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Experimental Performance Evaluations of CoMP and CA in Centralized Radio Access Networks

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Abstract According to International Mobile Telecommunication's requirements for 2020, next generation cellular networks such as 5G need to meet certain Key Performance Indicator (KPI) targets. Centralized-Radio Access Networks (C-RAN) is a novel technique that can address growing capacity needs of Mobile Network Operators (MNOs) due to ever increasing demands of their users. In order to meet stringent requirements of next generation cellular networks, C-RAN enabled techniques have attracted a lot attention due to their efficient spectrum (band, bandwidth) utilization (e.g. via carrier aggregation (CA)), spectrum efficiency (e.g. via Inter-Cell Interference Co-ordination and cancellation using Coordinated MultiPoint (CoMP) Transmission/Reception). In this paper, we investigate three different CA scenarios along with their benefits and limitations from the perspective of MNO. Additionally, we analyze inter - Baseband Unit (BBU) uplink (UL) CoMP feature as a real-world experimental C-RAN implementation in an operational suburban site of Istanbul in Turkey. Quantitative CA performance measurements demonstrate performance comparison of the considered three CA scenarios, and depending on each MNO's strategy, different CA gains are observed (e.g. LTE 1800 Mhz MNOs can benefit more from L800 umbrella coverage scenario). Our coordinated inter-BBU UL CoMP results indicate that around 7%, 9% and 6% gains can be achieved in UL cell, user and cell-edge user throughput respectively.

Keywords C-RAN · CA · CoMP · Interference Mitigation · Field Experiment

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1 Introduction

Mobile Network Operators (MNOs) are moving from coverage based deployment into capacity based deployment strategies because of mobile traffic expansion. This evolution can bring additional complexities due to heterogeneous networks including both macro and small cell deployments. As a consequence of aiming to overcome installation, maintenance and optimization costs, a new paradigm called Centralized RAN (C-RAN) has been proposed by network vendors [1].

C-RAN is an evolving radio network architecture where Baseband Units (BBUs) are pooled and centralized together to provide services to distant radio units named as Remote Radio Units (RRUs). It's introduced to accommodate growth in mobile networking ecosystem. One of the main benefits of C-RAN is its virtualization capability that can manage as many Base Stations (BSs) as the network needs. In C-RAN, base-band and channel processing units are virtualized in a centralized baseband pool. Such centralization enables better resource utilization (e.g. BSs) and dynamic traffic handling capabilities.

Together with C-RAN's advanced features, MNOs can have both enhanced Inter-Cell Interference Cancellation (eICIC) and complementary Carrier Aggregation (CA) techniques between macro and micro BSs, i.e.

in heterogeneous networks. Similarly, techniques such as Coordinated Multipoint (CoMP), CA, Single Frequency Network (SFN) can be utilized for improved network performance and efficiency between macro-macro BSs. Thanks to C-RAN's coordination capabilities, resource allocation over multi-cell networks can be performed in a centralized manner. This can increase system efficiency by more information (e.g channel or scheduling information, Channel Quality Indicator (CQI), quality-of-service (QoS) and load on cells) exchange with C-RAN coordinator or can improve performance quality of Cell Edge Users (CEUs), for instance in voice-over LTE transmissions. Inside a C-RAN network design, centralized site where BBU pool is located can be connected with remote sites. In remote sites, RRUs are present and are connected with centralized site via fronthaul network using high speed optical transport network either with active or passive wavelength-division multiplexing. The distance between centralized and remote site can be up to 40 km in theory [2] and 20 km in practice [3]. In this paper, we demonstrate experimental C-RAN trial results of activating CA feature for three different deployment strategies as well as inter BBU Uplink (UL) CoMP in one of the suburban experimental areas of city of Istanbul in Turkey.

1.1 Related Work

The evolution of C-RAN technology represents a key enabler in the upcoming 5G ecosystem. A good review of state-of-the art literature on C-RAN as well as the relevant technological definitions (e.g. CA, CoMP, SFN) are provided in [1]. Other survey articles [4,5] show the latest works in inter-cell interference cancellation methods on air interfaces together with backhaul systems including CoMP and CA, and provide some insights and requirements in that aspect towards 5G heterogeneous networks design. CA feature of Long Term Evolution Advanced (LTE-A) that can easily be enabled with C-RAN technology was first introduced in LTE Release 10. In the literature, there exists various works that are providing benefits and trade-offs of performing CA using simulation [6,7] and experimental analysis [8,9]. The authors in [6] have demonstrated the benefits of CA in LTE-A via simulations. The authors in [7] are comparing the performance gains as well as complexity levels of CA of three inter-band component carriers with the aggregation of two inter-band component carriers in a Long Term Evolution (LTE) system level simulator. Experimental evaluations using real-time equipment based on LTE-A to showcase the benefits of CA have been done in various works [8, 9]. Through experimental lab analysis in an LTE-A testbed, the authors in [9] have shown throughput performance gains of performing asymmetric CA for UL and Downlink (DL). Another experimental study in [10] demonstrate inter and intra-RAN CA schemes focusing on next generation 5G heterogeneous mobile networks. A single CA scenario is deployed in a commercial network to observe gains for throughput rates in [11]. An effective CA solution considering different factors such as channel, traffic demand and network load conditions in dense stadium environment is studied in [12]. The authors in [13] discuss about the standardization efforts where CA feature is enhanced using licensed and unlicensed carriers with licence-assisted access feature.

In Standard Developing Organizations, The 3rd Generation Partnership Project (3GPP) is leading the efforts for CoMP and have proposed it in different recent releases [14]. 3GPP technical report 36.819 is providing LTE physical layer aspects in Release 11 [14]. Interference rejection algorithms such as interference-rejection combining [15] have enabled the possibility of usage of multiple cell antennas for UL CoMP. CoMP which is released as LTE-A feature is expected to be an advanced for 5G New Radio (NR) as well [16]. The authors in [16] have provided an Software-Defined Networking and Network Function Virtualization based implementation of UL/DL CoMP. A comprehensive survey of CoMP for LTE-A is given in [17]. Advanced CA techniques that can adapt to interference, channel and traffic variations using schemes such as opportunistic communications, adaptive resource management and carrier selection and switching is studied in [18]. A new framework to increase the component carriers of CA systems is followed in [19]. A design of dynamic BS cluster formation for CoMP systems and joint application of CA with CoMP to increase the system throughput is studied in [20]. Energy efficiency of different DL CoMP techniques are evaluated in [21]. An analytic model for high availability analysis of user equipments (UEs) in heterogeneous cellular networks (HetNets) using the benefits of both CA with CoMP is analyzed in [22,23]. A carrier scheduling scheme to enhance QoS of mobile traffic using CA is studied in [24]. Synchronization requirements of new 5G technologies including CA and CoMP are analyzed in [25]. The effect of mobility aware clustering while using advance LTE features including CA and CoMP is discussed in [26].

In terms of field experiments, observations of CoMP implementation within C-RAN demonstrate UL CoMP gain between 50% and 100% in [27]. A field trial experiment of UL intra-site CoMP in one of the business district of Belgrade, Serbia is given in [28] where an improvement in terms of UL data throughput is demonstrated. In our recent work of [29], we have investigated the performance improvement of SFN deployment using C-RAN in one of the real-world experimental test site of a MNO in Istanbul, Turkey. However, note also that CoMP gain is highly dependent on different factors including load in the system and antenna characteristics. Therefore, field trials experimentation parameters should carefully be adjusted for optimal performance gains.

1.2 Our contributions

In this paper, we present experimental results for implementation of C-RAN techniques (focusing on CA and CoMP) together with radio and fronthaul sides inside one of the major MNO infrastructure's live network in Istanbul, Turkey. Although there have been many studies on showcasing the benefits of C-RAN, and many MNOs have already demonstrated their CA implementation and results in the past, none of the above works have demonstrated real-world implementations of C-RAN technologies especially in the context of CA and CoMP by studying different deployment scenarios that can be utilized depending on MNOs' different strategies. Using the advantages of high speed fiber connections, C-RAN can provide better user-experience in cell-edge areas thanks to improved site and cell coordination efforts of C-RAN. Moreover, in case there exists less fiber resources to multiple remote sites, active Dense Wavelength Division Multiplexing (DWDM) can be used that can manage traffic with high availability.

Our main contributions in this paper are following:

- We propose three different CA deployment scenarios for C-RAN and investigate their characteristics, potential benefits and limitations.
- We provide experimental Key Parameter Indicator (KPI) performance gains and differences of the considered three CA deployment as well as UL CoMP deployment scenarios over a real live network of a MNO's infrastructure.
- Our experimental results indicate up to 7%, 9% and 6% improvements in UL cell, user and CEU throughput respectively, even in low load conditions using inter-BBU UL CoMP deployment.

The rest of the paper is organized as follows: System model and concepts as well as general architecture of C-RAN is given in Section 2. We present the considered CA scenarios, their characteristics, benefits and limitations in Section 3. Section 4 is describing UL CoMP experimental testbed deployment details. In Section 5, experimental results of the considered CA scenarios as well as UL CoMP are provided. Finally, we provide conclusions and future work in Section 6. A summary table illustrating the abbreviations and their corresponding descriptions used throughout the paper are also given in Table 3.

2 System Model and Concepts for C-RAN

C-RAN (sometimes also referred to as Cloud-RAN) is an architecture for future cellular networks that was first introduced by Chine Mobile in 2010 [30]. C-RAN can support 2G, 3G, 4G and future cellular wireless access standards in order to ensure cloud-based architecture for radio access networks (RANs). It consists of three main components: **BBU pool**, **RRU networks** and **Fronthaul**. **BBU pool** is located at a centralized location. It consists of multiple BBUs with high computational and storage capabilities. Based on the current network demands, BBUs are processing resources and dynamically allocating them to RRUs. **RRU networks** are the wireless access points or towers similar to traditional cellular networks. **Fronthaul** is the connection layer between a BBU and a set of RRUs that can provide high bandwidth links to accommodate high speed requirements of RRUs. Optical fiber connection is one way of realizing fronthaul in real networks.

The main motivation of C-RAN is to allow inter-eNodeB coordination support such that sharing status information between cell and UE and joint scheduling between cells can be performed. Moreover it can move BBUs into a centralized location in order to utilize the resources, e.g. BSs, efficiently. C-RAN evolution from distributed radio access network can provide benefits in terms of providing simpler site installation, easier evolution with new hardware and technology, reduced cost and higher performance gains for MNOs. Hence, C-RAN architecture can pave the way for the implementation of latency sensitive applications via introducing features such as multi-access edge computing for vertical domains, e.g. for vehicular 5G communications.

2.1 LTE-A Features

For our analysis, we investigate the following two major features of LTE-A:

- **Inter-BBU CA:** In this feature, overlapping inter-eNodeB's inter-carrier neighbours can perform CA to enhance cell-edge user performance using inter-BBU communication of C-RAN. This will improve the throughput performance of CEUs and their quality-of-experience (QoE).
- **Inter-BBU UL CoMP:** In this feature, UL joint reception between eNodeBs can be utilized by shar-

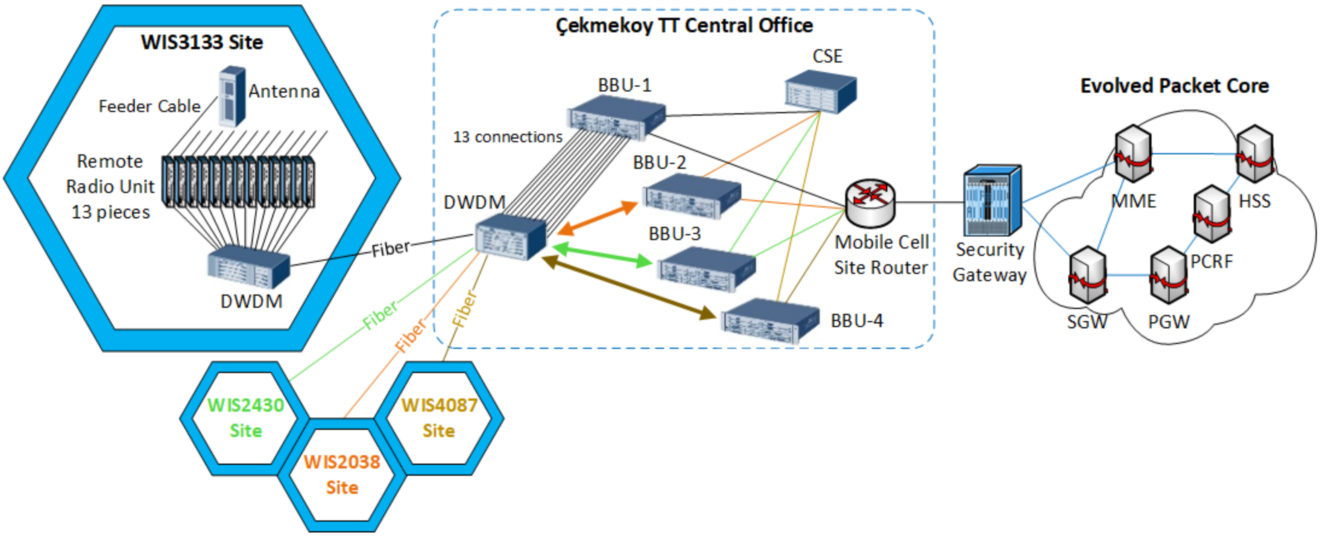


Fig. 1: General illustration of C-RAN architecture RRUs to backhaul network connection plan for one of the four considered trial sites.

ing channel status information and user data between cells to mitigate inter-cell interference using inter-BBU communication of C-RAN. Using this feature, UL signals are jointly received by multiple points. This feature can also improve cell coverage and performance, especially for CEUs.

2.2 C-RAN architecture and components

A general architecture of the experimental set-up used in this paper is shown in Fig. 1. This architecture demonstrates one of the four sites' connection plan from RRU to backhaul network. For evaluating the eICIC solutions, four sites are chosen from Cekmekoy cluster region. Moreover, all sites are connected to centralized location in Cekmekoy district for C-RAN with fronthaul connection. All LTE-A sites are centralized in this BBU pool of Cekmekoy district. In C-RAN architecture, the following components are present: Inside C-RAN centre location, the installed equipment are: four $\times$ BBUs for four trial sites, one switch for controlling C-RAN coordination features named as Controlling Switch Element (CSE) in Fig. 1, one Optical Service Network (OSN) equipment for DWDM transmission and one Global Positioning System (GPS) antenna connected C-RAN coordination switch for time synchronization purposes. For remote sites, one OSN equipment for each 3 sites ($WIS2038$, $WIS3133$, $WIS2430$), and two OSN equipments for other site ($WIS4087$) are used.

CSE is one of the main equipments used for BBU coordination and is used to connect different BBUs of RRUs to build coordinating cells.. The equipment used in trial experiments can support up to 60 BBUs. All LTE-A features for inter site CA and UL CoMP are all deployed over this controlling switch. A GPS antenna is also connected to the switch due to tight time synchronization requirements for BBU coordination.

3 Considered scenarios for inter and intra-BBU CA

In this section, we consider three scenarios for intra and inter-BBU CA. Note that in analysis below, E-UTRA Absolute Radio Frequency Channel Number (EARFCN) = 1450 sites are working with 1800 Mhz and named as $L1800$ and EARFCN = 6200 sites are with 800 Mhz and named as $L800$. In a typical CA system, there can be two serving cells: Primary Cell (PCell) and Secondary Cell (SCell). PCell is responsible for handling Radio Resource Control (RRC) connection and the primary operating frequency for UE. On the other hand, SCell is the secondary operating frequency which may be used to provide additional radio resource. The coverage range of PCell and SCell depends on the allocated frequencies. Using inter-site CA, different sites' PCell and SCell values can be combined in CA to obtain higher Packet Data Convergence Protocol (PDCP) throughput. In this case, PCell and SCell of RRUs can be selected based on the best signal quality by C-RAN. Therefore compared to conventional CA, the best cell of each carrier can be selected for inter-site CA. This can result in better and seamless CA in coverage mismatch areas.

3.1 Scenario I: Multi-carrier site

For inter and intra-BBU CA, the first considered scenario is named as *multi-carrier site* scenario as shown in Fig 2. In this scenario, all two trial sites ($L800$ and $L1800$) used for experiments have co-located LTE 800 Mhz and 1800 Mhz bands. CA feature can be activated both in intra-site and inter-site scenarios. Due to interest of experimental analysis on coverage issues for CEUs, we have performed our experimental studies on inter-BBU CA operational area which is at the cell-edge of both sites as pointed by Fig 2, i.e. the overlapped area of two sites.

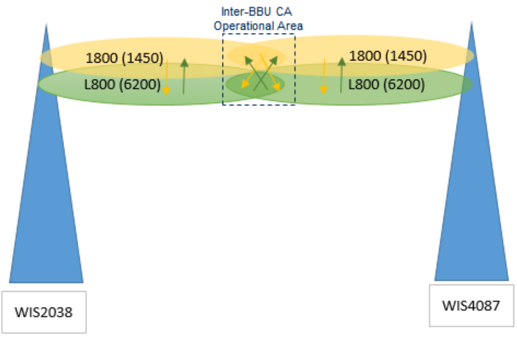


Fig. 2: Inter-BBU CA Scenario I: Multi-carrier site.

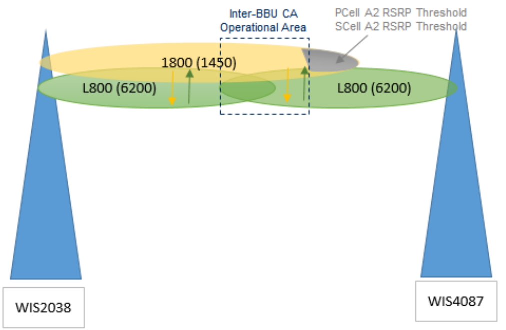


Fig. 3: Inter-BBU CA Scenario II: L1800 umbrella coverage.

3.2 Scenario II: L1800 umbrella coverage

For inter and intra-BBU CA, the second considered scenario is named as *L1800 umbrella coverage* as shown in Fig 3. In intra-site CA case, there will not be CA throughput gain for $L800$ in $WIS4087$ site. In inter-site CA case, CA throughput gain is available since SCell is covered with $WIS2038$. This coverage design represents

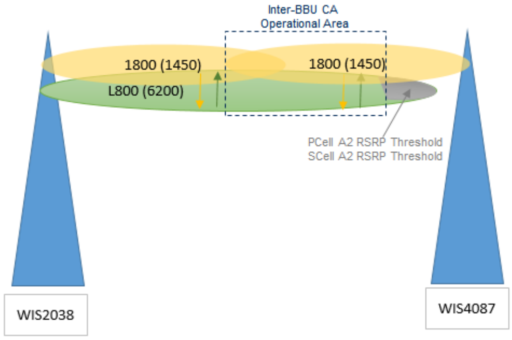


Fig. 4: Inter-BBU CA Scenario III: L800 umbrella coverage.

the condition when a MNO has dominant $L800$ single carrier sites in large areas. To satisfy CA coverage from dual carrier site of $WIS2038$, boosting the RF power or up-tilt of antenna is required for $L1800$ carrier to cover more CEUs. Since $L1800$ carrier has more capacity than $L800$ carrier, in this scenario the throughput of end users is expected to be high in cell edge areas. One of the main benefit of using this scenario is that due to lower number of $L1800$ sites, interference will be reduced. This can provide better national coverage. This can also increase the throughput of cell-center UEs. On the other hand, Scenario II is only suitable for MNOs that are providing nationwide $L1800$ coverage. Generally, the strategy of MNOs is to keep CEUs at lower frequencies, e.g. at $L800$ Mhz rather than 1800 Mhz to increase the coverage. Therefore, careful deployment is needed in order to obtain performance gains for CEUs.

3.3 Scenario III: L800 umbrella coverage

The third scenario is named as $L800$ *umbrella coverage* for inter and intra-BBU CA as shown in Fig 4. In intra-site CA case, there will be no CA throughput gain for $L1800$ in $WIS4087$ site. In inter-site CA case, CA throughput gain for $L1800$ in $WIS4087$ will be available, since SCells are covered from $WIS2038$. Therefore, larger CA gains can be obtained with intra-BBU compared to inter BBU case. Note that *L800 umbrella coverage* design may not be suitable for MNOs that have less number of $L1800$ single carrier sites in their BS inventories while providing national coverage. Moreover, capacity issue of $L800$ can also be a problem when this design is implemented in a commercial network. The consumption of DL Physical Resource Blocks (PRBs) can also lead to congestion issues if more users are selected from cell center.

Finally, comparisons of the considered three scenarios of CA in terms of their characteristics, benefits and limitations are summarized in Table 1.

4 Inter-BBU UL CoMP

LTE-A systems can suffer from intense interference problems. CoMP feature activation can potentially improve network coverage and spectral efficiency in LTE-A systems. The main advantage is to convert inter-cell interference into useful signal using joint interference mitigation algorithms. This is achieved with coordinating cells that can share both channel as well as data. CoMP can be utilized between macro-macro, micro-micro and macro-micro sites. In this paper, we only utilize CoMP between macro-macro BSs. Intra and inter-BBU CoMP are two of the deployment scenarios of UL CoMP based on 3GPP standards [31]. Intra-BBU UL CoMP is the easiest deployment due to existence of adequate communication between cells of same eNodeBs. On the other hand, inter-BBU deployment needs higher sensitive requirements on latency, jitter and capacity for fronthaul. Therefore, in this study our main focus is on performance gains on inter-BBU UL CoMP.

UL CoMP UEs are UEs whose signals are received by multiple antennas of multiple cells. For UL CoMP, two types of UEs can be defined: Cell-center UEs and CEUs benefiting from UL CoMP. UL CoMP CEUs are located at the cell-edge which are expected to gain from signal combining gains, hence from UL CoMP activation process. Hence, UL CoMP feature can be activated for these CEUs if there exists adequate PRBs. UL CoMP cell-center UEs are located inside the cell center and are affected by interference from CEUs. Hence, cell-center UEs are expected to benefit from interference mitigation gains of inter-BBU UL CoMP feature. In our experimental results for throughput metrics, UL CEU throughput considers only CEUs' throughput values, UL average user throughput considers both cell-center UEs and CEUs' throughput values and UL average cell throughput measures cell capacity. For interference and quality metrics, Physical Uplink Control Channel (PUCCH)/ Physical Uplink Shared Channel (PUSCH) Reference Signal Received Power (RSRP) and Received Signal Strength Indicator (RSSI) values in UL are monitored. RSRP measurements are important for UL signal receptions in eNodeBs, whereas RSSI measurements are important to measure the results of interference mitigation in the system. For Block Error Rate (BLER) measurements, two categories of Initial BLER (IBLER) and Residual BLER (RBLER) are utilized. IBLER is considered to be the Negative-Acknowledgement (NACK) that is received when eNodeB will have to retransmit the data in first instance.

If UE is unable to decode the data even after retransmission, UE will send another NACK and the eNodeB will have to retransmit again. However, there is a limit to these retransmissions and usually they are configurable. Commonly, these retransmissions are set to 4 and after 4 retransmissions, the eNodeB will not retransmit at Hybrid Automatic Repeat reQuest (HARQ) level and consider this as a RBLER.

UL CoMP provides two main gains for cell-center UEs and CEUs: First one is **signal combining gains** and second one is **Interference mitigation gains**. **Signal combining gains** are obtained for CEUs combining signals from two different cells. **Interference mitigation gains** are obtained for cell-center UEs that experience interference due to intra-frequency neighbor cell from UL CoMP CEUs. Together with joint interference rejection algorithms [15], cell-center UE's interference can be mitigated. The interference mitigation gain is proportional to the original interference received from UL CoMP CEUs.

5 Field Experiment Results

For evaluating the performances of CoMP as well as different CA scenarios, we deployed and tested CoMP and each CA's corresponding three scenarios individually in Cekmekoy suburban district of Istanbul, Turkey as shown in Fig. 6. For experimental trials, we used commercial Evolved Packet Core (EPC) and eNodeBs together with test and real UEs. For CA and UL-CoMP features, no changes were done in Radio Frequency (RF) plans. Testing area covers 1.0353 km^2. During field trial, up to four sites i.e. 12 FD-LTE carriers can be centralized. Each sector requires one common public radio interface connection whose capacity is highly dependent on Multiple Input Multiple Output (MIMO) and bandwidth configurations. Fig. 5 shows the BBU pool used in central location of C-RAN in Cekmekoy district in Istanbul. In order to evaluate the impact of C-RAN features, we have performed system performance comparisons over extensive test cases including throughput, traffic volume, BLER, PRB utilization and retransmission rates, Modulation Coding Scheme (MCS), RSSI and RSRP changes.

5.1 Site Configurations

Site connection plan from RRU to backhaul network connection for one of four sites is given in Fig. 6. Red circled area (1.0353 km^2) represents the C-RAN trial

Table 1: Considered three CA scenarios characteristics, limitations and benefits

CA Strategy	Characteristics	Limitations	Benefits
Scenario I: Multi-Carrier Site	PCell and SCell are present in both cell-sites. (WIS2038 & WIS4087)	Need to use both 800 and 1800 Mhz in each site. All the co-located sites must work in both bands. Hardware cost for BBU. Difficult to avoid interference on 800.	Higher CA gains in both for inter and intra-BBU cases. There is already intra-site CA, this model increases the performance of users in cell edge by doing inter-site CA.
Scenario II: L1800 Umbrella Coverage	PCell and SCell are present in WIS2038 and only PCell is present in WIS4087 cell-sites. 1800 Mhz is umbrella for WIS2038	More suitable for MNOs providing national L1800 coverage. Careful deployment needed to increase cell-edge users' performance.	Increase coverage in 1800 Mhz, because there is no counter 1800 site. Reduce interference in 1800. Improve performance of cell center users. Fewer 1800 Mhz bands are used.
Scenario III: L800 Umbrella Coverage	PCell and SCell are present in WIS2038 and only PCell is present in WIS4087 cell-sites. 800 Mhz is umbrella for WIS2038	More suitable for MNOs providing national L800 coverage. Less performance effect on cell edge users. If coverage with 1800 Mhz can not be achieved with surrounding sites, coverage gap can occur.	Higher CA gains in intra-BBU case and lower gains in inter-BBU case. If more users are taken from the cell center in narrow band then DL PRB Consumption will lead congestion.

Fig. 5: BBU pool used in central location of C-RAN in Cekmekoy district of Istanbul.

sites (for UL CoMP and CA) and purple circled area (2.99 km^2) represents the neighboring sites of the C-RAN trial sites (tier 1 sites) as also given in Table 2. Blue colored cells represent 1800 Mhz, whereas orange colored cells represent 900 Mhz sites. Additionally, sites starting with letter "W" and "U" represent 4G and 3G sites respectively. The distance to central office of radio sites is 0.93 km and Tier-1 site $WIS4956$ is co-located on central office. We collect hourly KPI monitoring values after activation of each feature. If there exists any KPI degradation, roll-backs to previous configurations are performed due to live network testings.

Table 2: Site distribution for trial and tier 1 sites

Trial's Sites	Tier 1 Sites
WIS2038	WIS4253
WIS4087	WIS4956
WIS3133	WIS2646
WIS2430	WIS3323
	WIS4285
	WIS2056
	UIS3525

5.2 Inter-BBU UL CoMP Performance Results

Our performance monitoring experiments for *Inter-BBU UL CoMP* were performed between 20 February 2017 and 04 March 2017. Inter-BBU UL CoMP is activated between 01 – 04 March 2017. For fair comparisons, we have again compared the performance differences with respect to exactly one week before inter-BBU UL CoMP activation, i.e. between 22 – 25 February 2017.

Fig. 7a and Fig. 7b illustrate the average UL CoMP values for MCS index and PRB utilization rates respectively. The average PUSCH MCS update results in Fig. 7a indicate that average UL acPUSCH MCS index relative to previous week has increased from 14.49 (yellow area) to 14.58 (blue area). Fig 7b shows that due to asymmetric traffic in DL and UL, UL PRB utilization rate (%) values are generally low (i.e. below 10%). However, we observe a slight increase in PRB usage rate from 9.08% (yellow area) to 9.13% (blue area) when CoMP is activated in blue region. This is because of the fact that CoMP implementation is expected to increase the signaling traffic due to usage of joint interference mitigation techniques.

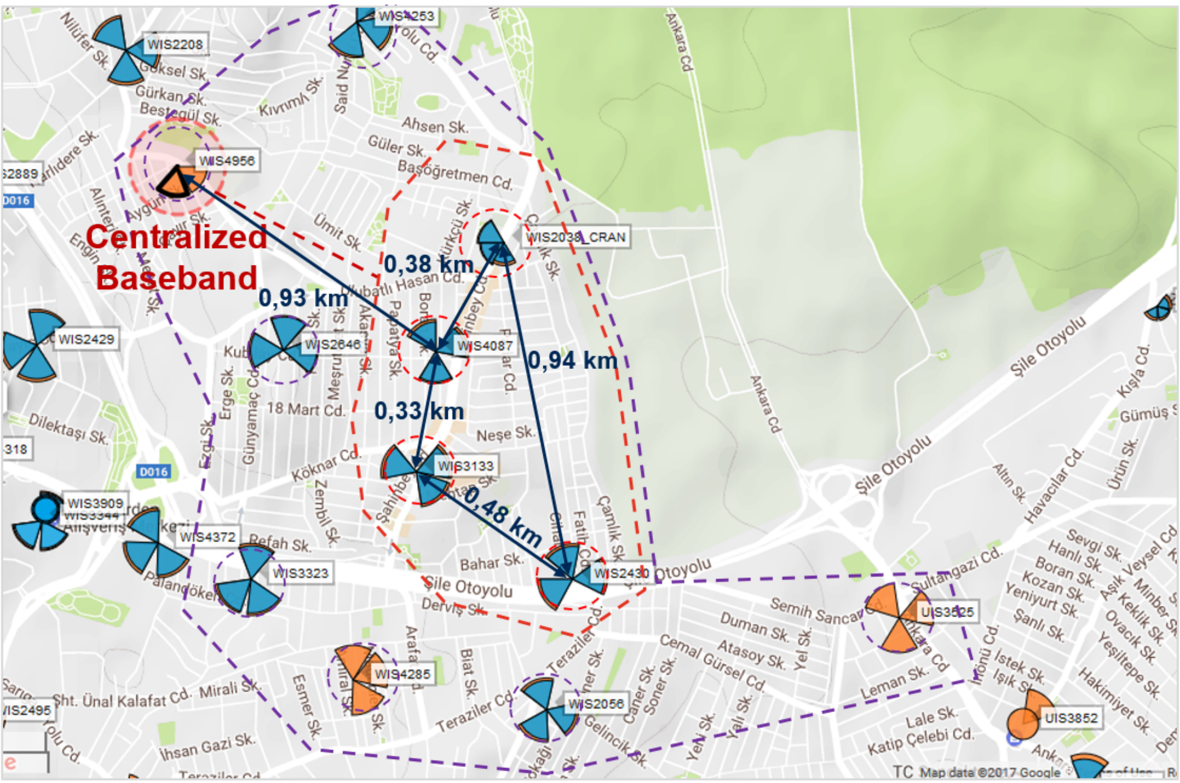
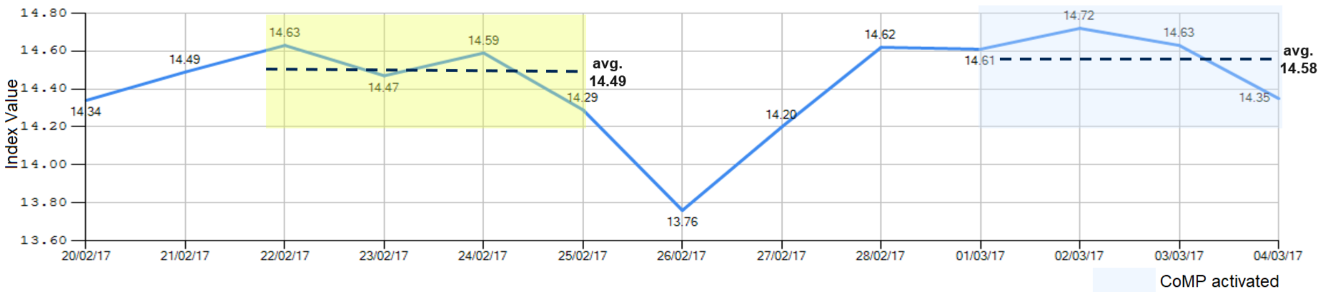
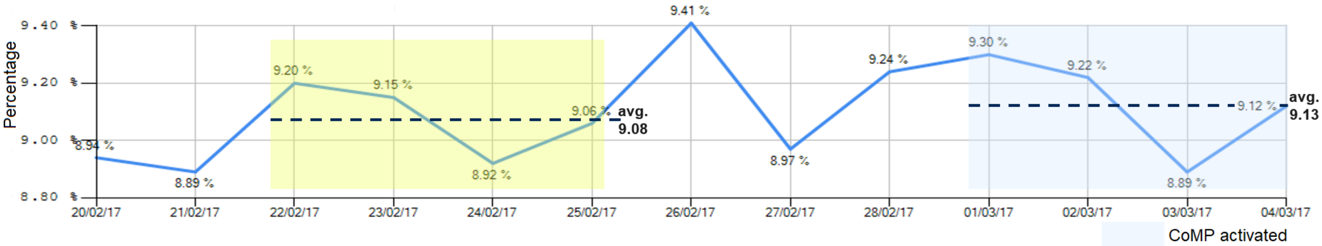


Fig. 6: Distribution of C-RAN experimental sites over Cekmekoy district in Istanbul, Turkey.

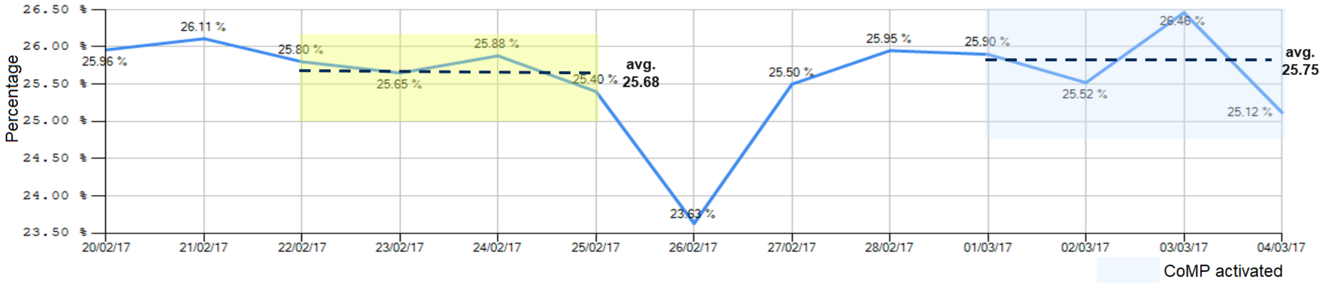


(a)

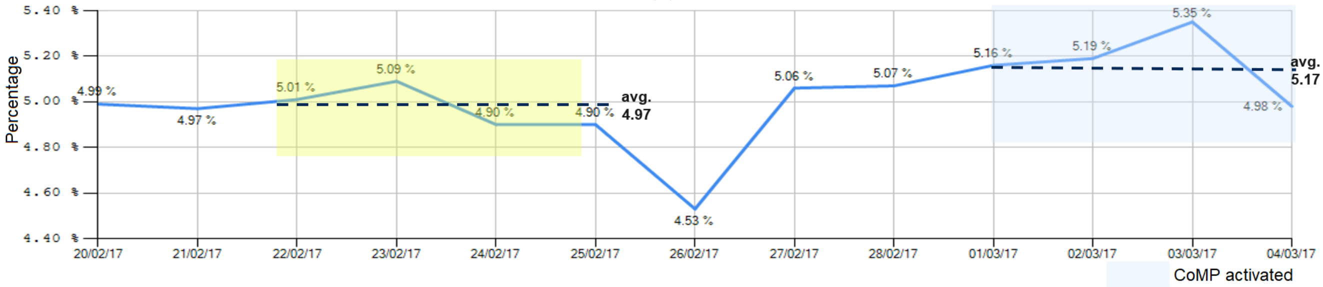


(b)

Fig. 7: Average UL CoMP (a) PUSCH MCS index values. (b) PRB utilization rate



(a)



(b)

Fig. 8: Percentage of KPIs for inter-BBU UL CoMP MAC (a) IBLER (b) RBLER

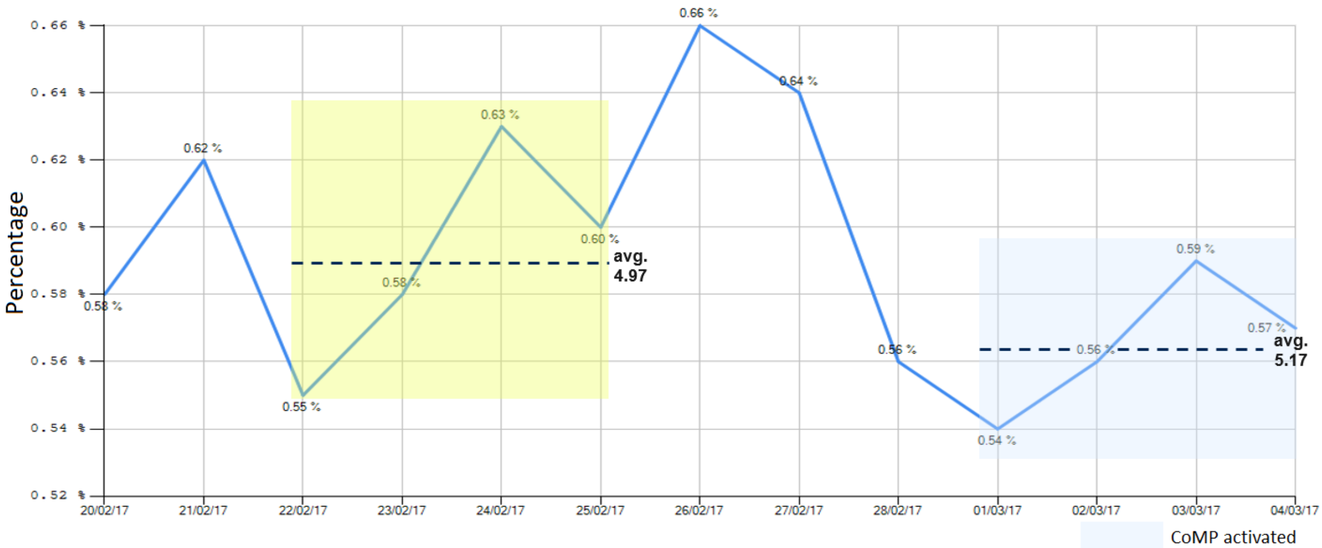
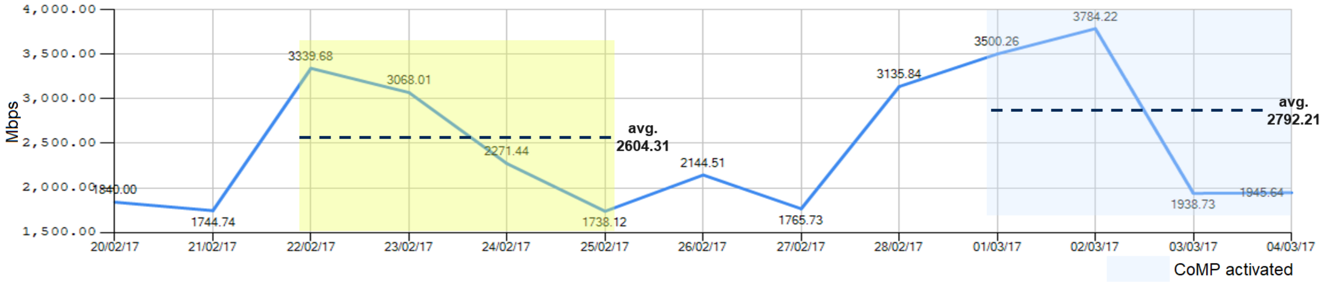


Fig. 9: Percentage of RLC retransmission rate (%).

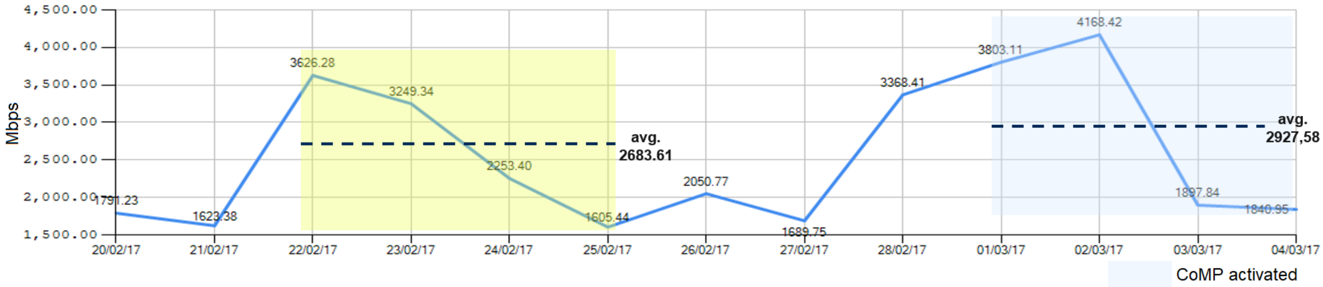
Fig. 8 shows the percentage of KPIs for inter-BBU UL CoMP Media Access Control (MAC) for IBLER (%) and RBLER (%) values. We can also observe from Fig. 8a and Fig. 8b that IBLER and RBLER on UL side have relatively increased due to the effect of higher MCS. In comparison, IBLER (%) has slightly increased from 25.58% (yellow area) to 25.75% (blue area) and RBLER (%) has increased from 4.97% (yellow area) to 5.17% (blue area).

Fig. 9 shows Radio Link Control (RLC) retransmission rate (%) results. In RLC acknowledgement mode, re-transmission starts at RLC level after HARQ re-transmission is completed at MAC level. In contrary to increased IBLER (%) and RBLER (%) values, average RLC BLER percentages have decreased from 0.590% (yellow area) to 0.565% (blue area) as observed in Fig. 9.

Fig. 10 shows inter-BBU UL CoMP for cell, user and CEU average throughput values over the observation duration. Cell UL average throughput values have increased from 2604.31 Mbps (yellow area) to 2792.21 Mbps (blue area) (UL cell throughput increase about 7.2%) as given in Fig. 10a. Additionally, UL user through-



(a)



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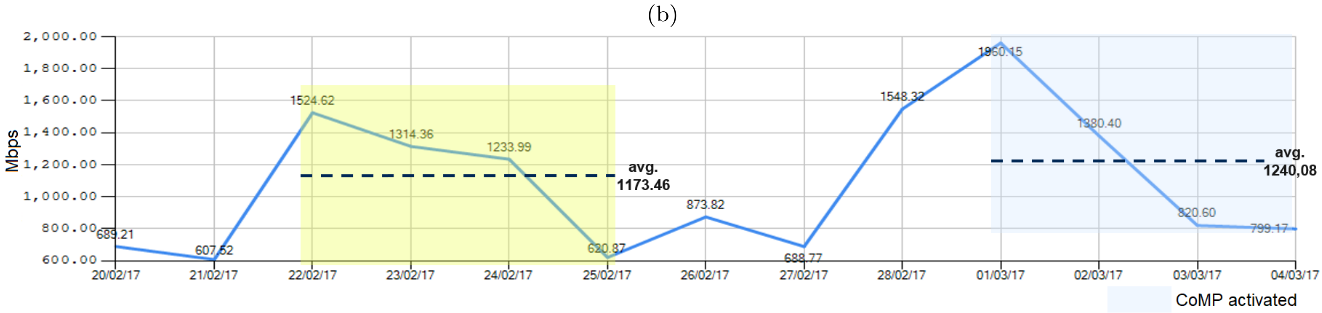


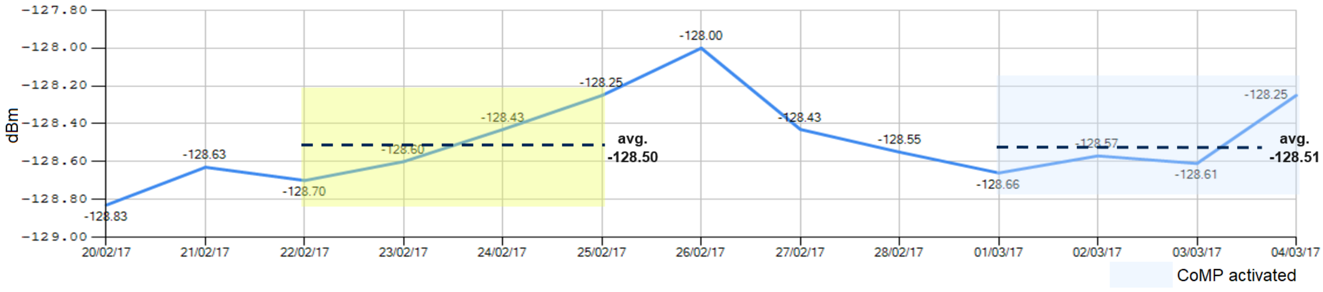
(c)

Fig. 10: Average throughput values for Inter-BBU UL CoMP (a) Cell throughput (b) User throughput (c) UL CEU throughput

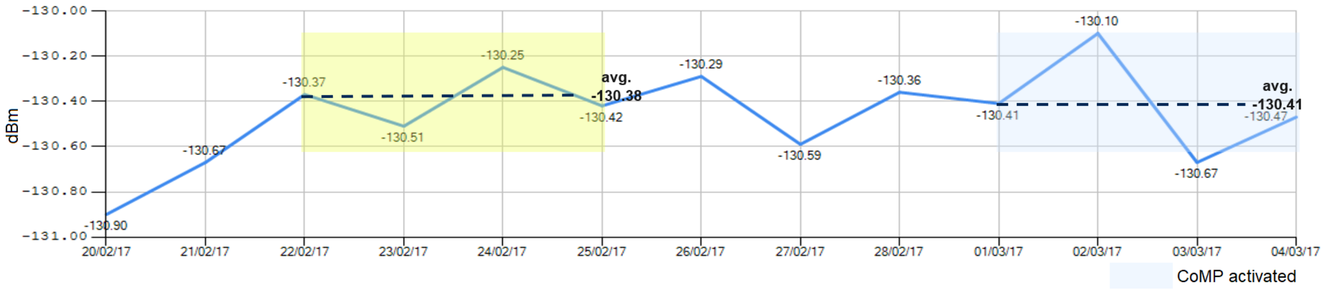
put values that consider both CEUs and cell-center UEs CoMP improvements show that the throughput have improved from 2683.61 Mbps (yellow area) to 2927.58 Mbps (blue area) (UL user throughput increase about 9.1%) as given in Fig. 10b. UL CoMP CEUs improvements in Fig. 10c show that the throughput increases from 1173.46 Mbps (yellow area) to 1240.08 Mbps (blue area) (an UL CEU throughput increase about 5.6%).

Fig. 11 shows the average counter values for Inter-BBU UL CoMP for RSRP PUCCH and PUSCH as well as RSSI PUCCH and RSSI PUSCH values over the observation duration. Fig. 11a shows that RSRP PUCCH values stays almost the same around -128.5 dBM, Fig. 11b shows that RSRP PUSCH values are around -130 dBM, Fig. 11c shows that RSSI PUCCH values stays almost the same around -115.9 dBM and Fig. 11d shows that RSSI PUSCH values are around -117.9 dBM. Hence, the key finding of Fig. 11 is that with and without UL CoMP feature activation, average counter values for inter-BBU UL CoMP have almost remained the same. Therefore, trial results demonstrate no significant impact on received RSSI and RSRP qualities.

Main Takeaways of CoMP experiments: Inter-BBU UL CoMP feature's target is to improve user experience in cell edge areas. Our KPI results in real-world experiments show that with this feature UL CEU peak throughput can be improved significantly. Even though the system is not fully loaded (due to low PRB utilization of Fig. 7b), thanks to interference mitigation techniques UL MCS values have increased on cell-edge and for CEUs. Moreover, RLC BLER values have decreased during UL CoMP activation process. These changes have also been reflected in overall throughput values although IBLER (%) and RBLER (%) values have slightly increased. In UL PRB utilization rate %, no overhead percentage increase is observed due to retransmissions. Nonetheless, UL CoMP behaviour heav-



(a)



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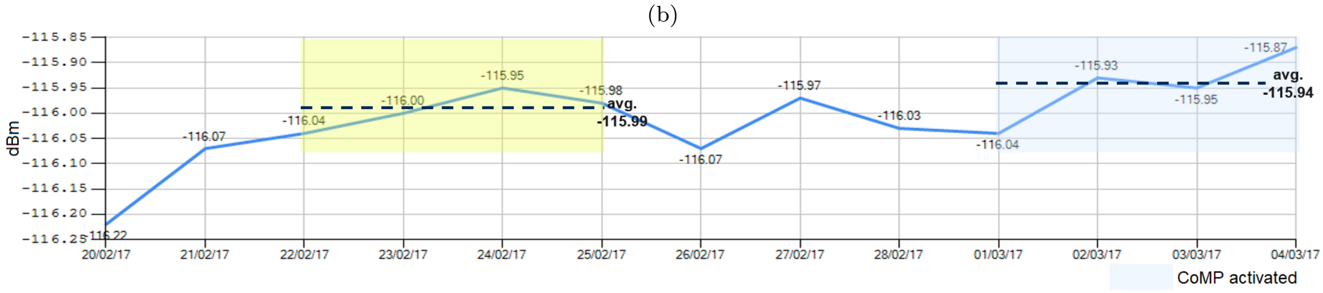

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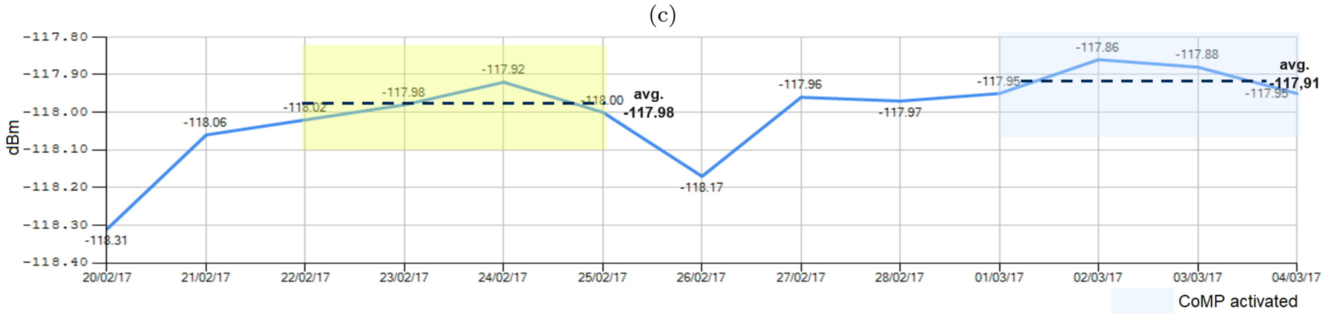


(d)

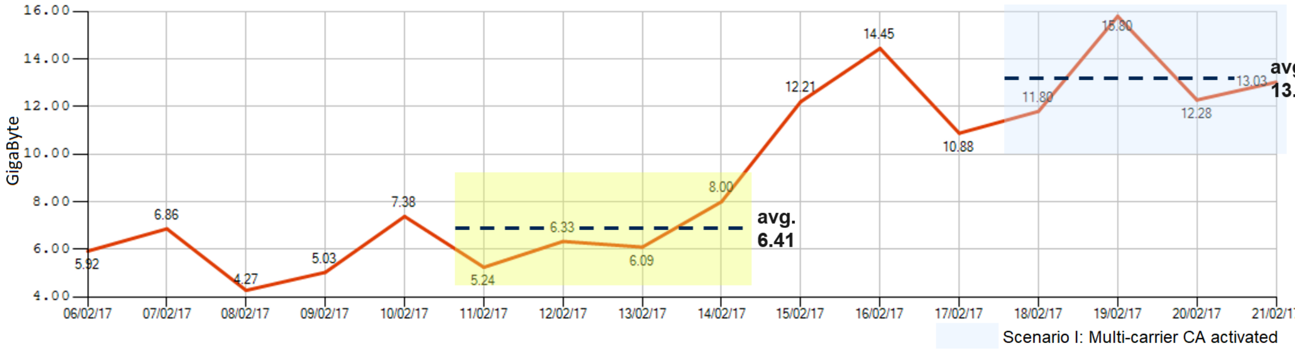
Fig. 11: Average counter values for inter-BBU UL CoMP (a) RSRP PUCCH (b) RSRP PUSCH (c) RSSI PUCCH (d) RSSI PUSCH

ily depends on the cell load and number of receive antennas. The main performance gains are expected to increase in high UL load and low receive antennas (e.g. two antennas) after UL CoMP is activated [14]. Therefore, enabling UL CoMP feature can be suitable for deployments in sites where high UL rates are needed, e.g. stadiums and shopping malls. In summary, our results indicate the following improvements of utilizing coordinated inter-BBU UL CoMP in comparison to non-activation scenario:

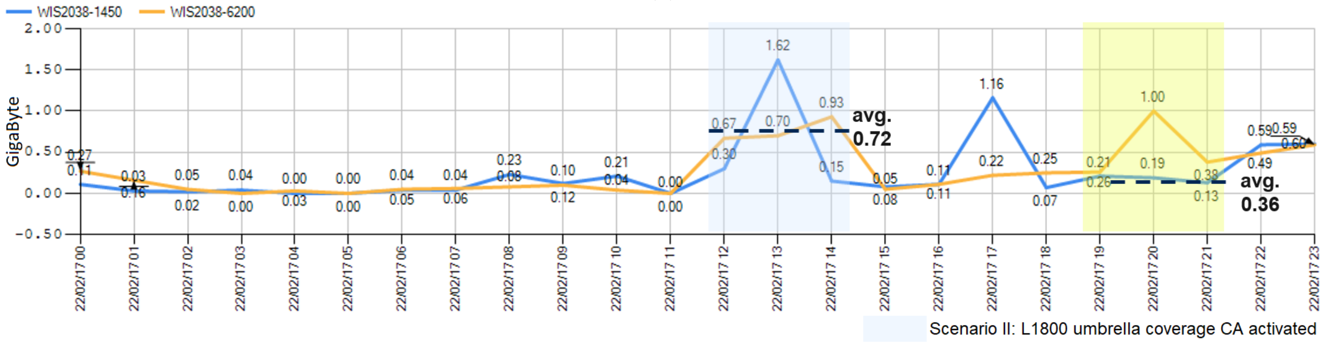
- UL cell throughput increased about 7%.
- UL user throughput increased about 9%.
- UL CEU throughput increased about 6%.

5.3 Inter-BBU CA Performance Results

For evaluation purposes of CA, we have used only two sites with cell-IDs $WIS2038$ and $WIS4087$ of Table 2 and Fig. 6 and have shown the experimental results of



(a)



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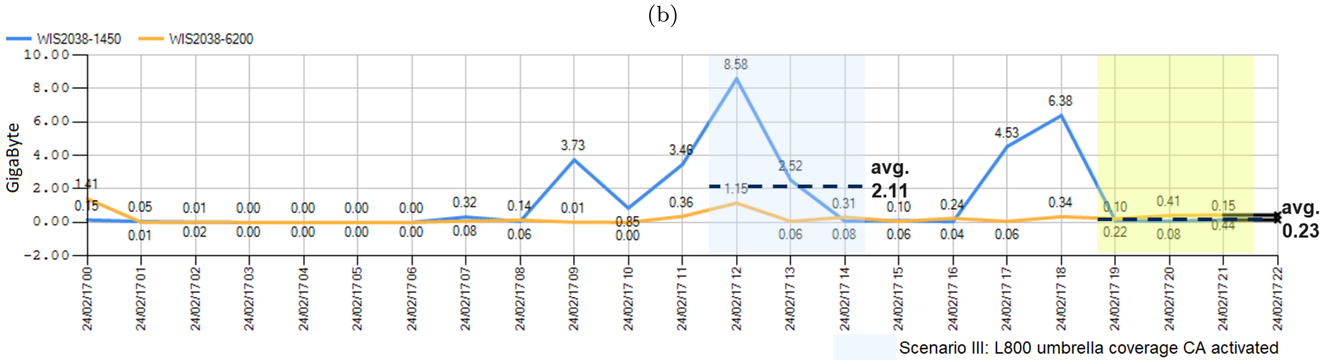

(c)

Fig. 12: Experimental results for average traffic volume (a) Scenario I: Multi-carrier (b) Scenario II: L1800 umbrella coverage (c) Scenario III: L800 umbrella coverage.

$WIS2038$ only (which performs umbrella coverage) for *Scenarios II and III.*

Fig. 12 and Fig. 13 depict the experimental trial results for the considered three scenarios experimented in suburban district of Cekmekoy in Istanbul, Turkey. Our experiments for *Scenario I* were done between $18-21$ February 2017 (4 days), *Scenario II* on 22 February 2017 and *Scenario III* on 24 February 2017. For *Scenario I:* we have performed long term daily measurements to observe the gains with respect to no CA activation period, i.e. (the KPI values are compared with the obtained average values of one week before, i.e. between $11-14$ February 2017 (4 days) for fair comparisons). For *Scenario II* and *Scenario III*, we have performed hourly measurements (the comparisons are done with busy hours (between $19:00-21:00$h) and non-busy hours (between $12:00-14:00$h traffic). The experiments are done with real-users in the operational cellular network. A general test site statistics for the C-RAN used for CA results are as follows: Average active CA users (per hour) for scenario I, II and III are 38, 5 and 4 respectively, number of RRUs and BBUs are 2, the observation duration of Scenario I is 16×24 hours whereas it is 23 and 22 hours for Scenario II and III respectively.

We have utilized $WIS2038$ and $WIS4087$ sites for two BBUs scenarios since their antennas face each other which results in higher interactions. The blue colored

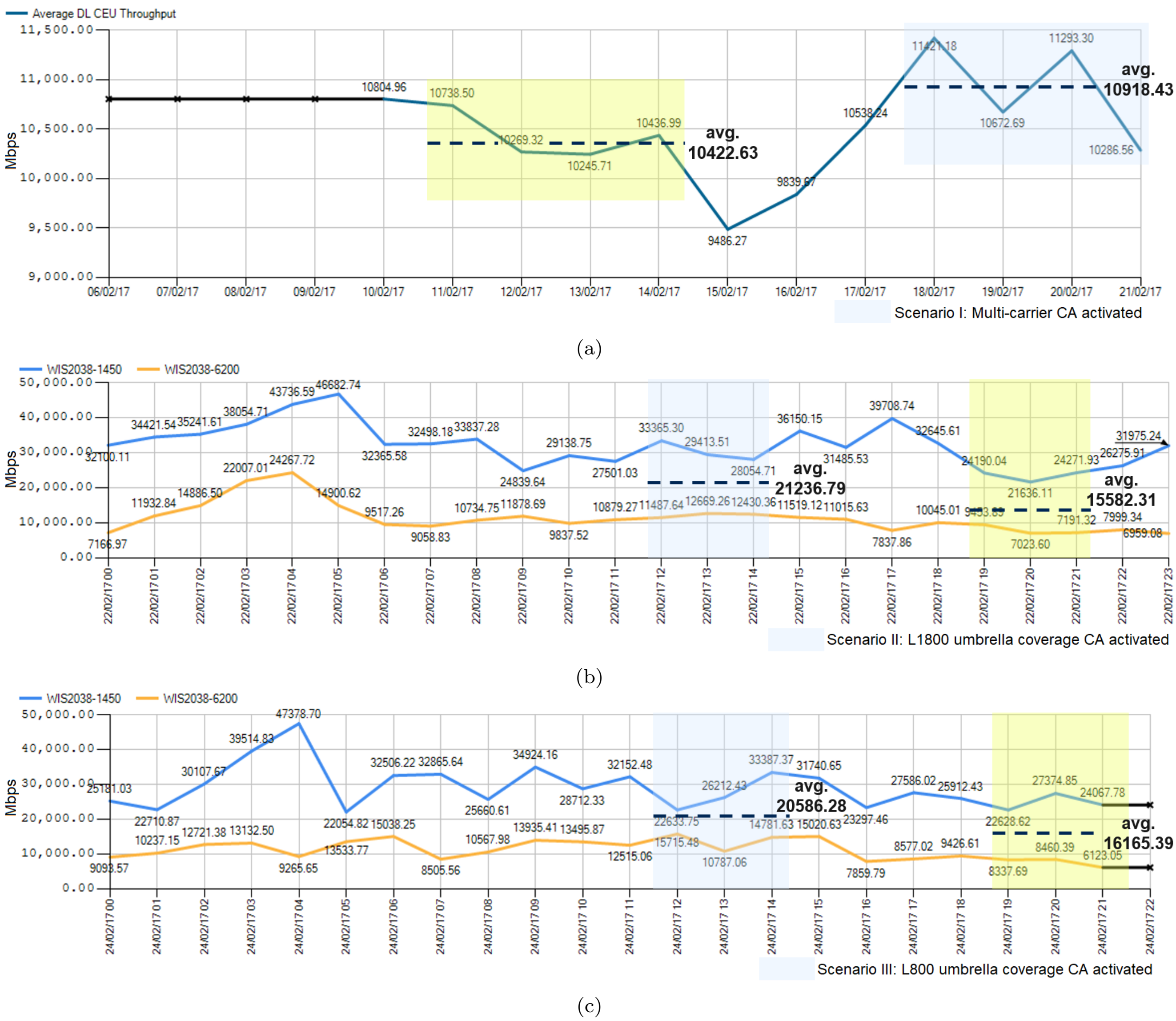

Fig. 13: Experimental results for average CEU DL throughput (a) Scenario I: Multi-carrier (b) Scenario II: L1800 umbrella coverage (c) Scenario III: L800 umbrella coverage.

days mark the period of time when inter-BBU CA feature is activated and yellow marked days mark the period one week (or busy hour traffic in hourly observation scenarios II and III) before the feature activation for fair comparisons in terms of improvements. From Fig. 12a, we can observe that in all the considered scenarios CA traffic volume improvements have been observed. More specifically, compared to exactly one week earlier values, *Scenario I: Multi-carrier site*'s average traffic volume (i.e. the average of two experimental sites) has improved from 6.41 GB to 13.22 GB (%106 traffic volume improvement), whereas compared to busy-hour traffic *Scenario II: L1800 Umbrella Coverage*'s average traffic volume has increased from 0.36 GB to 0.72 GB (%100 traffic volume improvement), and finally *Scenario III: L800 Umbrella Coverage*'s average traffic volume has increased from 2.11 GB to 0.23 GB (%817 traffic volume improvement). The main reason for higher traffic volume in Scenario I is due to higher interactions between the selected sites which creates higher overlapping areas.

Fig. 13 shows the average CEU DL throughput values for the considered three scenarios. In *Scenario I: Multi-carrier site* of Fig. 13a, the average CEU DL throughput increases from 10422.63 Mbps to 10918.43 Mbps corresponding to 4.7% increment. We can also observe from Fig. 13b and Fig. 13c that the DL CEU throughput values of *Scenario II* and *Scenario III* are also improved respectively after activating the CA feature in blue marked days in comparison with the no CA activated phase of yellow marked days corresponding to busy-hour traffic. Fig. 13b shows an increment from 15582.31 Mbps to 21236.79 Mbps which corresponds to 36% increment and Fig. 13c shows an increment from 16165.39 Mbps to 20586.28 Mbps which corresponds to 27.3% increment.

Main Takeaways of CA experiments: As expected after activation of inter-BBU CA feature, the throughput of CEUs and total traffic volume have increased. The experimental results demonstrate that even in non-busy hours, CA feature in all scenarios can boost transmission capabilities and expand bandwidth when compared with the busy hour traffic usage results. Note that in *Scenario I*, we have both PCell and SCell in two trial sites, i.e. in $WIS2038$ and $WIS4087$. This existence results in an improved aggregated PDCP throughput values for all UEs including CEUs. However, our results also indicate that very careful network planning and deployments such as having large inter-cell intersection areas, appropriate band configurations, considering user densities including CEU, etc) need to be done to observe the significant impact of inter-BBU CA feature in C-RAN on operational networks especially for CEUs.

Summary and main discussions on experimental results: The considered scenarios are selected from both technical and operational point of view to cover a wide range of MNO policies. Our results indicate that UL CoMP with C-RAN is beneficial for increasing UL coverage and throughput due to employment of interference mitigation techniques at BSs. In terms of performance gains, as long as the intersections between cell sites and user population on those intersecting sites exist, UL CoMP is expected to bring benefits to MNOs. Similarly in DL throughput, CA feature with C-RAN can also bring benefits to users of MNOs as long as the cell sites intersections are large. However, deploying CA and CoMP features with C-RAN needs very careful network planning to observe the real benefits. The considered sites need to satisfy certain conditions such as network topology (e.g. distance requirements between centralized location and/or between sites), conditions of the user behaviour in the considered sites (percentage of CEUs, handover rates between sites, etc), appropriate configurations (band, etc.) and enlarged inter-cell intersection areas depending on the traffic characteristics of the sites. In our experimental results to maximally benefit based on inter-site distance and cell site intersection areas, some of the bands in the cellular sites was switched off. The considered features can also be used in heterogeneous network environment with small cell and macro cells (in comparison with macro-macro cell utilization in this paper). However, deployment of C-RAN scenarios is highly dependent on the policies of MNOs such as investment strategies of MNO on fronthaul depending on the location (for urban, suburban or rural deployments), limitations on deployment strategy of high speed optical lines, fronthaul quality as well as CaPEX and OpEX concerns over C-RAN deployments.

The utilized sites in this paper are classical distributed sites and there exists live traffic on them. Therefore, the sites are centralized as a functionality testing of the considered scenarios since the centralization is done via the optical line that depends on the location of the nearby local datacenter. However, together with heterogeneous network plannings (macro and small cell deployments) and traffic maps of the region of deployments, the traffic over the network map can be densified with appropriate radio location planning, fiber infrastructure and optical mobile fronthaul deployments. This is especially expected to be one of the use cases of 5G where some areas may need different set of QoS requirements.

6 Conclusion and Future Work

Applying advanced C-RAN features will be significant for 5G networks and therefore, careful deployment strategies are needed. In this paper, we investigated performance results of three different CA features as well as UL CoMP feature in an experimental C-RAN based trial site in Cekmekoy suburban district of Istanbul in Turkey. First, we provided the proposed three CA scenarios' unique characteristics, benefits as well as some limitations on MNOs. Later, we performed experimental trials of these three CA scenarios as well as UL CoMP feature. Our results indicate that based on MNO's strategy and deployment scenarios of CA, there can be significant performance differences in some KPIs and anticipated gains. Our CA results demonstrated different level of increments on the throughput of CEUs as well as the total traffic volume in the network for all the considered three CA scenarios. Our UL CoMP results demonstrated that around 7%, 9% and 6% gains can be achieved in UL cell, user and CEU average throughput values respectively. These experimental results indicate that UL CoMP and CA are effective C-RAN features if appropriate network planning can be carried out in advance on the considered sites. As a future work, we are planning to investigate the performance comparisons of other LTE-A features in real-world experimental trials on live network. Moreover as complementary to experimental results which can be costly for large scale topologies and small time-scale optimization due

Table 3: A list of abbreviations and their corresponding descriptions used throughout the paper.

Abbreviation	Description	Abbreviation	Description
3GPP	3rd Generation Partnership Project	MCS	Modulation and Coding Scheme
BBU	Baseband Unit	MIMO	Multiple Input Multiple Output
BLER	Block Error Rate	MNO	Mobile Network Operator
BS	Base Station	OSN	Optical Service Network
CA	Carrier Aggregation	PCell	Primary Cell
CEU	Cell Edge User	PDCP	Packet Data Convergence Protocol
CoMP	Coordinated MultiPoint	PRB	Physical Resource Block
CQI	Channel Quality Indicator	PUCCH	Physical Uplink Common Channel
C-RAN	Centralized Radio Access Network	PUSCH	Physical Uplink Shared Channel
CSE	Controlling Switch Element	QoS	Quality-of-Service
DL	Downlink	RAN	Radio Access Network
DWDM	Dense Wavelength Division Multiplexing	RBLER	Residual BLER
HARQ	Hybrid Automatic Repeat reQuest	RF	Radio Frequency
eICIC	enhanced Inter-Cell Interference cancellation	RLC	Radio Link Control
EARFCN	E-UTRA Absolute Radio Frequency Channel Number	RRC	Radio Resource Control
EPC	Evolved Packet Core	RRU	Radio Remote Unit
GPS	Global Positioning System	RSRP	Reference Signals Received Power
IBLER	Initial BLER	RSSI	Received Signal Strength Indicator
KPI	Key Performance Indicator	SCell	Secondary Cell
LTE -A	Long Term Evolution Advanced	SFN	Single Frequency Network
MAC	Media Access Control	UE	User Equipment
-	-	UL	Uplink

to usage of real hardware, system level simulations to observe the benefits of the proposed CA and CoMP scenarios under different configuration conditions are left as a future work.

Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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