Endowment of Duplicated Serial Number for Window-controlled Selective-repeat ARQ

Window-controlled Selective-repeat ARQ에서 중복된 순차 번호의 부여

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Abstract

We consider a window-controlled selective-repeat ARQ scheme for error control between two adjacent nodes lying on a communication path. In this scheme, each packet to be transmitted is endowed with a serial number in a cyclic and sequential fashion. In turn, the transmitting node is not allowed to transmit a packet belonging to a window before every packet in the previous window is positively acknowledged. Such postponement of packet transmission incurs a degradation in throughput and delay performance. In this paper, aiming at improving packet delay performance, we employs a supplement scheme in which a serial number is duplicated within a frame. Classifying duplication rules into fixed, random and adaptive categories, we present candidate rules in each category and evaluate the packet delay performance induced by each duplication rule. From numerical examples, we observe that duplicating serial numbers, especially ADR-T2 effectively reduces mean packet delay for the forward channel characterized by a low packet error rate. We also reveal that such delay enhancement is achieved by a high probability of hitting local optimal window size.

Keywords: duplicated serial number, selective-repeat ARQ, window, packet delay time

요 약

통신 경로 상에 위치한 인접 노드간의 오류 제어를 위해 window-controlled selective repeat ARQ 방식을 고려한다. 이 방식에서 전송될 패킷은 순환적 그리고 순차적으로 순차 번호를 부여받는다. 한편 송신 노드는 이전 window에 소속된 모든 패킷에 대해 긍정적 응답을 받을 때까지 새 window에 소속된 패킷을 전송할 수 없으며, 이러한 전송의 연기로 인해 throughput 및 지연 성능의 저하가 야기된다. 본 논문에서는 지연 성능을 향상시키기 위한 방안으로 프레임 내에서 순차 번호를 중복 사용하는 부수적 방식을 고려한다. 이러한 중복 규칙을 고정형, 임의형, 적응형으로 분류하여 범주별 중복 규칙을 제시하고 각 중복 규칙에 따른 지연 성능을 평가한다. 계량적 분석 결과로부터 순차 번호를 중복 부여하여 (특히 ADR-T2의 도입으로) 평균 패킷 지연 시간을 효과적으로 줄일 수 있음을 관찰한다. 또한 이러한 지연 성능의 개선은 국지적으로 최적인 window 크기를 만족할 수 있는 확률의 증가에 기인함을 규명한다.

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Ⅰ.Introduction

An automatic repeat request (ARQ) scheme is a closed-loop error control method based on acknowledgements of the receiving node and retransmissions of the transmitting node [1][2][3][4][5]. According to the method of retransmitting packets, ARQ schemes are classified into three major categories; stop-and-wait ARQ, go-back-N ARQ and selective-repeat ARQ schemes. As with other ARQ schemes, a selective-repeat ARQ scheme is widely used to control errors occurring at packet transmission between two adjacent nodes. For example, a selective-repeat ARQ is performed at the radio link control (RLC) layer in wideband code division multiple access (W-CDMA) wireless cellular networks [6][7]. In a selective-repeat ARQ scheme, the transmitting node only retransmits packets which were infected with errors in the previous transmission and thus negatively acknowledged by the receiving node. Such retransmission rule of selective-repeat ARQ contributes to enhanced performance in throughput and packet delay (compared with stop-and-wait and go-back-N ARQ schemes). However, the transmitting node should endow each packet with a serial number to perceive packets to retransmit. Also, the receiving node should be equipped with a buffer for temporarily storing packets since the received packets need to be re-arranged in sequential order. As a way of reducing the time to re-order packets and avoiding the overflow at the receiving node, a window based transmission control technique has been applied to a selective-repeat ARQ scheme. A window is an ordered set of packets to be transmitted. (In this paper, windows are assumed to be disjoint.) In a window-controlled ARQ scheme, the transmitting node is not allowed to transmit a packet belonging to a window until every packet belonging to the previous window is positively acknowledged. Thus, the cycle of negative acknowledgement and retransmission is repeated as similar as in a stop-and-wait ARQ, even if packets belonging to the next window are accumulated at the transmitting node. Such postponement of packet transmission incurs an inferior resource utilization and results in degradation of throughput and delay performance, consequently.

As a supplement to a selective-repeat ARQ scheme in which the receiving node acknowledges a group of packets, a scheme of duplicating serial numbers within a group of packets was reported in [8]. Under the condition that the number of serial numbers assigned to the packets in each window is identically fixed (with an intention to fix the length of a field for writing serial number in a packet), the duplication scheme is shown to have superior throughput performance over the conventional non-duplication scheme [8]. However, since the window size, (i.e., the number of packets belonging to each window) is not identical, it is not clear that a fair comparison of throughput performance is made.

For improving packet delay performance in a window-controlled selective-repeat ARQ between two adjacent nodes lying on a communication path, we consider schemes of endowing packets to be transmitted within a frame with duplicated serial numbers. First, we classify rules of duplicating serial numbers into fixed, random and adaptive duplication categories. Secondly, we present candidate duplication rules in each category. Moreover, we propose random and adaptive duplication rules in addition to the fixed and adaptive rules which were released in previous works. Finally, using a simulation method, we investigate the effect of network parameters, (e.g., traffic load at the transmitting node, packet error rate on the forward channel, frame length, and window size) on the packet delay performance induced by each duplication rule. From the observations on packet delay performance, we test the validity of serial number duplication under the condition that window sizes are identically fixed.

In section 2, we describe a window-controlled selective-repeat ARQ scheme between two adjacent nodes lying on a communication path. In section 3, we classify the rules of duplicating serial numbers into three categories and present candidate duplication rules in each category. In section 4, using a simulation method, we investigate the effect of various network parameters on packet delay performance exhibited by each duplication rule. Based on the observations, we evaluate the validity of duplication rules.

II. Window-controlled Selective-repeat ARQ

In this section, we describe a window-controlled selective-repeat ARQ scheme for error control between two adjacent nodes lying on a communication path.

The transmitting node sends packets of identically fixed length through the forward channel. On the forward channel, time is divided into frames and each frame is again divided into a fixed number of slots. The number of slots belonging to a frame is set to be L. A slot is equal to the time to transmit a packet and the transmitting node always starts transmitting a packet at the beginning of a slot. Let τ be the slot duration time. Upon reception of the all packets delivered during a frame, the receiving node inspects each packet for errors and includes the error detection result (positive or negative) for each packet in an acknowledgement (ACK) message. Then, the receiving node sends the ACK message to the transmitting node through the reverse channel. As reading the ACK message, the transmitting node decides the packets to transmit in the upcoming frame.

In the window-controlled selective repeat ARQ scheme, a set of serial numbers, identified as $\{1,\cdots,\widehat{S}\}$ is provided at the transmitting node and each packet to be transmitted first time is endowed with a serial number in a sequential and cyclic fashion. Note that a serial number may be duplicated (as will be addressed in section 3). However, the transmitting node is only able to endow packets to transmit in a same frame with duplicates of a serial number. (If not, the transmitting node can not perceive packets to retransmit.) Windows are defined to be disjoint sets of packets to transmit. For $j \in \{1,2,\cdots\}$, let P_j denote the jth arriving packet at the transmitting node and $S_j^* \in \{1,\cdots,\widehat{S}\}$ be the serial number assigned to P_j. Then, for $i \in \{1,2,\cdots\}$, we set the ith window to be the set of packets $\{P_{C_i^{(1)}},\cdots,P_{C_i^{(2)}}\}$, where

$$\begin{aligned} C_1^{(1)} &= 1 \\ C_1^{(2)} &= \min\{j \in \{1,2,\cdots\} : S_j^* = \widehat{S},\ S_{j+1}^* = 1\} \\ C_{i+1}^{(1)} &= C_i^{(2)} + 1 \\ C_{i+1}^{(2)} &= \min\{j \in \{C_{i+1}^{(1)},\cdots\} : S_j^* = \widehat{S},\ S_{j+1}^* = 1\}. \end{aligned} \quad (1)$$

In conjunction with the set of serial numbers $\{1,\cdots,\widehat{S}\}$, the sequence of such windows are specified at the transmitting node, which is controlled not to transmit a packet belonging to a window until every packet belonging to the previous window is positively acknowledged.

For the window-controlled selective-repeat ARQ scheme, the transmitting node is logically equipped with three buffers identified as entry buffer, re-entry buffer and transmission buffer, where entry and re-entry buffers are infinite while the transmission buffer is limited to hold L packets. At the transmitting and receiving nodes, the procedure of the window-controlled selective-repeat ARQ scheme is summarized as follows:

(1) As a packet arrives at the transmitting node, (e.g., an SDU is delivered to the layer performing error control from the upper layer), the transmitting node immediately stores the packet at the bottom of the entry buffer.

(2) On receiving an ACK message for the packets delivered in a previous frame, the transmitting node stores the packets which are negatively acknowledged by the ACK message at the bottom of the re-entry buffer.

(3) At the end of kth frame, packets remaining at the re-entry buffer are sequentially (starting from the packet at the top of the buffer) transferred to the transmission buffer, if any. Note that a packet at the re-entry buffers was already endowed with a serial number and some packets may have a same serial number. Since a duplication of serial number is confined only within a frame, none of the packets with a same serial number shall be transferred to the transmission buffer, if the transmission buffer has no vacancies enough to store all of them.

(4) If there still remain vacancies at the transmission buffer after packets are transferred from the re-entry buffer, the transmitting node determines the number of packets at the entry buffer to be transferred to the transmission queue and endows each of them with a serial number according to a duplication rule. Note that the transmitting node is allowed to transmit a packet belonging to a new window only after every packet belonging to the previous window is positively acknowledged. Thus, the number of packets transferred from the entry buffer is affected by the remaining serial numbers for the current window (besides the vacancy at the transmission buffer and the occupancy at the entry buffer). Such process depends on the employed duplication rule, which will be described in section 3.

(5) As a frame begins, the transmitting node sequentially transmits packets residing at the transmission buffer via the forward channel.

(6) At the end of each frame, the receiving node inspects the packets delivered during the frame for errors and constructs an ACK message including the error detection result of each packet. Among the packets delivered during a frame, some packets may be endowed with an identical serial number. If errors are detected in one of such packets, all the packets are regraded as being infected with errors.

(7) The receiving node sends the constructed ACK message to the transmitting node across the reverse channel.

The process of the window-controlled selective-repeat ARQ scheme is depicted in figure 1.

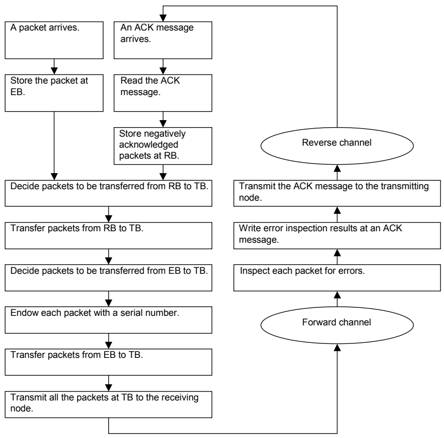

Fig. 1. Process of window-controlled selective-repeat ARQ scheme at transmitting and receiving nodes
그림 1. 송신 노드와 수신 노드에서 window-controlled selective-repeat ARQ 방식의 절차

III. Rule for Serial Number Duplication

In this section, we present rules of duplicating a serial number. Such duplication rules can be classified into fixed, random and adaptive duplication categories. For the description of duplication rules in each category, we introduce the following random variables. For $k \in \{1, 2, \cdots\}$, let X_k^E and X_k^R denote the numbers of packets residing at the entry and re-entry buffers, respectively, at the end of the kth frame. Before the $(k+1)$ st frame starts, the transmitting node transfers some of the X_k^E and X_k^R packets to the transmission buffer. Let N_k^E and N_k^R denote the numbers of packets transferred to the transmission buffer from the entry and re-entry buffers, respectively. A packet transferred from the entry buffer is endowed with a serial number. Recall that $\{1, \cdots, \widehat{S}\}$ is the set of serial numbers which will be assigned to the packets belonging to a same window. Let S_k denote the lowest serial number avaliable at the end of the kth frame. Set $U_k = \widehat{S} - S_k + 1$, which then indicates the number of serial numbers remaining at the end of the kth frame.

3.1. Fixed Duplication Rule

In the fixed duplication rule (FDR), the maximum number of duplicates of a serial number, denoted by $\widehat{M} \in \{1, 2, \cdots\}$ is prescribed and the transmitting node endows maximally $\widehat{M}$ packets with an identical serial number. Note that all the packets endowed with an identical serial number must be transmitted within a frame. In the fixed duplication rule, the number of packets transferred from the entry buffer to the transmission buffer (N_k^E) is determined by three factors - the number of available serial numbers (U_k), the vacancies at the transmission buffer ($L - N_k^R$) and the number of packets residing at the entry buffer (X_k^E) - as follows. For $k \in \{1, 2, \cdots\}$,

$$N_k^E = \min\{\widehat{M} U_k,\ L - N_k^R,\ X_k^E\}. \qquad (2)$$

Set $Q_k = \left\lceil \frac{N_k^E}{\widehat{M}} \right\rceil$. Then, we note that $N_k^E = Q_k \widehat{M} + R_k$ for a number $R_k \in \{0, \cdots, \widehat{M} - 1\}$, i.e., the number of packets transferred from the entry buffer is not necessarily an integral multiple of the maximum number of duplicates $\widehat{M}$. Recall that S_k is the lowest serial number available at the end of the kth frame. Then, the transmitting node endows the jth packet with the serial number $S_k + n$ for $n \in \{0, \cdots, Q_k - 1\}$ and $j \in \{n\widehat{M} + 1, \cdots, (n+1)\widehat{M}\}$. For $j \in \{Q_k \widehat{M} + 1, \cdots, Q_k \widehat{M} + R_k\}$, however, the jth packet is endowed with the serial number $S_k + Q_k$.

3.2. Random Duplication Rule

In a random duplication rule (RDR), a serial number is duplicated in a random fashion. In this paper, we propose three types of random duplication rules in which the maximum number of duplicates of a serial number is randomized in each frame. Once the maximum number of duplicates is determined according to such a random duplication rule, the transmitting node then endows each packet with a serial number following the FDR. For a serial number which is assigned to a packet to be transmitted in the $(k+1)$ st frame, we let $\widehat{M}_{k+1}$ denote the maximum number of duplicates hereafter.

(1) Random duplication rule of type 1

Recall that each frame consists of L slots. In the random duplication rule of type 1 (RDR-T1), $\widehat{M}_{k+1}$ is set to be a random variable having the discrete uniform distribution in $\{1, \cdots, L\}$, i.e.,

$$P(\widehat{M}_{k+1} = j) = \frac{1}{L} \cdot I_{\{j \in \{1, \cdots, L\}\}} \qquad (3)$$

for all $k \in \{1, 2, \cdots\}$. Also, $\widehat{M}_1, \widehat{M}_2, \cdots$ are set to be mutually independent.

(2) Random duplication rule of type 2

Recall that X_k^E is the number of packets remaining in the entry buffer at the end of the kth frame for $k \in \{1,2,\cdots\}$. In the random duplication rule of type 2 (RDR-T2), $\widehat{M}_{k+1}$ is defined to be a random variable which has a discrete uniform distribution in $\{1,\cdots,i\}$ for given $X_k^E = i \in \{1,2,\cdots\}$, i.e.,

$$P(\widehat{M}_{k+1} = j \mid X_k^E = i) = \frac{1}{i} \cdot I_{\{j \in \{1,\cdots,i\}\}} \quad (4)$$

for all $k \in \{0,1,\cdots\}$. Note that we set $\widehat{M}_{k+1} = 1$ almost surely if $X_k^E = 0$.

(3) Random duplication rule of type 3

Note that N_k^R is the number of packets transferred from the re-entry buffer to the transmission buffer at the end of the kth frame for $k \in \{1,2,\cdots\}$. Thus, the transmission buffer has vacancies of $L - N_k^R$ for the packets to be transferred from the entry buffer. In the random duplication rule of type 3 (RDR-T3), $\widehat{M}_{k+1}$ is defined to be a random variable as follows. For given $N_k^R = i \in \{0,\cdots,L-1\}$, $\widehat{M}_{k+1}$ is set to be a random variable having a discrete uniform distribution in $\{1,\cdots,L-i\}$, i.e.,

$$P(\widehat{M}_{k+1} = j \mid N_k^R = i) = \frac{1}{L-i} \cdot I_{\{j \in \{1,\cdots,L-i\}\}} \quad (5)$$

for all $k \in \{0,\cdots,L-1\}$. Note that no packet is transferred from the entry buffer to the transmission buffer if $N_k^R = L$, where we do not define $\widehat{M}_{k+1}$.

In RDR-T1, The mean and variance of maximum duplicate number $E(\widehat{M}_k)$ and $Var(\widehat{M}_k)$ are larger than the ones in either RDR-T2 or RDR-T3. Thus, the window sizes fluctuate highly in RDR-T1. We also note that $E(\widehat{M}_k)$ increases as the traffic load increases in RDR-T2, while $E(\widehat{M}_k)$ increases as the packet error rate increases in RDR-T3.

3.3. Adaptive Duplication Rule

The number of duplicates of a serial number can be determined concerning the current environment of the transmitting node. In [8], a sketch of an adaptive duplication rule (ADR) was addressed, where the number of serial numbers assigned in a frame is fixed and two numbers of duplicates are determined in each frame according to the number of serial numbers per frame. First, we review such an adaptive duplication rule, identified as the adaptive duplication rule of type 1 (ADR-T1). Secondly, based on the ADR-T1, we propose the adaptive duplication rule of type 2 (ADR-T2) in which the number of serial numbers assigned in a frame is adjusted according to the observed packet error rate.

(1) Adaptive duplication rule of type 1

The maximum number of serial numbers assigned in a frame, denoted by $\widehat{V}$ is prescribed in the ADR-T1. By use of $\widehat{V}$, the number of serial numbers assigned in the $(k+1)$st frame, denoted by V_k is defined as

$$V_k = \min\{\widehat{V},\ U_k\} \quad (6)$$

for $k \in \{1,2,\cdots\}$, where U_k is the number of serial numbers remaining at the end of the kth frame. Then, the number of packets transferred from the entry buffer to the transmission buffer is determined as

$$N_k^E = \min\{L - N_k^R,\ X_k^E\} \cdot I_{\{V_k \in \{1,2,\cdots\}\}} \quad (7)$$

for $k \in \{1,2,\cdots\}$. Such N_k^E packets must be endowed with serial numbers. Define two numbers of duplicates, denoted by $M_k^{(1)}$ and $M_k^{(2)}$ as follows:

$$M_k^{(1)} = \left\lceil \frac{N_k^E}{V_k} \right\rceil, \qquad M_k^{(2)} = \left\lceil \frac{N_k^E}{V_k} \right\rceil + 1 \quad (8)$$

for $k \in \{1,2,\cdots\}$. Then, for a number $R_k \in \{0,\cdots,V_k - 1\}$, we note that

$$\begin{aligned} N_k^E &= V_k M_k^{(1)} + R_k \\ &= [V_k - R_k] M_k^{(1)} + R_k M_k^{(2)} \end{aligned} \quad (9)$$

for $k \in \{1, 2, \cdots\}$. Recall that S_k is the lowest serial number available at the end of the kth frame. The transmitting node endows the $(iM_k^{(1)} + j)$th packet with the serial number $S_k + i - 1$ for $i \in \{1, \cdots, V_k - R_k\}$ and $i \in \{1, \cdots, M_k^{(1)}\}$. . For $i \in \{1, \cdots, R_k\}$, the $([V_k - R_k] M_k^{(1)} + iM_k^{(2)} + j)$th packet is endowed with the serial number $S_k + V_k - R_k + i - 1$ for all $j \in \{1, \cdots, M_k^{(2)}\}$.

(2) Adaptive duplication rule of type 2

In the ADR-T2, the maximum number of serial numbers per frame is adjusted in each frame based on the comparison of observed error rates. We set $\widehat{V}_k$ to be the maximum number of serial numbers which will be assigned in the $(k+1)$ st frame. Note $N_k^E + N_k^R$ packets are transmitted during the $(k+1)$ st frame. Let B_{k+1} denote the number of packets which are negatively acknowledged among the $N_k^E + N_k^R$ packets. Then, the maximum number of serial numbers is adjusted as follows:

$$\widehat{V}_{k+2} = \begin{cases} \widehat{V}_{k+1} + 1 & \text{if } \dfrac{B_{k+2}}{N_{k+1}^E + N_{k+1}^R} > \dfrac{B_{k+1}}{N_k^E + N_k^R} \\ \widehat{V}_{k+1} & \text{if } \dfrac{B_{k+2}}{N_{k+1}^E + N_{k+1}^R} = \dfrac{B_{k+1}}{N_k^E + N_k^R} \\ & \text{or } N_{k+1}^E + N_{k+1}^R = 0 \\ & \text{or } \widehat{V}_{k+1} = 1 \\ \widehat{V}_{k+1} - 1 & \text{if } \dfrac{B_{k+2}}{N_{k+1}^E + N_{k+1}^R} < \dfrac{B_{k+1}}{N_k^E + N_k^R} \end{cases}$$

(10)

As we can see in (10), comparing the local estimates of packet error rate in the $(k+1)$ st and $(k+2)$ nd frames, we increase the maximum number of serial numbers which will be assigned in the $(k+3)$ rd frame, if the packet error rate is increased. Otherwise, we decrease such maximum number. We note that such adjustment is based on the fact that duplicate number is increased as $\widehat{V}$ decreases and the frequency of retransmission is also increased in general.

IV. Evaluation of Packet Delay Performance

By using a simulation method, we investigate the packet delay performance exhibited by each duplication rule (which are introduced in section 3). Such delay performance is also affected by a number of network parameters, e.g., traffic load at the transmitting node, packet error rate on the forward channel, error rate of ACK message on the reverse channel, frame length, window size, and propagation delay time. For the evaluation of packet delay performance, we assume the following simulation environment.

(1) The sequence of packet arrival times at the transmitting node is a Bernoulli point process with parameter $\lambda \in [0, 1]$, i.e., a packet arrives during a slot with probability λ and no packet arrives with probability $1 - \lambda$. Also, the packet arrival event in a slot is mutually independent of the packet arrival event in another slot. When a packet arrives at the transmitting node in a slot, we assume that the packet arrives at the end of the slot.

(2) On the forward channel, errors occur in a packet with probability $\varepsilon \in [0, 1]$ and the error occurrence event in a packet is mutually independent of the error occurrence event in another packet.

(3) The reverse channel is a noiseless channel. Thus, no error occurs in any ACK message on the

reverse channel.

(4) The propagation delay time between the transmitting and receiving nodes is negligibly short such that an ACK message for the packets transmitted in a frame arrives at the transmitting node before the end of the first slot of the next frame.

(5) A packet is said to depart from the transmitting node when the packet is positively acknowledged by an ACK message. The delay time of a packet is defined to be the time elapsed from the moment the packet arrives until it departs from the transmitting node. Let D_j denote the delay time of the jth packet. Suppose that there exists a random variable D such that $D_j \xrightarrow{d} D$ as $j \rightarrow \infty$. Then, the mean of packet delay time is defined to be $E(D)$. Suppose that we have n samples $D_1(\omega), \cdots, D_n(\omega)$ in a simulation. Then, we estimate $E(D)$ by $\frac{1}{n}\sum_{j=1}^{n} D_j(\omega)$ from the ergodicity of the delay time sequence.

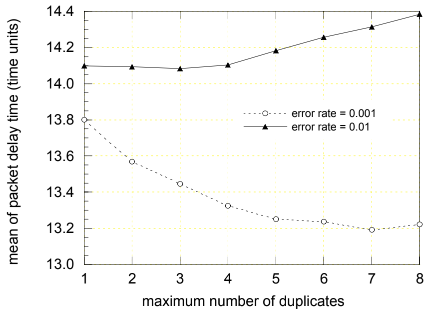

Fig. 2. Mean of packet delay time with respect to maximum number of duplicates of a serial number (duplication rule: FDR, $W=64$, $L=8$, $\lambda=0.5$, $\varepsilon \in \{0.01, 0.001\}$
그림 2. 순차 번호의 최대 중복 수에 따른 평균 패킷 지연 시간 (중복 규칙: FDR, $W=64$, $L=8$, $\lambda=0.5$, $\varepsilon \in \{0.01, 0.001\}$)

Figure 2 shows the mean and standard deviation of packet delay time with respect to the maximum number of duplicates ($\widehat{M}$). In this figure, FDR is used for duplicating a serial number, where the frame length (L) is fixed at 8 (slots) and the traffic load at the transmitting node (λ) is set to be 0.5 (packets/time unit). Also, the packet error rate at the forward channel (ε) is assumed to be in $\{0.01, 0.001\}$. For a fair comparison of delay performance, the window size is set to be as close to 64 (packets) as possible by adjusting the number of serial numbers ($\widehat{S}$). In figure 2, we observe that there exists a non-trivial optimal $\widehat{M}$ which minimizing mean of packet delay time. We also notice that such optimal number increases as the packet error rate decreases.

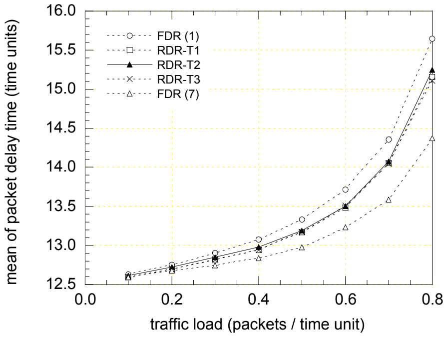

Fig. 3. Mean of packet delay time with respect to traffic load (duplication rules: FDR, RDR-T1, RDR-T2, and RDR-T3, $W=100$, $L=8$, $\lambda \in \{0.1,\cdots,0.8\}$, $\varepsilon=0.001$)
그림 3. 트래픽 부하에 따른 평균 패킷 지연 시간 (중복 규칙: FDR, RDR-T1, RDR-T2, and RDR-T3, $W=100$, $L=8$, $\lambda \in \{0.1,\cdots,0.8\}$, $\varepsilon=0.001$)

Figure 3 shows the mean of packet delay time with respect to the traffic load at the transmitting node. In this figure, FDR and RDR are used for duplicating a serial number. The frame length is set to be 8 (slots) and the packet error rate at the forward channel is fixed to 0.001. Also, the window size is set to be close to 100 (packets) as possible. Over the whole range of traffic load $\{0.1,\cdots,0.8\}$, we observe that RDR's exhibit superior delay performance than the FDR without duplication, (i.e., $\widehat{M}=1$). Among the RDR's, RDR-T1 and RDR-T3 are shown to induce lower mean delay than RDR-T2 and no significant difference is noticed between the mean delay times of RDR-T1 and RDR-T3. Recall that RDR-T1 invokes the highest mean and variance of maximum duplicate number among the three RDR's. Considering a relatively low packet error rate, we also note that a few packets may reside in the re-entry buffer in RDR-T3 and the maximum number of duplicates is thus similar to the one in RDR-T1. Such facts explain the delay performance of RDR's in this environment.

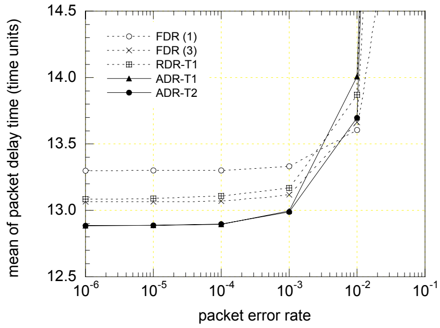

Fig. 4. Mean of packet delay time with respect to packet error rate (duplication rules: FDR, RDR-T1, ADR-T1, and ADR-T2, $W=100$, $L=8$, $\lambda=0.5$, $\varepsilon \in \{10^{-6},\cdots,10^{-1}\}$)
그림 4. 패킷 오류율에 따른 평균 패킷 지연 시간 (중복 규칙: FDR, RDR-T1, ADR-T1, and ADR-T2, $W=100$, $L=8$, $\lambda=0.5$, $\varepsilon \in \{10^{-6},\cdots,10^{-1}\}$)

Figure 4 shows the mean of packet delay time with respect to the packet error rate at the forward channel. In this figure, ADR-T1 and ADR-T2 are used in addition to FDR and RDR-T1. The frame length is set to be 8 (slots) and the traffic load at the transmitting node is fixed to 0.5 (packets/time unit). Also, the window size is set to be 100 (packets). In figure 4, we observe that duplicating serial numbers is effective when the packet error rate is relatively low. In comparison with the conventional non-duplication rule, however, all of the duplication rules exhibit degraded performance in packet delay as the packet error rate increases. Such phenomenon is explained by noting that for given packet arrival pattern, there exists a locally optimal finite window size minimizing the mean packet delay. Duplicating serial numbers incurs a fluctuation in window size and raises the probability of hitting an optimal window size. Thus, duplication rules exhibits superior delay performance. On the other hand, the frequency of retransmission is apparently increased as the packet error rate increases. For a relatively heavy error rate, the high retransmission rate is dominant over the high probability of hitting optimal window size so that the non-duplicating rule induces lower mean delay. In figure 4, we also notice that ADR-T2 invokes a lower mean of packet delay time than ADR-T1.

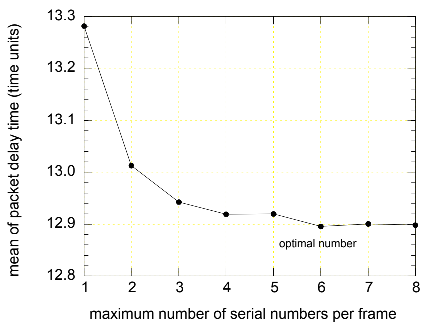

Fig. 5. Mean of packet delay time with respect to maximum number of serial numbers assigned in a frame (duplication rules: ADR-T1, $W=100$, $L=8$, $\lambda=0.5$, $\varepsilon=0.01$)
그림 5. 프레임 당 부여할 수 있는 최대 순차 번호의 수에 따른 평균 패킷 지연 시간 (중복 규칙: ADR-T1, $W=100$, $L=8$, $\lambda=0.5$, $\varepsilon=0.01$)

Figure 5 provides a clue to explain this observation. In figure 5, the mean of packet delay time is illustrated with respect to the maximum number of serial numbers which can be assigned within a frame. From this figure, we observe that there exist a non-trivial optimal number minimizing the mean packet delay. We note that AD R-T2 chases such optimal number by adjusting the maximum number of serial numbers according to the estimate of packet error rate.

V. Conclusions

In this paper, we considered a window-controlled selective-repeat ARQ scheme for error control between two adjacent nodes lying on a communication path. Aiming at improving packet delay performance, we employed a supplement scheme in which a serial number is duplicated within a frame. Classifying duplication rules into fixed, random and adaptive categories, we presented candidate duplication rules in each category. For the evaluation of packet delay performance exhibited by each duplication rule, we investigated the effect of various network parameters on the mean of packet delay time by a simulation method. From numerical example, we observed that duplicating serial numbers, especially ADR-T2 can effectively reduce the mean packet delay compared with the conventional non-duplication scheme. We also revealed that such reduction is due to the existence of a locally optimal finite window size minimizing mean packet delay.

References

[1] S. Lin, D. Costello and M. Miller, "Automatic Repeat Request Error Control Schemes," IEEE Communications Magazine, vol. 22, no. 12, pp. 5-17, December 1984.

[2] M. Schwartz, Telecommunication Networks - Protocols, Modeling and Analysis. Addison-Wesley, 1987.

[3] J. Spragins, J. Hammond and K. Pawlikowski, Telecommunications - Protocols and Design. Addison-Wesley, 1994.

[4] S. Wicker, Error Control Systems for Digital Communication and Storage. Prentice-Hall, 1995.

[5] R. Ziemer and R. Peterson, Introduction to Digital Communication. Prentice-Hall, 2001.

[6] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, "Radio Link Control (RLC) Protocol Specification," 3GPP TS 25.322 version 5.3.0, December 2002.

[7] H. Holma and A. Toskala, WCDMA for UMTS - Radio Access for Third Generation Mobile Communications. John Wiley & Sons, 2000.

[8] S. Otsuki and H. Sato, "Shared Sequence Number ARQ scheme for Multimedia Wireless Communication Systems," Proceedings of IEEE Vehicular Technology Conference, pp. 53-57, 1999.

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