Uplink Control for Low Latency HARQ in TDD Carrier Aggregation

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Abstract— **A higher data rate and lower latency are two main features of Long Term Evolution Advanced (LTE-A). In order to support a higher peak data rate, carrier aggregation (CA) is implemented into LTE-A systems to provide sufficient bandwidth for data transmission. However, there is a problem in achieving lower latency. Time Division Duplexing (TDD) systems may not have a sufficient number of uplink subframes to transmit downlink hybrid automatic repeat request (HARQ) feedback, which results in additional latency compared with Frequency Division Duplexing (FDD) systems. In TDD CA systems, the downlink HARQ round trip time (RTT) of a component carrier (CC) is related to its TDD configuration. In this paper, a low latency downlink HARQ feedback method for TDD CA systems is proposed to shorten the transmission delay. The serving eNB determines whether to allocate the physical uplink control channel (PUCCH) to a new CC by comparing the downlink HARQ RTT of that CC to that of the primary cell. If the downlink HARQ RTT can be reduced, the eNB will allocate the PUCCH to this new CC. By using this method, the downlink HARQ RTT of TDD CA systems can be significantly reduced.**

Keywords-carrier aggregation; HARQ; time division duplexing; round trip time; PUCCH

I. INTRODUCTION

Support for a wider bandwidth is one of the most important enhancements for Long Term Evolution Advanced (LTE-A). To achieve this, carrier aggregation (CA) was introduced to support simultaneously backward compatibility to sets of LTE user equipment (UEs) and higher peak data rates to LTE-A UEs [1]. Both continuous CA and discontinuous CA are necessary and applicable. Figure 1 shows an allocation example of a continuous wider bandwidth, e.g., 100 MHz, to meet the peak data rate requirement. At the same time, LTE-A terminals should be capable of transmitting with a bandwidth wider than 20 MHz (the bandwidth of a component carrier (CC)), e.g., 40 MHz or even up to 100 MHz [2].

For each UE performing CA, there are one Primary cell (PCell) and one or more (no more than four) secondary cells (SCells). The PCell provides security input and non-access stratum (NAS) mobility information [3]. In addition, as specified in [3], the physical uplink control channel (PUCCH) resources, which are used to transmit downlink feedback, can only be configured in the PCell. The SCells only provide additional radio resources to the UE. Due to the lack of PUCCH, all downlink feedback from the SCells including the downlink hybrid automatic repeat request (HARQ) feedback is transmitted via the PCell PUCCH.

For Time Division Duplexing (TDD) CA systems, each CC has its own TDD configuration that specifies its uplink and downlink subframe pattern for TDD transmission. There are seven TDD configurations as listed in Table I. The letters ‘D’ and ‘U’ indicate that a certain subframe is used for the downlink or uplink transmission. The letter ‘S’ corresponds to a special subframe that can only transmit the physical downlink shared channel (PDSCH) and the acknowledgement/negative acknowledgement (ACK/NACK) signal in the physical uplink shared channel (PUSCH). Due to the special features of TDD systems, a UE that is ready for downlink feedback may not immediately transmit the ACK/NACK information. The UE must wait for the next uplink subframe [4] [5].

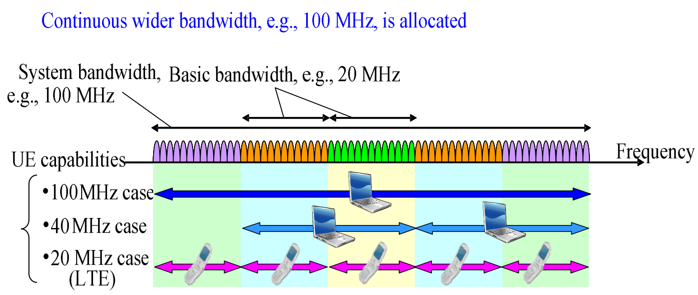

Figure 1. Continuous wider bandwidth.

TABLE I. TDD CONFIGURATIONS

TDD Configuration	Subframe Number									
	0	1	2	3	4	5	6	7	8	9
0	D	S	U	U	U	D	S	U	U	U
1	D	S	U	U	D	D	S	U	U	D
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

This paper investigates methods for downlink HARQ feedback to reduce the downlink HARQ round trip time (RTT) in TDD CA systems to the most extent. When allocating an SCell to a UE, the serving eNB calculates the downlink HARQ

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RTT for the new SCell based on its TDD configuration. If the RTT is shorter than that for the PCell, the eNB will configure a dependent PUCCH for this SCell to transmit the downlink HARQ feedback. Otherwise, the downlink feedback of this SCell is transmitted via the PCell PUCCH as normal. Based on the eNB decision when configuring new SCells, the downlink HARQ RTT can be significantly reduced.

The rest of the paper is organized as follows. In Section II, the method used to calculate the downlink HARQ RTT in LTE-A is described. Section III gives details regarding the proposed method, and Section IV gives the corresponding analysis. Finally, Section V gives our overall conclusion based on the analysis.

II. DOWNLINK HARQ RTT IN TDD CA

In LTE Rel-11, there are scenarios in which CCs must be aggregated based on different TDD configurations. As shown in Fig. 2, two existing TDD systems are allocated to operator 1 and operator 2, respectively. Operator 1 implements TDD configuration 1 in its system, while operator 2 implements TDD configuration 2. If frequency resources that are close to the existing TDD bands are allocated to operator 3, operator 3 will be required to use the same TDD configurations to avoid severe interference from the existing TDD systems. Therefore, when CA is launched in the TDD system of operator 3, CC aggregation with different TDD configurations should be supported.

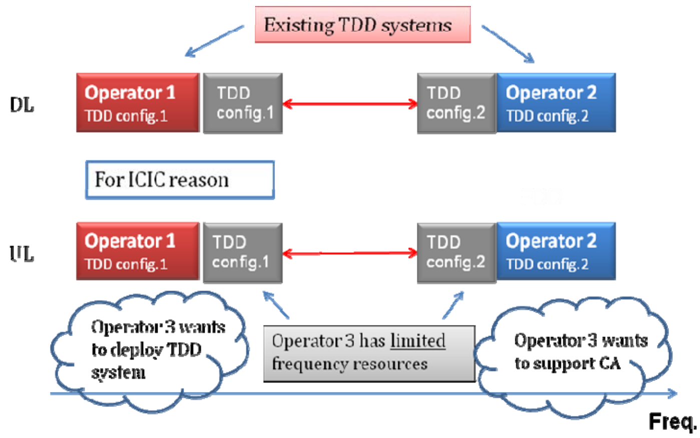

Figure 2. Scenarios for CA with different TDD configurations.

When CCs with different TDD configurations are aggregated, the downlink HARQ feedback of all the CCs are transmitted via the PCell PUCCH, which is specified in [3]. Therefore, even if an SCell has an uplink subframe to transmit the downlink HARQ feedback, it must use or wait for the PCell uplink subframe, which may result in higher latency.

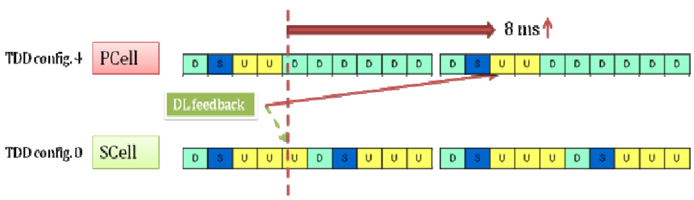

Figure 3. Example of higher latency in TDD CA.

For example, as is shown in Fig. 3, a UE aggregates the PCell with TDD configuration 4 and an SCell with TDD configuration 0. When the downlink feedback of the SCell is ready for transmission at the fifth subframe (subframe No. 4), it must wait for the uplink subframe of the PCell, which consequently introduces an 8-ms delay.

Normally, the RTT is used to scale the latency performance of the downlink HARQ feedback [6] [7]. In this paper, the RTT is defined as the time period for downlink HARQ retransmission. Based on common understanding, it is assumed that when an eNB or a UE receives uplink data or downlink data, 3 ms will be consumed to deal with the received data and to prepare the counterpart ACK/NACK message for transmission. Thus, the RTT can be calculated based on this assumption. Let us consider the first subframe (subframe No. 0) of TDD configuration 0 (downlink subframe) as an example. When a UE receives downlink data in subframe 0, it requires 3 ms (3 subframes) to deal with the received data. Then, at the time slot of subframe 3, the UE is able to send the ACK/NACK message. After the eNB's dealing with the ACK/NACK message, the time slot for subframe 7 arrives, which is an uplink subframe. The eNB must wait until the next downlink subframe (subframe 0) to retransmit the downlink data. Hence, the downlink HARQ RTT is 10 ms, which is the time period between subframe 0 to subframe 9 (the subframe before downlink data can be retransmitted).

Using the above mentioned method, the RTTs of each subframe with various TDD configurations can be calculated. In Table II, the RTTs of the downlink HARQ feedback with different TDD configurations are listed. This table shows different latencies for cells with different TDD configurations .

TABLE II. DOWNLINK HARQ RTT FOR DIFFERENT TDD CONFIGURATIONS

TDD Config.	Subframe *n*									
	0	1	2	3	4	5	6	7	8	9
0	10	10	-	-	-	10	10	-	-	-
1	11	10	-	-	10	11	10	-	-	10
2	11	10	-	8	12	11	10	-	8	12
3	8	15	-	-	-	11	10	9	8	8
4	16	15	-	-	12	11	10	9	8	8
5	16	15	-	13	12	11	10	9	8	17
6	9	10	-	-	-	11	10	-	-	10

However, if it is the case for the aggregation of different TDD configurations, all the downlink HARQ feedback from the SCells must be transmitted via the PCell uplink subframe. Hence, the RTT calculation method is slightly different in this case. Let us assume that the PCell is configured with TDD configuration 4, and the SCell is configured with TDD configuration 0. Again, we take the first subframe (subframe No. 0) of TDD configuration 0 (downlink subframe) as an example. When a UE receives downlink data in subframe 0, it requires 3 ms (3 subframes) to deal with the received data.

Then, at the time slot for subframe 3, the UE is able to send the ACK/NACK message via the PCell. However, subframe 3 for the PCell with TDD configuration 4 is a downlink subframe, so the transmission must be delayed to the next uplink subframe (subframe 2 in the next radio frame). After eNB receives and deals with the ACK/NACK message, it is the time slot for subframe 6 (special subframe of SCell), where the downlink retransmission can be performed. Hence, the downlink HARQ RTT is 16 ms, which is the time period between subframe 0 to subframe 5 in the next radio frame.

The RTTs for the downlink HARQ feedback with different SCell TDD configurations and a fixed PCell TDD configuration (TDD configuration 4) are given in Table III as an example. It is clear that the average RTT value in Table III is larger than that in Table II. Hence, we should try to develop an effective method for the downlink HARQ feedback to improve the latency performance.

TABLE III. DOWNLINK HARQ RTT VIA PCELL FOR DIFFERENT TDD CONFIGURATIONS WITH FIXED PCELL TDD CONFIGURATION 4

TDD Config.	Subframe *n*									
	0	1	2	3	4	5	6	7	8	9
0	16	15	-	-	-	11	10	-	-	-
1	16	15	-	-	12	11	10	-	-	10
2	16	15	-	13	12	11	10	-	8	8
3	16	15	-	-	-	11	10	9	8	8
4(PCell)	16	15	-	-	12	11	10	9	8	8
5	16	15	-	13	12	11	10	9	8	17
6	16	15	-	-	-	11	10	-	-	8

III. PROPOSED METHOD FOR DOWNLINK HARQ FEEDBACK

As described in Section II, when CCs with different TDD configurations are aggregated, there may be higher latency for the SCell downlink HARQ feedback due to a lack of an SCell PUCCH. As a result, even if the SCell has more sufficient uplink subframes to transmit downlink HARQ feedback than the PCell, the ACK/NACK message transmission must be delayed until the PCell uplink subframe is available. In order to achieve low latency in TDD CA systems, this paper proposes an effective method to address the problem.

With the assumption of 3 ms to deal with the received data both on the eNB side and UE side, we can calculate all the RTTs of each subframe with each TDD configuration and the fixed PCell configuration (from configuration 0 to configuration 6). Consequently, we obtain 7 tables that are similar to Table III. In Table III, the average RTT value of each TDD configuration can be calculated. For instance, the SCell with TDD configuration 0 has the average RTT value of 13 ms ((16 ms+15 ms+11 ms+10 ms)/4=13 ms). When compared with the SCell with TDD configuration 0 in Table II, the RTT value is larger. Hence, when a PCell has TDD configuration 4 and a new SCell has TDD configuration 0, the eNB should allocate the PUCCH to the SCell. The main factor guiding this choice is the latency performance, i.e., RTT, of these two TDD configurations. An overall table (Table IV) can be generated based on this method. What worth mentioning is that if the assumed time for dealing with the received data changes at the eNB or UE, the table may change accordingly.

Table IV shows which is the better choice of SCell feedback or PCell feedback based on an RTT comparison. When allocating a new SCell to a UE, the eNB first compares the TDD configurations of the PCell and SCell, and then it decides whether to perform downlink HARQ feedback on the PCell or this SCell. If the eNB determines to send feedback on this new SCell, it will check whether there is any SCell with the same TDD configuration as the new SCell for this UE. This behavior aims to avoid unnecessary PUCCH configuration, which can help to lower the signaling overhead in the system. If there is no such SCell, the eNB will configure the PUCCH, which is the radio resource to transmit the downlink HARQ feedback, for the SCell. However, if there exists such an SCell, the eNB will not configure the PUCCH. After receiving the SCell configuration radio resource control (RRC) signaling from the eNB, the UE searches the existing SCells with the same TDD configuration as this new SCell. Subsequently, the UE will transmit the new SCell downlink feedback via the existing SCell PUCCH.

TABLE IV. DECISION TABLE BASED ON DIFFERENT TDD CONFIGURATIONS

○ Feedback on SCell
× Feedback on PCell

PCell TDD Config \ SCell TDD Config	0	1	2	3	4	5	6
0	×	×	×	×	×	×	×
1	○	×	×	×	×	×	○
2	○	○	×	○	×	×	○
3	○	○	×	×	×	×	○
4	○	○	○	○	×	×	○
5	○	○	○	○	○	×	○
6	○	×	×	×	×	×	×

A flow chart for the proposed method is given in Fig. 4.

This method is based on the eNB decision. The signaling structure requires some modification because of the newly introduced PUCCH configuration procedure for the SCells. Some new information elements (IEs) must be introduced to indicate the PUCCH configuration, which requires some modifications to the current specifications.

If the new eNB module for comparing TDD configurations is not welcome, this proposed method can be implemented in another way. The decision module can be moved to the UE side. That is, the eNB always allocates the PUCCH to new SCells. When a UE receives the new SCell configuration, it compares the TDD configuration of this SCell with that of the PCell according to Table IV. If the result is ‘feedback on

PCell,' the UE will ignore the configured PUCCH for this SCell. Downlink HARQ feedback will be transmitted via the PCell, although there is an available PUCCH. Otherwise, if the result is 'feedback on SCell,' the UE will naturally use the configured PUCCH for the SCell. If the decision module is moved to the UE side, the UE should provide additional storage space to store the comparison table. The table should not be deleted except when the eNB wants to update the content of this table.

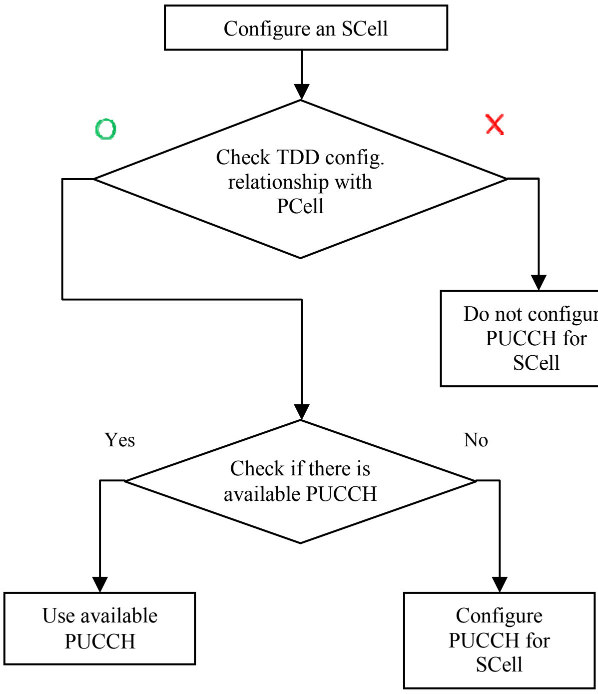

Figure 4. Example of higher latency in TDD CA.

IV. EFFECTIVENESS AND IMPACT ANALYSIS

Based on above analysis, the proposed method can decrease the RTT of the downlink HARQ feedback.

Table V(a) shows the feedback via the PCell, which is the traditional method in LTE Rel-10. Table V(b) shows the RTT gain using the proposed method when the PCell is configured with TDD configuration 4. We find that a significant gain is achieved when an SCell has many more uplink subframes than that for the PCell. For the PCell with TDD configuration 4, the downlink HARQ RTT of the SCell with TDD configuration 0 will be reduced by up to 23.1% compared to Table V(a). The reason for this is that there are many more uplink subframes in TDD configuration 0 than those in TDD configuration 4. Using the proposed method, these uplink subframes can be efficiently utilized. For the case of the PCell with TDD configuration 4 and the SCell with TDD configuration 5, the PCell has more uplink subframes to transmit downlink HARQ feedback. As a result, if we insist on transmitting downlink HARQ feedback on this SCell, the uplink subframe of the PCell will not be fully utilized. Therefore, the eNB will not configure the PUCCH to this SCell to avoid introducing higher latency. Another comparison graph (based on Table V) between conventional method and proposed method is shown in Fig. 5, which is easier to show and compare the average RTTs for each TDD configuration.

After analyzing the effectiveness, some impacts on current standard brought by the proposed methods need to be emphasized. Since a new eNB behavior for configuring the PUCCH for SCells will be introduced, new information elements that indicate the SCell PUCCH configuration should be added to the current specifications [8] [9].

TABLE V. RTT VAVLUES FOR (A) CONVENTIONAL METHOD AND (B) PROPOSED METHOD

(a)

UL-DL Configuration	Subframe *n*										Average RTT Value
	0	1	2	3	4	5	6	7	8	9	
0	16	15	-	-	-	11	10	-	-	-	13
1	16	15	-	-	12	11	10	-	-	8	12
2	16	15	-	13	12	11	10	-	8	8	11.625
3	16	15	-	-	-	11	10	9	8	8	11
4(PCell)	16	15	-	-	12	11	10	9	8	8	10.625
5	16	15	-	13	12	11	10	9	8	8	11.33
6	16	15	-	-	-	11	10	-	-	8	12

(b)

UL-DL Configuration	Subframe *n*										Average RTT Value	
	0	1	2	3	4	5	6	7	8	9		
0	10	10	-	-	-	10	10	-	-	-	10	23.1%
1	11	10	-	-	10	11	10	-	-	10	10.33	13.9%
2	11	10	-	8	12	11	10	-	8	12	10.25	11.8%
3	8	15	-	-	-	11	10	9	8	8	9.86	10.4%
4	16	15	-	-	12	11	10	9	8	8	10.625	0%
5	16	15	-	13	12	11	10	9	8	8	11.33	0%
6	9	10	-	-	-	11	10	-	-	10	10	16.7%

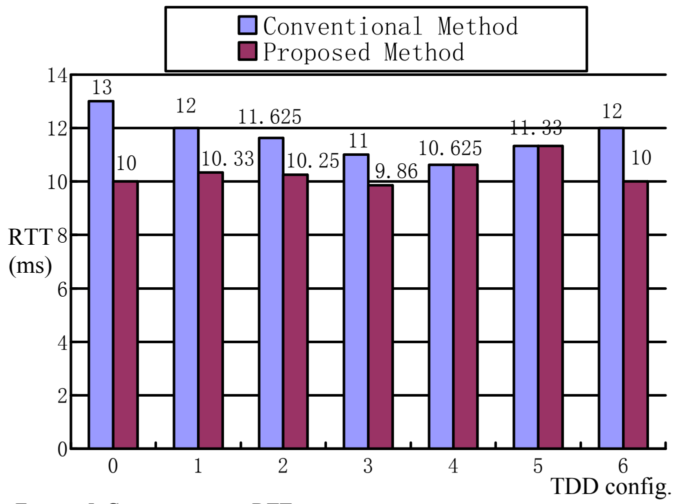

FIGURE 5. COMPARISON OF RTT VALUES FOR CONVENTIONAL METHOD AND PROPOSED METHOD.

First, the PUCCH configuration procedure for the SCell should be specified. As is shown in Fig. 6, in LTE Rel-10, the PUCCH is configured by the two IEs, *PysicalConfigDedicated* and *RRCConnectionReconfiguration*, to the PCell. We can use the same method to configure the SCell PUCCH. Two new IEs, *PUCCH-ConfigDedicatedSCell* and *PUCCH-ConfigCommonSCell* (shown in Fig. 7), must be introduced.

This is considered to be a small modification to the current 3GPP standardizations [10].

In addition, there are corresponding changes on the UE side. When the eNB always configures the PUCCH for all the SCells, a new UE behavior for ignoring the configured PUCCH should be introduced.

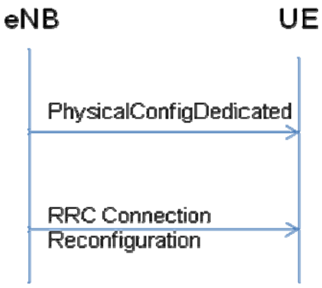

Figure 6. PUCCH configuration procedure in LTE Rel-10.

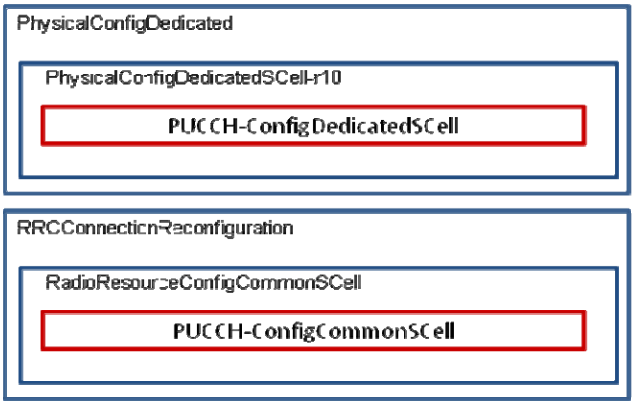

Figure 7. New IEs for PUCCH configuration for SCells.

V. CONCLUSIONS

This paper proposed a low latency downlink HARQ feedback method for TDD CA systems to improve the transmission delay performance. The serving eNB determines whether to allocate the PUCCH to a new SCell by comparing this SCell downlink HARQ RTT to that for the PCell. If there is any gain in terms of latency, the eNB will configure the PUCCH to the new SCell after confirming that there are no SCells with the same TDD configuration for this UE. Another application method is to have the eNB always configure the PUCCH for SCells, and have the UE determine whether or not to ignore the PUCCH configuration. Although there is some small impact on the current 3GPP specifications, these modifications are both reasonable and acceptable based on the analysis. The most important point is that by using the proposed method the downlink HARQ RTT of TDD CA systems can be significantly decreased.

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