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LETTER

High-Throughput Primary Cell Frequency Switching for Multi-RAT Carrier Aggregation

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SUMMARY Among the five carrier aggregation (CA) deployment scenarios, the most preferred scenario is Scenario 1, which maximizes CA gain by fully overlapping a primary cell (PCell) and one or more secondary cells (SCells). It is possible since the same frequency band is used between component carriers (CCs) so nearly the same coverage is expected. However, Scenario 1 cannot guarantee high throughput in multi-radio access technology carrier aggregation (multi-RAT CA) which is actively being researched. Different carrier frequency characteristics in multi-RAT CA makes it hard to accurately match different frequency ranges. If the ranges of PCell and SCell differ, high throughput may not be obtained despite the CA operation. We found a coverage mismatch of approximately 37% between the PCell and SCell in the deployed network and realized a reduced CA gain in those areas. In this paper, we propose a novel PCell change approach named "PCell frequency switching (PFS)" to guarantee high throughput against cell coverage mismatch in multi-RAT CA deployment scenario 1. The experiment results show that the throughput increased by 9.7% on average and especially by 80.9% around the cell edge area when PFS is applied instead of the legacy CA handover operation.

key words: *carrier aggregation, multi-RAT CA, CA cell coverage mismatch, PCell inter-frequency handover, CA mobility*

1. Introduction

Carrier aggregation (CA) has been regarded as a major feature in Long Term Evolution-Advanced (LTE-A) [1]–[3] to meet the high data rate demands. Clearly, the purpose of the CA is to provide a higher throughput to the user equipment (UE). Out of the five CA deployment scenarios [4] introduced by the 10th release of the 3rd generation partnership project (3GPP), as shown in Fig. 1, the CA deployment scenario 1 (hereinafter referred to as Scenario 1) is the most preferred because it can maximize the CA gain by completely overlapping both the primary cell (PCell) and the secondary cell (SCell). In addition, the operator can reduce the number of Radio Resource Control (RRC) reconfiguration messages for dynamic configuration by mapping the PCell and the SCell in advance. And the PCC (Primary Component Carrier) can be fixed. These are possible because Scenario 1 is based on the premise that the coverage between CCs is completely matched. Nearly the same coverage is expected since the same frequency band is used between CCs. Nowadays, multi-radio access technology (multi-RAT) CA [5], [6] is

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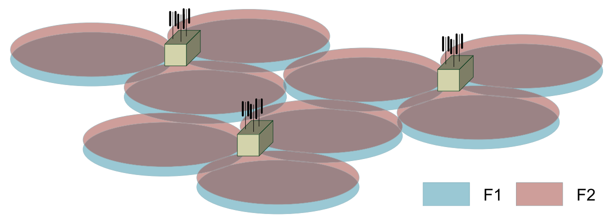


Fig. 1 CA deployment Scenario 1.

emerging for more efficient utilization of the available spectrum. However, applying Scenario 1 to multi-RAT CA is another problem. The signal strength may vary depending on the carrier frequency characteristics between the multi-RAT CA cells, and thus cause CA cell coverage mismatch. This is in contrast to the basic premise of the same coverage, which means that it may not work properly with multi-RAT CAs.

The 3GPP release 10 specification [7] defines a new event A6 that enables SCell changes without changing the PCell when the neighbor cells are better offset than the SCell. However, it can cause continuous SCell change so-called ping-pong if only the SCell is considered regardless of the PCell condition. In addition, event A6 is only available conditionally, depending on the deployed network configuration. In Scenario 1, event A6 is not required because dynamic SCell management does not need to be considered under the CC coverage match conditions. Several CA movement schemes have been proposed to improve CA operation. Two dynamic PCell change methods [8] enable the PCell to dynamically change the carrier frequency of the SCell. The scheme is based on the legacy handover that considers only the PCell's quality. It can lead unnecessary handover if the SCell quality is good enough. Moreover, in this case, the throughput can be reduced in the target cell if the cell does not provide CA. The CA-based fractional soft handover scheme [9] proposes performing soft handover partially for VoIP services to lower the probability of handover outage. However, all the above-mentioned studies do not discuss the CA cell coverage mismatch problem and its solution.

In this study, we investigated the problems related to the coverage mismatch between the PCell and SCell in Scenario 1 considering multi-RAT CA and propose a novel solution. It is worth noting that we do not focus on designing a whole multi-RAT CA scheme. Instead, we propose a new primary cell changing method that can be applied to multi-RAT CA. More specifically, we introduce a novel handover decision algorithm for CA, named PCell frequency switching (PFS), and evaluate the performance through experiments conducted in indoor and outdoor network environments.

2. Coverage Mismatch between CA Cells

We deployed Scenario 1 by using different frequency bands in the real LTE-A network, collected the PCell Identity (PCID) distribution for each carrier through a driving test, and measured the signal to interference plus noise ratio (SINR) and throughput by using 2 types of user equipment (UE), CA UE and non-CA UE. It is worth noting that the deployed Scenario 1 with the LTE-A network is the same situation as the one with multi-RAT CA environment in that both of them use different frequency bands. Table 1 shows the parameters and values used for environment configuration. We used three UEs, that is, one CA UE and two non-CA UEs. The CA UE was used to attach collocated cells (PCell 1.8GHz-SCell 800MHz). Non-CA UE#1 and non-CA UE#2 were used to attach 1800 and 800 MHz cells, respectively.

In the tests, we collected the UE log by shuttling 4.7 Km east to west and 3.2 Km north to south from the intersection by the car. Then, we analyzed the PCIDs of the SCell of the CA UE and the non-CA UE#2 every 1 second from the collected log. We detected 65 PCIDs and they were the same 2,110 times and differed 1,235 times. Each color in Fig. 2 represents a different PCID. It shows that these PCIDs of the CA SCell and the non-CA cell differ in some regions. We also checked the SINR and throughput of the UEs. Figure 3 (a) compares the measured SINR and throughput of the CA SCell and Non-CA Cell using the 800 MHz band. The SCell SINR and throughput of the CA UE were significantly reduced according to the regions where PCIDs are different. The dotted line in Fig. 3 refers to those regions. In these areas, the SCell's reference signal received power (RSRP) can be in a very low state since the operation in Scenario 1 is based on coverage matching between the PCell and the SCell so that dynamic SCell management is not needed. After all, the performance degradation would be unavoidable and the prediction that the throughput of the CA UE will always be higher than the non-CA UE cannot be guaranteed. In Fig. 3 (b), the SINR and throughput of the CA UE are lower than the non-CA UE#2. We define this state as CA cell coverage mismatch. In our PCID distribution comparison check, CA cell coverage mismatch ratio was approximately 37%.

Figure 4 describes the CA cell coverage mismatch situation in detail and Table 2 shows the actual values measured in the environment of Fig. 4, indicating that the throughput of the CA UE attached to cell 0 is approximately 22 Mbps, whereas the throughput of the non-CA UE attached to cell 1 is approximately 30 Mbps. This is because the non-CA UE has better RSRP and SINR conditions than the CA UE for the PCell. And, the CA UE's SCell is almost ineffective.

Table 1 Environment configuration.

Parameter	Value
Deployment Scenario	1
Number of CCs	2
Carrier Frequency	1.8GHz(PCell), 800MHz(SCell)
a1-Threshold	-89 dBm
a2-Threshold	-100 dBm
a3-Offset	2 dB
Time To Trigger	100 ms
Trigger Quantity	RSRP

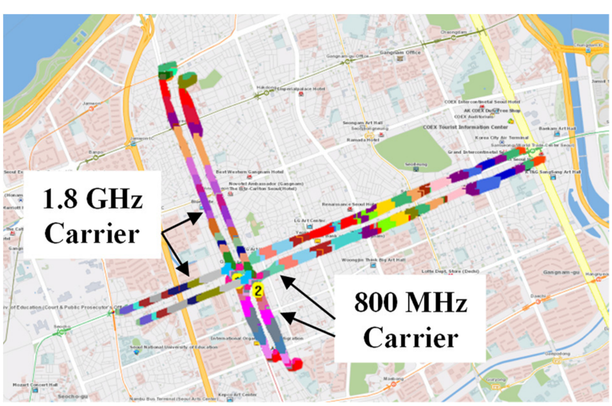


Fig. 2 PCID distribution comparison.

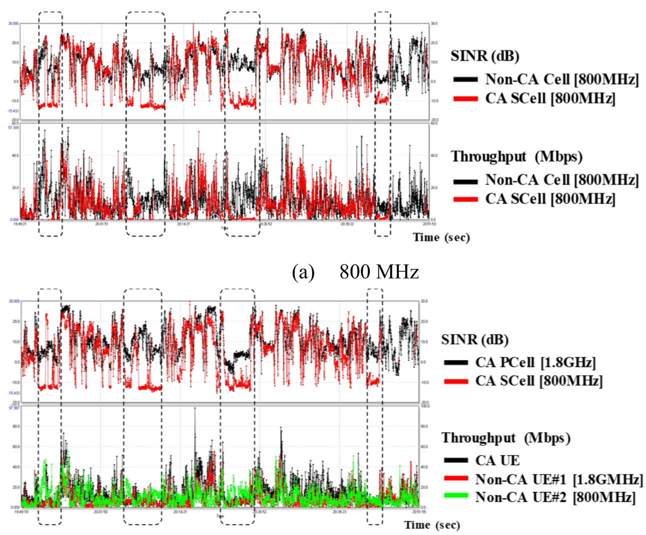


Fig. 3 SINR and throughput comparison.

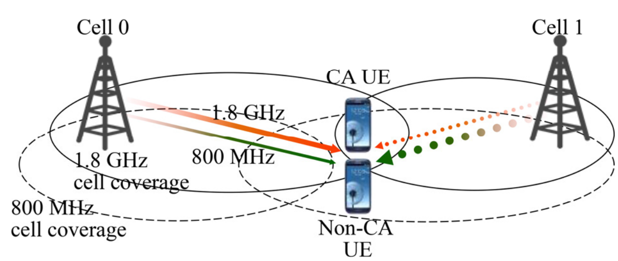


Fig. 4 CA cell coverage mismatch.

Table 2 Measured value.

		Cell 0	Cell 1
1.8 GHz	RSRP	-70.4 dBm	-76.9 dBm
	SINR	8.3 dB	1.6 dB
	Throughput	15.6 Mbps	7.5 Mbps
800 MHz	RSRP	-77.2 dBm	-63.5 dBm
	SINR	-1.4 dB	12.7 dB
	Throughput	6.7 Mbps	30.3 Mbps

Eventually, the throughput of the non-CA UE can be higher than that of the CA UE. If the CA UE moves to cell 1, the throughput will be approximately 37 Mbps. However, the legacy handover is not triggered because the handover conditions are not met. In this study, we address this problem case and provide a solution.

3. PCell Frequency Switching

In Sect. 2, we described the CA cell coverage mismatch problem when different frequency bands are configured for Scenario 1. A CA cell coverage mismatch does not occur in the central region of cells, where the signal strength of the PCell and the SCell is extremely strong. The PCell based legacy handover can move the UE to another cell, even if the coverage of the CA cell is mismatched. Typically, this occurs in the cell boundary region. In this case, since the new PCell and SCell are newly configured, the low throughput problem due to the CA cell coverage mismatch can be avoided. Therefore, we do not need to consider cell coverage discrepancies for a cell's center and edge regions. We need to consider other regions for the cell coverage mismatch.

Figure 5 shows the event configuration and process flow combining the PFS and legacy handover scheme for the SCell configured CA UE. The dotted line represents PFS in the legacy handover scheme. In the case of a legacy handover, the UE is configured to report events A2 and A3. Event A2 will be triggered if the estimated quality of the serving cell is below a certain threshold and event A3 will be reported for intra-frequency handover. Here, the UE is attached to the cell through initial random access, handover, and so on. If event A2 is reported, the UE is configured to report events A1 and A3 for inter-frequency, and it starts searching for cells of another carrier frequency whose quality is offset better than that of the serving cell. When event A1 is received, the UE returns to the initial state in which event A2 is configured to be reported. When event A3 is received, the UE can move to the target cell and add one or more new SCells to the PCell. The events are defined as follows:

Event A1: Serving becomes better than threshold
Event A2: Serving becomes worse than threshold
Event A3: Neighbor becomes offset better than serving

The PCell inter-frequency handover scheme is also applicable to CA cells [10]. However, legacy handover may not operate effectively. The legacy CA handover scheme

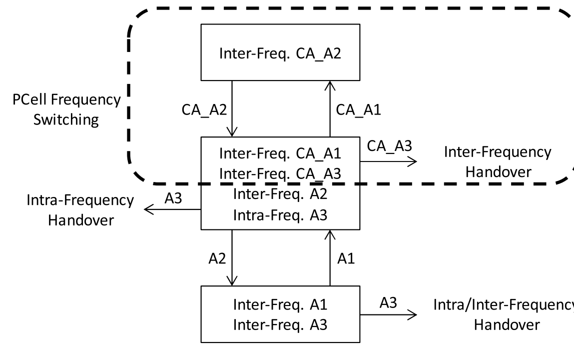


Fig. 5 Event configuration and processing flow for PFS.

only considers the PCell quality and it may not work effectively when the CA cell range is mismatched. In the handover decision, only the PCell state is considered; this can considerably reduce throughput during CA cell coverage mismatch. Therefore, we propose a novel PFS for CA UEs in a SCell configured PCell to consider CA cell coverage mismatches. Although the legacy CA handover occurs based only on the PCell condition, the PFS enables a CA UE to change its PCell through inter-frequency handover to other neighboring cells if SCell's signal strength is low and the neighboring cell's signal strength is offset better than that of the current PCell. This method allows the CA UE to quickly switch to another PCell in case of CA cell coverage mismatch, therefore guaranteeing that the CA UE always has higher throughput than the non-CA UE. The newly defined events in PFS are as follows:

Event CA_A1: Serving SCell becomes better than threshold_CA (threshold_CA > threshold for Event A1)
Event CA_A2: Serving SCell becomes worse than threshold_CA (threshold_CA > threshold for Event A2)
Event CA_A3: Neighbor becomes offset_CA better than serving PCell (offset_CA >= offset for Event A3)

During PFS, the CA UE is configured to report an event CA_A2 for when the estimated quality of the SCell is below a certain threshold. When event CA_A2 is reported, the CA UE is configured to report events CA_A3 and CA_A1, and the neighbor cell is scanned for intra or inter carrier frequency that is better offset than that of the serving PCell. When event CA_A1 is received, the UE returns to the initial state in which event CA_A2 was configured to be reported. When the event CA_A3 is received, implying that the current SCell is inefficient even though the PCell quality is not too bad, the UE moves to the target cell, that is, an adjacent cell with good carrier quality. The collocated SCell is added based on the new PCell. If CA_A3 is not triggered and the quality of the PCell worsens, legacy intra- or inter-frequency handover that only considers the PCell quality will work.

Figure 6 shows how the PFS differs from the legacy inter-frequency handover scheme. The dark grey area represents the additional gain obtained using the PFS scheme instead of the inter-frequency handover.

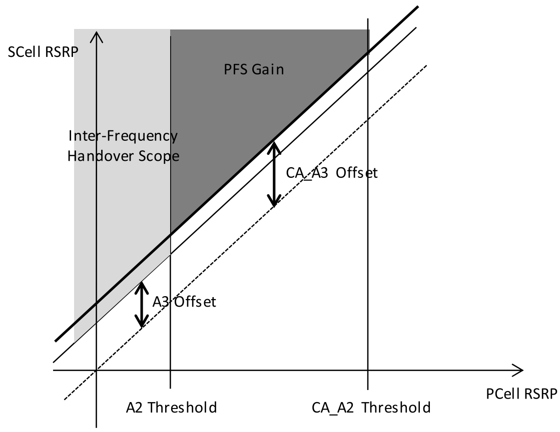


Fig. 6 PFS gain.

4. Performance Evaluation

We conducted indoor and outdoor experiments to verify performance differences between the legacy handover scheme and PFS. In case of the legacy handover, PCC is fixed at 1800 MHz, whereas inter-frequency handover is possible in the PFS. Table 1 shows the basic environment configuration, and Table 3 shows the newly added parameters and values for PFS.

In the indoor test, we manually created a CA cell coverage mismatch situation by adjusting the signal strength of each antenna and compared the throughput with that of legacy handover scheme under the same condition. Figure 7 describes the logical indoor experiment environment. We configured the cell type for Cell 0 and Cell 1 as collocated cell (PCell 1.8GHz – SCell 800MHz) via NMS. We adjusted the attenuator applied to the cable connected to each RRH to meet the SINR in Table 4. The attenuated cable is connected to both CA UEs via RF power dividers, so that the same RF power is applied simultaneously. Based on this, both UEs were attached to Cell 0 and the traffic server sent FTP traffic to the UE. Then, we increased the attenuator value for Cell 0's 1.8GHz RRH to be 0.5dB SINR. The legacy handover scheme considers the PCell quality only. In case of the legacy handover scheme, PCell frequency was fixed to 1800 MHz. Meanwhile, the PCell was changed to an 800 MHz carrier when PFS was applied. This implies that PFS triggered inter-frequency handover to provide higher throughput under the same condition. Figure 8 shows that the throughputs of the legacy handover scheme and PFS are approximately 14Mbps and 25Mbps, respectively. In conclusion, PFS represents 78.6% higher throughput than that of the legacy handover scheme.

In addition, the legacy handover scheme and PFS were applied to actual deployed networks to measure throughput and number of handovers; here, the same network conditions and test methods as previous outdoor tests were applied using two CA UEs. Table 5 shows outdoor experiment results. Compared to the legacy handover scheme, the number of intra-frequency handovers is less, and the number of inter-frequency handovers is 82 times more when applying PFS. This implies that the PFS changes the PCell through inter-frequency handover more often for better channel conditions before the intra-frequency handover occurs. The to-

Table 3 New experiment configuration for PFS.

Parameter	Value
CA_a1-Threshold	-69 dBm
CA_a2-Threshold	-80 dBm
CA-a3-Offset	3 dB

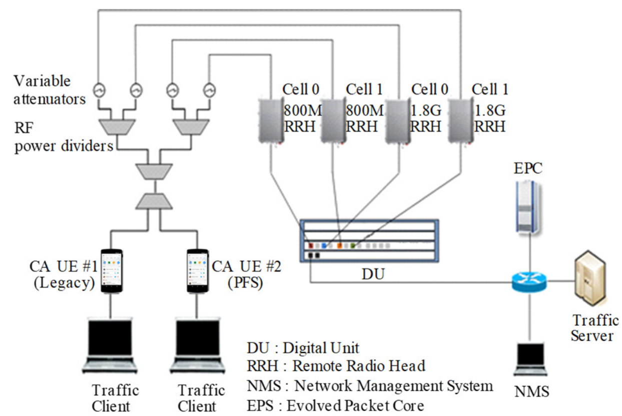
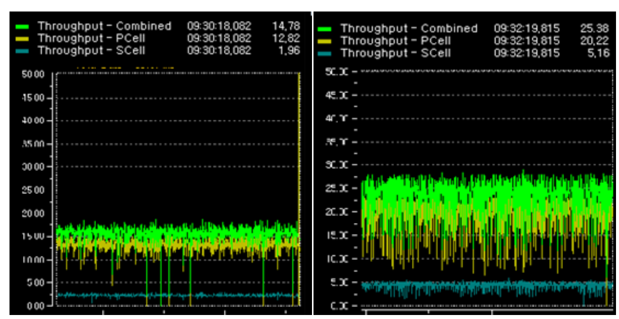


Fig. 7 Indoor experiment environment.

Table 4 SINR condition for indoor experiment (dB)

	Cell 0	Cell 1
1.8 GHz	12.0	-5.0
800 MHz	-8.0	3.0



(a) Legacy Handover (b) PFS

Fig. 8 Indoor experiment results.

Table 5 Outdoor experiment results.

(a) Throughput (Mbps)

	Average	Cell Edge
Legacy Handover	42.1	8.9
PFS	46.2	16.1

(b) Number of Occurrences

	Intra-Freq. Handover	Inter-Freq. Handover	Total
Legacy Handover	155	0	155
PFS	91	82	173

tal number of handover occurrences increased 11.6% in PFS and the average throughput increased by 9.7% on average, especially by 80.9% around the cell edge area when PFS is applied.

5. Conclusion

In the five CA deployment scenarios, only Scenario 1 assumes the ideal case, in which the coverage of CA cells is the same throughout. However, it is very difficult to precisely match CA cells with different frequency characteristics. Therefore, the coverage mismatch between multi-RAT CA cells must be considered in the operation of Scenario 1. When we measured our deployed networks, we found a CA cell coverage mismatch of approximately 37% between the PCell and SCell and determined that the CA gain was reduced in that area. To cope with CA cell coverage mismatches for CA UEs, we proposed PFS by considering both PCell and SCell's signal strengths to provide higher throughput to CA UEs, considering realistic network conditions.

Two performance experiments were conducted to verify the proposed method's effectiveness in the deployed network. PFS showed that it handles CA cell coverage mismatches and provides higher throughput for CA UEs than the legacy handover scheme. Our PFS shows 9.7% higher throughput on average and 80.9% around the cell edge. Therefore, PFS can cover practical cases of CA deployments and contribute to higher throughput for CA UEs in multi-RAT CA environments. In this paper, we applied PFS by using 2 CCs, that is, one SCell. In our future work, we plan to expand PFS by using three or more CCs and using scenarios other than Scenario 1. Furthermore, we plan to evaluate PFS in the real multi-RAT CA environments in order to consider the impact of modified Radio Link Control (RLC) layer and so on.

Acknowledgments

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