Control Channel Design for Carrier Aggregation between LTE FDD and LTE TDD Systems

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***Abstract*— Carrier aggregation (CA) has been proposed within 3GPP to aggregate multiple component carriers (CCs) in LTE-Advanced system to achieve higher peak data rate. In this paper, we propose CA between FDD and TDD carriers in order to utilize FDD and TDD spectrums more efficiently. By comparing the differences in control channel between LTE FDD and TDD specifications, three problems in the case of CA between FDD and TDD carriers are identified, and we then propose the respective solutions and analyze their pros and cons. It is shown that CA between FDD and TDD carriers can provide system flexibility and performance benefits for the operators which own both FDD and TDD spectrums.**

I. Introduction

The future wireless communication systems are expected to provide much higher peak data rate than the current 3G cellular systems to fulfill the rapidly growing mobile data services. The next-generation IMT-Advanced standards are now shaped to support up to 1 Gbps data rate for low-mobility users [1]. To satisfy such high data rate requirement, very wide spectrum bandwidth is required. For example, a maximum of 100 MHz bandwidth is assumed for the IMT-Advanced system [2].

As a promising candidate for IMT-Advanced standards, LTE-Advanced specification is currently in the standardization process within 3GPP. In order to allow backwards compatibility with the conventional LTE specification which uses up to 20 MHz spectrum bandwidth, and provide flexible and scalable upgrade to LTE-Advanced system, the concept of carrier aggregation (CA) has been proposed as a key technology for LTE-Advanced system. CA enables multiple component carriers (CCs) to be aggregated to form a wider overall system bandwidth, therefore the peak data rate of the LTE-Advanced system can be significantly increased to achieve the target of IMT-Advanced.

Two types of CA approaches have been proposed, including continuous CA and non-continuous CA [3]. For the continuous CA approach, the multiple CCs are adjacent to each other; therefore, one fast Fourier transform (FFT) module and one radio frequency (RF) frontend can be used to implement continuous CA. However, due to the fact that the spectrums currently allocated are scattered and a continuous 100 MHz bandwidth is unlikely to be available for LTE-Advanced system, the non-continuous CA approach seems more practical [4].

Although the non-continuous CA approach provides the possibility of integrating multiple fragmented spectrums, the current CA research only focuses on the aggregation of either FDD or TDD carriers, and the aggregation between FDD and TDD carriers has not attracted enough attention. Taking into account the fact that some operators may be licensed to possess both FDD and TDD spectrums, it will be more economically beneficial to utilize them jointly. Furthermore, from technical point of view, CA between FDD and TDD carriers can offer the following performance advantages:

- The problem of spectrum resource shortage can be alleviated, and the operators can utilize the licensed FDD and TDD spectrums more flexibly.
- Load balancing between FDD and TDD systems can be realized more efficiently without the need to perform inter-mode handover.
- Combining FDD carriers with TDD carriers is more advantageous to support asymmetric traffic, as the radio of uplink (UL) and downlink (DL) resource can be configured flexibly on TDD carriers.
- It can help to reduce large control information latency in comparison with LTE TDD system and provide signaling load balancing.
- Since FDD and TDD carriers may experience different propagation and interference environment, interference coordination can be done in a more flexible manner by making use of cross-carrier scheduling.

Because CA between FDD and TDD carriers can improve spectral utilization and make the two systems complement each other, it will potentially be a promising feature for LTE-Advanced system. However, due to the differences between LTE FDD and TDD specifications, especially in control signaling format and subframe timing, there exist several problems in realizing such aggregation. In this paper, we will first point out the potential problems related to CA between FDD and TDD carriers, and then propose our solutions.

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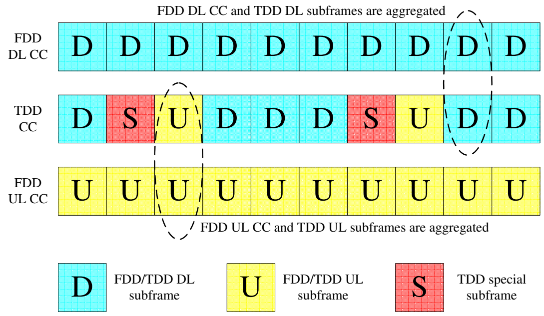

Fig. 1. Carrier aggregation between FDD and TDD carriers.

The rest of this paper is organized as follows. In section II, we introduce some important concepts related to CA. Three problems in the context of CA between FDD and TDD carriers are described and their solutions are presented in Section III, IV and V, respectively. Finally, Section VI concludes this paper.

II. Carrier Aggregation Concepts

In the design of new mechanisms for CA between FDD and TDD carriers, some basic principles which have been adopted in the current LTE-Advanced standardization process have to be followed to allow the backwards compatibility. In this section, we will introduce some important concepts in the context of CA.

A. Primary Serving Cell (PCell)

It has been agreed within 3GPP that when CA is configured the user will have only one radio resource control (RRC) connection with the network [5]. This RRC connection will be established in one particular serving cell to convey security input and non-access stratum (NAS) mobility information upon RRC connection establishment/re-establishment/handover procedures. The serving cell in which the RRC connection resides is referred to as the primary serving cell, also abbreviated as PCell in 3GPP; all other serving cells are called secondary serving cells (SCells). CCs corresponding to PCell and SCell are termed primary CC (PCC) and secondary CC (SCC), respectively.

When a user attempts to access the network, it can arbitrarily choose an UL carrier as the UL PCC to start the random access procedures. PCell can then be changed with handover procedure after the user is admitted. There is an important constraint defined with PCell that physical uplink control channel (PUCCH) which carries hybrid automatic repeat request (HARQ) feedback information is only conveyed by UL PCC [5]. This constraint has to be borne in mind when the CA concept is extended to combine both FDD and TDD carriers, since the two systems have different subframe timing structures.

B. Cross-Carrier Scheduling

Cross-carrier scheduling enables the physical downlink shared channel (PDSCH) and physical uplink shared channel (PUSCH) resource to be scheduled by physical downlink control channel (PDCCH) on other carriers. This is realized by adding the 3-bit carrier indication field (CIF) in downlink control information (DCI) format.

Note that CIF is only possible in user-specific search space which is relevant to the DL assignment and UL grant information for user data. Furthermore, the configuration for the presence of CIF is also user-specific, which means that users configured with and without cross-carrier scheduling can be scheduled simultaneously.

C. Carrier Aggregation between FDD and TDD Carriers

CA between FDD and TDD carriers is illustrated in Fig. 1. For the DL, all the subframes on FDD DL carrier can be aggregated with the DL subframes on TDD carrier; similarly for the UL, all the subframes on FDD UL carrier can be aggregated with the UL subframes on TDD carrier.

Firstly, depending on the PCC configuration, we have identified two problems as follows:

1) When a TDD CC is configured as the PCC, PUCCH which carries HARQ feedback will locate on the TDD PCC. Due to longer HARQ round trip time (RRT) on TDD CC, the number of HARQ processes on FDD CC should be increased to exceed eight. Therefore, the original 3-bit HARQ process number (HPN) in DCI on FDD CC is not adequate to indicate all HARQ processes on FDD CC.
2) On the other hand, when an FDD CC is configured as the PCC, PUCCH will locate on the FDD UL PCC. Due to shorter HARQ RTT on FDD CC, the number of HARQ processes on TDD CC will not exceed eight, and therefore 3-bit HARQ HPN is enough. Thus, there will be 1 redundant bit in HPN field of DCI on TDD DL CC. Furthermore, since PUCCH is present on FDD UL PCC in each subframe, it's not required to feed back ACK/NACK signals of multiple subframes in one UL subframe; therefore, the 2-bit downlink assignment index (DAI) field in TDD DCI is no longer needed.

Secondly, in the case of cross-carrier scheduling, one problem will occur when an FDD CC is cross-scheduled by a TDD CC:

3) Since multiple FDD DL and/or UL subframes may be scheduled in one TDD DL subframe, a mechanism is required to differentiate the multiple scheduled subframes to avoid ambiguity. In addition, because in this case a large number of scheduling information may be transmitted in one TDD DL subframe, the probability of PDCCH blocking will be increased.

In the sequel, we will discuss the above three problems in more details and propose our solutions.

III. Problem 1: HPN Extension on FDD CC

A. Problem Description

In order to fully utilize channel resource, multiple-process HARQ protocol is employed between eNodeB and UE. The number of HARQ processes depends on the HARQ RRT, which consists of both transmission and processing delay.

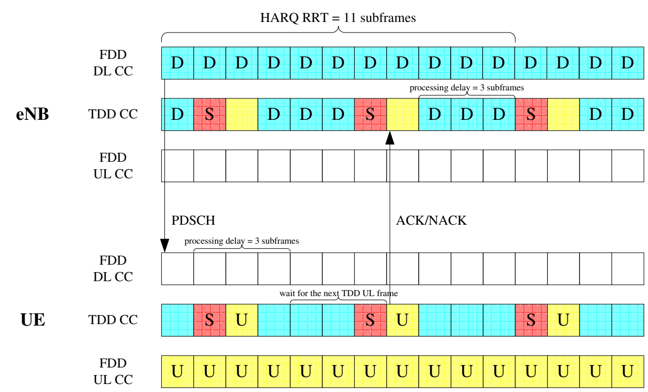

Fig. 2. HARQ process number should be increased for FDD CC if a TDD CC is configured as the PCC.

For FDD mode, assuming a processing delay of 3 ms on one direction, if a UE receives DL transmission in the n-th subframe, it will send back the corresponding ACK/NACK in the $(n+4)$-th subframe, and the eNodeB can finish decoding the ACK/NACK in the $(n+7)$-th subframe; therefore, the number of HARQ processes is fixed as 8 and a 3-bit HPN field in DCI is adequate to indicate the HARQ process for each DL assignment. However, for TDD mode, due to the fact that the UL transmission is discontinuous, the UE cannot always find an UL subframe for ACK/NACK feedback; therefore, the UE needs to wait until an UL subframe arrives. Under different TDD DL/UL configurations, the interval between PDSCH and ACK/NACK ranges from 4 to 13 ms [7], and therefore, the HPN field in TDD DCI is 4 bits in length [6].

In the case of CA between FDD and TDD carriers, when a TDD CC is configured as the PCC, the ACK/NACK will be carried by TDD PCC as described in Section II-A, and thus the RRT for FDD CC will exceed 8 as exemplified in Fig. 2, therefore, the number of HARQ processes should be increased accordingly and the original 3-bit HPN in FDD DCI[1] is not enough to indicate all HARQ processes.

B. Proposed Solutions

1) HPN extension from 3 bits to 4 bits: HPN extension is a straightforward approach to address more HARQ processes, and one more bit should be added into the HPN field to indicate up to 16 HARQ processes. In the case that a TDD CC is configured as the PCC, a new RRC signaling should be defined to notify the UE to adopt the 4-bit HPN for FDD CC, and once a UE is scheduled, the eNodeB should use the 4-bit HPN in stead of the conventional 3-bit one and the UE should interpret the DCI in the new way accordingly.

Since more DCI bit will be conveyed in this solution, the reliability of PDCCH may be a little degraded, especially for the users located on the cell edge.

2) Implicit indication by PDCCH location: As there is one additional bit to be indicated to the UE, the eNodeB may divide the UE-specific PDCCH search space into two parts and signal the relation between the two subspaces and the additional bit through RRC signaling. Consequently, if a UE detects a DCI destined to itself, it can deduce the additional one HPN bit from the PDCCH location the corresponding DCI resides.

[1]If cross-carrier scheduling is not used, the FDD DCI is still carried on FDD DL CC and should comply with the FDD DCI format.

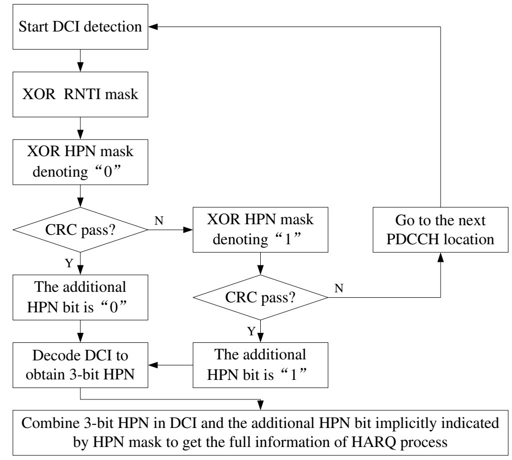

Fig. 3. Operations on UE side to detect full HARQ process information.

The PDCCH blocking probability may be increased in this solution, because the eNodeB can only select the PDCCH from a subset of the UE-specific search space.

3) CRC masking: In the current LTE specification, a 16-bit CRC sequence is calculated for each DCI for error detection. Rather than appending the resulting CRC sequence directly after the DCI, the CRC field is masked by the 16-bit radio network temporary identifier (RNTI) of the target UE through a bitwise exclusive-or (XOR) operation; therefore, the UE can judge whether a DCI is destined for itself by XORing its RNTI again before CRC check.

In our solution, an HPN mask is introduced for the UE, which consists of two 16-bit sequences and each of them represents the additional HPN bit "0" or "1", respectively. On the transmitting side, the eNodeB shall apply both RNTI and HPN masks after CRC calculation; while on the receiving side, the UE shall XOR both RNTI and HPN masks before CRC check, as demonstrated in Fig. 3. As long as the number of UEs in a cell is limited, the superposition of the RNTI and HPN masks will not collide between UEs by carefully defining the HPN mask. This solution will not degrade the reliability of PDCCH in comparison to the aforementioned HPN extension solution, because no more information bit is added.

C. Performance Evaluation

We compare UE throughput on a 10 MHz FDD CC in a typical urban microcell with cell radius 500 meters under the conventional 3-bit HPN and the extended HPN. The eNodeB and the UE are both equipped with a single antenna. It is assumed that a TDD CC with DL/UL configuration 2 is configured as the PCC [8]. The cumulative distribution function (CDF) of UE throughput is plotted in Fig. 4. As can be seen that, because some subframes can not be scheduled due to the lack of HARQ processes under the 3-bit HPN, UE throughput is remarkably less than that under the extended HPN.

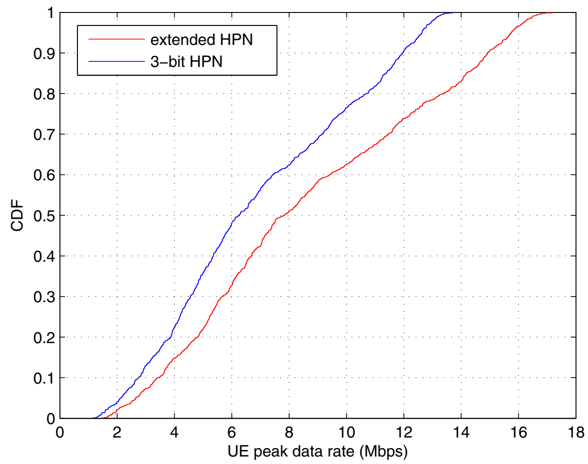

Fig. 4. UE throughput under the 3-bit HPN and the extended HPN.

IV. Problem 2: Redundancy Bits in TDD DCI

A. Problem Description

In LTE TDD system, due to the fact that there does not exist a one-to-one mapping between DL and UL subframes, multiple ACK/NACK feedbacks corresponding to multiple DL subframes may be transmitted in a single UL subframe. Bundling and multiplexing are two standard approaches to aggregate multiple ACK/NACK signals in one PUCCH in LTE TDD specification [7]. However, if the UE misses any PDCCH, it will not be aware of the associated PDSCH transmission. A mechanism is required for the UE to detect missing PDCCHs such that the UE can perform ACK/NACK aggregation correctly in order to inform the eNodeB to re-transmit the unreceived PDSCH data. The 2-bit DAI field in TDD DCI format is used to denote the accumulative number of PDCCHs up to the present subframe [7]. The UE will compare DAI value with the actual number of received PDCCHs. According to the comparison result, the UE is able to know if there is any PDCCH missing.

In the case of CA between FDD and TDD carriers, if an FDD CC is configured as the PCC, the ACK/NACK for TDD DL subframes will be sent back by the FDD UL PCC as described in Section II-A. If the PDSCH in TDD DL subframe occurs in the n-th subframe, the UE can always find the PUCCH for ACK/NACK on the FDD UL PCC in the $n+4$ subframe. Therefore, one FDD UL subframe will at most carry one ACK/NACK for TDD DL subframe, and there is thus no need to use the 2-bit DAI to indicate the accumulative number of PDCCHs in TDD DCI. In addition, as the ACK/NACK feedback for TDD DL subframes can be transmitted to the eNodeB in every subframe on FDD UL PCC, the HARQ RTT can be retained as 8 subframes as for LTE FDD system; therefore, 3-bit HPN can be enough to indicate all HARQ processes on TDD CC, and 1 bit in the HPN field for conventional LTE TDD system seems redundant.

To summarize, there will be 1-bit redundancy in HPN field and 2-bit redundancy in DAI field in TDD DCI provided that an FDD CC is configured as the PCC.

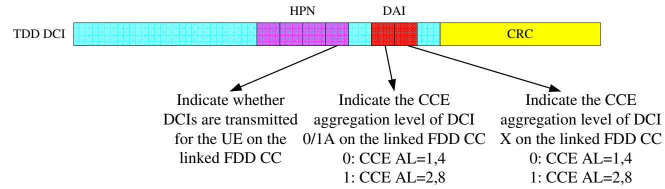

Fig. 5. An example of reusing the 3 redundant bits in TDD DCI.

B. Proposed Solutions

1) Omit the 3 bits in TDD DCI: In the case of CA between FDD and TDD carriers, there could be two configurations for TDD DCI: 1) if a TDD CC is configured as the PCC, the TDD DCI format will remain the same as in conventional LTE TDD specification; that is, the HPN field is 4 bits in length and the 2-bit DAI field is used; 2) if an FDD CC is configured as the PCC, the redundant 3 bits will be omitted to reduce the overhead.

As the energy per information bit in DCI can be increased when the 3 redundant bits are omitted, PDCCH reliability will be improved, which can translate into better cell coverage.

Note that the configuration of TDD DCI is UE-specific and depends on the PCC type. The switch between the two configurations is based on PCell configuration information.

2) Employ the 3 bits for other use: An alternative solution is to employ the 3 redundant bits for other use in the case that an FDD CC is configured as the PCC. In this paper, we propose to reuse the 3 bits to reduce the complexity of PDCCH blind decoding, as shown in Fig. 5.

For this purpose, a link between an FDD CC and a TDD CC can be established through RRC signaling. The UE shall first attempt to blind decode the PDCCH on TDD CC. Based on the TDD DCI, the UE can further decode the PDCCH on the linked FDD CC with some *a priori* knowledge to reduce the complexity of blind decoding. For example, one of the 3 redundant bits in the TDD DCI can be used to indicate whether the linked FDD CC is scheduled for the UE in the current subframe, and if not, the UE needs not to perform any blind decoding on FDD CC at all, thus largely reducing decoding complexity; the rest 2 redundant bits can signal the UE of the control channel element (CCE) aggregation level of DCI on the linked FDD CC, which can also help to reduce blind decoding attempts.

C. Performance Evaluation

The average number of PDCCH blind decoding on FDD CC are compared under the conventional approach and the second proposed approach. In the conventional approach, since the UE has no any *a priori* knowledge, it has to finish the complete 44 blind decoding attempts [9]. In comparison, by utilizing the redundant bits to provide extra information on blind decoding, the number of blind decoding can be significantly reduced for FDD CC, which will translate into energy saving to prolong battery lifetime of the UE. As revealed in Fig. 6, this benefit is the most remarkable for TDD DL/UL configuration 5, since in this configuration we have the most number of DL subframes to provide extra blind decoding information for FDD CC.

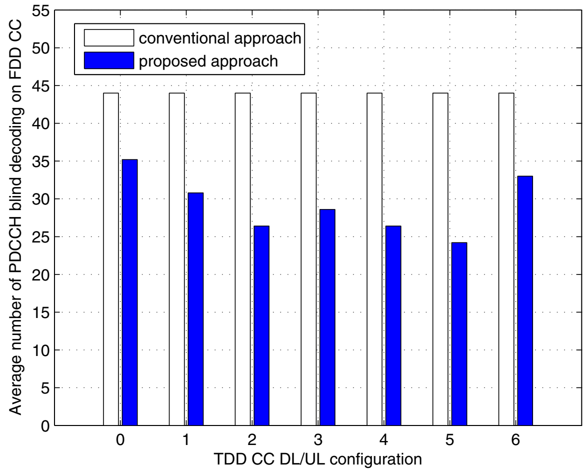

Fig. 6. The number of PDCCH blind decoding on FDD CC under the conventional and the proposed approaches.

V. Problem 3: PDCCH Ambiguity

A. Problem Description

In LTE TDD system, multiple UL subframes may be scheduled in one DL subframe, especially when the number of UL subframes is configured larger than that of DL subframes. Therefore, the 2-bit field of "UL index" is used to indicate the UL subframe location [6].

In the case of CA between FDD and TDD carriers, if an FDD CC is cross-carrier scheduled by a TDD CC, the PDCCH for the FDD CC will locate on the TDD CC. Due to the fact that DL transmission on the TDD CC is not continuous, one cannot always find a DL subframe on the TDD CC to carry PDCCH for the DL or UL subframe on the FDD CC according to the same subframe timing relation given in LTE FDD specification. Therefore, some DL/UL subframes on FDD CC which have not an associated TDD DL subframe cannot be scheduled, and the peak data rate for the UE will be reduced.

B. Proposed Solutions

1) Subframe index indicator: A potential solution is, as in the LTE TDD system, to use an indicator like the "UL index" field to differentiate the multiple FDD DL and/or UL subframes to avoid the problem of PDCCH ambiguity.

However, since a large number of DCIs corresponding to DL assignments and UL grants for multiple FDD DL/UL subframes may be transmitted in one TDD DL subframe, the probability of PDCCH blocking will be increased.

2) Subframe bundling: When an FDD CC is cross-carrier scheduled by a TDD CC, the multiple consecutive DL or UL subframes associated with the same TDD DL subframe can be bundled for scheduling, as illustrated in Fig. 7. Once a DCI for DL assignment or UL grant is issued, it will be applied to all bundled subframes, which means that the same resource allocation pattern indicated by the DCI will be used for each bundled subframe. In addition, the same modulation and coding scheme (MCS) and a single HARQ process could be used for the bundled subframes to reduce DCI signaling complexity, therefore, the data carried in these

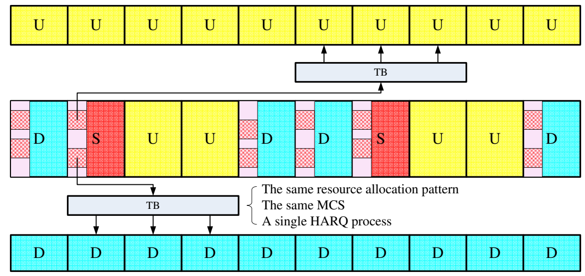

Fig. 7. Subframe bundling (assuming DCIs are issued in the DwPTS part of the special subframe).

bundled subframes will form one transmission block (TB) from the medium access control (MAC) layer perspective.

The bundling rule is based on the DL/UL configuration of the TDD CC, which is known to both the eNodeB and the UE. Therefore, no additional signaling is needed to inform the UE of the bundling relationship between TDD DL subframe and FDD UL/DL subframes.

VI. Conclusions

Carrier aggregation between LTE FDD and LTE TDD systems will improve spectrum flexibility for the operators owning both FDD and TDD spectrums. In the paper, we investigate the possibility of providing such aggregation in LTE-Advanced system. By comparing the differences of LTE FDD and TDD specifications in control signaling format and subframe timing, three problems are identified, two of which are related to the primary serving cell configuration and the rest one is concerned with cross-carrier scheduling. We propose solutions with respect to the three problems and analyze their pros and cons, respectively.

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