논문 2007-44TC-8-7

Snowball 방식: 3GPP ARQ를 위한 대체 수락 제어 방식

(Snowball Scheme: An Alternative Admission Control Scheme for 3GPP ARQ)

신 우 철*, 박 진 경*, 하 준*, 최 천 원**

(Woo Cheol Shin, Jin Kyung Park, Jun Ha, and Cheon Won Choi)

요 약

신뢰할 수 있는 데이타 전송을 위해 3GPP RLC 명세서는 window 기반의 수락 제어 방식이 곁들어진 selective-repeat ARQ 방식을 채택하였다. 이러한 3GPP ARQ는 selective-repeat ARQ 부류에 속하고 따라서 재정렬 문제가 내재한다. 길고 불규칙한 재정렬 시간은 throughput 및 지연 성능의 열화를 불러오고 재정렬 버퍼의 범람을 초래할 수 있다. 또한 지연과 상실에 모두 민감한 서비스를 위해 재정렬 시간은 반드시 조절되어야 한다. 이러한 재정렬의 위해를 인지하고 3GPP ARQ의 원래 수락 제어 방식을 대체하여 재정렬 버퍼의 점유량을 억제하기 위한 snowball 방식을 제안한다. Snowball 방식은 재정렬 버퍼에 남아있는 기존의 DATA PDU에 인접하지 않은 새 DATA PDU를 거부하는 특징을 갖는다. 이러한 고의적 거부는 재정렬 버퍼의 점유량을 낮추는 반면 throughput 및 지연 성능을 악화시킬 수 있다. 따라서 해석적 근사 방법을 개발하여 snowball 방식이 포화 점유량 및 throughput에 비치는 영향을 조사한다. 또한 모의 실험 방법으로 실제 환경에서 최고 점유량, 정규화된 throughput 그리고 평균 지연을 평가한다. 모의 실험 결과로부터 3GPP ARQ의 원래 수락 제어 방식에 비해 snowball 방식은 점유 및 throughput 성능을 모두 고양할 수 있음을 확인한다.

Abstract

For provisioning reliable data transmission, the 3GPP RLC specification adopted a selective-repeat ARQ scheme assisted by a window-based admission control scheme. In the 3GPP ARQ, which is a member of the selective-repeat ARQ clan, inheres the reordering problem. A long and irregular reordering time results in the degradation of throughput and delay performance, and may incur the overflow of the reordering buffer. Furthermore, the reordering time must be regulated to meet the requirements of some services which are loss-sensitive and delay-sensitive as well. Perceiving the reordering hazard, we propose an alternative, identified as snowball scheme, to the original admission control scheme of the 3GPP ARQ with aiming at deflating the occupancy of the reordering buffer. A unique feature of the snowball scheme is to reject a new DATA PDU if it is non-adjacent to any DATA PDU sojourning at the reordering buffer. Such an intentional rejection apparently reduces the occupancy of the reordering buffer while it may deteriorate the throughput and delay performance. Developing an analytical approximation method, we investigate the effect of snowball scheme on the saturated occupancy and throughput. Also, we, using a simulation method, evaluate the peak occupancy, normalized throughput and average delay in the practical environment. From the simulation results, we reveal that the snowball scheme is able to enhance occupancy performance as well as throughput performance compared with the original admission control scheme of the 3GPP ARQ.

Keywords : 3GPP ARQ, admission control, occupancy, throughput, delay

* 학생회원, ** 정회원, 단국대학교 공과대학 전자컴퓨터공학부
(School of Electronics and Computer Engineering, Dankook University)
※ The present research was conducted by the research fund of Dankook University in 2005.
접수일자: 2007년7월6일, 수정완료일: 2007년7월30일

I. Introduction

In 1998, the 3rd Generation Partnership Project (3GPP) was founded with the aim of providing globally applicable technical specifications for a third generation mobile system based on wideband code division multiple access (W-CDMA) technologies. Since then, the 3GPP has released a number of specifications including radio link control (RLC) specification.

For provisioning reliable data transmission, the 3GPP RLC specification adopted a selective-repeat automatic repeat request (ARQ) scheme assisted by a window-based admission control scheme[1]. In the 3GPP ARQ, the transmitting station (TS) sends DATA PDU's and the receiving station (RS) returns STATUS PDU's as acknowledgements. Then, the TS sends the negatively acknowledged DATA PDU's again according to a selective-repeat ARQ. In the 3GPP ARQ, a window is formed at the RS so that a DATA PDU is rejected at the RS if its sequence number does not belong to the current window. (Note that a long-term evolution is being defined in 3GPP[2]. While a hybrid ARQ scheme is introduced at the MAC layer, the ARQ scheme defined by RLC specification is fundamentally unchanged in the long-term evolution.) The 3GPP ARQ, which is a member of the selective-repeat ARQ clan, inheres the reordering problem. A long and irregular reordering time results in the degradation of throughput and delay performance, and may incur the overflow of the reordering buffer[3]. Furthermore, the reordering time must be regulated to meet the requirements of some services which are both loss-sensitive and delay-sensitive[4].

Perceiving the reordering hazard, we propose an alternative, identified as snowball scheme, to the original admission control scheme of the 3GPP ARQ with aiming at deflating the occupancy of the reordering buffer. A unique feature of the snowball scheme is to reject a new DATA PDU if it is non-adjacent to any DATA PDU sojourning at the reordering buffer. Once a DATA PDU is admitted, adjacent DATA PDU's are gathered around the DATA PDU. Such a group of DATA PDU's grows like a snowball until it vanishes as all the DATA PDU's of the group depart from the reordering buffer. Compared with the original admission control scheme of the 3GPP ARQ, the snowball scheme apparently reduces the occupancy of the reordering buffer by intentionally rejecting a non-adjacent DATA PDU. The intentional rejection of such a DATA PDU, however, leads to the retransmission of the DATA PDU, which may deteriorates the throughput and delay performance.

To evaluate the snowball scheme, we first adopt a Markov approximation on the occupancy of the reordering buffer, and develop an analytical method for calculating the occupancy distribution and throughput in the saturated environment. Secondly, assuming a practical environment, we investigate the peak occupancy, normalized throughput and average delay of the snowball and original schemes by using a simulation method.

In section Ⅱ, we describe the algorithm of the snowball admission control scheme. In section Ⅲ, we present an analytical method to calculate occupancy distribution and throughput in the saturated environment. Section Ⅳ is devoted to simulation results demonstrating the performance of the snowball scheme in comparison with the original admission control scheme of the 3GPP ARQ.

Ⅱ. Algorithm

The 3GPP ARQ employs a window-based admission control scheme for regulating the occupancy of the reordering buffer. We propose an alternative, identified as snowball scheme, to the original admission control scheme. In this section, we first review the original scheme of the 3GPP ARQ and then describe the algorithm of the snowball scheme.

1. 3GPP ARQ

In the 3GPP ARQ, the TS is logically equipped with entry and re-entry buffers. When a new DATA PDU arrives at the TS, the TS immediately stores the DATA PDU at the bottom of the entry buffer and endows it with a sequence number. When the TS receives a STATUS PDU from the RS, the TS identifies negatively acknowledged DATA PDU's.

Then, the TS sequentially stores these DATA PDU's at the bottom of the re-entry buffer. When the TS is ready to send a DATA PDU, the TS chooses a DATA PDU from either entry buffer or re-entry buffer. The DATA PDU's at the re-entry buffer are always granted higher priority over the ones at the entry buffer. Thus, the TS chooses the DATA PDU at the head of the entry buffer only when the re-entry buffer is empty.

Upon reception of a DATA PDU, the RS inspects the DATA PDU for errors. If the RS detects no error on the DATA PDU, the RS attains the sequence number of the DATA PDU. A time-varying set (of the sequence numbers) of DATA PDU's, designated as window, is formed at the RS. Suppose that W is prescribed for the window size. At time $t \in (0, \infty)$, let $M(t)+1$ be the sequence number of the DATA PDU that the RS expects to receive. Then, the window at time t is defined as

$$W(t) = \{M(t)+1, \cdots, M(t)+W\}. \tag{1}$$

Suppose that the RS receives a DATA PDU at time t. Assume that no error is detected on the DATA PDU and the sequence number of the DATA PDU is identified as k. Then, the DATA PDU of sequence number k is either admitted or rejected according to an admission control scheme. Let $O(t)$ denote the set (of the sequence numbers) of DATA PDU's which reside in the reordering buffer at time t. Hereafter, we call $O(t)$ the occupant set. If the DATA PDU is admitted, the occupant set may be changed to $O(t+\Delta t)$. Also, the window may be updated to $W(t+\Delta t)$. The receiving station records the list of currently admitted DATA PDU's on a STATUS PDU. Through the reverse channel, the receiving station then sends STATUS PDU's periodically.

2. Original Admission Control Scheme

At time t, suppose that the RS receives the DATA PDU of sequence number k and detects no error on it. Then, the original admission control scheme simply admits the DATA PDU if k belongs to the window $W(t)$. Otherwise, the DATA PDU is rejected. The details of the original scheme is as follows:

(1) Suppose that $k \in \{1, \cdots, M(t)\}$. Then the DATA PDU is rejected.

(2) Suppose that $k = M(t)+1$ and $M(t)+2 \in O(t)$. Then the DATA PDU is admitted. Define

$$j^* = \max\{j \in \{2, \cdots, W\}: \{M(t)+2, \cdots, M(t)+j\} \subset O(t)\} \tag{2}$$

Then, the window is updated to $W(t+\Delta t)$ such that $M(t+\Delta t) = M(t)+j^*$. The occupant set is also changed to $O(t+\Delta t) = O(t) \setminus \{1, \cdots, j^*\}$.

(3) Suppose that $k = M(t)+1$ and $M(t)+2 \notin O(t)$. Then, the DATA PDU is admitted. The window is updated to $W(t+\Delta t)$ such that $M(t+\Delta t) = M(t)+1$. However, the occupant set is not changed, i.e. $O(t+\Delta t) = O(t)$.

(4) Suppose $k \in \{M(t)+2, \cdots, M(t)+W\} \setminus O(t)$. Then, the DATA PDU is admitted. The window is not updated, i.e. $W(t+\Delta t) = W(t)$. However, the occupant set is changed to $O(t+\Delta t) = O(t) \cup \{k\}$.

(5) Suppose that $k \in O(t)$. Then, the DATA PDU is rejected.

(6) Suppose $k \in \{M(t)+W+1, M(t)+W+2, \cdots\}$. Then, the DATA PDU is rejected.

3. Snowball Admission Control Scheme

A DATA PDU of sequence number k_1 is said to be adjacent to a DATA PDU of sequence number k_2 if k_1 is equal to either k_2-1 or k_2+1. At time t, suppose that the RS receives the DATA PDU of sequence number k and detects no error on it. Then, the snowball admission control scheme admits the DATA PDU only if k belongs to the window $W(t)$ and the DATA PDU is adjacent to a DATA PDU belonging to the occupant set $O(t)$. Otherwise, the DATA PDU is rejected. As a result, there remains only one occupant set, if any, which consists of adjacent DATA PDU's. Such an occupant set grows like a snowball until it vanishes as all the DATA PDU's belonging to it depart together from the reordering buffer. For describing the details of the snowball scheme, we introduce two variables $L(t)$ and $H(t)$, which denote the lowest and highest sequence numbers in the occupant set $O(t)$, respectively, if $O(t) \neq \varnothing$.

(1) Suppose that $O(t) = \varnothing$.
 (1.1) If $k \in \{1, \cdots, M(t)\}$, the DATA PDU is rejected.
 (1.2) If $k = M(t)+1$, the DATA PDU is admitted. The window is updated to $W(t+\Delta t)$ such that $M(t+\Delta t) = M(t)+1$. However, the occupant set is not changed.
 (1.3) If $k \in \{M(t)+2, \cdots, M(t)+W\}$, the DATA PDU is admitted. The window is not updated. However, the occupant set is changed to $O(t+\Delta t) = \{k\}$ where $.L(t+\Delta t) = H(t+\Delta t) = k$
 (1.4) If $k \in \{M(t)+W+1, M(t)+W+2, \cdots\}$, the DATA PDU is rejected.
(2) Suppose that $O(t) \neq \varnothing$.
 (2.1) If $k \in \{1, \cdots, M(t)\}$, the DATA PDU is rejected.
 (2.2) If $k = M(t)+1$ and $L(t) = M(t)+2$, the DATA PDU is admitted. The window is updated to $W(t+\Delta t)$ such that $M(t+\Delta t) = H(t)+1$. The occupant set is also changed to $O(t+\Delta t) = \varnothing$.
 (2.3) If $k = M(t)+1$ and $L(t) \in \{M(t)+3, \cdots, M(t)+W\}$, the DATA PDU is admitted. The window is updated to $W(t+\Delta t)$ such that $M(t+\Delta t) = M(t)+1$. However, the occupant set is not changed.
 (2.4) If $k = L(t)-1$ and $L(t) \in \{M(t)+3, \cdots, M(t)+W\}$, the DATA PDU is admitted. The window is not updated. However, the occupant set is changed to $O(t+\Delta t)$ such that $L(t+\Delta t) = L(t)-1$ and $H(t+\Delta t) = H(t)$.
 (2.5) If $k = H(t)+1$ and $H(t) \in \{M(t)+2, \cdots, M(t)+W-1\}$, the DATA PDU is admitted. The window is not updated. However, the occupant set is changed to $O(t+\Delta t)$ such that $L(t+\Delta t) = L(t)$ and $H(t+\Delta t) = H(t)+1$.
 (2.6) If $k \in \{M(t)+W+1, M(t)+W+2, \cdots\}$, the DATA PDU is rejected.

III. Analysis of Saturated Occupancy and Throughput

In this section, we analytically calculate the occupancy distribution and throughput induced by each of snowball and original admission control schemes when the TS is saturated with DATA PDU's.

1. Environment for Analysis

For the analysis of occupancy and throughput, we assume the following environment: The TS is saturated with DATA PDU's, i.e. it always has infinite number of DATA PDU's to send. Time is slotted. Let τ denote the slot duration time. Through the Bernoulli forward channel, where errors independently occur in each slot identically with probability ϵ, the TS sends a DATA PDU in every slot. Once the RS receives a DATA PDU, the RS perfectly detects errors, if any. The length of the status report period is equal to the slot duration time. At the end of each slot, the RS thus constructs a STATUS PDU, which is sent to the TS via the noiseless reverse channel. Also, both of the STATUS PDU transmission time and the propagation delay between the TS and RS are negligibly short. Thus, as soon as a STATUS PDU is sent by the RS, it is immediately transferred to the TS. Consequently, the TS acquires the result of the attempt on DATA PDU delivery at the end of the same slot in which the TS has sent the DATA PDU. After reading a STATUS PDU, the TS chooses a DATA PDU to send in the next slot according to a random selection discipline, i.e. the TS equally likely selects one among the unacknowledged DATA PDU's belonging to the window. Note that the TS chooses a DATA PDU according to a FCFS discipline (rather than such a random selection discipline) in the 3GPP ARQ. The random selection discipline is only employed to clearly demonstrate the effect of the snowball scheme on the occupancy and throughput performance.

2. Markov Approximation

Recall that W denotes the window size. Noting that the RS can have at most $W-1$ DATA PDU's in the reordering buffer, we then model the reordering buffer as a structure in which W rooms are arrayed. At the start of the nth slot, the window $W((n-1)\tau)=\{M((n-1)\tau)+1,\cdots,M((n-1)\tau)+W\}$. In the model of the reordering buffer, the jth room is either occupied already by the DATA PDU of sequence number $M((n-1)\tau)+j$ or reserved for it.

Let $Y_n^{(j)}\in\{0,1\}$ represent the occupancy state of the jth room at the start of the nth slot such that the jth room is occupied by a DATA PDU if $Y_n^{(j)}=1$ while it is vacant if $Y_n^{(j)}=0$. In the nth slot, a DATA PDU is selected only depending on the value of Y_n and sent through the Bernoulli forward channel. Thus, $\{(Y_n^{(1)},\cdots,Y_n^{(W)}),\ n=1,2,\cdots\}$ is apparently a Markov chain on the state space $S_Y=\{0\}\times\{0,1\}^{W-1}$. Theoretically, we can calculate the transition probability function and obtain the steady state distribution for the Markov chain. However, the size of the state space increases exponentially as the window size increases. For a large window size, the computation of the steady state distribution is thus an almost intractable problem.

Perceiving the intractability, we propose the following Markov approximation for the sake of exactness: Define

$$X_n=\sum_{j=1}^{W} I_{\{Y_n^{(j)}=1\}} \tag{3}$$

for $n\in\{1,2,\cdots\}$. Note that X_n represents the number of rooms occupied by DATA PDU's. Then, $\{X_n,n=1,2,\cdots\}$ is a chain on the state space $S_X=\{0,\cdots,W-1\}$. From (3), we easily find a map from S_X to S_Y such that state $\{j\}$ in S_X corresponds to as many as $\binom{W-1}{j}$ states in S_Y. Suppose that Y_n sojourns uniformly in the corresponding $\binom{W-1}{j}$ states when X_n lies in state $\{j\}\subset S_X$. Then, $\{X_n,n=1,2,\cdots\}$ is a homogeneous Markov chain.

In figures 1 and 2, we illustrate the assumption of uniform sojourn when the window size W is 3. These figures show the state transition diagrams of the chains $\{Y_n,n=1,2,\cdots\}$ and $\{X_n,n=1,2,\cdots\}$, respectively. The states $\{(010)\}$ and $\{(001)\}$ in figure 1 correspond to the state $\{1\}$ in figure 2. Under the assumption of uniform sojourn, $\{X_n,n=1,2,\cdots\}$ is a homogeneous Markov chain with transition probability function p such that

$$\begin{aligned} p(1,0) &= \frac{1}{2}q((010),(000)) \\ p(1,1) &= \frac{1}{2}q((010),(010))+\frac{1}{2}q((001),(010)) \\ &\quad +\frac{1}{2}q((001),(001)) \\ p(1,2) &= \frac{1}{2}q((010),(011))+\frac{1}{2}q((001),(011)) \end{aligned} \tag{4}$$

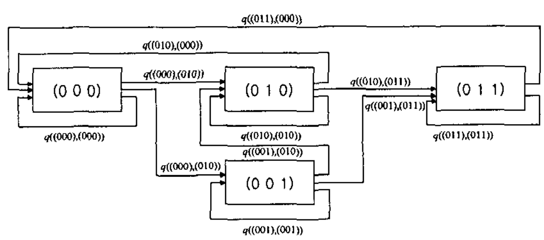


그림 1. $\{Y_n,n=1,2,\cdots\}$의 state diagram
Fig. 1. State diagram of $\{Y_n,n=1,2,\cdots\}$.

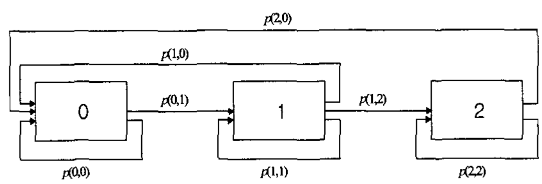


그림 2. $\{X_n,n=1,2,\cdots\}$의 state diagram
Fig. 2. State diagram of $\{X_n,n=1,2,\cdots\}$.

3. Analysis of Original Admission Control Scheme

Suppose that $X_n = i \in \{0, \cdots, W-2\}$, i.e. i rooms are occupied at the start of the nth slot. Note that the window $W((n-1)\tau) = \{M((n-1)\tau)+1, \cdots, M((n-1)\tau)+W\}$ at the start of the nth slot. Then, the TS chooses a DATA PDU among the $W-i$ candidates in the window and sends it in the nth slot. Suppose that the sequence number of the DATA PDU is k. If the DATA PDU is not the DATA PDU destined to occupy the first room, (i.e. $k \neq M((n-1)\tau)+1$), then the DATA PDU is stored at the reordering buffer hence $X_{n+1} = i+1$. Otherwise, $X_{n+1} = j \in \{0, \cdots, i\}$ provided that all the $i-j$ rooms from the 2nd to the $(i-j+1)$st room are occupied at the start of the nth slot. There are $\binom{W-i+j-2}{j}$ ways to occupy $i-j$ rooms from the 2nd to the $(i-j+1)$st room while i rooms are occupied. Also, the probability that the TS chooses the DATA PDU of sequence number $M((n-1)\tau)+1$ is equal to $\frac{1}{W-i}$. Noting the assumption of uniform sojourn, we calculate the transition probability function p_O of the homogeneous Markov chain $\{X_n, n=1,2,\cdots\}$ as follows:

$$p_O(i,0) = \frac{1}{\binom{W-1}{i}} \frac{1}{W-i}(1-\epsilon)$$

$$p_O(i,j) = \frac{\binom{W-i+j-2}{j}}{\binom{W-1}{i}} \frac{1}{W-i}(1-\epsilon)$$

$$p_O(i,i) = \frac{W-i-1}{W-1} \frac{1}{W-i}(1-\epsilon) + \epsilon$$

$$p_O(i,i+1) = \frac{W-i-1}{W-i}(1-\epsilon) \quad , \qquad (5)$$

for $i \in \{0, \cdots, W-1\}$ and $j \in \{1, \cdots, i-1\}$. Since the state space S_X is finite, there exists a stationary mass, which is also the steady state mass. Let g_O denote the steady state mass. From the stationary equations, we then calculate $g_O(j)$ for $j \in \{0, \cdots, W-1\}$ numerically. In table 1, we compare the exact and approximate steady state masses for the number of rooms occupied in the reordering buffer. From this comparison, we observe that the Markov approximation based on the assumption of uniform sojourn produces a precise steady state mass for the number of occupied rooms.

When the TS is saturated, we employ the peak occupancy and normalized throughput as performance measures. First, the peak occupancy is defined as the 99th percentile of the occupancy distribution at steady state. Let ζ_O denote the peak occupancy incurred by the original admission control scheme. Then, ζ_O is expressed as

$$\zeta_O = \min\left\{m \in \{0, \cdots, W-1\} : \sum_{j=m}^{W-1} g_O(j) \geq 0.01\right\}. \qquad (6)$$

Secondly, the normalized throughput is defined as the average number of DATA PDU's which depart from the reordering buffer in a slot. Let η_O denote the normalized throughput of the original scheme. If the DATA PDU destined to occupy the first room is delivered without errors, at least one DATA PDU departs from the reordering buffer. Also, the number of DATA PDU's departing from the reordering buffer is determined by the number of rooms which are consecutively occupied from the second room. From these facts, we derive an expression of normalized

표 1. 재정렬 버퍼에서 점유된 방의 수가 갖는 정확한 안정 상태 질량과 근사 안정 상태 질량의 비교 (원래 방식)

Table 1. Comparison of the exact and approximate steady state masses for the number of rooms occupied in the reordering buffer. (Original scheme)

number of rooms occupied	$W=2$		$W=3$		$W=4$	
	exact	approx.	exact	approx.	exact	approx.
0	0.667	0.667	0.444	0.429	0.300	0.301
1	0.333	0.333	0.370	0.381	0.302	0.318
2			0.185	0.190	0.266	0.254
3					0.133	0.127

throughput as

$$\eta_O = g_O(0)(1-\epsilon)\frac{1}{W} + \sum_{j=1}^{W-1}[g_O(j)(1-\epsilon)\frac{1}{W-j} \times \sum_{k=1}^{j}\frac{\binom{W-k-2}{j-k}}{\binom{W-1}{j}}(k+1)] \quad (7)$$

4. Analysis of Snowball Admission Control Scheme

Suppose that $X_n = i \in \{0,\cdots, W-2\}$, i.e. i rooms are occupied at the start of the nth slot. As in the original scheme, the TS chooses a DATA PDU among the $W-i$ candidates in the window and sends it in the nth slot. Suppose that the sequence number of the DATA PDU is k. Then, the snowball scheme admits the DATA PDU only if k is equal to one of $M((n-1)\tau)+1$, $L((n-1)\tau)-1$ and $H((n-1)\tau)+1$. (Recall that $L(t)$ and $H(t)$ are lowest and highest sequence numbers, respectively, in the occupant set $O(t)$.) Suppose that $k = M((n-1)\tau)+1$.

If $L((n-1)\tau)-1 = M((n-1)\tau)+1$, then the second room is already occupied. Thus, all the DATA PDU's in the occupant set (together with the DATA PDU k) depart from the reordering buffer at the end of the nth slot. As a result, no DATA PDU remains at the start of the $(n+1)$st slot, i.e. $X_{n+1} = 0$. Otherwise, only the DATA PDU k departs and the DATA PDU's in the occupant set stay in the reordering buffer. Therefore, $X_{n+1} = X_n = i$. Suppose that $k \neq M((n-1)\tau)+1$. If k is equal to either $L((n-1)\tau)-1$ or $H((n-1)\tau)+1$, the DATA PDU is stored at the reordering buffer. Thus, we have $X_{n+1} = X_n + 1 = i+1$. Otherwise, the DATA PDU is rejected and the occupant set is not changed so that $X_{n+1} = X_n = i$. From state $\{i\}$, the Markov chain $\{X_n, n = 1,2,\cdots\}$ is only able to make a transition to one of the states $\{0\}$, $\{i\}$ and $\{i+1\}$. Note that the sequence number k is equal to one of $M((n-1)\tau)+1$, $L((n-1)\tau)-1$ and $H((n-1)\tau)+1$ with probability $\frac{1}{W-i}$. Also, there can be $W-i$ kinds of occupant set when $X_n = i$. Reminding the assumption of uniform sojourn, we obtain the transition probability function p_S of the Markov chain $\{X_n, n = 1,2,\cdots\}$ as follows:

$$p_S(i,0) = \frac{1}{(W-i)^2}(1-\epsilon)$$
$$p_S(i,i) = \frac{(W-i-1)^2}{(W-i)^2}(1-\epsilon)+\epsilon$$
$$p_S(i,i+1) = \frac{2(W-i-1)}{(W-i)^2}(1-\epsilon) \quad (8)$$

for $i \in \{0,\cdots, W-1\}$. Since the state space S_X is finite, there exists a stationary mass, which is also the steady state mass. Let g_S denote the steady state mass. From the stationary equations, we then calculate $g_S(j)$ for $j \in \{0,\cdots, W-1\}$ numerically. In table 2, we compare the exact and approximate steady state masses for the number of rooms occupied in the reordering buffer. From this comparison, we observe that the Markov approximation based on the assumption of uniform sojourn produces a precise steady state mass for the number of occupied rooms.

Let ζ_S denote the peak occupancy incurred by the snowball admission control scheme. Then, ζ_S is expressed as same as (6) except that g_O is replaced

표 2. 재정렬 버퍼에서 점유된 방의 수가 갖는 정확한 안정 상태 질량과 근사 안정 상태 질량의 비교 (Snowball 방식)

Table 2. Comparison of the exact and approximate steady state masses for the number of rooms occupied in the reordering buffer. (Snowball scheme)

number of rooms occupied	$W=2$		$W=3$		$W=4$	
	exact	approx.	exact	approx.	exact	approx.
0	0.667	0.667	0.444	0.429	0.299	0.282
1	0.333	0.333	0.370	0.381	0.393	0.380
2			0.185	0.190	0.206	0.225
3					0.103	0.113

with g_S. Let η_S denote the normalized throughput of the snowball scheme. Suppose that j DATA PDU's sojourn at the start of a slot in steady state. Assume that the DATA PDU destined to occupy the first room is delivered to the RS without errors. If the occupant set occupies the second room, then all j DATA PDU's depart together with the new DATA PDU. Otherwise, only the new DATA PDU departs from the reordering buffer. From these facts, we derive an expression of normalized throughput as

$$\eta_S = \sum_{j=0}^{W-1} g_S(j)(1-\epsilon)\frac{W}{(W-j)^2}. \qquad (9)$$

5. Performance Comparison

Using the analytical method, we evaluate the peak occupancy and normalized throughput of the snowball and original admission control schemes when the TS is saturated.

Figure 3 shows (a) peak occupancy and (b) normalized throughput with respect to window size. In this figure, the error rate is set to be 0.1 on the forward channel. We observe that the snowball scheme exhibits lower peak occupancy than the original scheme, which is attained at the expense of throughput performance, however.

Figure 4 shows (a) peak occupancy and (b) normalized throughput with respect to the error rate on the forward channel. In this figure, we set the window size to be 150 (DATA PDU's). We notice that the snowball scheme trades off the throughput performance against enhanced occupancy performance.

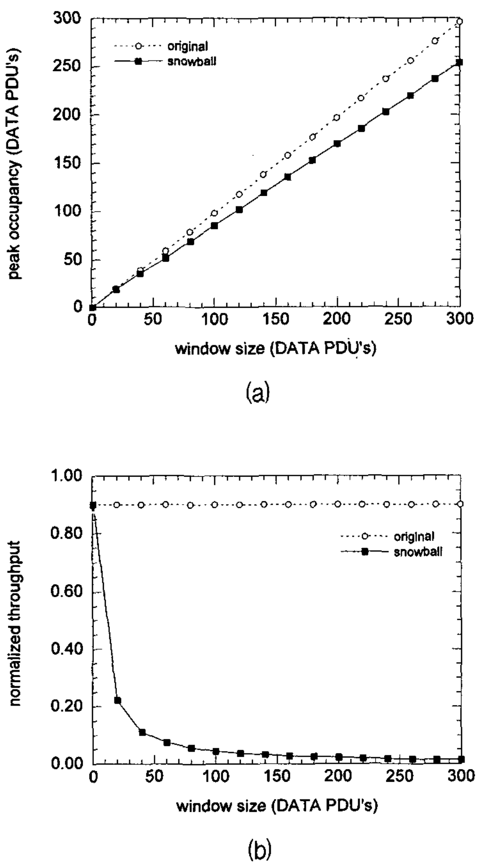


그림 3. Window 크기에 따른 최고 점유량과 정규화된 throughput

Fig. 3. Peak occupancy and normalized throughput vs. window size. (error rate on forward channel = 0.1)

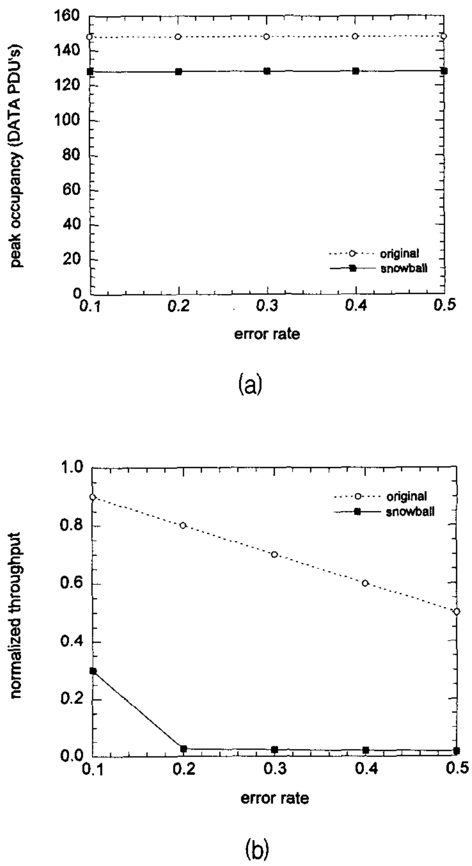


그림 4. 순방향채널에서 오류율에 따른 최고 점유량과 throughput

Fig. 4. Peak occupancy and normalized throughput vs. error rate on forward channel. (window size = 150 DATA PDU's)

Ⅳ. Simulation

In this section, we evaluate occupancy, throughput and delay performance of the snowball and original admission control schemes by a simulation method.

1. Simulation Environment

The simulation environment is as follows: The TS sends DATA PDU's through the forward channel while the RS sends STATUS PDU's across the reverse channel. We assume that both of the forward and reverse channels are slotted and well synchronized. Also, we model the forward and reverse channels as independent and identical two-state Gilbert channels[5]. Note that a two-state Gilbert channel is completely characterized by a Markov chain representing the fate of error occurrence. For $n \in \{1,2,\cdots\}$, let $S_n \in \{0,1\}$ denote the fate of error occurrence in the nth slot on the forward (or reverse) channel such that $S_n = 1$ represents that errors definitely occur if a DATA PDU (or STATUS PDU) is sent in the nth slot. Then, $\{S_n, n=1,2,\cdots\}$ is a Markov chain. The Markov chain is also completely constructed by two parameters: error rate (ϵ) and average length of error burst (ϕ). In the simulation, we employ three kinds of two-state Gilbert channel as summarized in table 3. Channel 1 is a Bernoulli channel. In each slot, errors independently occur identically with probability 0.122688. Channel 2 is constructed with the values of ϵ and ϕ introduced in [4]. Note that these parameter values are the estimates based on simulation results. On the other hand, approximate values of ϵ and ϕ are derived based on Jake's model[5]. Channel 3 is made with these parameter values. During a slot, the TS is able to send at most a single DATA PDU. The RS sends STATUS PDU's periodically.

In the 3GPP RLC, the status report may be triggered by the TS's polling or the RS's detecting a missing DATA PDU. However, we only consider the periodic status report.) The length of the status report period is an integral multiple of the slot

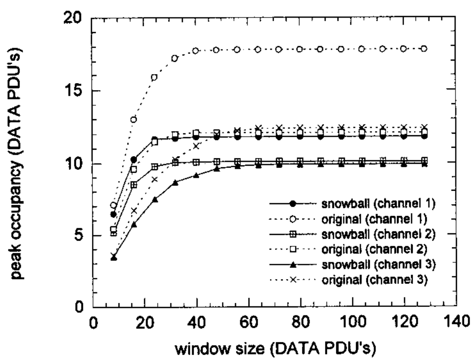
표 3. 순방향 채널과 역방향 채널의 모형
Table 3. Models for forward and reverse channels.

channel model	error rate	average length of error burst
channel 1	0.122688	1.139845
channel 2	0.122688	3.078258
channel 3	0.122688	7.736507

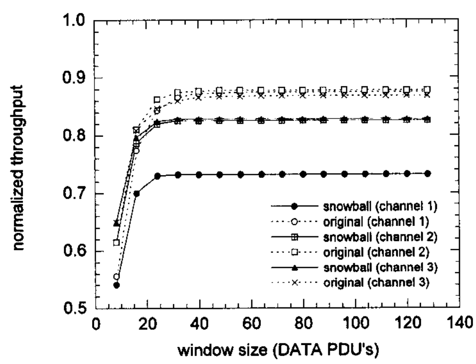
duration time. In addition, the propagation delay between the TS and RS is negligibly short compared with the slot duration time.

2. Simulation Results

Recall that the peak occupancy is the 99th percentile of the number of DATA PDU's which reside in the reordering buffer at steady state. Figure

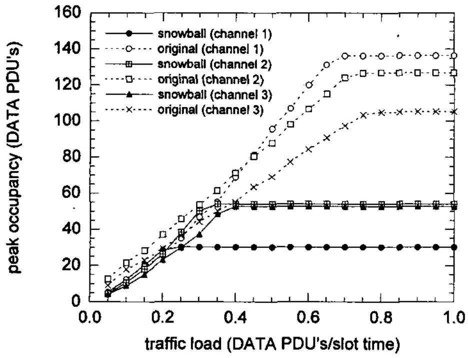


(a)

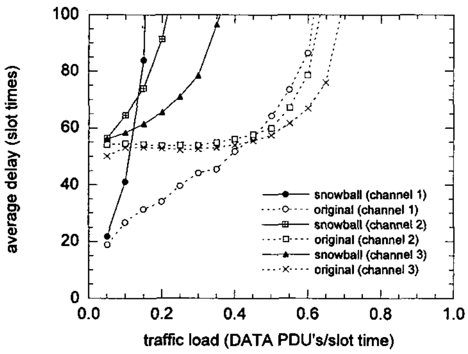


(b)

그림 5. Window 크기에 따른 최고 점유량과 정규화된 throughput
Fig. 5. Peak occupancy and normalized throughput vs. window size. (length of status report period = 8 slot times)



(a)



(b)

그림 6. 트래픽 부하에 따른 최고 점유량과 평균 지연

Fig. 6. Peak occupancy and average delay vs. traffic load. (window size = 128 DATA PDU's, length of status report period = 64 slot times)

5 shows (a) peak occupancy and (b) normalized throughput with respect to the window size. In this figure, we assume that the TS is saturated and the RS sends a STATUS PDU every 8 slot times. We observe that the snowball scheme reduces the peak occupancy compared with the original scheme. However, the snowball scheme incurs inferior throughput than the original scheme for given window size. In figure 5, we also notice that the snowball shows the best performance with channel 3 while it works worst across channel 1. From this observation, we postulate that the snowball scheme performs better on slower fading channel.

We define the delay to be the time elapsed from the moment that a DATA PDU arrives at the TS until the DATA PDU departs from the reordering

표 4. 서로 다른 window 크기를 갖는 snowball 수락 제어 방식과 원래 수락 제어 방식의 비교

Table 4. Comparison of snowball and original admission control schemes with non-identical window sizes.

	Snowball scheme $W=140$	Original scheme $W=80$
peak occupancy	75.112	92.263
normalized throughput	0.625	0.594

buffer of the RS. Figure 6 shows (a) peak occupancy and (b) average delay with respect to the traffic load at the TS. In this figure, we set that the window size is equal to 128 (DATA PDU's) and the RS sends a STATUS PDU every 64 slot times. In figure 6, we observe that the snowball scheme deflates the occupancy of the reordering buffer at the expense of delay performance.

In figure 5, we observed that the snowball scheme, in comparison with the original scheme, trades off throughput performance against better occupancy performance for given window size. In table 4, we demonstrate that the snowball scheme is able to attain lower occupancy as well as higher throughput at the expense of window size. In this table, we compare the snowball scheme with window size of 140 with the original scheme with window size of 80. We assume channel 3 and set the length of status report period to be 64 (slot times). In table 4, we observe that snowball scheme exhibits superior performance in both of occupancy and throughput to the original scheme.

V. Conclusions

The 3GPP ARQ, which is a member of the selective-repeat ARQ clan, inheres the reordering problem. Aiming at deflating the occupancy of the reordering buffer, we proposed the snowball scheme as an alternative to the window-based admission control scheme of the 3GPP ARQ. Contrary to the original admission control scheme, the snowball scheme is characterized by a unique feature that a new DATA PDU is rejected if it is non-adjacent to any DATA PDU in the reordering buffer. To evaluate the snowball scheme, we, by adopting a Markov approximation, developed an analytical method to calculate the saturated occupancy distribution and throughput. From the numerical examples made by use of the analytical method, we observed that the snowball scheme trades off the throughput performance against better occupancy performance. From the simulation results in a practical environment, we also noticed that the snowball scheme is able to enhance both of occupancy performance and throughput performance compared with the original scheme of the 3GPP ARQ.

참 고 문 헌

[1] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, "Radio Link Control (RLC) Protocol Specification," *3GPP TS 25.322 version 7.2.0*, September 2006.

[2] H. Ekström, A. Furuskär, J. Karlsson, M. Meyer, S. Parkvall, J. Torsner, and M. Wahlqvist, "Technical Solutions for the 3G Long-term Evolution," *IEEE Communications Magazine*, vol. 44, no. 3, pp. 38-45, March 2006.

[3] E. Weldon, "An Improved Selective-repeat ARQ Strategy," *IEEE Transactions on Communications*, vol. 30, no. 3, pp. 480-486, March 1982.

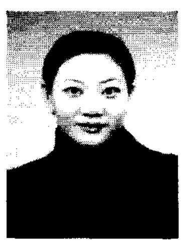
[4] C. Chiasserini and M. Meo, "Impact of ARQ Protocol on QoS in 3GPP Systems," *IEEE Transactions on Vehicular Technology*, vol. 52, no. 1, pp. 205-215, January 2003.

[5] A. Chockalingam, M. Zorzi, L. Milstein, and P. Venkataram, "Performance of a Wireless Access Protocol on Correlated Rayleigh-fading Channels with Capture," *IEEE Transactions on Communications*, vol. 46, no. 5, pp. 644-655, May 1998.

저자 소개

신 우 철(학생회원)
2002년 단국대학교 대학원 정보통신학과 석사.
2007년 현재 단국대학교 대학원 전자컴퓨터공학과 박사 과정.
<주관심분야 : 오류 제어, 무선망, 큐잉 이론>

하 준(학생회원)
2002년 단국대학교 대학원 전자컴퓨터공학과 석사.
2007년 현재 단국대학교 대학원 전자컴퓨터공학과 박사 과정.
<주관심분야 : 데이타 트래픽 모형화, 무선망, 큐잉 이론>



박 진 경(학생회원)
2002년 단국대학교 대학원 정보통신학과 석사.
2007년 현재 단국대학교 대학원 전자컴퓨터공학과 박사 과정.
<주관심분야 : 매체 접근 제어, 무선망, 큐잉 이론>

최 천 원(정회원)
1986년 서울대학교 공과대학 전자공학과 학사.
1988년 서울대학교 대학원 전자공학과 석사.
1996년 University of California at Los Angeles 전기공학과 박사
2007년 현재 단국대학교 공과대학 전자컴퓨터 공학부 부교수
<주관심분야 : 매체 접근 제어, 오류 제어, 무선망, 큐잉 이론>