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A Comparative Study of Dual Connectivity in Heterogeneous LTE-Advanced Networks

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Abstract

To accommodate fast growing mobile traffic, many network operators make efforts to increase the number of small cells especially in urban hot spot areas. 3rd Generation Partnership Project (3GPP), a global standard organization for wireless telecommunication, introduced dual connectivity, i.e., inter-eNB (evolved Node B) carrier aggregation for small cell deployment. With dual connectivity, a user equipment (UE) can have two simultaneous connections to macro and small cell eNBs, which leads to improve user data rate and mobility robustness within the small cell cloud. In this paper, we examine the recently developed 3GPP standard on dual connectivity in heterogeneous macro-small cell networks, and present a comparative study of dual connectivity.

Keywords: Small cell, Dual connectivity, Inter-eNB carrier aggregation, LTE-Advanced

1 Introduction

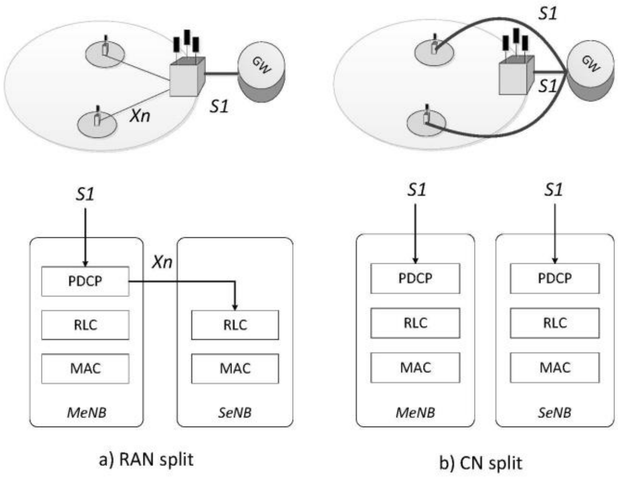
Increasing data hungry smart mobile devices are devouring quickly wireless bandwidth in current the 3rd generation (3G) and the fourth generation (4G) cellular networks. In order to deal with such growing traffic, several approaches on different dimensions can be considered such as using broadband in above 6 GHz frequency spectrum, massive antenna diversity in spatial domain, deploying many small cells, etc. Among them, small cell densification is one of most effective methods at system complexity point of view [1].

Major benefits from the small cells are increasing network capacity, per-user data rate, network coverage and Quality of Service (QoS) with relatively lower expense for network operators; a pico evolved NodeB (eNB) is cheaper due to lower capability than a macro eNB. Standard organizations such as IEEE and 3GPP make effort to publish standards about the small cell networks. The 3GPP started a new small cell enhancement (SCE) study in Rel-12 focusing on indoor and outdoor pico cells on above 3.5 GHz such as higher modulation scheme, small cell on-off and discovery, radio interface based synchronization and dual connectivity [2]. The dual connectivity allows an user equipment (UE) to have two concurrent connections to a master eNB (MeNB) of macro cells and a secondary eNB (SeNB) of small cells.

In this paper, we present a comparative study on 3GPP Rel-12 dual connectivity standards with an in-depth evaluation of its performance. We explain dual connectivity features on the user and control plane together with challenges and adopted solutions comparing to previous Rel-10/11 CA. We evaluate the dual connectivity performance in terms of average per-user throughput and delay using the OPNET LTE simulator in which we developed standard radio protocols for the dual connectivity with our scheduling algorithm.

2 Dual Connectivity in Heterogeneous Small Cell Networks

The dual connectivity is introduced to improve per-user data throughput, mobility robustness and signaling overhead reduction allowing UEs to have dual connections to macro eNB (MeNB) and small eNB (SeNB) simultaneously in the heterogeneous small cell networks (See Figure 1) [3]. For instance, UEs can separate control and data transmission planes by sending control messages to the MeNB and user data to the SeNB. Accordingly, UEs does not need handover between small cells while the UE is connected to the overlaid MeNB as an anchor point in macro cell area [4].



a) RAN split b) CN split

Figure 1. RAN split vs. CN split

Figure 1 shows two different architectures of dual connectivity, i.e., radio access network (RAN) split and core network (CN) split. In the RAN split, SeNBs are branched from installed MeNBs via backhaul (X2), but they are connected directly to the serving gateway (S-GW) in the CN split. There are pros and cons between them. Direct backhaul of the CN split can carry large traffic from the SeNBs while the the MeNB can be bottleneck in the RAN split. However, the CN split causes control overhead in the CNs with frequent handover between the SeNBs (e.g., data path switch). An UE could achieve higher data rate by transmitting a single RB in both eNBs (i.e., bearer split) in the RAN split rather than the CN split. Still scheduling routing packets between the MeNB and SeNB for the bearer split is challenge due to backhaul latency (e.g., approximately 10 to 20 msec), which may require reordering in receive packet data convergence protocol (PDCP) and degrades throughput in higher layer like Transmission Control Protocol (TCP).

From now, control and user plane issues for dual connectivity are discussed comparing to Rel-10/11 CA such as system information, signal flow, initial channel access, bearer management, power allocation, etc.

2.1 System Information

System information (SI) of each serving cell is provided UEs by periodic broadcasting or dedicated RRC signaling. The dedicated RRC signaling was introduced for Rel-10/11 CA in order to delivery SCells' SI to UEs. For the dual connectivity, an UE is receiving directly SI broadcast in all serving cells. Or, SIs of SCG's cells are carried by dedicated signaling from a MeNB. The third approach is hybrid approach of previous two, UEs receive system frame numbers (SFN) directly from PSCell and others by dedicated signaling. 3GPP had determined to use the third approach assuming that SFNs of MCG and SCG respectively are not synchronized.

2.2 Signal flows

For addition, modification and release of the SeNB's SCells, the MeNB initiates the procedure to add or release SCells of the SeNB upon receiving the Measurement Report from the UE. Specifically, this procedure could be initiated when the MeNB detects change in macro cell load (e.g., congestion in the macro cell) or receives the Resource Status Update from the SeNB (e.g., an cell load or a radio problem). The SeNB status may trigger the MeNB to add (e.g., SeNB under utilization) or to release SCells (e.g., SeNB overload). When sending SCG-ConfigInfo to the SeNB for SCell configuration, the MeNB provides the identifier of the SCell to be added or released (e.g., frequency and physical cell ID (PCI)) and any restriction to be considered (e.g., restriction to avoid exceeding UE capabilities by both eNBs). Then the SeNB decides its configuration within the restriction. Alternatively, the MeNB could inform the SeNB of the current UE configuration together with its capabilities for reference. Based on the information the SeNB configures by itself without exceeding UE capabilities. After the SeNB decides the SCG configuration, it forwards results to the MeNB by using SCellToAddModList or SCellToReleaseList for adding or releasing, respectively. The MeNB forwards the SCell configuration to the UE using a message container in the RRC Connection Reconfiguration without modifying message content sent by the SeNB.

2.3 Random access

Contention-based random access (CB-RA) is purposed for uplink power and timing adjustment to the eNB at the first time for uplink transmission [5]. The CB-RA in SCells of the SeNB has been allowed for the dual connectivity in Rel-12 because the MeNB does not know whether the UE needs RA for uplink transmission in the SeNB. Otherwise, the MeNB asks the SeNB's SCell RA resource and orders an UE to perform Non CB-RA in the SCell with the received RA information, or the MeNB asks the SeNB to initiate the Non CB-RA in own cell. In addition, the UE receives random access response (RAR) through the PCell within RAR window, which prevents blind search in common search space (CSS) of the SCells which consumes the UE's process power and causes delay. However, it causes RAR window increase due to backhaul delay to receive the RAR from the SeNB which limits the preamble resource in dual connectivity. From this reason, CB-RA procedure is decided to perform in PSCell of the SeNB.

2.4 Buffer status report

Buffer status report (BSR) is triggered by newly incoming UL data or high priority UL data, or by a timer periodically configured by an eNB. The buffer status of bearers is identified in the Medium Access Control (MAC) layer, so an UE with dual connectivity has two different LC group (LCG) for each MAC for the MeNB and the SeNB. Considering latency of the X2 interface and complexity to manage the unified LCGs, it is reasonable that each eNB manages own LCG separately same as legacy scheme. The UE reports buffer status of each LCGs to the MeNB and SeNB, separately. However, LC priority cannot be fulfilled. For example, if two LCs with same priority belong to different MACs and the MeNB MAC has higher priority LCs than the SeNB, the one LC in the SeNB can involve in higher priority LCG than the other in the MeNB.

2.5 Power headroom report

Dual connectivity has separate schedulers in the MeNB and SeNB, who control the uplink transmission power of the same UE. Each eNB scheduler does not know power situation of the UE in the other eNB, which leads to transmission power shortage in the UE. Thus both eNB can exchange power headroom and corresponding uplink resource information for the UE to schedule appropriate uplink resource against the UE power budget. Another approach is extending current power headroom report (PHR) to include all serving cells' power headroom values, which requires a new PHR format that includes two type 2 fields (i.e., simultaneous physical uplink shared channel (PUSCH) and PUCCH transmission) for each eNB. This PHR should be reported twice to the MeNB and SeNB.

Under power shortage from imperfect scheduling, an UE scales down transmission power of each channel based on priority (e.g., hybrid automatic repeat request acknowledgment (HARQ-ACK), schedule request (SR) > channel state information (CSI) > PUSCH). For example, PUSCH with uplink control information (UCI) should be advanced than another without the UCI because UCI is more important than normal user data.

2.6 Discontinuous reception

It is difficult to apply a single DRX to the MeNB and SeNB since the eNBs are not synchronized timely and have different system frame number (SFN). Thus, the UE has two DRX cycles for each eNB wherein the UE operates on combined DRX cycle; it wakes up when at least one of DRX cycles is on-status and sleeps when all are in on-status. Challenge is how to maximize power saving with multiple DRX cycles. One possible solution is that both eNBs negotiate DRX cycles to synchronize on-status as much as possible. Both eNBs make effort to select common long DRX cycle and exchange it via X2 interface which has periodic on-duration and is easy to synchronize compared to short DRX cycle.

3 Performance Comparison

3.1. Simulation Setup

We investigate the CN and RAN split architectures in terms of average UE throughput and delay. For this, we implemented aforementioned radio protocol functionalities for dual connectivity on top of OPNET LTE simulator and evaluated the performance with simulation parameters shown in Table 1.

Table 1. Simulation parameters

Parameters	Macro cell	Small cell
Inter Site Distance	500 m	100 m
Number of cells	7	4/macro
Number of UEs	32	20
Bandwidth	10 MHz	10 MHz
Carrier frequency	2 GHz	3.5 GHz
Tx power	46 dBm	30 dBm
eNB antenna gain	15 dBi	5 dBi
TCP version	CUBIC	CUBIC

UE throughput is measured in TCP layer of FTP application in which the UE finishes downloading a single file with size 4 Mbits every *t* seconds (i.e., 4000/*t* Kbps) and it may download dozens of files according to traffic model during the entire simulation time. We derives average throughput of all single file reception during the simulation time for the UE. The FTP traffic model is described in 3GPP TR 36.814. We define 3 levels of cell load at the macro cell: 10 second reading time for low load (i.e., average 30% macro resource (PUSCH) occupancy), 5 seconds for medium load (i.e., average 60%) and 3.3 seconds for high load (i.e., average 90%). The cell load is varying with FTP reading time. Reading time is time interval between end of previous file download and beginning of user request for the next file.

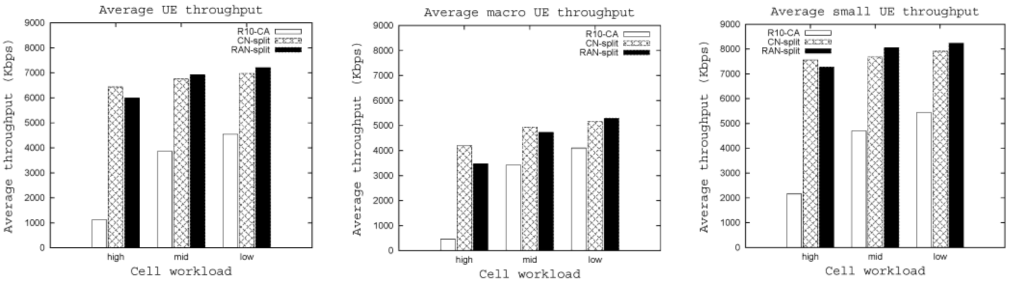
In order to make load balancing between eNBs in the split model, we implemented our scheduling algorithm with a flow control mechanism in the MeNB or S-GW, which is based on metrics such as capacity of macro/small cells and queue status in both cells. Per-packet scheduling causes a packet disordering problem in an upper layer like PDCP which decreases overall throughput. Thus, the MeNB calculates periodically bearer split ratio between macro and small cells, e.g., a radio frame (10 msec) and forwards data with the ratio, where the flow control scheme deals with data loss and delay in X2 interface. Since the small cells have usually better channel quality (e.g., wideband SINR) and more available resource (e.g., physical resource block (PRB) utilization) with a few serving UEs rather than a macro cell, the MeNB would forward most of user data to the SeNB according to our simulation (e.g., only about 5% UE data are transferred via MeNB in the high workload).

3.2. Throughput Gain of Dual Connectivity

First, we compare the performance between Rel-10/11 CA and Rel-12 dual connectivity. In our simulation, we assume that the center macro cell is a PCell and the co-located SCell, almost the same size of the PCell, is overlapped with the PCell. We also assume that 70% UEs closer to the MeNB are applicable to CA while other 30% edge UEs are not appropriate because of inter-cell interference and transmission power shortage.

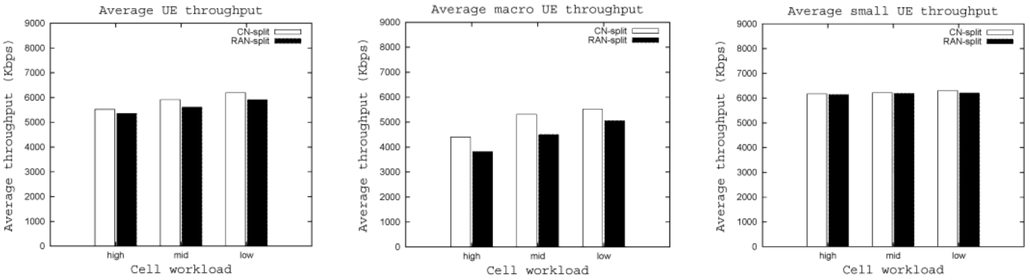
From the simulation results, the average UE throughput of legacy Rel-10/11

CA compared to the dual connectivity is significantly lower as shown in Figure 2(a). Figure 2(b) shows throughput comparison of UEs who operate without Rel-10/11 CA or single connectivity to the macro cell. The single connected UE (i.e., non-CA UEs in dual connectivity) achieve better than the non-CA UEs of legacy Rel-10/11 CA (i.e., legacy non-CA) since the legacy non-CA UEs are located around macro cell edge as mentioned before while the non-CA UEs in dual connectivity exist both cell center and edge area. Moreover carrier frequencies in the cell edge area would suffer from inter-cell interference with neighbor macro cells.



(a) UE (b) non-CA UE (c) CA UE

Figure 2: Average UE throughput in uniform small cell distribution



(a) UE (b) non-CA UE (c) CA UE

Figure 3: Average UE throughput in edge small cell distribution

As can be seen in the CA UE throughput in Figure 2(c), the CA UEs with dual connectivity also outperforms the legacy Rel-10/11 CA. 70% of total UEs are severed by a single SCell in the Rel-10/11 CA except the PCell while the same number of UEs is served by four SCells of SeNBs in dual connectivity. To say, more resources in SCells are available to two third of all UEs in case of the dual connectivity. The CA UE with dual connectivity experiences better channel condition since small cells are less interfered from neighbor small cells compared to the macro cell edge. In the simulation topology, the small cells are deployed not to interfere each other with minimum required distance.

3.3. CN Split vs. RAN split

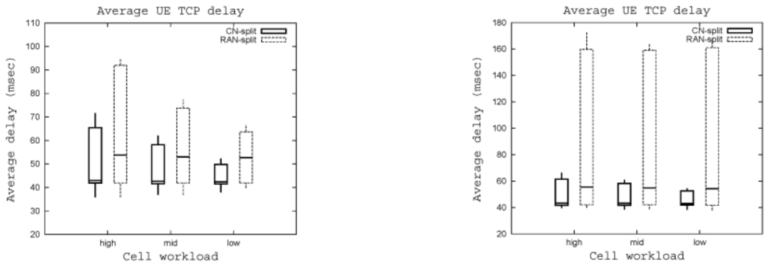
For comparison between CN and RAN split, we simulate with two different SeNB distributions. In the random distribution, small cells are distributed uniformly within the macro cell while located in edges in the edge distribution, which is one of candidate deployment scenarios to improve edge user throughput.

As results seen in the Figure 2(c), the bearer split in the RAN split can achieve slight performance gain compared to non-bearer split in the low and medium cell load. In the high cell load, however the UE throughput of the bearer split is even worse than the non-bearer split. In the SeNB edge distribution of Figure 3, limitation of the bearer split seems clearer; average CA UE throughput of RAN and CN split are comparable as shown in Figure 3(c). Weaker macro signal would reduce receive data rate and cause more packets loss, which leads to PDCP re-ordering delay and finally decrease UE throughput.

In Figure 2(b) and Figure 3(b), the non-CA UE throughput in dual connectivity is shown better in CN split since those non-CA UEs can have less macro cell resource in the RAN split that utilizes macro cell resource for a split bearer especially in high cell load.

3.4. End-to-end Delay

Figure 4 shows the end-to-end transmission delay in TCP layer to explain relation between the delay and performance. In random SeNB distribution, there is about 10 msec difference between RAN and CN split, which is almost equal to X2 latency. Considering the 10 msec is near one round trip time (RTT) (i.e., 8 msec) for a single MAC PDU, it does not affect seriously on high layer like PDCP requiring long re-ordering time. Note that the average delay in each cell load is similar but variance is different because the MeNB reduces number of transmissions through the macro cell as the cell load increases. However, only a few packets delivered via the MeNB that suffer serious PDCP re-ordering can cause UE throughput reduction. Such effect of the delay variance appears clearly in SeNB edge distribution as shown in Figure 4(b). The average delay increases only about 10 msec from the uniform distribution case since the MeNB reduces transmissions on the macro cell as data rate becomes lower with weaker receive signal and packet loss probability increases. However the maximum delay is approximately 160 msec that is double of random case, which increases considerably PDCP re-ordering time. From this reason, the average UE throughput decreases 1 to 2 Mbps from random to edge distribution.



(a) Random distribution (b) Edge distribution

Figure 4. Average UE TCP delay with different small cell deployment.

4 Conclusion

In this paper, we presented a study on the performance of 3GPP Rel-12 dual connectivity with a bearer splitting algorithm as one of attractive features in heterogeneous macro-small cell networks. As we investigated, dual connectivity can be used dynamically. The MeNB can offload an entire bearer in high cell load like the CN split and partially with bearer split in low cell load. As future works, we have still many challenges to resolve and improve the dual connectivity as discussed in the paper such as uplink bearer split, RRC diversity, etc.

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