On the Performance of an Indicator-Based Stall Avoidance Mechanism for High-Speed Downlink Packet Access Systems

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Abstract—**The stall of delivering medium access control (MAC) layer data to the upper layer is a serious problem when a negative acknowledgement (NACK) control signal becomes an acknowledgement (ACK) signal, especially for a high-speed mobile terminal during handoff. Stall avoidance mechanisms aim to reduce such the transmission delay and keep in-sequence delivery of the MAC layer data to the upper layer. Recently, for providing high-speed downlink packet access (HSDPA) in the wideband code-division multiple access system, an indicator-based stall avoidance (ISA) mechanism was proposed to remove the nonrecoverable gap in the received out-of-sequence packets. In this paper, we derive the closed-form expression for the gap-processing time of the ISA mechanism when applying the multiprocess stop-and-wait (SAW) hybrid automatic repeat request (HARQ) mechanism. The derived analytical formulas can be used to understand performance tradeoffs between the gap-processing time and throughput in terms of various numbers of users and parallel processes when implementing the multiprocess SAW HARQ mechanism in the HSDPA system.**

Index Terms—**Gap processing time, HARQ, HSDPA, multiprocess SAW HARQ, stall, stall avoidance.**

I. INTRODUCTION

HIGH-SPEED downlink packet access (HSDPA) is becoming an important feature for the wideband code-division multiple access (WCDMA) system [1]. The objective of HSDPA in the WCDMA system is to provide a packet data service at rates up to 10 Mb/s [2], [3]. This challenging goal is achieved by integrating many techniques in both the physical and medium access control (MAC) layers, including adaptive modulation and coding [4]–[6], fast packet scheduling [7]–[11], fast cell selection [12], multiple-input–multiple-output (MIMO) antenna processing [13], [14], buffer overflow control [15], and the fast hybrid automatic repeat request (HARQ) mechanism [16]. In this paper, we investigate the performance issues of the MAC layer fast HARQ mechanism. The HSDPA for the WCDMA system adopts the multiprocess stop-and-wait (SAW) HARQ mechanism to enhance channel utilization [17]–[22]. Nevertheless, the so-called stall problem of the multiprocess SAW HARQ mechanism can be a bottleneck when delivering the MAC layer data to the upper layer and can seriously degrade the quality of service (QoS) from the higher layer user's perspective.

Specifically, the stall issue is defined as the situation when the transmitter mistakenly believes that a particular packet has already successfully reached the destination while the receiver is still waiting for that lost or damaged packet in the retransmission process. The stall issue usually occurs when the negative acknowledgement (NACK) control signal is changed to an acknowledgement (ACK) control packet due to transmission errors in the wireless link. In this case, the transmitter will never send this packet and will make the receiver wait for that lost packet forever. It has been reported that the probability of the NACK signal becoming the ACK signal can be as high as 10^{-2} for a high-speed mobile during handoff [23], [24]. Thus, resolving the stall problem is the key to reducing the transmission delay in wireless data networks [25].

In the literature, some stall avoidance mechanisms have been reported [25]–[29]. The basic idea of these stall avoidance mechanisms is to inform the receiver to stop waiting for the missing and nonrecoverable packets. With a notice issued by a stall avoidance mechanism, the receiver starts forwarding all the received in-sequence packets to the upper layers even with a gap in a series of packets. As a result, the higher layer protocol stack can earlier request the transmitter to retransmit the missing packet. In [26], a timer-based stall avoidance mechanism was proposed to trigger a counter as soon as a gap appears in the HARQ reordering buffer. When the counter expires, the receiver starts forwarding received packets to the upper layer. In addition to using a timer, a window-based stall avoidance mechanism in [27] utilized a sliding window to detect the stall situation earlier than the expiration of the timer. Recently, in [25], [28], and [29], the indicator-based stall avoidance (ISA) mechanism applied the new data indicator (NDI) to monitor the activity of each HARQ process, thereby enhancing the capability to recognize the stall situation in sending the MAC layer data to the higher protocol layer. The basic principles of the ISA mechanism can be briefly introduced as follows. As long as all the HARQ processes are transmitting some other packets, instead of the expected missing packet, it is implied that the missing packet will not be retransmitted by the sender. Thus, the receiver activates the process of forwarding data to

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the upper layer even before the timer expires or the window-based mechanism takes any action. The performances of the above stall avoidance mechanisms were evaluated by extensive simulations in [16], [30], and [31]. It was shown that a good cooperation between the radio link control (RLC) and MAC layers can reduce the peer-to-peer service data unit delay.

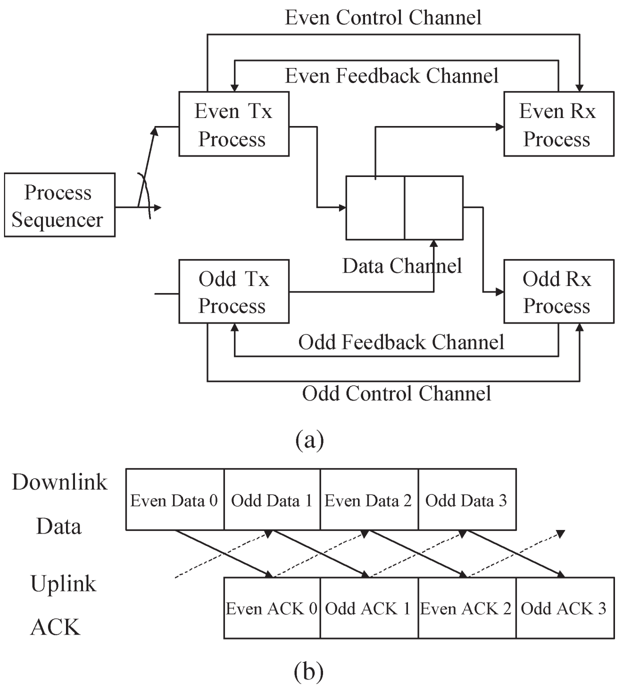
This paper includes two major contributions. 1) We introduce the term "gap-processing time" to evaluate the performance of different stall avoidance mechanisms. The gap-processing time is defined as the duration starting when the sequence of MAC layer data have a gap due to an NACK-to-ACK error until the receiver recognizes that this gap cannot be recovered by the MAC layer retransmission scheme. 2) We present the closed-form expression for the gap-processing time of the ISA mechanism in the multiprocess SAW HARQ mechanism. The gap-processing time is related to the MAC layer scheduling policy. Currently, two scheduling policies are considered for the HSDPA system to allocate radio resource to multiple users, namely 1) scheduling-by-bundle policy and 2) interleaving scheduling policy [28], [29]. The former policy schedules each user by a series of time slots, while the latter policy schedules time slots for multiple users one at a time. Therefore, with the scheduling-by-bundle policy, the gap in the reordering buffer can be detected earlier by consecutively receiving a series of packets. However, the scheduling-by-bundle policy does not exploit multiuser diversity gain. Thus, the interleaving scheduling policy is adopted more commonly in current systems, since it can exploit the multiuser diversity gain [9], [10]. We will focus on the interleaving scheduling policy to derive the analytical model for the gap-processing time of the ISA mechanism. The relations between the gap-processing time and some system parameters in the physical layer and the MAC layer, such as packet error rates, the number of users, and the number of parallel processes in the HARQ mechanism, can be investigated by the developed analytical model. Since the gap-processing time affects the delay performance and quality of service significantly, the developed analytical approach can help evaluate the overall performance of the HSDPA system from the higher layer user's perspective while considering the lower physical layer impact.

The rest of this paper is organized as follows. In Section II, we discuss the background for the stall issue in the multiprocess SAW HARQ mechanism. Section III describes the ISA mechanism. In Section IV, we derive the closed-form expression for the average gap-processing time of the ISA mechanism. In Section V, we validate the accuracy of the derived analytical results by simulations and then calculate the gap-processing time of the ISA mechanism for different design parameters in the Rayleigh fading channel. Section VI gives our concluding remarks.

II. BACKGROUND

A. *Multiprocess SAW HARQ Mechanism*

The multiprocess SAW HARQ mechanism is one of key techniques to provide the HSDPA service in the WCDMA system [1]. The basic idea of the multiprocess SAW HARQ mechanism is to implement multiple parallel processes to fully utilize channel capacity, i.e., realize the so-called "keeping the pipe full" concept. Fig. 1(a) illustrates a dual-process SAW HARQ device consisting of an even process and an odd process to service one user [32]. As shown in Fig. 1(b), while the even process is waiting for the acknowledgement of packet 0 from the receiver, the odd process starts sending packet 1. With two processes sending data alternatively, the dual-process SAW HARQ mechanism can utilize the channel capacity more effectively and achieve higher throughput. In general, the required number of parallel processes (N) to fully utilize the channel capacity can be approximated by $N = \mathrm{RTT}/\mathrm{TTI}$, where RTT is the round trip time, and the time transmission interval (TTI) indicates how often data arrive from the higher layer to the physical layer.



(a)

(b)

Fig. 1. Dual-process SAW HARQ mechanism with single user. (a) Structure. (b) Timeline.

Fig. 2 shows a scenario where a dual-process SAW HARQ device is serving multiple users. All the pairs of the source and destination devices share one downlink data channel. Thus, in the multiuser case, a system scheduler is responsible for selecting a particular customer to possess the right of using the shared channel.

B. *Stall Issue*

The stall of delivering the MAC layer data to the upper layer is an important issue when providing real-time services (such as the streaming video or music) in the wireless channel. The stall issue is the dilemma for the receiver waiting for a missing packet that will no longer be sent by the transmitter. Fig. 3 shows an example of the stall issue in a dual-process SAW HARQ mechanism. In the figure, an NACK-to-ACK error occurs when the first receive process sends a NACK signal for the lost packet 0 in the feedback channel. In this situation,

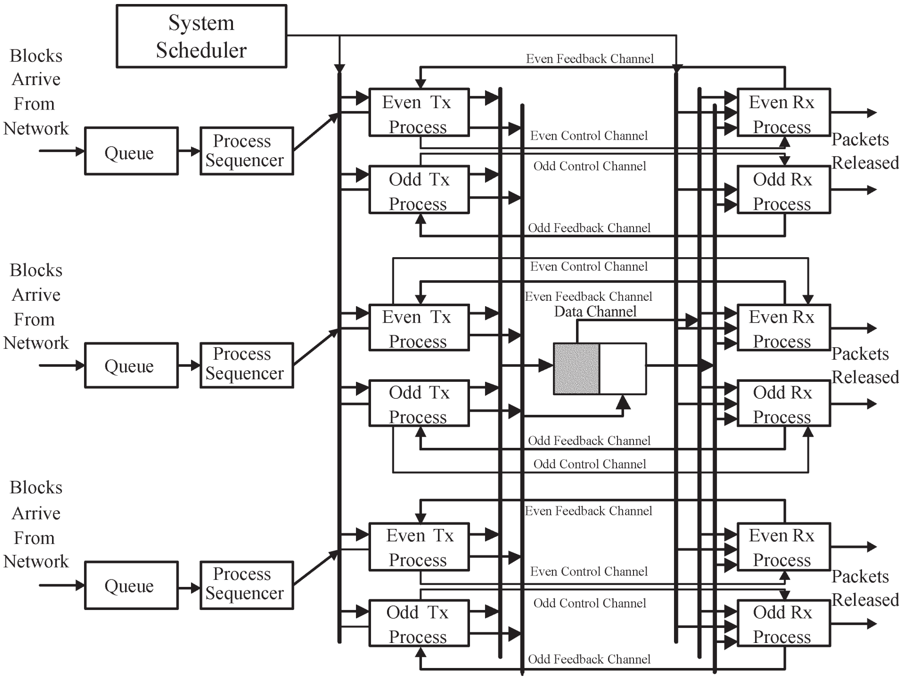


Fig. 2. Dual-process SAW HARQ mechanism with multiple users.

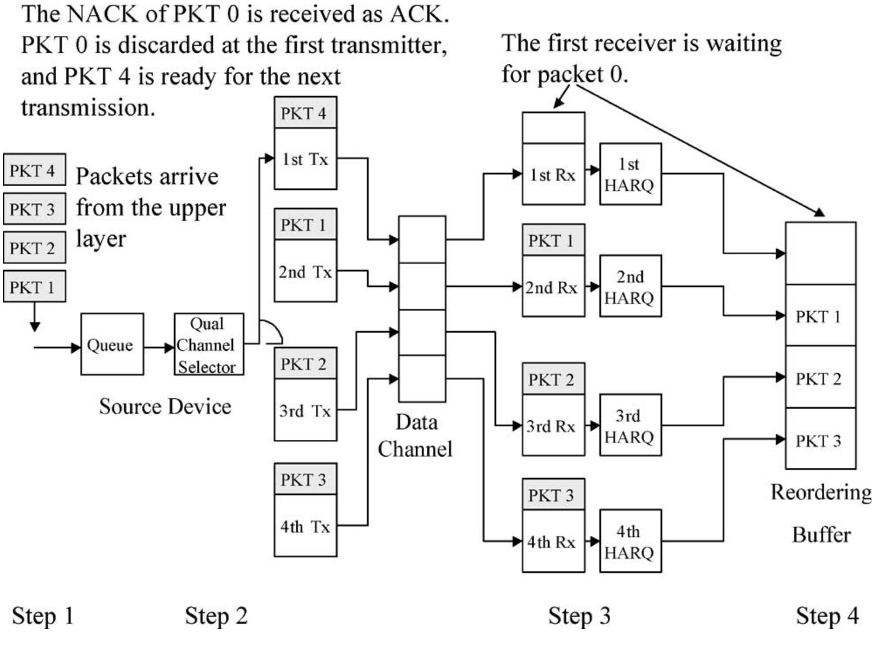


Fig. 3. Example of the stall issue in a dual-process SAW HARQ, where packet 0 is lost and packets 1, 2, and 3 are successfully received in the reordering buffer.

the first transmit process starts sending packet 4, because it mistakenly believes that packet 0 has already successfully reached the destination. Clearly, packet 0 will never be sent again, but the first receive process will continue waiting for packet 0. As a result, delivering MAC layer data to the upper layer is stalled, thereby degrading higher layer QoS performance for the delay-sensitive services.

C. Gap-Processing Time

In this paper, the gap-processing time is used as a performance measure to quantify the impact of the stall issue on the multiprocess SAW HARQ mechanism. Here, a gap means an idle space reserved for a lost packet in the reordering buffer of the receiver. Two types of gaps can be categorized in HSDPA, namely 1) Type-I gap and 2) Type-II gap. If it is still possibly recovered in future retransmissions, we call this type of gap the Type-I gap. In contrast, Type-II gap is the one that will never be sent again by the transmitter due to an NACK-to-ACK error. Obviously, Type-II gap will stall the process of sending packets to the upper layer.

The gap-processing time is defined as the duration when a gap appears in the reordering buffer until the receiver confirms that it belongs to a Type-II gap. An HARQ process usually

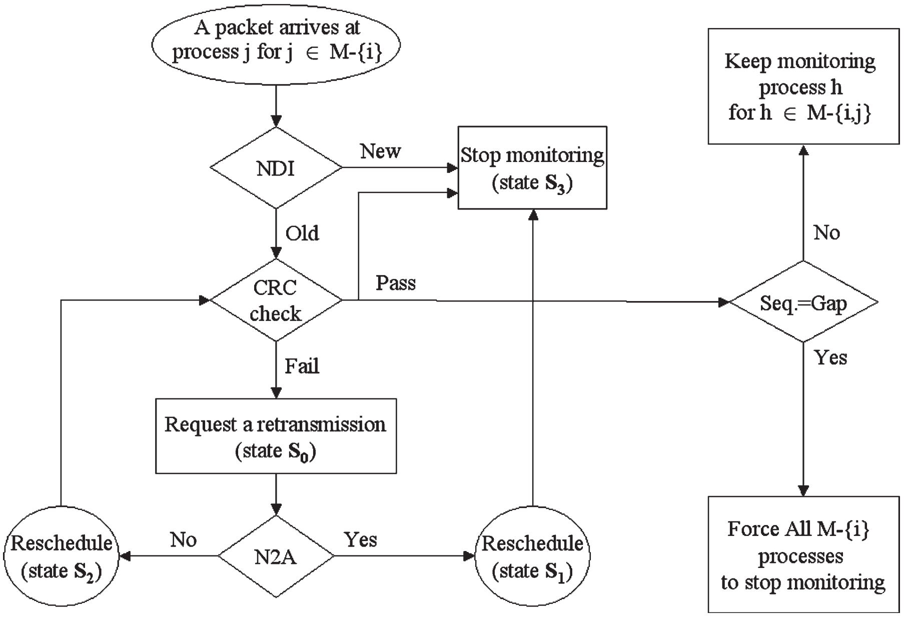


Fig. 4. Monitoring procedure of the ISA mechanism with respect to a particular process.

cannot easily distinguish a Type-II gap from a Type-I gap. Thus, a stall avoidance mechanism is required to detect the occurrence of the Type-II gap for the HSDPA system and then to trigger the receiver to flush out the available packets in the reordering buffer to the upper layer.

III. ISA MECHANISM

A. Principles

The ISA scheme introduced the NDI to monitor the activity of each process in the multiprocess SAW HARQ mechanism [25], [28], [29]. The NDI is simply a one-bit tag transmitted in the control channel. The status of the NDI is toggled whenever a new data packet is sent or remained to be the same for the retransmitted packets. The basic principles of the ISA mechanism is illustrated in Fig. 6. We assume that a gap for packet PKT* appears in the reordering buffer and process i receives packet PKT^+ with a sequence number larger than PKT*. If it is a Type-I gap, the missing packet PKT* may be transmitted by other $M - \{i\}$ processes, where M is the set of all parallel processes in the SAW HARQ mechanism. In contrast, if it is a Type-II gap, it will not be recovered by the MAC layer retransmission scheme. Note that an HARQ process with current transmission sequence number (TSN) will have a higher TSN for the subsequent packets. Thus, process i will not be able to transmit PKT*. Then, the ISA mechanism is initialized and starts monitoring the states of all the other processes $M - \{i\}$. If these processes transmit new packets or other missing packets except for the expected PKT*, it is implied that the gap PKT* observed by receiving PKT^+ in process i will not be transmitted again. In this case, these processes terminate the monitoring procedures (i.e., enter the STOP state). Now, PKT* can be confirmed to be a Type-II gap. Hence, the stall avoidance mechanism starts the process of forwarding the received packets to the upper layer.

Note that the performance of the ISA mechanism highly relies on the robustness of the NDI. On one hand, from the receiver perspective, if the control signal is damaged due to transmission errors, the receiver cannot attain NDI information. Without the aid of NDI, the monitoring procedure of the ISA mechanism for a Type-II gap will be terminated. In this situation, the receiver should wait for a new control signal and then resume the monitoring procedure of the ISA mechanism [25]. As a result, the gap-processing time will be further delayed. Moreover, the receiving packet in the traffic channel corresponding to the missing control signal will be dropped, because even if this packet passes the cyclic redundancy check (CRC) test, the receiver cannot determine to which process this packet belongs without the information of process identification carried by the control signal. On the other hand, from the transmitter perspective, the transmitter will randomly receive an erroneous NACK or ACK signal. If an erroneous NACK is received, the dropped data packet due to an erroneous control packet with the NDI information will be retransmitted. On the contrary, if an erroneous ACK is received, the dropped packet will not be retransmitted and a new Type-II gap appears in the reordering buffer at the receiving side. The analysis to include the effect of damaged NDI goes beyond the scope of this paper. Here, we only focus on the performance analysis of the ISA mechanism with the correct NDI information.

B. Problem Formulation

Referring to Fig. 4, we explain the monitoring procedure of the ISA mechanism with respect to each HARQ process. Fig. 5 shows the state transition diagram of the monitoring procedure. Table I lists the nomenclatures of the symbols used in the following. The state of a SAW HARQ process can be categorized into three different states, namely 1) the REQUEST state;

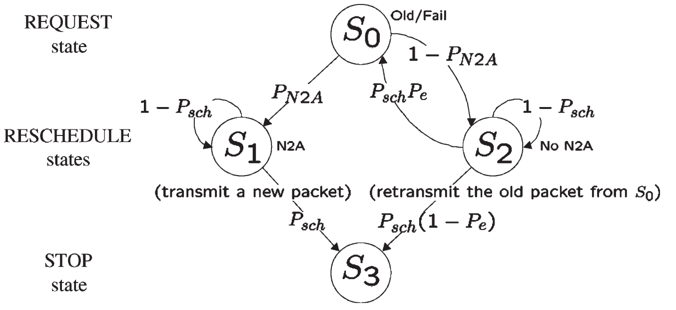


Fig. 5. State transition diagram for the ISA mechanism.

TABLE I
NOMENCLATURES OF SYMBOLS

M	No. of parallel processes in SAW H-ARQ mechanism
S_0	REQUEST state
S_1, S_2	RESCHEDULE states
S_3	STOP state
x_n	State variable at the n-th transmission
P_e	Packet error rate
P_{old}	Probability of generating a retransmitted packet
P_{new}	Probability of generating a new packet
P_{sch}	Probability of a process being scheduled
P_{N2A}	Probability of a NACK-to-ACK error

2) the RESCHEDULE states; and 3) the STOP state. These three states are explained as follows.

1) REQUEST state (S_0): The REQUEST state (S_0) of a particular process in the SAW HARQ mechanism is the situation when a retransmitted packet is in error. Since the transmitted packet fails the CRC test, the TSN of this packet cannot be known. Denote x_n the state variable at the nth transmission. Then, we have

$$P(x_0 = S_0) = P_{\text{old}} P_e \tag{1}$$

where P_{old} is the probability of generating a retransmitted packet, and P_e is its associated packet error rate (i.e., the probability of failing the CRC test for a packet). While the receiver requests retransmissions, the missing PKT* may be still possibly transmitted by this HARQ process. The stall avoidance mechanism continues monitoring the state of this process until the receiver obtains the TSN information (i.e., the retransmitted packet passes the CRC), or the NDI changes to the NEW state. During this period, the HARQ process moves to the RESCHEDULE state, which will be discussed next.

2) RESCHEDULE states (S_1 and S_2): After the REQUEST state S_0, the receive process sends a NACK control signal back to its transmit process through its feedback control channel and then enters the RESCHEDULE state S_1 or S_2. If an NACK-to-ACK error occurs, the process transits to state S_1; otherwise, it changes to state S_2.

   a) The case with an NACK-to-ACK error (S_1): Denote P_{N2A} as the probability of a NACK becoming an ACK. From Fig. 4, we have the following initial condition for state S_1:

   $$P(x_0 = S_1) = P_{\text{old}} P_e P_{\text{N2A}}. \tag{2}$$

   The process will be latched in the reschedule state until it is scheduled to transmit a certain packet. Let the probability of a process being scheduled be P_{sch}. Then, as shown in the left part of Fig. 5, the state transition probability between the REQUEST state S_0 and the RESCHEDULE state S_1 can be expressed as

   $$P(x_n = S_1) = P(x_n = S_0)P_{\text{N2A}} + P(x_{n-1} = S_1)(1 - P_{\text{sch}}). \tag{3}$$

   In this case, the NDI in the control channel will be changed to the NEW state for the subsequent packet and move to the STOP state, which will be discussed later.

   b) The case without an NACK-to-ACK error (S_2): Referring to Fig. 4, the initial condition of S_2 can be written as

   $$P(x_0 = S_2) = P_{\text{old}} P_e (1 - P_{\text{N2A}}). \tag{4}$$

   In this paper, the retransmitted packet will be scheduled for transmission with probability P_{sch} for the sake of fairness concern [18], [22]. Similar to the explanation in S_1, the HARQ process will remain in state S_2 until it is scheduled for transmission. Thus, from the right branch of Fig. 5, we have

   $$P(x_n = S_2) = P(x_n = S_0)(1 - P_{\text{N2A}}) + P(x_{n-1} = S_2)(1 - P_{\text{sch}}). \tag{5}$$

   If the retransmitted packet in state S_2 fails the CRC test, the HARQ process returns to the REQUEST state S_0 and the TSN information cannot be obtained. From Fig. 4, the state transition probability from S_2 to S_0 can be expressed as

   $$P(x_{n+1} = S_0) = P(x_n = S_2) P_{\text{sch}} P_e. \tag{6}$$

   On the other hand, if the retransmitted packet in state S_2 passes the CRC test, the TSN information can be known, and the HARQ process moves to the STOP state (S_3), which will be discussed next.

3) STOP state (S_3): When the receiver receives a new packet or a retransmitted packet successfully, the state of the HARQ process will change to the STOP state (S_3). If this new packet is received, the stall avoidance mechanism knows that the missing packet will not be transmitted by this HARQ process.
   If the retransmitted old packet is received, the stall avoidance mechanism can check the TSN to judge whether the received packet is the missing packet (PKT*) or not. If so, as shown in Fig. 4, the ISA mechanism will terminate the monitoring procedures of all the HARQ processes, because the hole in the receiving buffer is already filled. If not, the stall avoidance mechanism confirm that the missing packet will never be retransmitted by this process either. The reason for this argument can be explained as follows. Due to the requirement of chase combining, it is usually the same pair of transmit and receive processes

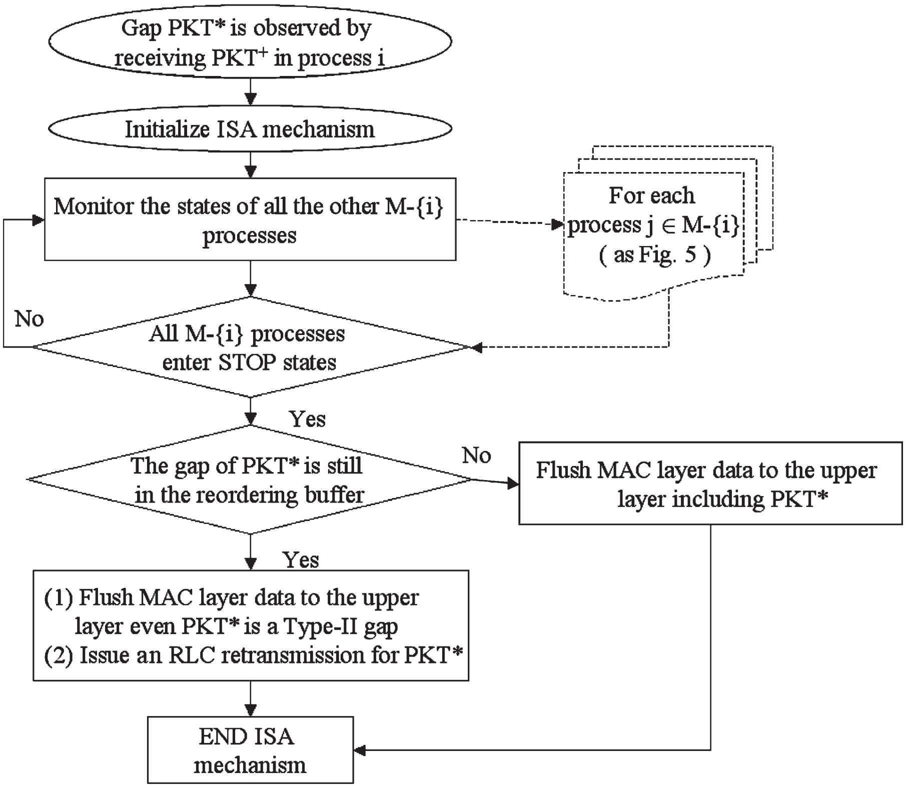


Fig. 6. Flowchart of the operations for the ISA mechanism.

that is responsible for retransmitting the missing packet. That is, if a packet (PKT*) is lost during the transmission in a certain HARQ process (Pr*), other parallel HARQ processes will not send the packet PKT* for process Pr*. Consequently, process Pr* will be responsible for transmitting packet PKT* before sending any other packets. As a result, when the TSN for the retransmitted packet is decoded successfully in a process and is not equal to that of the missing PKT*, the stall avoidance mechanism stop monitoring this process.

According to the above discussions and Figs. 4 and 6, the state transmission between RESCHEDULE states and S_3 can be expressed as

$$\begin{aligned} P(x_n = S_3) = &\,\text{Prob(receive a new packet due} \\ &\qquad \text{to an NACK-to-ACK error)} \\ &+ \text{Prob(receive an old packet} \\ &\qquad \text{and decode TSN successfully)} \\ = &\,P(x_{n-1} = S_1)P_{\text{sch}} \\ &+ P(x_{n-1} = S_2)P_{\text{sch}}(1 - P_e). \end{aligned} \tag{7}$$

The initial condition of the STOP state S_3 can be written as

$$P(x_0 = S_3) = P_{\text{new}} + P_{\text{old}}(1 - P_e) \tag{8}$$

where P_{new} is the probability of generating a new packet.

As shown in Fig. 6, when all the HARQ processes are in the STOP state and the gap for the missing packet PKT* still exists in the reordering buffer, then, this gap can be identified as an unrecoverable Type-II gap. Now, the stall avoidance mechanism can initiate the process of forwarding the received in-sequence packets with this Type-II gap from the MAC layer to the upper layer. In the meanwhile, an RLC layer retransmission request is issued for the missing packet PKT*. Next, we give an example to illustrate the function of the ISA mechanism.

C. Example

In this example, we consider a dual-process SAW HARQ mechanism. These four parallel HARQ processes are shared by multiple users. Thus, different HARQ processes may be assigned to transmit its data packets for a particular user depending on the multiple users' requests in different cycles. Table II illustrates an example of the states of the dual-process SAW HARQ mechanism for a user from cycles i to $i + 5$. Here, the period of one cycle is equal to four TTIs. Each field in the table is filled with a triplet variable (TSN, S_C, NDI). S_C is one of the following three events in the feedback control channel: 1) receive an ACK without errors (denoted by ACK); 2) receive a NACK without errors (denoted by NACK); and 3) an NACK-to-ACK error occurs (denoted by $N \rightarrow A$). NDI is either NEW or OLD. Empty fields in the table mean that the time slots that are assigned to other users or idle. In this example, we want to show that both the NDI in the control channel and the TSN in the data channel can be used to identify an unrecoverable Type-II gap. In this example, assume that packets with TSN $= 0{-}9$ of a particular user have been transmitted successfully by cycle $i - 1$. Now, this target user has five packets with TSN $= 10{-}14$ requested for transmissions from

TABLE II
EXAMPLE OF A TYPE-II GAP BEING REMOVED BY THE INDICATION OF RECEIVING BOTH NEW AND OLD PACKETS IN A FOUR-PROCESS SAW HARQ MECHANISM

	Process ID in 4-process SAW HARQ			
	Process 1 (TSN,S_C,NDI)	Process 2 (TSN,S_C,NDI)	Process 3 (TSN,S_C,NDI)	Process 4 (TSN,S_C,NDI)
Cycle i-1	...	...	...	...
Cycle i	(10,N→A,NEW)		(11,NACK,NEW)	
Cycle i+1				(12,NACK,NEW)
Cycle i+2		(13,ACK,NEW)	(11,ACK,OLD)	
Cycle i+3				(12,NACK,OLD)
Cycle i+4				(12,ACK,OLD)
Cycle i+5	(14,NACK,NEW)			

the RLC layer. In the MAC layer, a scheduler will assign a number of HARQ processes to transmit these packets for this user in every four-TTI cycle.

1) In cycle i, processes 1 and 3 send packets 10 and 11 for the target user, respectively, and both processes 2 and 4 are idle or used by other users. Assume that packet 10 is lost and its NACK signal is changed to an ACK signal, while the NACK signal of packet 11 is successfully sent to the corresponding process in the transmitter. The states of the four processes are $(-,-,-,-)$, where "$-$" stands for the NULL state. Note that the NACK signal for packet 10 is changed to ACK. The problem here is how the receiver knows the occurrence of the NACK-to-ACK error. This can be done by the help of the stall avoidance mechanism.
2) In cycle $i+1$, packet 12 is scheduled for transmission in process 4. Assume that this packet reaches the receiver successfully but fails the CRC test. Hence, a NACK signal is issued to request a retransmission. Up to now, packets 10–12 are lost in processes 1, 3, and 4, respectively. The HARQ mechanism still believes that these packets can be recovered by the normal retransmission procedures. Since the stall avoidance mechanism has not started yet, the states of the four parallel HARQ processes are still in $(-,-,-,-)$.
3) In the second TTI of cycle $i+2$, process 2 receives a new packet 13. In receiving packet 13, the receiver moves this packet to the reordering buffer of this user and makes this HARQ available for other new packets in the next cycle. However, packets 10–12 have not been received yet; hence, three holes for packets 10–12 occur in the reordering buffer. To ensure that these gaps can be filled in future transmissions, the stall avoidance mechanism is initiated to identify whether these missing packets are either recoverable Type-I gaps or unrecoverable Type-II gaps. Since packets 10–12 will be transmitted by processes 1, 3, and 4 from a receiver viewpoint, the stall avoidance mechanism starts to monitor the states of these processes. In the current situation with a new packet arriving at process 2, the states of the four parallel HARQ processes are $(-,S_3,-,-)$ according to Fig. 4.

   In the third TTI of cycle $i+2$, process 3 receives a retransmitted old packet 11 and passes the CRC test. Note that due to the requirement of Chase combining, the retransmitted packet 11 is sent by the same HARQ process 3 in cycles i and $i+2$. Since the hole of packet 11 is filled in the reordering buffer, the reordering buffer contains packets 11 and 13. Meanwhile, process 3 enters the STOP state according to Fig. 6. Thus, the states of four HARQ processes change to $(-,S_3,S_3,-)$, and the stall avoidance mechanism keeps monitoring the states of processes 1 and 4.
4) In the fourth TTI of cycle $i+3$, process 4 is scheduled to transmit an old packet 12 for the target user. Assume that packet 12 fails the CRC test again. According to Fig. 4, process 4 enters the REQUEST state (S_0) and the states of the four parallel processes become $(-,S_3,S_3,S_0)$. During the REQUEST state S_0, the receive process of the HARQ process 4 requests a retransmission for packet 12 by sending a NACK signal to the corresponding transmit process. Assume that this NACK signal successfully reaches the transmit process, the state of process 4 changes to the RESCHEDULE state (S_2). Thus, the states of the four parallel HARQ processes are now $(-,S_3,S_3,S_2)$.
5) In the fourth TTI of cycle $i+4$, process 4 is scheduled to retransmit packet 12 for the target user. This time, packet 12 passes the CRC test, and the TSN of packet 12 is obtained. Based on the information of TSN, packet 12 is moved to the reordering buffer and fills its gap. From Fig. 4, the state of process 4 enters the STOP state, and the states of the four processes become $(-,S_3,S_3,S_3)$. At this stage, packets 11–13 are in the reordering buffer, and an empty space is reserved for the missing packet 10. The stall avoidance mechanism continues monitoring process 1, which is the only left process possibly transmitting packet 10.
6) In cycle $i+5$, process 1 transmits a new packet 14, because the NACK signal of packet 10 is reverted to an ACK signal due to transmission errors in cycle i in the feedback control channel. Here, we assume that the new packet 14 is lost and that a NACK signal is sent back to the corresponding process in the transmitter. Since packet 14 is a new packet, the NDI in the control channel becomes the NEW state. Without the information of TSN of this packet in the traffic channel, process 4 enters the STOP state (S_3). This shows the advantage of using NDI to shorten the gap-processing time in the HARQ mechanism. According to Fig. 4, the status of the four parallel HARQ processes now becomes (S_3,S_3,S_3,S_3). Because the four processes are all in the STOP state and the gap

for packet 10 is still in the reordering buffer, it is implied that the missing packet 10 is a nonrecoverable Type-II gap. Hence, the HARQ process should no longer wait for packet 10. Consequently, the available in-sequence packets 11–13 should be forwarded to the upper layer, and an RLC layer retransmission request is issued for packet 10.

In the above example, we have shown how the ISA mechanism can recognize Type-II gap with the aid of NDIs in the control channel and TSNs in the data channel. In the considered example, the NDIs of processes 1 and 2 are used to confirm that these two processes do not possibly retransmit the missing packet 10. In addition, the information of TSN of processes 3 and 4 in the user data channel is used to judge that these two processes will not transmit the missing packet 10 either. With the cooperation of the NDI in the control channel and the TSN in the data traffic channel, the ISA can realize the fast physical/MAC layer retransmission for the HARQ mechanism. In the following section, we will present the analysis of the gap-processing time of the ISA mechanism according to state transition diagram shown in Fig. 5.

IV. ANALYSIS

In this section, we present an analytical formula to calculate the average gap-processing time of the ISA mechanism. The average gap-processing time is an important performance metric for the high-speed retransmission mechanism in both the MAC and RLC layers. For example, if a Type-II gap occurs, the received packets are queued in the reordering buffer of the MAC layer. Thus, a longer gap-processing time causes a higher overflow probability in the MAC layer reordering buffer. Furthermore, a Type-II gap will trigger an RLC retransmission. Thus, if the gap-processing time is too long, a large-sized buffer in the RLC layer is required to accommodate the packets forwarded from the MAC layer. However, it is difficult to evaluate the gap-processing time of the ISA mechanism in an analytical way. The gap-processing time is a function with parameters from both the physical and the MAC layers. For example, in the physical layer, the packet error rate and the probability of a NACK becoming an ACK should be incorporated in this function, while in the MAC layer, the impact of the scheduling policy on the gap-processing time should also be considered. Hence, to make the analysis tractable, we have made the following assumptions.

1) A fair scheduler independently assigns each process to each user with a probability of $P_{\text{sch}} = 1/K$, where K is the number of users in the system.
2) Because an NACK-to-ACK error usually occurs when a mobile terminal moves at high speeds, it is assumed that the fast changing channel is modeled by an independent Rayleigh fading channel from one packet to another packet.
3) In the receiving end, a reordering buffer is assigned to a user to handle the received packets from multiple parallel HARQ processes.
4) Effects of incremental redundancy and Chase combining have yet to be considered in the analytical model. Thus, the provided analysis can be viewed as a worst case analysis compared to the cases applying incremental redundancy and Chase combining.
5) The feedback delay of sending an ACK or a NACK in an individual HARQ process is not taken into account in the gap-processing time. In HSDPA, multiple parallel HARQ processes transmit data packets alternately to fully utilize the channel capacity. Thus, the feedback delay of sending control signals does not affect the gap-processing time. In the feedback channel, only the impact of NACK-to-ACK errors is considered.

Now, we prove that the average gap-processing time of the ISA mechanism for the multiple parallel HARQ processes can be calculated by the following proposition.

Proposition 1: Consider an M-process SAW HARQ process. For a given packet error rate (P_e) and the probability of an NACK-to-ACK error (P_{N2A}), define the probability of generating new packets and old packets as

$$P_{\text{new}} = (1 - P_e) + P_e P_{\text{N2A}} \tag{9}$$

and

$$P_{\text{old}} = P_e(1 - P_{\text{N2A}}) \tag{10}$$

respectively. Then, the gap-processing time for the ISA method can be calculated as

$$\begin{aligned}\overline{\text{GPT}} = \sum_{k=1}^{C} \Bigg\{ & kMP_{\text{sch}}(1-P_{\text{sch}})^{k-1} \left[\sum_{i=0}^{k-1} P(x_i = S_3)\right]^{M-1} \\ & + \sum_{m=2}^{M} (m-1+kM) \sum_{\ell=1}^{k} P_{\text{sch}}(1-P_{\text{sch}})^{\ell-1} \\ & \times \left[\sum_{i=0}^{k} P(x_i = S_3)\right]^{m-2} P(x_k = S_3) \\ & \times \left[\sum_{j=0}^{k-1} P(x_j = S_3)\right]^{M-m} \Bigg\}\end{aligned} \tag{11}$$

where

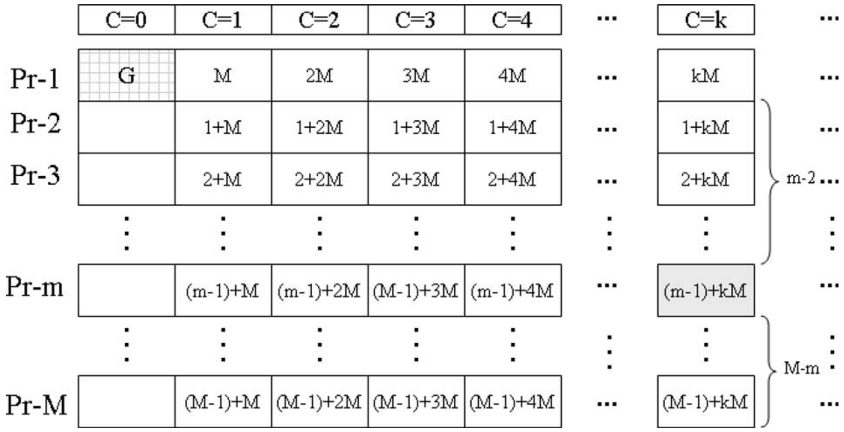
$$P(x_0 = S_3) = P_{\text{new}} + P_{\text{old}}(1 - P_e)$$

and

$$\begin{aligned}P(x_n = S_3) = {} & P_{\text{old}} P_{\text{sch}} \left[P_e P_{\text{N2A}} + P_{\text{old}}(1 - P_e)\right] \\ & \times \left[P_{\text{sch}} P_{\text{old}} + (1 - P_{\text{sch}})\right]^{n-1}, \qquad n \geq 1.\end{aligned} \tag{12}$$

The parameter C in (11) is the required number of cycles to involve all processes in the M-process SAW HARQ to remove a Type-II gap, and the other parameters M, P_{sch}, and $P(x_n = S_3)$ are already defined in Section III.

Proof: Assume that a Type-II gap appears in cycle 0 of process Pr-1 as shown in Fig. 7. We now consider the



	C=0	C=1	C=2	C=3	C=4	⋯	C=k	⋯
Pr-1	G	M	2M	3M	4M	⋯	kM	⋯
Pr-2		1+M	1+2M	1+3M	1+4M	⋯	1+kM	⋯
Pr-3		2+M	2+2M	2+3M	2+4M	⋯	2+kM	⋯
⋮		⋮	⋮	⋮	⋮	⋮	⋮	⋮
Pr-m		(m-1)+M	(m-1)+2M	(M-1)+3M	(m-1)+4M	⋯	(m-1)+kM	⋯
⋮		⋮	⋮	⋮	⋮	⋮	⋮	⋮
Pr-M		(M-1)+M	(M-1)+2M	(M-1)+3M	(M-1)+4M	⋯	(M-1)+kM	⋯

Fig. 7. Gap-processing time of the ISA mechanism.

following two possible scenarios to calculate the average gap-processing time.

I) Type-II gap can be removed at process 1: When all the SAW HARQ processes except Pr-1 enter the STOP state (S_3), the gap will be removed at process 1 when process 1 enters the STOP state in the future. Process 1 will transmit a new packet whenever it is scheduled to transmit a packet in the kth cycle, because the NACK signal for the missing packet is contaminated to be an ACK signal. Hence, this new packet sent by process 1 is associated with a NEW NDI state. Consequently, the state of process 1 enters the STOP state at the kth cycle. Since all M processes enter the STOP state and the gap of the missing packet is still in the reordering buffer, the receiver can judge whether or not the missing packet is a Type-II gap, and it will never be retransmitted. In this case, the receiver takes a period of kM TTIs to remove this Type-II gap from the reordering buffer, where other $(M-1)$ processes turn to the STOP state before the kth cycle. Let A and B be the events that process 1 is scheduling for transmission at the kth cycle, and let all the other $(M-1)$ processes enter the STOP state before the kth cycle, respectively. Then, it follows that

$$P(A) = P_{\text{sch}}(1-P_{\text{sch}})^{k-1} \tag{13}$$

and

$$P(B) = \left[\sum_{i=0}^{k-1} P(x_i = S_3)\right]^{M-1}. \tag{14}$$

Recall that

$$\begin{aligned} P(x_n = S_3) = {} & P(x_{n-1} = S_1)P_{\text{sch}} \\ & + P(x_{n-1} = S_2)P_{\text{sch}}(1-P_e), \qquad n \geq 1. \end{aligned}$$

By iteratively substituting (2)–(6) into (7), we obtain

$$\begin{aligned} P(x_n = S_3) = {} & P_{\text{old}}P_{\text{sch}}\left[P_e P_{\text{N2A}} + P_{\text{old}}(1-P_e)\right] \\ & \times \left[P_{\text{sch}}P_{\text{old}} + (1-P_{\text{sch}})\right]^{n-1}, \qquad n \geq 1. \end{aligned} \tag{15}$$

Because events A and B are mutually independent, the probability of the Type-II gap being removed in the kth cycle of process 1 can be expressed as

$$P(A \cap B) = P(A)P(B). \tag{16}$$

Combining (13)–(15), the average gap-processing time to remove a Type-II gap at process 1 is

$$\begin{aligned} \overline{\text{GPT}}_1 &= \sum_{k=1}^{C} kM \times P(A)P(B) \\ &= \sum_{k=1}^{C} kM \times P_{\text{sch}}(1-P_{\text{sch}})^{k-1} \\ &\quad \times \left[\sum_{i=0}^{k-1} P(x_i = S_3)\right]^{M-1} \end{aligned} \tag{17}$$

where C is the required number of cycles of involving all processes in the M-process SAW HARQ to remove a Type-II gap.

II) Type-II gap can be removed at process m for $m \geq 2$: Assume that the Type-II gap is removed in the kth cycle of process m, where $m \geq 2$ and $k \geq 1$. In this case, the gap-processing time is $(m-1+kM)$ TTIs, as shown in Fig. 7. Denote $P_\alpha(m,k)$ as the probability of process m removing the Type-II gap in the kth cycle for different combinations of k and m. Then, the average gap-processing time for the Type-II gap being removed at process m, where $m \geq 2$, can be expressed as

$$\overline{\text{GPT}}_2 = \sum_{k=1}^{C}\sum_{m=2}^{M}(m-1+kM)P_\alpha(m,k) \tag{18}$$

where C is defined in (17). The probability $P_\alpha(m,k)$ is the joint probability of the following four independent events:

$$\begin{cases} P_{E1} = P(\text{Process 1 enters the STOP state within} \\ \qquad\qquad \text{the } k\text{th cycle}) \\ P_{E2} = P(\text{The first } m-2 \text{ processes enter the STOP} \\ \qquad\qquad \text{state within the } k\text{th cycle}) \\ P_{E3} = P(\text{Process } m \text{ enters the STOP state at the} \\ \qquad\qquad k\text{th cycle}) \\ P_{E4} = P(\text{The last } M-m \text{ processes enter the STOP} \\ \qquad\qquad \text{state before the } k\text{th cycle}). \end{cases}$$

Note that

$$P_\alpha(m,k) = P_{E1}P_{E2}P_{E3}P_{E4}. \tag{19}$$

Similar to the procedures of deriving (13) and (14), we can rewrite (19) as

$$\begin{cases} P_{E1} = \sum_{\ell=1}^{k} P_{\text{sch}}(1-P_{\text{sch}})^{\ell-1} \\ P_{E2} = \left[\sum_{i=0}^{k} P(x_i = S_3)\right]^{m-2} \\ P_{E3} = P(x_k = S_3) \\ P_{E4} = \left[\sum_{j=0}^{k-1} P(x_j = S_3)\right]^{M-m}. \end{cases} \tag{20}$$

Substituting (19) and (20) into (18), we can have the probability of removing the Type-II gap at process m, where $m \geq 2$, as

$$\begin{aligned} \overline{\text{GPT}}_2 &= \sum_{k=1}^{C}\sum_{m=2}^{M}(m-1+kM)P_\alpha(m,k) \\ &= \sum_{k=1}^{C}\sum_{m=2}^{M}(m-1+kM)\overbrace{\sum_{\ell=1}^{k} P_{\text{sch}}(1-P_{\text{sch}})^{\ell-1}}^{\text{Process 1}} \\ &\quad \times \overbrace{\left[\sum_{i=0}^{k} P(x_i = S_3)\right]^{m-2}}^{\text{The first } m-2 \text{ processes}} \overbrace{P(x_k = S_3)}^{\text{Process } m} \\ &\quad \times \overbrace{\left[\sum_{j=0}^{k-1} P(x_j = S_3)\right]^{M-m}}^{\text{The last } M-m \text{ processes}}. \end{aligned} \tag{21}$$

Note that the value of C can be obtained by satisfying the following equation:

$$\begin{aligned} &\sum_{k=1}^{C}\left\{P_{\text{sch}}(1-P_{\text{sch}})^{k-1}\left[\sum_{i=0}^{k-1} P(x_i = S_3)\right]^{M-1}\right. \\ &\quad + \sum_{m=2}^{M}\sum_{\ell=1}^{k} P_{\text{sch}}(1-P_{\text{sch}})^{\ell-1}\left[\sum_{i=0}^{k} P(x_i = S_3)\right]^{m-2} \\ &\quad \left.\times P(x_k = S_3)\left[\sum_{j=0}^{k-1} P(x_j = S_3)\right]^{M-m}\right\} = 1. \end{aligned} \tag{22}$$

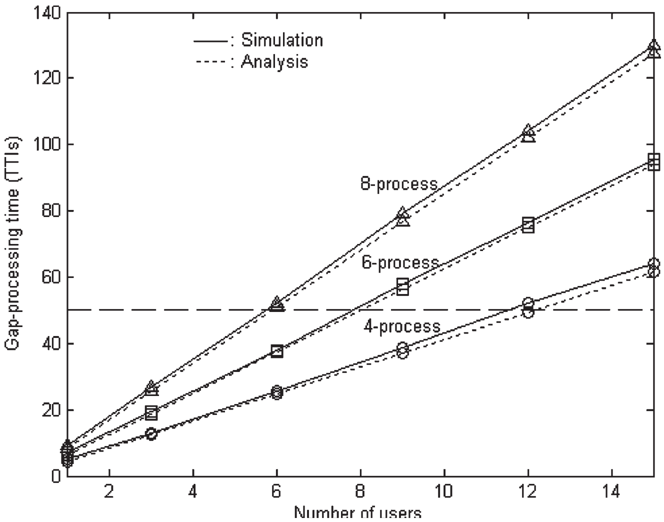


Fig. 8. Impact of number of users on the average gap-processing time for four-, six-, and eight-process SAW HARQ mechanisms in a Rayleigh channel with Doppler frequency of 100 Hz and $P_e = 0.12$.

With (17) and (21), the average gap-processing time for the ISA mechanism with multiuser communications is equal to

$$\begin{aligned} \overline{\text{GPT}} &= \overline{\text{GPT}}_1 + \overline{\text{GPT}}_2 \\ &= \sum_{k=1}^{C}\left\{kMP_{\text{sch}}(1-P_{\text{sch}})^{k-1}\left[\sum_{i=0}^{k-1} P(x_i = S_3)\right]^{M-1}\right. \\ &\quad + \sum_{m=2}^{M}(m-1+kM)\sum_{\ell=1}^{k} P_{\text{sch}}(1-P_{\text{sch}})^{\ell-1} \\ &\quad \times \left[\sum_{i=0}^{k} P(x_i = S_3)\right]^{m-2} P(x_k = S_3) \\ &\quad \left.\times \left[\sum_{j=0}^{k-1} P(x_j = S_3)\right]^{M-m}\right\}. \end{aligned} \tag{23}$$

■

The accuracy of the analytical formula for estimating the gap-processing time will be validated by simulations in Section V.

V. NUMERICAL RESULTS

In this section, through simulations and analysis, we investigate the performance of the ISA mechanism in the Rayleigh fading channel. In the considered case, each process in the multiprocess SAW HARQ mechanism is shared by multiple users based on the Round-Robin scheduling policy.

Fig. 8 compares the average gap-processing time of the multiprocess SAW HARQ mechanism for various numbers of processes. We consider a time-varying Rayleigh fading channel with the Doppler frequency equal to 100 Hz, which is the case

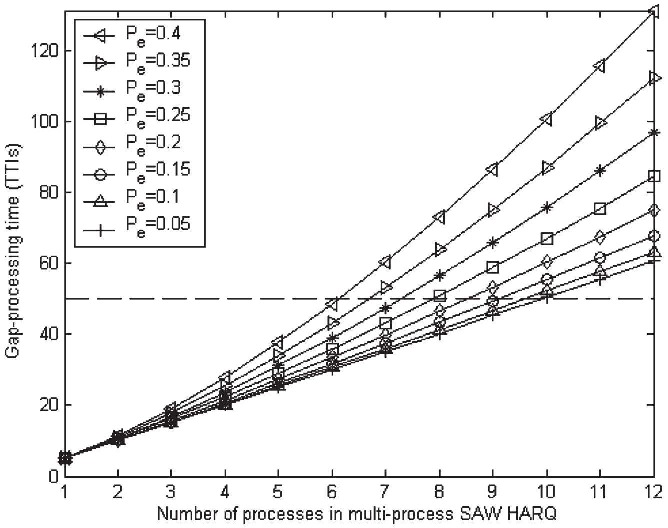


Fig. 9. Impact of number of processes in the multiprocess SAW HARQ mechanism on the performance of average gap-processing time for different P_es with five users in the system.

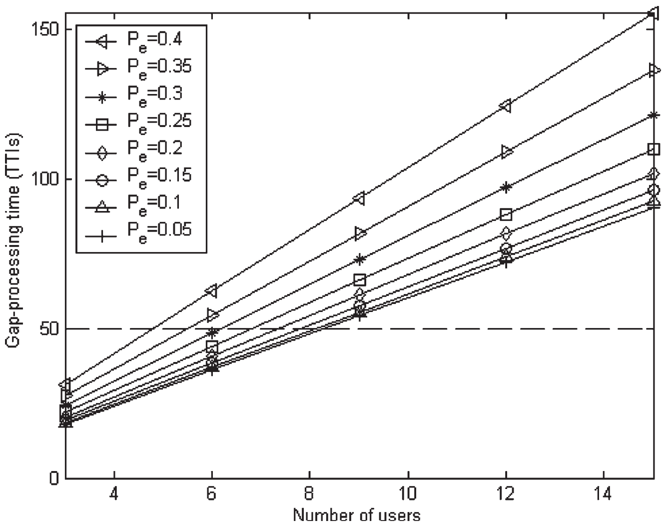


Fig. 10. Impact of the number of users on the average gap-processing time with various packet error rates in a six-process SAW HARQ mechanism.

when a mobile moves at the speeds of 54 km/h with a carrier frequency of 2 GHz. Let the packet error rate (P_e) be 0.12. As shown in the figure, the more parallel processes there are in the SAW HARQ mechanism, the longer the average gap-processing time. The analytical results are validated by the simulation results. In the case with nine users, the average gap-processing times for the M-process SAQ HARQ mechanism are 38.84, 57.86, and 79.23 TTIs for $M = 4, 6,$ and 8, respectively. Each TTI is equal to 2 ms. One can observe that the average gap-processing time of the eight-process SAW HARQ mechanism is about two times higher than that of the four-process SAW HARQ mechanism. From [31], delay is suggested to be less than 50 TTIs (i.e., 0.1 s) in order to provide an acceptable QoS. The developed analytical formula of average gap-processing time can be used to compute the appropriate number of allowable users in the system. For instance, based on the results shown in the figure, five users can be allowed to stay in an eight-process SAW HARQ system, whereas 11 users can be supported in a system with four parallel SAW HARQ processes. This example shows that the gap-processing time significantly affects the RLC retransmission delay, thereby becoming an important issue in QoS provisioning when the number of users is large.

One of the advantages in the proposed analytical models is to abstract physical layer impacts into some key parameters, such as packet error rates (P_e). Since users may have various traffic types and accordingly different requirements on P_e, the developed analytical model can quickly estimate the gap-processing time for various values of P_e and various numbers of parallel HARQ processes, as shown in Fig. 9. In the case with five users, we see that when $P_e < 0.2$, the gap-processing time is linearly proportional to the number of processes in the multiprocess SAW HARQ mechanism. However, if $P_e > 0.25$, the gap-processing time exponentially increases as the number of the parallel processes of the SAW HARQ mechanism increases. This observation indicates that the sharply increasing gap-processing time cannot be ignored when the P_e requirement is stringent. For example, as the delay constraint is set to be less than 50 TTIs, the allowable numbers of parallel SAW HARQ processes are 5 and 10 for $P_e = 0.4$ and 0.05, respectively. An interesting research topic is to determine the optimal number of parallel SAW HARQ processes to improve the overall system performance by taking both throughput and gap-processing time into account.

Another interesting application of the developed analytical model is to evaluate the number of allowable users in the system from the QoS provision perspective. Fig. 10 illustrates the average gap-processing time against the number of users for various P_e requirement in a six-process SAW HARQ mechanism. As shown in the figure, as the number of users increases, the gap-processing time increases linearly. The slope of the performance curve between the gap-processing time against the number of users with high P_e region is steeper than that with low P_e region. Furthermore, for a required RLC delay constraint, the higher the value of P_e, the fewer the number of users that can be supported by the system. For example, for an RLC delay constraint of 50 TTIs, the allowable numbers of users in the system with a 50-TTI delay limit are 4 and 8 when $P_e = 0.4$ and 0.05, respectively. The reason for this phenomenon is that the TSN information in the data traffic channel can be obtained earlier when the P_e is lower. With the aid of the TSN information, the indicator-based stall mechanism can enter the STOP state earlier. Thus, in a channel with high P_e, it is implied that a suitable call admission control scheme is necessary for the SAW HARQ system to guarantee the QoS provisioning.

VI. CONCLUSION

In this paper, we have presented a closed-form expression for the average gap-processing time of the ISA mechanism for the HSDPA system. If an NACK-to-ACK error occurs in the MAC layer HARQ mechanism, a nonrecoverable gap also appears in the reordering buffer of the received packets for a specific user. Longer gap-processing time will delay the necessary higher layer RLC retransmissions, thereby degrading the system performance seriously from a higher layer user perspective. Thus, it is important to develop an analytical method to calculate the gap-processing time from both the physical layer and MAC perspectives without time-consuming simulations.

The developed analytical model can facilitate the evaluation of the gap-processing time of the multiprocess SAW HARQ mechanism in the HSDPA system for different packet error rates, the numbers of allowable users, and the numbers of parallel processes in the SAW HARQ mechanism. From our analytical and simulation results in a Rayleigh fading channel, we find that throughput enhancement by adding the parallel processes in the SAW HARQ mechanism comes at the cost of longer average gap-processing time. For moderate packet error rates, the gap-processing time is linearly proportional to the number of users and the number of the parallel HARQ processes. However, in the situation of high packet error rates, the average gap-processing time almost exponentially increases when the number of parallel SAW HARQ processes increases.

Possible future research topics that can be extended from this work include the following: 1) to incorporate the effect of incremental redundancy and Chase combining in the gap-processing time analysis for the multiple parallel HARQ mechanism and 2) to develop efficient admission control and scheduling algorithms for the HSDPA system subject to the gap-processing time constraint.

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