Module Count-Based Overflow-Control Scheme for UMTS High-Speed Downlink Packet Access

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***Abstract*—In the universal mobile telecommunication system, the user equipment (UE) communicates with all cells in the active set through the air interface. Multiple radio links between the UE and the cells may reduce the transmission speed due to interference. In high-speed downlink packet access (HSDPA), only one serving cell is selected in the active set for high-speed downlink transmission. When the radio link quality between the serving cell and the UE degrades below some threshold, the best cell (in terms of the radio characteristics) in the active set is selected as the new serving cell and the UE switches from the old serving cell to the new serving cell. This action is referred to as *frame synchronization*. The frame-synchronization information may be delivered through more than one wireless transmission, which introduces long delay for the frame-synchronization process. In this paper, we propose an overflow-control scheme with module count for HSDPA, which guarantees that the frame-synchronization information is delivered through *one* wireless transmission and that when the UE switches wireless link to the new serving cell, no packet frames are lost.**

***Index Terms*—High-speed downlink packet access (HSDPA), module count, overflow control, universal mobile telecommunication system (UMTS), UMTS terrestrial radio-access network (UTRAN).**

I. Introduction

UNIVERSAL MOBILE telecommunication services (UMTS) [7] is designed to support high-speed wireless data transmission, which provides streaming, interactive, and background services with better quality of services as compared with the second-generation mobile networks. To further increase the speed of downlink transmission, feasibility studies have been conducted by the Third-Generation Partnership Project (3GPP) [1]–[4]. Furthermore, several studies have been contributed to support high-speed downlink packet access (HSDPA) [8]–[10], [12], [14]. In these studies, the major enhancements include adaptive modulation and coding (AMC), fast hybrid automatic repeat request (FHARQ), and fast cell selection (FCS). In this paper, we will focus on the overflow issue that may be caused by FCS.

As shown in Fig. 1, UMTS terrestrial radio access network (UTRAN) consists of node Bs and radio network controllers (RNCs). An RNC is connected to several node Bs through an asynchronous transfer mode (ATM) network [Fig. 1*(a)*]. To access the UMTS services, a user equipment (UE) communicates with cells (node Bs) in an active set through the air interface Uu based on the wide-band code-division multiple-access (WCDMA) technology [Fig. 1*(b)*] [5] and a cell may serve several UEs at the same time. For every UTRAN communication session of a UE, an active set of cells is defined [6]. If the quality of the wireless link between the UE and a cell is above some signal strength threshold θ_1, this cell is included in the active set. When the quality of the wireless link of a cell in the active set is below another threshold θ_2 (where $\theta_2 < \theta_1$), the cell is removed from the active set. In a standard UTRAN data session, the UE communicates with all cells in the active set. This approach can not support high-speed downlink transmission because multiple wireless links between several cells and a UE may increase the overall interference within the UTRAN.

3GPP TS 25.308 [4] and TR 25.950 [3] proposed an approach to support HSDPA [2]–[4], where a UE only communicates with one cell (called the serving cell) in the active set and a serving cell may serve different UEs. This serving cell is selected by the fast cell-selection procedure [2] based on the common pilot-channel received signal-code power measurements of the cells in the active set. Two physical channels, high-speed physical-downlink shared channel (HS-PDSCH) and dedicated physical-control channel (DPCCH) are used for downlink packet-frame transmission and uplink/downlink signaling, respectively. While multiple cells may be members in the active set, only one transmits packet frames to the UE at any time in the HSDPA mode. Therefore, the interference within a cell is potentially decreased and the system capacity is increased. In HSDPA, the RNC sends packet frames to all cells in the active set. Each of the nonserving cells queues the packet frames in a buffer. On the other hand, the serving cell forwards the packet frames to the UE. The stop-and-wait hybrid automatic repeat request (SAW-hybrid ARQ) [17] algorithm is exercised between the UE and the serving cell for flow control of wireless transmission. If the link quality for current

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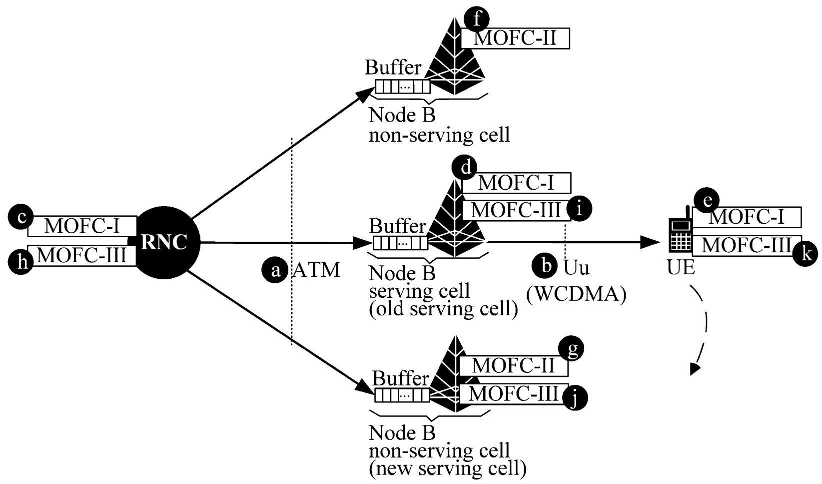

Fig. 1. UTRAN architecture.

high-speed downlink transmission degrades below a threshold θ_2, the cell with the best link quality in the active set is selected by the network as the new serving cell. Then, the next packet frames are transmitted from the new serving cell to the UE. In HSDPA, two issues must be addressed.

Buffer Overflow Issue: The buffer in a nonserving cell may be full and a mechanism is required to avoid buffer overflow at that cell.

Frame Synchronization Issue: When the UE switches to a new serving cell for downlink packet access, the new serving cell should be informed of the status of the buffer (i.e., the number of packet frames received by the UE) in the old serving cell and appropriately drop the redundant packet frames in the buffer. This action is referred to as *frame synchronization* [3].

Our previous study proposed schemes to resolve the above two issues. Details can found in [15] and [16]. In the previously proposed schemes, the information needed for frame synchronization is carried by the uplink DPCCH. When the size of frame-synchronization information exceeds the capacity of one uplink DPCCH message, this information must be carried through multiple uplink DPCCH messages. In this paper, we propose module count-based overflow control (MOFC) to guarantee that the frame-synchronization information is delivered through *one uplink DPCCH message*. This paper is organized as follows. First, we describe the MOFC scheme in Section II. Then, we prove that the proposed scheme functions correctly in Section III. Finally, we compare the performance of MOFC with the previously proposed schemes.

II. Module-Count-Based Overflow-Control Scheme

The MOFC scheme consists of three procedures: MOFC-I, MOFC-II, and MOFC-III. The relationship among these procedures is shown in Fig. 1. By exercising MOFC-I, the packet frames are delivered from the RNC to the UE through the serving cell Cell_s [see *(c), (d),* and *(e)*]. MOFC-II is executed by a nonserving cell to avoid buffer overflow [see *(f)* and *(g)*]. MOFC-III is exercised for frame synchronization when the UE switches the wireless link from the old serving cell to the new serving cell [see *(h), (i), (j),* and *(k)*]. The notation used in this paper is listed in the Appendix. Details of MOFC-I, MOFC-II, and MOFC-III are described as follows.

A. MOFC-I and MOFC-II

In HSDPA, the RNC sends packet frames to all node Bs in the active set. The serving cell forwards the packet frames to the UE. On the other hand, the nonserving cells execute MOFC-II to buffer the received packet frames without actually sending them to the UE. Let N_i be the buffer size of Cell_i. Fig. 2 illustrates the timing diagram for MOFC-I, which consists of two parts: Part 1 is exercised between the RNC and Cell_s and Part 2 is exercised between Cell_s and the UE.

Part 1: A window-based flow-control algorithm with window size w is exercised between the RNC and Cell_s. Since the ATM link [see Fig. 1*(a)*] is considered to be reliable, we assume that no packet frame is lost or corrupted during transmission. Therefore, we do not consider packet frame retransmission at the ATM link. If the rare events of packet-frame loss do occur, these lost packet frames can be recovered by higher level protocols.

The RNC maintains a counter CS_{RNC} to record the number of packet frames that have been transmitted to the cells in the active set. Every time the RNC sends a packet frame [see Fig. 2*(a)*], it increments CS_{RNC} by one.

After transmitting w packet frames, the RNC suspends the transmission until it receives an ack_s message sent from Cell_s [see Fig. 2*(b)*]. The ack_s message allows the RNC to transmit the packet frames of the next window. A counter CR_s is maintained by Cell_s to count the number of packet frames received from the RNC. Another counter CS_s is maintained by Cell_s to record the number of packet frames sent to the UE. When a packet frame arrives at Cell_s, Cell_s stores the packet frame at the tail of the buffer and increments CR_s by one.

After all packet frames in a window have been received, Cell_s computes the number K_s of packet frames currently stored in the buffer, where $K_s = CR_s - CS_s$. Cell_s checks if there is free space to accommodate the packet frames

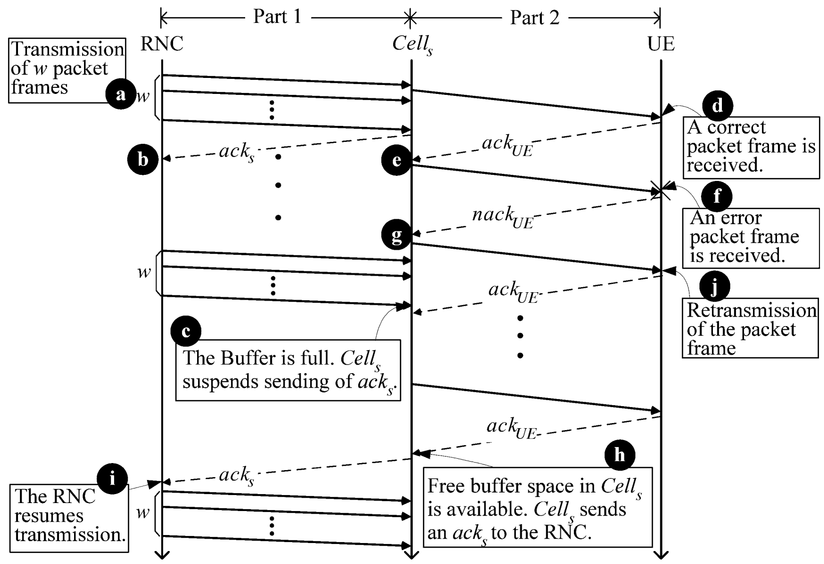

Fig. 2. Timing diagram for MOFC-I.

of the next window and determines if it should send the ack_s message to the RNC. The window-based flow-control mechanism is described by considering the K_s value in the following two cases.

Case MOFC-I.1. $K_s \leq N_s - w$: Cell_s sends ack_s to the RNC, which allows the RNC to deliver the packet frames of the next window [see Fig. 2*(b)*].

Case MOFC-I.2. $K_s > N_s - w$: No action is taken. In this case, Cell_s does not send ack_s to the RNC and the subsequent packet-frame transmission is suspended [see Fig. 2*(c)*].

The RNC is allowed to send next packet frames only in Case MOFC-I.1 (when $K_s \leq N_s - w$). This restriction ensures that Cell_s has enough buffer space to accommodate the packet frames of the next window.

Part 2: The SAW-hybrid ARQ flow-control algorithm [17] is exercised between the UE and Cell_s [see Fig. 1*(b)*]. Since errors may occur during unreliable wireless transmission, the packet frames received by the UE may be incorrect. Two types of acknowledgment messages, $\mathrm{ack}_{\mathrm{UE}}$ and $\mathrm{nack}_{\mathrm{UE}}$, will be sent from the UE to Cell_s, which indicate if the UE receives correct or error-packet frames from Cell_s, respectively. Each time, Cell_s sends a packet frame to the UE and waits for an acknowledgment from the UE. The UE maintains a counter CR_{UE} to record the number of packet frames that have been correctly received from Cell_s. If the UE receives a correct packet frame from Cell_s [see Fig. 2*(d)*], it increments CR_{UE} by one. Then, the UE sends $\mathrm{ack}_{\mathrm{UE}}$ to Cell_s [see Fig. 2*(e)*]. If an error-packet frame is received [see Fig. 2*(f)*], the UE replies Cell_s a $\mathrm{nack}_{\mathrm{UE}}$ message [see Fig. 2*(g)*].

If Cell_s receives $\mathrm{ack}_{\mathrm{UE}}$ from the UE, it increments CS_s by one and drops the transmitted packet frame. If Cell_s receives $\mathrm{nack}_{\mathrm{UE}}$, it retransmits the packet frame [see Fig. 2*(j)*]. After successfully sending a packet frame to the UE, Cell_s determines if it should send ack_s to the RNC by checking the number of packet frames currently stored in the buffer (i.e., K_s). Two cases are considered, as follows.

Case MOFC-I.3. If Cell_s has not suspended the transmission of ack_s, no action is taken.

Case MOFC-I.4. If Cell_s has suspended the transmission of ack_s, it calculates the number K_s of packet frames currently stored in the buffer; specifically, $K_s = CR_s - CS_s$. If $K_s > N_s - w$, Cell_s takes no action (i.e., the buffer space is not large enough and the transmission from the RNC to Cell_s is still suspended). On the other hand, if $K_s \leq N_s - w$, Cell_s sends ack_s to the RNC to trigger packet-frame delivery of the next window [see Figs. 2*(h)* and *(i)*].

Note that the variable K_s can be accessed and updated by parts 1 and 2 of MOFC-I. If these two parts are executed in parallel, then the accesses and modifications to K_s must be atomic operations. Most likely, parts 1 and 2 of MOFC-I are alternatively executed in sequence.

Every nonserving cell Cell_i exercises MOFC-II to avoid buffer overflow. In Cell_i, two counters CR_i and CS_i are maintained to record the numbers of packet frames that have been received from the RNC and deleted by Cell_i, respectively. When Cell_i receives a packet frame from the RNC, it recalculates K_i as $CR_i - CS_i$. Two cases are considered, as follows.

Case MOFC-II.1. If $K_i < N_i$ (i.e., the buffer has enough space to accommodate the incoming packet frame), Cell_i adds the received packet frame at the tail of the buffer, and increments CR_i by one.

Case MOFC-II.2. If $K_i = N_i$ (i.e., the buffer is full), Cell_i deletes a packet frame at the head of the buffer and increments CS_i by one. Cell_i adds the newly received packet frame at the tail of the buffer and increments CR_i by one. This case guarantees that the buffer of Cell_i always has space to accommodate the incoming packet frame. In Section II-B, we will show that every old packet frame deleted in this step is already received by the UE.

B. Determination of Buffer Sizes

In MOFC, if the radio link quality between the serving cell and UE degrades below the threshold θ_2, the best cell in the active set is selected as the new serving cell. To switch the wireless transmission link from the old serving cell Cell_s to the new serving cell Cell_i, frame synchronization is required. The frame-synchronization information, i.e., the CR_{UE} value, is sent from the UE to Cell_i. Then, Cell_i computes N_{sync}, the number of packet frames that have been received by the UE but are still in Cell_i's buffer. That is

$$N_{\mathrm{sync}} = CR_{\mathrm{UE}} - CS_i.$$

When Cell_i becomes the serving cell, it deletes the first N_{sync} packet frames in the buffer and then transmits the next packet frames in the buffer to the UE. Note that CR_{UE} should always be no less than CS_i. Otherwise (i.e., $CR_{\mathrm{UE}} < CS_i$), it means that Cell_i has dropped packet frames that have not been received by the UE. These packet frames are lost when the UE switches the wireless link to Cell_i. Consider two constants: B_1 and B_2. In [16], we proved the following theorem.

Theorem 1: Let the buffer sizes of the serving cell Cell_s and every nonserving cell Cell_i be $N_s = B_1$ and $N_i = B_2$, respectively. If $B_1 \le B_2 - w$, then when MOFC-I and MOFC-II are exercised, it is guaranteed that CR_{UE} is always no less than CS_i.

Following Theorem 1, we set $B_1 = B_2 - w$ in MOFC so that the nonserving cells can safely delete the old packet frames in the buffer. Another issue to be addressed by MOFC is the avoidance of multiple DPCCH message delivery. At frame synchronization, the CR_{UE} value may be larger than the number that can be carried in one uplink DPCCH message. If so, the CR_{UE} value must be delivered through multiple DPCCH messages [15], [16], which results in a long frame-synchronization delay. To resolve this issue, MOFC uses the module operation to tailor the CR_{UE} value to a smaller value CR^*_{UE}, which can be accommodated in one uplink DPCCH message. After receiving the CR^*_{UE} value, the nonserving cell Cell_i determines N_{sync} based on Theorem 2, described as follows.

Theorem 2: Let x be a nonnegative integer. Let $CR^*_{\mathrm{UE}} = CR_{\mathrm{UE}} \bmod x$ and $CS^*_i = CS_i \bmod x$. If

$$0 \le CR_{\mathrm{UE}} - CS_i < x \tag{1}$$

then

$$N_{\mathrm{sync}} = CR_{\mathrm{UE}} - CS_i = \begin{cases} CR^*_{\mathrm{UE}} - CS^*_i \\ \quad \text{if } CR^*_{\mathrm{UE}} - CS^*_i \ge 0. \\ x + CR^*_{\mathrm{UE}} - CS^*_i \\ \quad \text{if } CR^*_{\mathrm{UE}} - CS^*_i < 0. \end{cases}$$

Proof: Let $a = \lfloor CR_{\mathrm{UE}}/x \rfloor$ and $b = \lfloor CS_i/x \rfloor$. Then, it is apparent that

$$CR_{\mathrm{UE}} = ax + CR^*_{\mathrm{UE}} \tag{2}$$

and

$$CS_i = bx + CS^*_i \tag{3}$$

where both a and b are nonnegative integers. By subtracting (2) from (3), we have

$$CR_{\mathrm{UE}} - CS_i = (a-b)x + (CR^*_{\mathrm{UE}} - CS^*_i) \tag{4}$$

From (1) and (4), we have

$$0 \le (a-b)x + (CR^*_{\mathrm{UE}} - CS^*_i) < x. \tag{5}$$

Since $0 \le CR^*_{\mathrm{UE}} < x$ and $0 \le CS^*_i < x$, $CR^*_{\mathrm{UE}} - CS^*_i$ is bounded in the range

$$-x < CR^*_{\mathrm{UE}} - CS^*_i < x. \tag{6}$$

Based on Inequality (6), we consider the following two cases.

Case I: If $CR^*_{\mathrm{UE}} - CS^*_i \ge 0$, then from (6) we have $0 \le CR^*_{\mathrm{UE}} - CS^*_i < x$. Consider the relationship between a and b. If $a > b$, then $(a-b)x + (CR^*_{\mathrm{UE}} - CS^*_i) \ge x$, which contradicts (5). If $a < b$, then $(a-b)x + (CR^*_{\mathrm{UE}} - CS^*_i) < 0$, which also contradicts (5). Therefore, a must be equal to b in this case and (4) can be rewritten as $CR_{\mathrm{UE}} - CS_i = CR^*_{\mathrm{UE}} - CS^*_i$.

Case II: If $CR^*_{\mathrm{UE}} - CS^*_i < 0$, then from (6), $-x < CR^*_{\mathrm{UE}} - CS^*_i < 0$. If $a \le b$, then $(a-b)x + (CR^*_{\mathrm{UE}} - CS^*_i) < 0$, which contradicts (5). On the other hand, if $a - b \ge 2$, then $(a-b)x + (CR^*_{\mathrm{UE}} - CS^*_i) > x$, which also contradicts (5). Therefore, $a - b = 1$. In this case, (4) is rewritten as $CR_{\mathrm{UE}} - CS_i = x + CR^*_{\mathrm{UE}} - CS^*_i$.

The above two cases complete the proof. ■

In UTRAN, the transmission rate of the wire-line link between the RNC and a node B is much higher than that of the wireless link between the UE and a node B. Since node Bs and the RNCs are connected by ATM links [see Fig. 1*(a)*], the overall transmission rate is about 50 Mb/s [11], [13]. On the other hand, a node B and all UEs in its coverage area are connected by the WCDMA radio links [see Fig. 1*(b)*] and the overall downlink wireless-transmission rate is 3.84 Mb/s [11]. Let the transmission delays from the RNC to Cell_s and Cell_i be $t_{A,1}$ and $t_{A,2}$, respectively. Without loss of generality, $t_{A,1} \approx t_{A,2}$. Let the transmission delay from Cell_s to the UE be t_W. Then, from the above description, $t_W \gg t_{A,2}$ and $t_W + t_{A,1} \gg t_{A,2}$, which implies that if a packet frame is received by the UE, the packet frame is also received by Cell_i. Thus, for any nonserving cell Cell_i, we have $CR_{\mathrm{UE}} \le CR_i$. When a nonserving cell Cell_i exercises MOFC-II, if $CS_i > 0$ (i.e., some packet frames have been dropped), it means that the buffer is full at Cell_i and $CR_i = CS_i + B_2$. Therefore, if $CS_i > 0$, then

$$CR_{\mathrm{UE}} \le CS_i + B_2 \quad \text{or} \quad CR_{\mathrm{UE}} - CS_i < B_2 + 1. \tag{7}$$

Since we set $B_1 = B_2 - w$ in MOFC, from Theorem 1 and (7) we have

$$0 \le CR_{\mathrm{UE}} - CS_i < B_2 + 1. \tag{8}$$

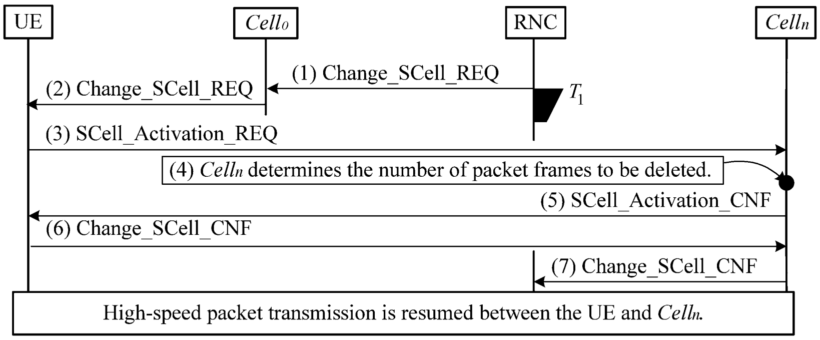

Fig. 3. Message flow for MOFC-III.

If the value of x is B_2+1, then from Theorem 2 and (8) we have

$$N_{\text{sync}} = CR_{\text{UE}} - CS_i = \begin{cases} CR^*_{\text{UE}} - CS^*_i \\ \quad \text{if } CR^*_{\text{UE}} - CS^*_i \geq 0. \\ B_2 + 1 + CR^*_{\text{UE}} - CS^*_i \\ \quad \text{if } CR^*_{\text{UE}} - CS^*_i < 0 \end{cases}$$

where $CR^*_{\text{UE}} = CR_{\text{UE}} \bmod (B_2+1)$ and $CS^*_i = CS_i \bmod (B_2+1)$. Then, a nonserving cell can use the CR^*_{UE} value to correctly determine the N_{sync} value. Thus, we have the following lemma.

Lemma 1: Let N^* denote the maximum value of the number that can be accommodated in one uplink DPCCH message. To transmit CR^*_{UE} in one uplink DPCCH message, $CR^*_{\text{UE}} = CR_{\text{UE}} \bmod (B_2+1)$ must be no larger than N^*. That is, the inequality $B_2 + 1 \leq N^*$ must hold.

From the above discussion, we can determine B_1 and B_2 as follows. We first set $B_2 = N^* - 1$. Then, we set $B_1 = B_2 - w$.

C. MOFC-III

To switch the wireless link from the old serving cell Cell_o to the new serving cell Cell_n, MOFC-III is executed among the UE, Cell_o, Cell_n and the RNC for frame synchronization. We utilize Theorem 2 to guarantee that the frame-synchronization information can be delivered in one uplink DPCCH message. Suppose that b bits are used to hold frame-synchronization information in a uplink DPCCH message. In MOFC-III, the value $2^b - 1$ is used to represent the symbol NULL (which indicates that the UE did not receive any packet frame from the old serving cell Cell_o). The maximum number that can be accommodated in one DPCCH message is $N^* = 2^b - 2$. Fig. 3 illustrates the message flow for MOFC-III. In this message flow, Steps 1, 2, 6, and 7 are defined in *Specification 3G TS25.308* [4]. In this document, frame synchronization is left as an open issue. In this paper, we address this issue by adding Steps 3–5. The details are given as follows.

Step 1. Based on the radio quality measurement report sent from the UE, the RNC determines the need of radio link switching for the UE. The RNC first selects a new serving cell Cell_n and instructs Cell_n to reserve an HS-PDSCH channel for the UE for downlink packet-frame transmission. Then, the RNC sends Cell_o a Change_SCell_REQ message (where the ID of the new serving cell Cell_n is specified in this message) and starts the T_1 timer. The RNC expects to receive the Change_SCell_CNF message (see Step 7) before the T_1 timer expires. If the T_1 timer expires, the RNC may choose to resend the Change_SCell_REQ message or to exit MOFC-III.

Step 2. When Cell_o receives the Change_SCell_REQ message, it stops high-speed downlink packet-frame transmission to the UE. Cell_o forwards the Change_SCell_REQ message to the UE, where the ID of Cell_n is contained in the message. Then, Cell_o adjusts its buffer size as $N_o = B_2$ and then executes MOFC-II to process the packet frames received from the RNC. At this point, Cell_o becomes a nonserving cell.

Step 3. Upon receipt of the Change_SCell_REQ message, the UE is aware of the change of the serving cell to Cell_n. The UE checks the value of CR_{UE}. If no packet frame is received by the UE (i.e., $CR_{\text{UE}} = 0$), then the UE sets $CR^*_{\text{UE}} \leftarrow \text{NULL}$. Otherwise (i.e., $CR_{\text{UE}} > 0$), $CR^*_{\text{UE}} \leftarrow CR_{\text{UE}} \bmod (B_2+1)$. The UE sends an SCell_Activation_REQ message to Cell_n through the uplink DPCCH (where CR^*_{UE} is specified in this message). Since $B_2 = N^* - 1$, the CR^*_{UE} value can be fitted in one uplink DPCCH message.

Steps 4 and 5. Upon receipt of the SCell_Activation_REQ message, Cell_n determines the number of packet frames to be deleted from the buffer for frame synchronization. Based on the value of CR^*_{UE}, two cases are considered, as follows.

Case 4.1: $CR^*_{\text{UE}} = \text{NULL}$, i.e., the UE did not receive any packet frame before switching the wireless link and no packet frame should be deleted.

Case 4.2: $CR^*_{\text{UE}} \neq \text{NULL}$, i.e., the UE has received some packet frames before switching the wireless link. Cell_n first tailors CS_n to a smaller value CS^*_n; specifically, $CS^*_n = CS_n \bmod (B_2+1)$. If $CR^*_{\text{UE}} - CS^*_n \geq 0$, then Cell_n deletes $CR^*_{\text{UE}} - CS^*_n$ packet frames at the head of the buffer. Otherwise (i.e., $CR^*_{\text{UE}} - CS^*_n < 0$), Cell_n deletes $B_2 + 1 + CR^*_{\text{UE}} - CS^*_n$ packet frames at the head of the buffer.

Cell_n adjusts its buffer size as $N_n = B_1$ and then sends the UE an SCell_Activation_CNF message.

Steps 6 and 7. UE is informed that Cell_n has performed frame synchronization when it receives the SCell_Activation_CNF message from Cell_n. The UE then sends a Change_SCell_CNF message to the RNC through Cell_n.

At this point, Cell_n starts high-speed downlink packet-frame transmission to the UE by executing MOFC-I.

III. Correctness Proof for Frame Synchronization

This section proves the correctness of MOFC-III. In Lemma 2, we first prove that before frame synchronization, the new serving cell Cell_n, did not delete any packet frames that have not been received by the UE. Then, from Theorem 2 and Lemmas 1 and 2, Theorem 3 concludes that MOFC-III correctly performs frame synchronization with one uplink DPCCH message delivery.

Lemma 2: Before Step 4 in MOFC-III is executed, the new serving cell Cell_n did not delete any packet frames that have not been received by the UE.

Proof: Before Step 4 in MOFC-III is executed, Cell_n is a nonserving cell (that executes MOFC-II to avoid buffer overflow). The buffer size of Cell_n is set as $N_n = B_2$. Since $B_2 = B_1 + w$, Theorem 1 guarantees that $CR_{\mathrm{UE}} \geq CS_n$ (that is, the number of packet frames received by the UE is larger than those dropped by Cell_n). Therefore, for the packet frames that have not been received by the UE, none were deleted by the new serving cell Cell_n. ■

Theorem 3: MOFC-III correctly performs frame synchronization with one uplink DPCCH message delivery.

Proof: From Lemma 2, Cell_n does not drop any packet frames that have not been received by the UE. Lemma 1 guarantees that the CR^*_{UE} value is carried in one uplink DPCCH message as Step 3 in MOFC-III is executed. From Theorem 2, if the UE has received packet frames at Cell_o (i.e., $CR^*_{\mathrm{UE}} \neq \mathrm{NULL}$), Cell_n correctly deletes the packet frames that have been received by the UE but are still queued in the buffer of Cell_n (see Case 4.2 in MOFC-III). If no packet frames have been received by the UE at Cell_o (i.e., $CR^*_{\mathrm{UE}} = \mathrm{NULL}$), Cell_n does not delete any packet frame in its buffer (see Case 4.1 in MOFC-III). Therefore, after MOFC-III is executed, Cell_n correctly transmits the subsequent packet frames to the UE. ■

IV. Numerical Examples

In this section, we elaborate on the improvement of MOFC over several schemes proposed in our previous studies [15], [16], including basic overflow control (BOFC), network-based overflow control (NOFC), and combined BOFC and NOFC (COFC). Details of these schemes and the modeling technique used in this section can be found in [15] and [16]. BOFC, NOFC, and COFC are briefly described as follows.

BOFC. In this scheme, if the size of the frame-synchronization information exceeds the capacity of one uplink DPCCH message, the information is carried by multiple uplink DPCCH messages.

NOFC. This scheme guarantees one uplink DPCCH message delivery by exchanging the frame-synchronization information through the network between the old and new serving cells.

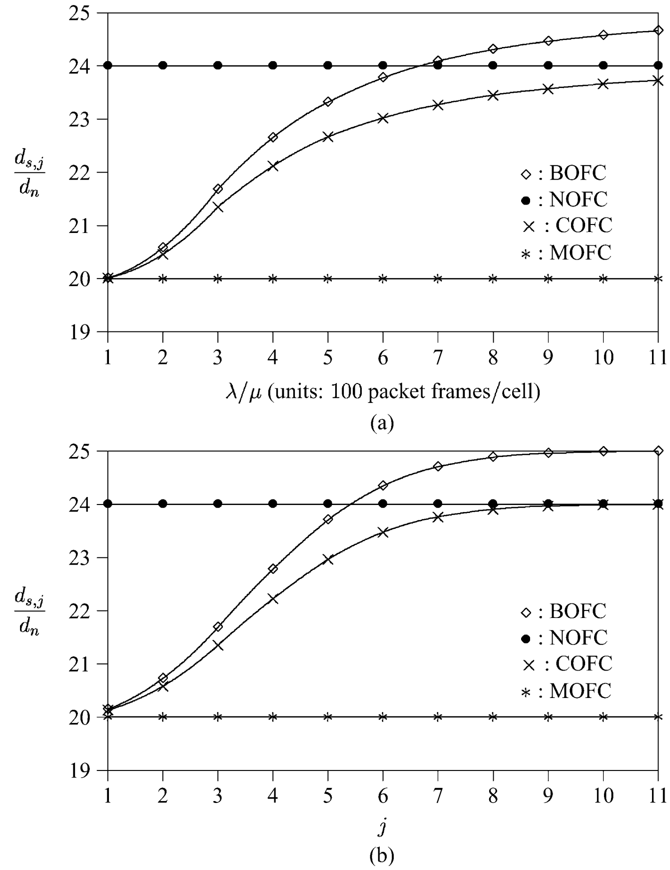

Fig. 4. Performance comparison among MOFC, BOFC, NOFC, and COFC ($d_r = 5d_n; N^* = 1023$). (a) Effects of $\lambda/\mu (j = 3)$. (b) Effects of $j (\lambda/\mu = 300)$.

COFC. This scheme takes advantage of both BOFC and NOFC. The old serving cell decides whether to transmit frame-synchronization information through the network (using NOFC) or to uplink DPCCH messages (using BOFC).

Consider the net cost $d_{s,j}$ for frame synchronization when the UE switches from the jth cell to the $j+1$st cell; specifically,

$$d_{s,j} = n_{r,j} d_r + n_{n,j} d_n \tag{9}$$

where $n_{r,j}$ ($n_{n,j}$) is the number of messages delivered through uplink DPCCH (ATM network) for frame synchronization and d_r (d_n) is the expected transmission delays in the air interface (ATM network). For MOFC-III, it is clear that $d_{s,j} = 4d_r$ (see Fig. 3). Based on the modeling technique developed in [15], Fig. 4 plots the $d_{s,j}/d_n$ curves for the four frame-synchronization schemes. In this figure, λ is the downlink packet frame arrival rate, $1/\mu$ is the average interval that the UE connects to a serving cell, and j represents the jth serving cell switching performed by the UE for a downlink-transmission session. The figure indicates that MOFC outperforms BOFC, NOFC, and COFC. When λ/μ becomes large (i.e., more packet frames are received by the UE at a cell) or j becomes large (i.e., more serving cell switching performed by the UE), the improvement becomes more significant.

V. CONCLUSION

This paper described an overflow-control scheme with module count to support UMTS HSDPA mechanism specified in 3GPP TS 25.308 and TR 25.950. We first introduced HSDPA and then discussed the issues regarding buffer overflow and long frame-synchronization delay, which were not resolved in 3GPP TS 25.308 and TR 25.950. Specifically, when the UE switches the wireless link from the old serving cell to the new serving cell, the size of frame-synchronization information may exceed the capacity of an uplink DPCCH message. In this case, this information must be carried through multiple uplink DPCCH messages, which results in a long delay for frame synchronization. To resolve the above issues, we proposed the MOFC scheme. Our scheme guarantees that the information needed for frame synchronization is carried by one uplink DPCCH message delivery. Also, when the buffer of a nonserving cell is full, the previously received packet frames in the buffer can be safely dropped and after the UE has switched wireless link to the new serving cell, no packet frames are lost. We have proved that the MOFC scheme is correct. Then, we used numerical examples to illustrate the improvement of MOFC over several previously proposed schemes. Our study indicated that MOFC may significantly outperform the previously proposed schemes. The MOFC scheme is pending U.S. and R.O.C. patents.

APPENDIX
NOTATION

The notation used in this paper is given below.

- B_1 (B_2): buffer size of the serving cell (nonserving cell).
- CR_i (CR_s): counter maintained by the nonserving cell Cell_i (serving cell Cell_s). This counter records the number of received packet frames that are sent from the RNC.
- CS_i (CS_s): counter maintained by the nonserving cell Cell_i (serving cell Cell_s). This counter records the number of packet frames that have been processed by Cell_i (Cell_s). For Cell_i, CS_i is the number of packet frames deleted from the buffer. For Cell_s, CS_s is the number of packet frames that have been received by the UE.
- K_i (K_s): number of packet frames currently stored in the buffer of the nonserving cell Cell_i (the serving cell Cell_s).
- CS_{RNC}: counter maintained by the RNC to record the number of packet frames that have been received by the serving cell.
- CR_{UE}: counter maintained by the UE to count the number of the received packet frames (which are sent from Cell_s).
- N_i: maximum number of packet frames that can be accommodated in the buffer of Cell_i.
- N^*: maximum value of the number that can be carried through one uplink DPCCH message.
- w: window size of the window-based flow-control algorithm exercised for downlink transmission from the RNC to the serving cell.

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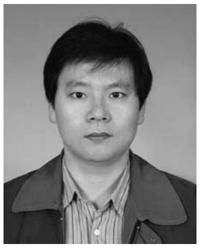

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