, the receiver can make a decision whether a retransmission identified by a nak_id has failed or succeeded and request another retransmission to the transmitter, before the retransmission timer expires.

Ⅲ. Delay Analysis Model

In this section, we introduce an analysis model for the transport delay of the NAK-based SR-ARQ protocol with and without the RA scheme. Let define the transport delay as the time from a packet's first transmission until its successful arrival at the receiver [2]. By analyzing the transport delay, we can evaluate the efficiency of a NAK-based SR-ARQ's loss recovery procedure as well as its delay performance. To get a simple closed-form equation for the mean transport delay of the NAK-based SR-ARQ protocol, we assume that

1) The time is slotted and the slot time is fixed as s seconds and corresponds to a single packet transmission.
2) The transmitter serves new arrival packets on a FCFS (First Come First Serve) basis.
3) A retransmission is always prior to a transmission of a new packet.
4) Packet losses on a wireless link occur following the Bernoulli process with the probability p.
5) The receiver detects all of the lost (or corrupted) packets exactly, and immediately requests a retransmission for the lost (or corrupted) packet to the transmitter.
6) Feedback messages are error free.
7) The transmitter has an infinite queue for the new packets and retransmissions, and the receiver has an infinite queue for the ordered delivery of packets to high layer protocols.
8) On receiving a NAK message, the transmitter immediately retransmits a requested packet.
9) The round trip time is fixed as t_{rtt}. Assuming of symmetric links, the one-way delay becomes $\frac{1}{2}t_{rtt}$.
10) The retransmission timeout value is t_{rto}.
11) SR-ARQ has a finite retransmission persistence. The retransmission persistence is defined as the maximum number of retransmission attempts, denoted by r and we assume that $r \geq 2$.

3.1 Mean Transport Delay

In the NAK-based SR-ARQ protocol, the transport delay, t, is composed to loss detection times and packet transmission delay replaced by the round-trip time (t_{rtt}) or the one-way delay ($\frac{1}{2}t_{rtt}$), as shown in Fig. 3. Let n denote the number of transmission attempts for a successful packet delivery. According to n, the transport delay is expressed as

$$t = \sum_{k=1}^{n} t_k \tag{1}$$

where t_k denotes the time taken by the kth transmission trial of a packet, and is defined as

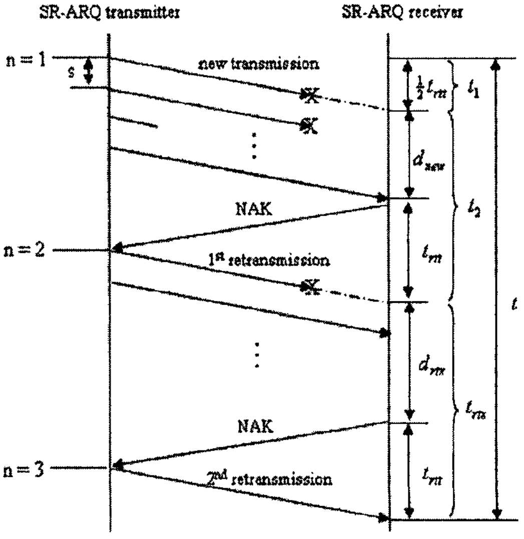

Fig. 3. Delay components consisting the transport delay of the NAK-based SR-ARQ protocol

$$t_k = \begin{cases} \frac{1}{2} t_{rtt} & ,k=1 \\ d_{\text{new}} + t_{rtt} & ,k=2 \\ d_{rtx} + t_{rtt} & ,k=3,...,r+1 \end{cases} \quad (2)$$

where d_{new} and d_{rtx} denote the loss detection time for a original packet and a retransmitted packet, respectively. The loss detection times are defined as a random variable that has a different distribution according to the SR-ARQ's loss recovery procedure. We will explain in details how to derive the loss recovery times in the following subsection. Assuming the independent packet losses following the Bernoulli process, n is the random variable that has the following distribution.

$$P(n=k) = (1-p)p^{k-1} \ , \ 1 \le k \le r+1 \quad (3)$$

From (1), the mean transport delay, $E[t]$, is derived as

$$E[t] = E[E[t|n]] \quad (4)$$

where $E[t|n]$ is given by

$$E[t|n] = E[\sum_{k=1}^{n} t_k]. \quad (5)$$

Since t_3, ..., t_{r+1} are identical under the above assumptions, all of them can be replaced by one random variable, t_{rtx} and Equ. (5) can be expressed as follows.

$$E[\sum_{k=1}^{n} t_k] = \begin{cases} E[t_1] & ,n=1 \\ E[t_1]+E[t_2] & ,n=2 \\ E[t_1]+E[t_2]+(n-2)E[t_{rtx}] & ,3 \le n \le r+1 \end{cases} \quad (6)$$

Then, we have

$$E[t] = E[t_1]P(n=1) + (E[t_1]+E[t_2])P(n=2) \ . \\ + \sum_{k=3}^{r+1} \mathrm{E}[\mathrm{t}_1] + \mathrm{E}[\mathrm{t}_2] + (\mathrm{k}-2)\mathrm{E}[\mathrm{t}_{\mathrm{rtx}}])\mathrm{P}(\mathrm{n}=\mathrm{k}) \quad (7)$$

Substituting (3) into (7), $E[t]$ is derived as

$$E[t] = (1-p^{r+1})E[t_1] + (p-p^{r+1})E[t_2] \\ + (\frac{p^2 - rp^{r+1} + (r-1)p^{r+2}}{1-p})E[t_{rtx}] \quad (8)$$

where

$$E[t_1] = 1/2t_{rtt} \\ E[t_2] = t_{rtt} + E[d_{new}] \\ E[t_{rtx}] = t_{rtt} + E[d_{rtx}]$$

Here, $E[d_{\text{new}}]$ and $E[d_{rtx}]$ denote the mean value of d_{new} and d_{rtx}, respectively.

Now, to get the mean transport delay, we should derive the unknown terms in Equ. (8): $E[d_{\text{new}}]$ and $E[d_{rtx}]$. The following subsection explains how to calculate them.

3.2 Loss Detection Time

In this section, we define two random variables, d_{new} and d_{rtx} that are determined by the SR-ARQ's loss recovery procedure.

d_{new} is defined as the time that taken by the receiver to detect it when an original packet loss occurs. With or without the RA scheme, the receiver can detect an original packet loss by receiving a following original packet without an error, as shown in Fig. 4 and 5. Assuming that packet losses occur independently, d_{new} has the geometric distribution.

$$P(d_{new} = i \times s) = \alpha(1-\alpha)^{i-1}, i = 1,2,3,... \quad (9)$$

where α denotes the probability that there is a

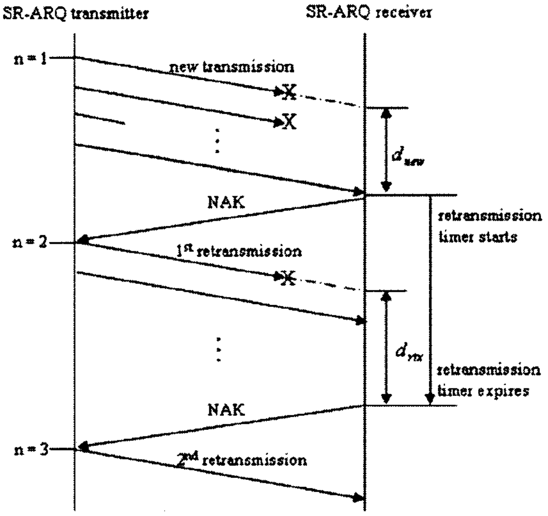

Fig. 4. An example of the conventional NAK-based SR-ARQ's operation for a packet loss

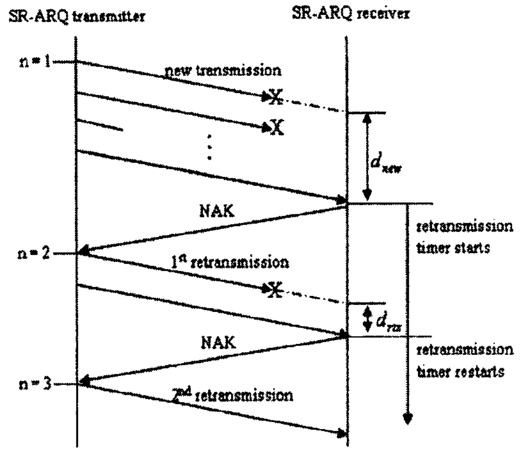

Fig. 5. An example of the RA scheme's operation for a packet loss

packet to be sent by the transmitter, and a given transmission is an original packet not in error. Let be c and c_{rtx} the total number of packets in the transmitter and the number of packets in the retransmission queue of the transmitter, respectively. Recalling the assumption that a retransmission is always prior to a new packet transmission, α is given by

$$\alpha = P(c > 0 \mathrm{and} c_{\mathrm{rtx}} = 0)(1-\mathrm{p}). \tag{10}$$

d_{rtx} is defined as the time from a retransmission failure to detecting it at the receiver. In the case of the conventional NAK-based SR-ARQ protocol without the RA scheme, d_{rtx} has a constant value, $t_{rto} - t_{rtt}$ because a retransmission loss can be detected by only the retransmission timeout event. On the other hand, the NAK-based SR-ARQ protocol with the RA scheme is probable to detect a retransmission failure before the retransmission timer expires by using the additional information about the retransmissions. The receiver can detect a retransmission loss on receiving a following packet with nak_ack. As explained before, since nak_ack is delivered to the receiver by all the data packets including retransmitted packets, d_{rtx} has the following distribution in the case of the NAK-based SR-ARQ protocol with the RA scheme.

$$P(d_{rtx} = i \times s) \tag{11}$$
$$= \begin{cases} \beta(1-\beta)^{i-1} & , 1 \le i \le \dfrac{t_{rto} - t_{rtt}}{s} - 1 \\ (1-\beta)^{\frac{t_{rto} - t_{rtt}}{s} - 1} & , i = \dfrac{t_{rto} - t_{rtt}}{s} \end{cases}$$

where β denotes the probability that a packet with the RA information, nak_ack, is correctly delivered to the receiver.

$$\beta = P(c > 0)(1-p) \tag{12}$$

Now, if α and β are calculated, we can derive the mean value of the transport delay as well as d_{new} and d_{rtx}. The transmitter is modeled by the network queuing model, as shown in Fig. 6. Let λ, λ_{new} and λ_{rtx} denote the total packet arrival rate, the new packet arrival rate, and the arrival rate of retransmitted packets, respectively. By the Jackson's theorem[7], $\lambda = \lambda_{new} + \lambda_{rtx}$ and the arrival rate of retransmitted packets is given by

$$\lambda_{rtx} = \lambda p P(n \le r) \tag{13}$$

where $P(n \le r) = \sum_{n=1}^{r} (1-p)p^{n-1}$, recalling the assumption of random and independent packet losses. Then, the total packet arrival rate becomes

$$\lambda = \lambda_{new} + \lambda_{rtx} = \frac{\lambda_{new}}{1-p+p^{r+1}}. \tag{14}$$

By the general queuing theory, $P(c > 0)$ is equal to the probability that the server is busy, which is also defined as the traffic load ($\rho = \lambda/\mu$). Therefore, form (14), $P(c > 0)$ is given by

$$P(c > 0) = \rho = \frac{\lambda_{new}}{(1-p+p^{r+1})\mu}. \tag{15}$$

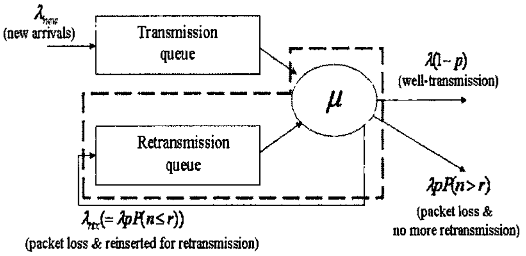

Fig. 6. Network queuing model for the NAK-based SR-ARQ transmitter

Next, recalling that a retransmission is always prior to a new packet transmission, we can separate the retransmission queue from the network queuing model of SR-ARQ in Fig. 6. $P(c_{rtx}=0)$ is calculated as follows.

$$P(c_{rtx}=0)=1-\rho_{rtx}=1-\frac{(p-p^{r+1})\lambda_{new}}{(1-p+p^{r+1})\mu} \quad (16)$$

where $\rho_{rtx}=\lambda_{rtx}/\mu$.

Consequently, if we assume that λ_{new} and p are given, $E[d_{new}]$ and $E[d_{rtx}]$ are expressed with all known values as follows. For the conventional NAK-based SR-ARQ without the RA scheme

$$E[d_{new}]=\frac{(1-p+p^{r+1})^2}{s(1-p)(p-p^{r+1})\lambda_{new}^2}. \quad (17)$$
$$E[d_{rtx}]=t_{rto}-t_{rtt}$$

For the NAK-based SR-ARQ with the RA scheme

$$E[d_{new}]=\frac{(1-p+p^{r+1})^2}{s(1-p)(p-p^{r+1})\lambda_{new}^2} \quad (18)$$
$$E[d_{rtx}]=\frac{s\left(1-(1-\beta)^{\frac{t_{rto}-t_{rtt}}{s}}\right)}{\beta}$$

where $\beta=\dfrac{s(1-p)\lambda_{new}}{1-p+p^{r+1}}$.

Ⅳ. Results and Discussion

The mean transport delay statistics for both NAK-based SR-ARQ protocols with and without the RA scheme have been computed according to the above analysis for various values of the packet loss rate (p) and the retransmission persistence (r). To test the accuracy, we performed simulations using the OPNET simulator[8]. Also, the simulation results show the data transmission reliability and the average resequencing delay, which is defined as the waiting time of the packet in the resequencing buffer of the receiver[2],[4]. For simulations, a NAK-based SR-ARQ protocol is implemented. The implementation includes three parts, a NAK-based SR-ARQ transmitter, a NAK-based SR-ARQ receiver, and a wireless link connecting the transmitter and receiver. The RA scheme is implemented on both sides of the transmitter and receiver. In the following figures, ρ_{new} means the input traffic load of the NAK-based SR-ARQ transmitter that is given by λ_{new}/μ. The input traffic is generated by a traffic source following the Poisson process that is placed on the NAK-based SR-ARQ transmitter. Simulations have been performed under the same assumption in Section III and we have summarized the values of parameters used for simulations in Table I.

Fig. 7 shows the mean transport delay, obtained using (8), as a function of p in the heavy traffic load condition ($\rho_{new}=0.7$). The overall results show that every lines of the transport delay increases as

Table 1. Simulation Parameters

Item	Value
input traffic load (ρ_{new})	0.3 and 0.7
service interval (s)	5 msec
packet size	300 bytes
retransmission persistence (r)	10 and 2
transmission queue size	infinity
retransmission queue size	infinity
t_{rtt}	50 msec
t_{rto}	200 msec
packet loss rate (p)	0.01 ~ 0.25

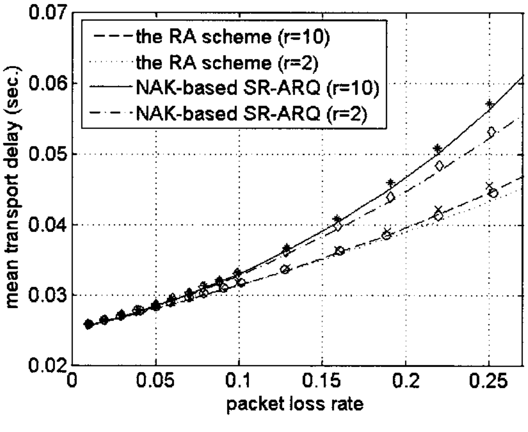

Fig. 7. The mean transport delay as a function of p, for heavy traffic load ($\rho_{new}=0.7$); analytical result (line) and simulation result (marker)

p increases. It is very straightforward considering that the number of retransmissions required for a successful packet transmission increases as p increases. Another general observation is that larger values of r produce longer transport delays. Also, the simulation results show a good agreement with the analytical predictions. It should be noted that the SR-ARQ with the RA scheme always outperforms the conventional SR-ARQ in terms of the transport delay. Moreover, the difference between the two increases as p increases, which can be explained by the frequency of retransmission timeout events. Without the RA scheme, a high value of p introduces a large number of retransmission failures that correspond to a large number of retransmission timeouts. On the other hand, using the RA scheme avoids almost all the retransmission timeouts caused by retransmission failures. Exceptionally, a retransmission timeout is inevitable when no more new packets are received after a retransmission failure. Fig. 8 shows the effect of a traffic amount on the transport delay in both NAK-based SR-ARQ protocols with and without the RA scheme. As the traffic load decreases, the possibility that the transmitter sends a new packet decreases. That means that it takes more time that the receiver gets a new packet that may indicate which packet is lost in transit. When the traffic load is larger, the NAK-based SR-ARQ has lower transport delay because the receiver is able to have more opportunity to detect packet losses.

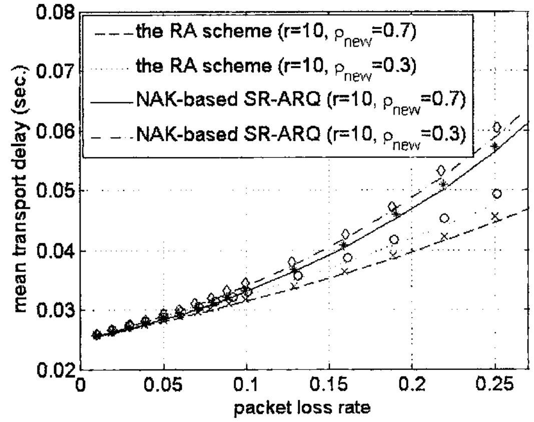

Fig. 8. The mean transport delay as a function of p, for heavy traffic load ($\rho_{new}=0.7$), and low traffic load ($\rho_{new}=0.3$); analytical result (line) and simulation result (marker)

Fig. 9 compares the average re-sequencing delay of the SR-ARQ with the RA scheme to that of the conventional SR-ARQ. The overall shape of this figure is very similar as Fig. 7. Unlike the transport delay that is individual to a packet, however, the re-sequencing delay is cumulative in that a packet loss may affect a group of packets that have been already delivered to the receiver. Therefore, the RA scheme benefits the re-sequencing delay more than the transport delay for a given value of p.

Fig. 10 and 11 show the general performance of the NAK-based SR-ARQ with and without the RA scheme. The RA scheme improves the delay

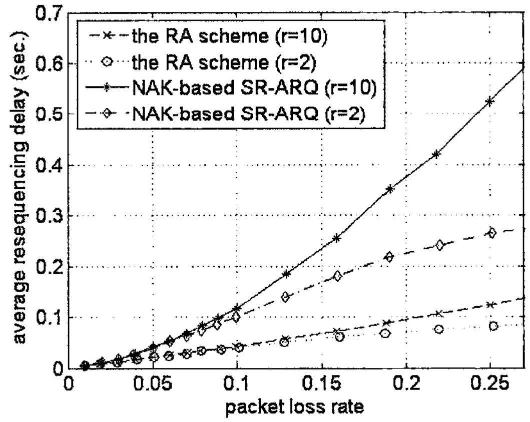

Fig. 9. The average resequencing delay as a function of p, for heavy traffic load ($\rho_{new}=0.7$)

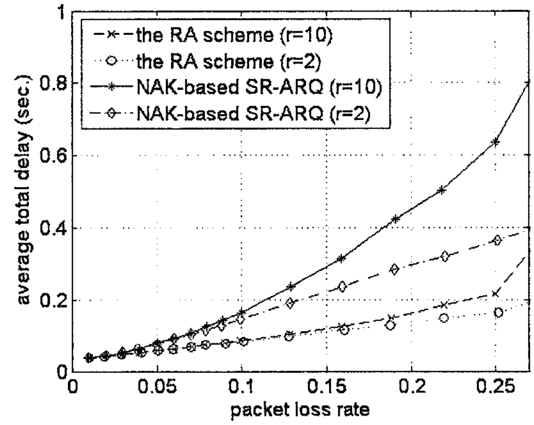

Fig. 10. The average total delay as a function of p, for heavy traffic load ($\rho_{new}=0.7$)

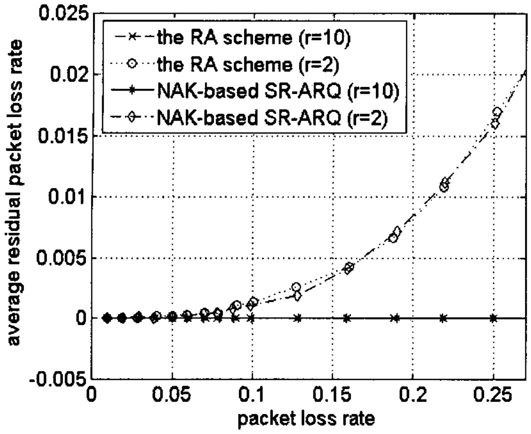

Fig. 11. The average residual packet loss rate as a function of p, for heavy traffic load ($\rho_{new} = 0.7$)

performance by reducing the loss recovery time, while supporting the data transmission reliability similar with the conventional NAK-based SR-ARQ protocol. In Fig. 11, the residual packet loss rate means the loss rate after recovery in the NAK-based SR-ARQ protocol. Implementing the RA scheme requires some number of additional bits included in both directional data for identification of retransmission processes. However, considering the significant improvement in terms of the transport and re-sequencing delay and the recent progress in broadband wireless communications, we believe that the additional bits may be regarded as trivial.

V. Conclusion

In this paper, we have introduced a simple analytical model for the mean transport delay of both NAK-based SR-ARQ protocols with and without the RA scheme. Our analysis model showed the effects of the retransmission persistence and the traffic load on the transport delay, which can be also used to evaluate the loss recovery procedure of NAK-based SR-ARQ. The simulation results have showed a good agreement with the analytical predictions. Both analysis and simulation results showed that the RA scheme considerably improves the delay performance of the NAK-based SR-ARQ protocol by supporting fast detection and recovery of retransmitted failures. We believe that the analysis model clearly explains how the RA scheme improve the loss recovery procedure of the NAK-based SR-ARQ protocol.

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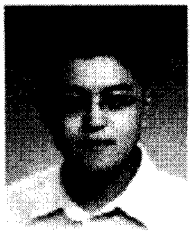

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