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Deployment of Beyond 4G Wireless Communication Networks with Carrier Aggregation

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Abstract—With the growing demand for a new blend of applications, the users dependency on the internet is increasing day by day. Mobile internet users are giving more attention to their own experiences, especially in terms of communication reliability, high data rates and service stability on move. This increase in the demand is causing saturation of existing radio frequency bands. To address these challenges, researchers are investigating the best approaches, Carrier Aggregation (CA) is one of the newest innovations, which seems to fulfill the demands of the future spectrum, also CA is one the most important feature for Long Term Evolution - Advanced (LTE-Advanced). For this purpose to get the upcoming International Mobile Telecommunication Advanced (IMT-Advanced) mobile requirements (1 Gb/s peak data rate), the CA scheme is presented by 3GPP, which would sustain a high data rate using widespread frequency bandwidth up to 100 MHz. Technical issues such as aggregation structure, its implementations, deployment scenarios, control signal techniques, and challenges for CA technique in LTE-Advanced, with consideration of backward compatibility, are highlighted in this paper. Also, performance evaluation in macro-cellular scenarios through a simulation approach is presented, which shows the benefits of applying CA, low-complexity multi-band schedulers in service quality, system capacity enhancement and concluded that enhanced multi-band scheduler is less complex than the general multi-band scheduler, which performs better for a cell radius longer than 1800 m (and a PLR threshold of 2%).

Keywords—Component carrier, carrier aggregation, LTE-Advanced, scheduling, spectrum management.

I. Introduction

By 2020 the number of subscriptions that include mobile broadband, mobile PCs, tablets, router, and IoT devices are expected to grow up to more than 9 billion, also new applications and services will require even higher data rates. Multiple Input Multiple Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) are two base technologies, that will be enablers for 5G and beyond. Along with these CA is a technique that can improve the coverage, throughput, resource reuse, system capacity, service quality, and user experience. The telecommunication industry has observed a high data rate application services, offering a high quality of services in a cost-effective way for mobile applications, which has become very essential for operators to meet customer requirements. For this purpose, the international telecommunication union introduced a global standard initiative [1] IMT-Advanced technique contains new capabilities for offering a wide range of services and applications for telecommunication. For supporting service demand and enhanced user, IMT-Advanced recognized peak data rate of 100 Mb/s for high-speed movement also 1 Gb/s for lower speed mobility. ITM-Advanced is upkeep for variable bandwidths with encouraging to support up to 10 MHz [2]. Similarly to Third Generation Partnership Project (3GPP) Long Term Evolution-Advanced (LTE-A), IMT-Advanced can be supported by different spectrum bands, that justifying the need for the system to have the capability to support aggregation of a different carrier to provide high data rate, that is the demand of today users. Based on the requirements and observations, the 3GPP has identified CA as a major feature for achieving improved data rates. It is worth noting that the bandwidth aggregation basic concept has been used in 3G. Similarly, there are options in High-Speed Packet Access (HSPA) evaluation, to aggregate up to four carriers for Downlinks (DL), up to two carriers for Uplink (UL) and both the carriers are considered contiguous. In release 8/9 of 3GPP LTE different carrier bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz are used that provide support for several deployments, plus spectrum plans. Succeeding the desires of 100 MHz Bandwidth (BW) of system, Release 10 of 3GPP LTE has presented CA one of the foremost important structures of LTE-Advanced to balance the bandwidth afar 20 MHz. CA Release 10 described in [3], up to 100 MHz system bandwidth can be achieved by concurrently aggregating up to 5 CCs of 20 MHz, according to user equipment compatibility. To acknowledge better network advancements, it is important to guarantee backward compatibility for an LTE-Advanced design, thus LTE Release 10 UE and LTE Release 8/9 might be able to be sustained in the consistent carrier deployed by Release 10 eNode Bs (eNBs). CA is very well-defined for Release 10, and establishes that every Component Carrier (CC) is companionable for LTE Release 8/9 [3] and also one of BW expressed in Release 8/9. It has similarly permit reuse of RF in Release 8/9 schemes and implementation in UE and eNB. There was no option in release 10 to aggregate in UL however in downlink just two CC might be aggregated; in Release 11, it was upgraded up to two CC in UL aggregation; Frequency Division Duplex (FDD) and Time Division Duplex (TDD) carrier aggregation added in Release 12. In Release 13, the CC improved from count 5 to 32. It will be a huge value for that, which expending a huge block of unlicensed spectrum in 5 GHz band. Furthermore, with carrier aggregation hardware circuitry is complex, not because of this reason that the number of CC is more in CA, while with the reason that receiving

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different frequencies, multiple signals produce intermodulation results which interferes with the required signals. Depending on the capabilities mobile terminal of UE can receive one or several CCs. It is likewise feasible to aggregate a different total of CC, ultimately of different BW in UL and DL, with the limitation that the number of CC in UL is not greater than the number of CC in DL. In each direction (UL, DL) using carrier aggregation, one of the CC essential be nominated the Primary Component Carrier (PCC), whereas the rest are named Secondary Component Carrier (SCC) shown in Fig. 1. Radio resource control connection will always be handled by the primary serving cell. In idle mode, the UE listens to system information block broadcast message through Primary serving cell and sends the uplink control information through the uplink control channel of it. All the control signalling is handled by PCC. Unlike PCC there can be multiple SCC. The SCC can be adding or remove as require for UE, while the PCC is only changing at handover occurrence.

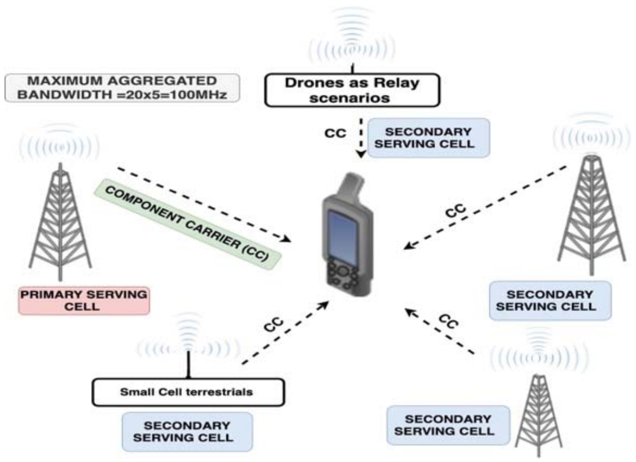

Fig. 1 Basic understanding of CA in heterogeneous networks with small cells

In the framework of a European 4G communications network scenario, e.g., available bandwidth and radio frequency bands for Portugal (bands 7 and 20), multi-band scheduling algorithms are explored to optimize average cellular capacity, service performance and the users perceived quality. Compared to [4], [5] and [6], in this work, we are considering a true uniform distribution of users within the cell and we consider the Mersenne Twister pseudo-random generator to generate truly random distributions while obtaining simulation results for packet loss ratio (PLR), goodput and average delay.

A sample of mobile user distribution produced by the LTE-Sim [7] during simulations are presented in Fig. 2 for the code provided by developers and in Fig. 3 after the code update from [8].

Fig. 2 is a representation of the deployment of 100 000 different locations for the users in the coverage area from an eNB with the original LTE-Sim code, where only the radial position of each user was generated by considering the uniform distribution. In fact, the old versions of LTE-Sim used to generate most of the user's positions closer to the central eNB.

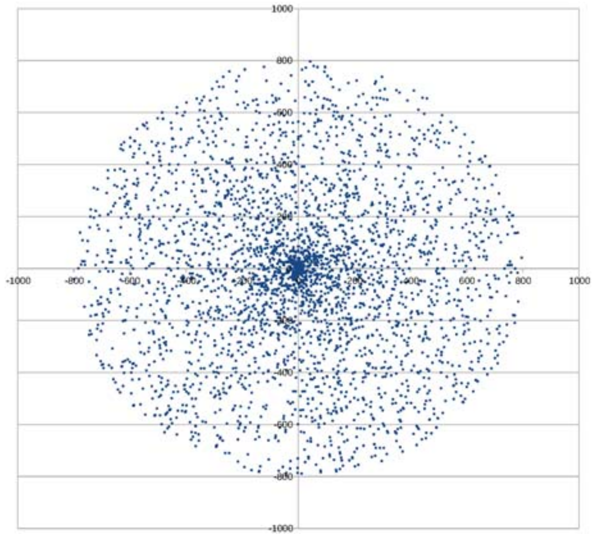

Fig. 2 Original non-uniform distribution of users, where just the distance to cell centre for each mobile user was generated by considering the uniform distribution

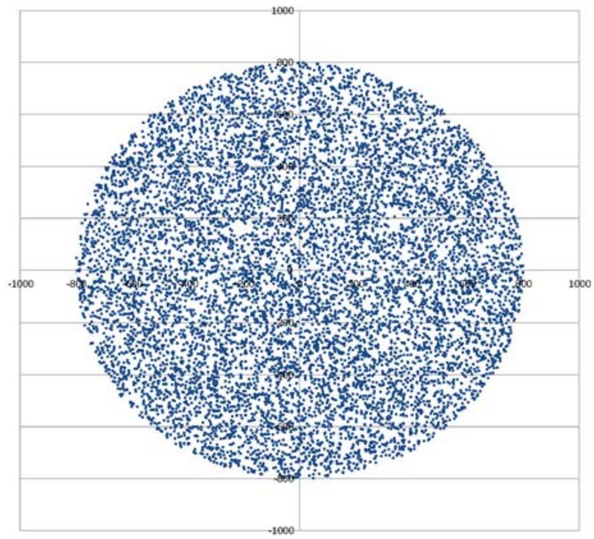

Fig. 3 Truly uniform distribution of users in simulations.

In this work, aiming at obtaining a truly uniformly random distribution of users within the cell, the simulator has been updated, as in [8], in order to generate the normalized distance of the user to the cell-centre as the square root of a uniform distribution. Fig. 3 presents a sample of the change in user positions resulting from this update in the LTE-Sim code.

In Section II, this work introduces aspects of carrier aggregation and discusses the challenges in the provision of contiguous and non-contiguous carrier aggregation. The discussion of the underlying deployment scenarios is followed by an overview of the functionality and terminology, which includes specificities of the protocol stack, radio resource management, and configuration of different types of user equipment, primary versus secondary cell management, as well as the illustration of UE/eNB implementation. In Section III performance evaluation of macrocellular scenarios is explored through a simulation approach by considering macrocellular scenarios implemented in LTE-Sim. Results for PLR, goodput, and average delay are compared for different multi-band schedulers. Conclusions and suggestions for further research are presented at the end of the paper.

II. Carrier Aggregation

According to the CC arrangement, two main types of carrier aggregation are identified [9], [3]:

- Intra-band CA - It is using a single band, as shown in Fig. 4.a), and has two main types, intra-band contiguous and intra-band non-contiguous. In intra-band contiguous aggregation, the carriers are adjacent to each other. In this case, only one transceiver is required within the terminal or UE, where more is required when the channels are not adjacent. The complexity of intra-band non-contiguous carrier aggregation is higher, as it uses the carrier of the same band but not the adjacent one, because of this the signal cannot be treated as a single signal that increases the complexity and cost of the system.
- Inter-band non-contiguous CA - This type of CA using different bands, as shown in Fig. 4.b), due to the existence of carriers from different operating bands, it is more challenging, as there is a need for multiple transceivers to receive or transmit the signal that enhances complexity, power requirement, cost, and creating space constraints.

The provision for contiguous and non-contiguous CA of CCs through distinctive BW provides substantial flexibility aimed at competent spectrum utilization and continuing changing of frequencies formerly used by other radio access schemes. According to physical layer perception, contiguous CA is simple to implement without making numerous changes to the structure of the physical layer of the LTE system [10]. By using a single Fast Fourier transform (FFT), it is possible to obtain contiguous CA for LTE-Advanced UE block (also by using RF block). However, keeping the backward compatibility for LTE schemes, in case of non-contiguous CA several radiofrequency and fast Fourier transfer modules will be required. For the UL, in LTE-Advanced the focus is presently on non-contagious CA, because of the challenges arising from the simultaneous transmission on various non-contiguous CCs, and underlying device linearity limitations. In Release 10, these two cases intra-band and inter-band are considered in the DL. Nevertheless, the particular RF desires are already developed in [11]. Usually, instead spectral efficiency carrier aggregation is amid to improve data rates.

A. CA Deployment Scenarios

Different deployment scenarios are shown in Fig. 5. These scenarios have been considered through the design of LTE-Advanced CA, demonstrated using two CC denoted by frequencies F1 and F2. Usually, in many deployment scenarios, for different CCs the eNB antennas are collocated and have consistent beam patterns/directions. In scenario 1 (identical coverage), if CCs are belonging to a similar band or frequency separation is short then almost equal coverage will be provided for all CCs. Scenario 2 (diverse coverage)

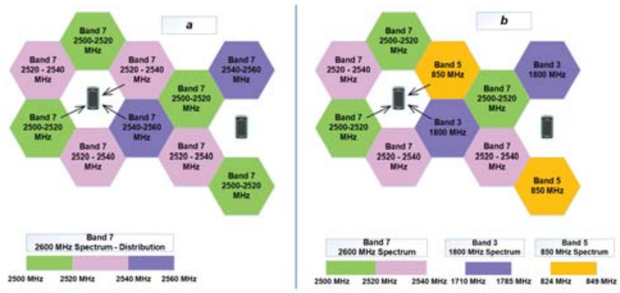

Fig. 4 Explanation of CA types: (a) intra-band and (b) inter band

corresponds to larger frequency separation between CCs, providing different coverage. Similarly, in an alike band, CCs could be deployed at eNBs with diverse transmit power planes to offer diverse coverage footprints for inter-cell interference management commitments [3], the place at which the coverage of CCs overlapping the CA allows higher user throughput, to shift the beam across the carriers. In scenario 3 different patterns or beam directions are used for different CCs for improving the throughput at the cell edge. Finally, in scenario 4 two frequency bands are being considered; one is the lowest frequency and the other one is high frequency. One CC, typically in low frequency, offers macro coverage while another CC, which considers higher frequency, uses Remote Radio Head (RRH) units to absorb traffic from a hotspot. Using optical fibre the RRH is connected to eNB, thus permitting the aggregation of CCs among the macrocell and RRH cells based on the same CA framework for collocated cells. This type of deployment permits the operators to advance system throughput by means of low-cost RRH device [12]. Among different deployment scenarios most efficient can be decided according to different factors, like either the service locations are rural, urban, or suburban, and where around there are hotspots in an area or not. A probable near possible scenario which present deployment using legacy frequency band (e.g., 2.6 GHz) to offer adequate coverage through the service area, and new bands (e.g., 3.5 GHz) are used to assist traffic in an additional cost-effective way. This is estimated to use CA in a heterogeneous network for flexible use of spectrum, varying with operators requirements [13]. In all cases of CA, even inside a single eNB different LTE-Advanced user equipment will be configured with different CCs [14]. The CCs which will be the part of the configuring set of the serving cell might be non-contagious or contiguous, it depends on the UEs deployment scenarios and UEs capabilities. Respectively one CC is configured for DL and UL when UE primary establishes or re-establishes Radio Resource Control (RRC) linking with eNB, which is referred to as carrier component PCC which agrees to Primary Cell (PCell). The DL CC being titled is DL primary CC, and resultant UL CC being titled is UL PCC, according to the traffic load need the UE may be connecting with one or more CCs, which is titled as component carrier SCCs for SCells, the DL and UL concern with it are termed as DL and UL secondary CCs of SCCs [9]. The handling of DL/UL SCCs though UE is moreover configurable using eNB. The UE equipment is served by the same eNB but the PCC and SCCs configurations are user-specific, which can be different for the different user equipment, as shown in Fig. 6. Different users may not be using the same carrier component as their PCC. In eNb it is clear that CC can be used as the PCC for one user equipment and assists as an SCC for another UE. The PCC is able to be considered like anchor CC of UE and thus cast-off for fundamental functionalities, as like radio link breakdown checking, etc. [15]. Dedicated signal information is sent through SCCs, the DL and UL resources can be scheduled on the SCCs using the control channel of PCC. This technique is estimated to be the best aimed at interference management for control channels in regards to heterogeneous networks and permit load corresponding through diverse cell layers. DL and UL PCCs are most of the time rubout and can be selected, such that they can provide the best signal feature, i.e., based on measurements of Reference Signal Received Power (RSRP) or Reference Signal Received Quality (RSRQ). The UE moves in the area related to eNB, the PCC can change to the CC that can provide the best signal quality, the change of PCC also can be performed by eNB kept in consideration load balancing [3]. DL SCCs can be dynamically activated and deactivated depending on carrier loading, buffered data amount, and quality of service. In LTE with FDD, considering the options frequency gap and bandwidth through system information signalling, DL and UL carriers are eternally paired. While the CA asymmetric of LTE-Advanced is accompanying in two-directions. CCs for two directions can not be the same to improve the spectrum efficiency. As in this framework, UE configured CA might require cooperation with eNB on uneven figures of DL/UL CCs, hence the usage of UL SCCs of certain of the SCells is not configured. Unlike defined in LTE, the DL CCs might be linked to UL CCs with duplex gaps. The asymmetric CA might produce uncertainty in downlink CC collection since this is tough for LTE-Advanced eNB that distinguishes the CC to UE anchors in the downlink. In mode time division duplex CA asymmetric can also be accomplished by changing the allocated time slots ratio for DL and UL transmission. This plan streamlines the resource allocation association among the DL and UL channels [10].

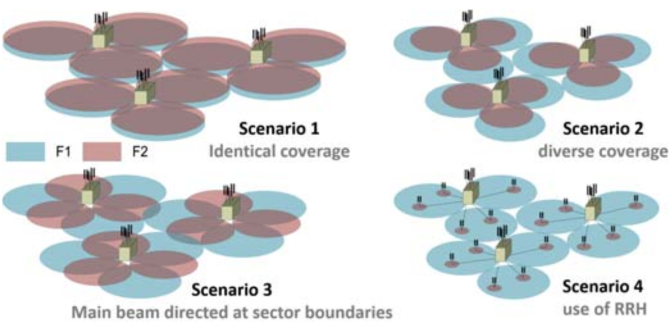

Fig. 5 3GPP CA deployment scenarios, adapted from [16]

B. *Functionality and Terminology*

a) Protocol Stack

The overview of the DL user plan protocol stack at the base station is shown in Fig. 7, also the mapping for furthermost important Radio Resource Management (RRM) functionalities for CA is presented. Every user has a minimum only one barrier that is presented by default radio bearer. Mapping the data to defaulting bearer depends on operator end polices that configure using the traffic flow template. Adding to the radio bearer, users can have further bearers configuration. As per radio bearer, it has one Packet Data Convergence Protocol (PDCP) also one Radio Link Control (RLC). The packet data convergence protocol containing functionalities like security, segmentation, robust header compression, and radio link control contain outer automatic repeat requests. The radio link control and packet data convergence protocol LTE-Release-8 are in paper [17]. The Interface among RLC and Medium Access Control (MAC) indicated consistent channels. Every user has MAC that using for control of multiplexing data that coming from consistent channel to the user, it also controls how the data are transmitted on the accessible CCs. As shown, there is one Hybrid Automatic Repeat Request (HARQ) unit per CC, also for each CC there is a separate transport channel that means the interference among MAC and physical layer. The transport blocks sending diverse CCs sent using different schemes of coding, modulation schemes, and MIMO coding schemes, these all should be independent. The later permits that data per CC can be sent using open-loop transmit diversity, however, the data on alternative CC are transmitted by twin stream closed-loop pre-coding. So, the self-governing link adjustment for every CC to get advantage from optimally corresponding the transmission through diverse CCs agrees to the experienced radio circumstances. The technique also uses different transmit power settings for CC thus according to principle they will have a level of coverage which is also explained in [3]. The control plane stack of LTE Release-8 is also applied to LTE-Advanced with numerous CCs. Likewise, idle approach mobility techniques of LTE Rel-8 are similarly applied in a network deploying carrier aggregation. This is further acceptable for the network to configure a single subset of CCs for the purpose of idle mode camping.

b) Radio Resource Management

LTE-Advanced and LTE Release-8 have many similarities in regards to RRM framework. The admission control process is accomplished at the BS prior to form first-hand radio bearers and to configure related quality of service parameters, the LTE-Advance and LTE Release-8 service parameters for excellence are the same [18].

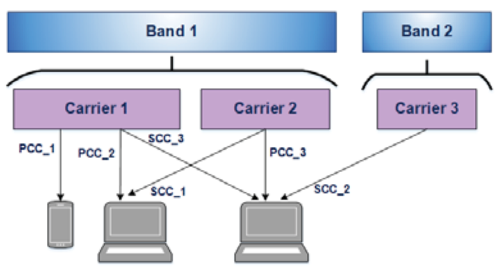

Fig. 6 Configuration for different types of user equipment, adapted from [11]

The CC configuration block is an important block in reference to system performance optimization, also for preventive the power consumption of users. For the best approach of system performance, they must have the same load on diverse CCs, so own-cell load information is desirable as input, also to assist the outstanding CC configuration and balancing of load [19]. LTE-Advanced users assist multiple CCs, Guaranteed Bit Rate (GBR), QoS parameters like the QoS and Class Identifier (QCI) to determine the required number of CCs for the user; the Aggregated Maximum Bit Rate (AMBR), QCI and GBR provide useful information. For example, a single carrier component will be allocated to a user that has a single call or streaming connection but still is able to satisfy the user's QoS necessities. The aggregated maximum bit rate can be used for the top effort traffic for evaluation of almost the best CC by considering their size. By allocating only one CC to this type of usage, user benefits that terminal power utilization is sustained lesser compared to the case wherever the user has assigned more CC set. The proper CC configuration algorithm is under Base Station (BS) vendor specification. As shown in Fig. 7, packet scheduling and additional functionalities are tightly coupled for dynamically deactivating CCs configured as SCells for different users. It has also further anticipated supplementary control means to additionally reduce the users power utilization. Accordingly, the user may be schedulable only on activated CCs but not on deactivated CCs. Besides, the user cannot provide Channel State Information (CSI) for deactivated CCs when required for a base station for frequency domain packet scheduling and radio-channel-aware link adaptation [17]. Via MAC signalling the SCell is activated and deactivated autonomously [3]. Furthermore, it is also possible to set the timer for deactivation. Hence, the activated Secondary Cell (SCell) spontaneously gets deactivated without sending a deactivation message if, for a given set of time, no traffic is detected on the CC. By evading that Configured SCells are de-activated, they are obviously activated before being schedulable. Primary Cell (PCell) needs to be always activated for the user and there is no substance to any deactivation techniques. The lively Packet Scheduler (PS) at stage layer 2 is accountable for scheduling qualified users on configured and activated CCs. In the LTE Release-8 PS framework [17], the lowest frequency domain scheduling resolution inside every CC is a Physical Resource Block (PRB) which contains 12 sub-carriers per PRB, establishing a corresponding bandwidth of 180 kHz. The main objective of PS from multi-user frequency domain scheduling is to obtain diversity through assigning the PRB to diverse users which practice best channel services; with carrier aggregation the LTE-Advanced PS functionality is quite the same as PS for LTE Release-8. Nevertheless, LTE-Advanced PS is permissible to manage users through multiple CCs. LTE-Advanced relies on a self-governing link adaptation, transport blocks, and HARQ for every CC that open multiple implementations ways of the scheduler, e.g., techniques of scheduling can be complete in parallel for dissimilar CCs, counting certain management that certifies sprite and combined control for users scheduled on multiple CCs [3]. Sending commands on the control channel is used in LTE Release-8 for user dynamic scheduling facilitation that called the Physical Dedicated Control Channel (PDCCH), which is time multiplexed before the data channel in every Transmission Time Interval (TTI) [9]. Every PDCCH is restricted just to one CC. The per-user similar address does not depend on the CC where it is arranged, in 3GPP LTE terminology it is entitled as Cell Radio Network Temporary Identifier (C-RNTI). Though, the eNB in LTE-Advanced is allowed to forward a scheduling grant on each CC for the propose of scheduling the user on alternative CC, the cross-CC scheduling functionality is unified using attaching a so-called Carrier Indicator Field (CIF) to the DL Control Information (DCI). For user allocation UL and DL traffic the DCI to indicate it while CIF to find on which required CC, the data of the user are transmitted. Payload size increasing marginally when the CIF is attached to the DCI, the transmission data are constant, due to weaker coding the link functioning is somewhat poorer. On per UE basis, the configuration of every user and interpretation of the CIF are semi-statical and therefore complete backward companionable with legacy Release-8 manipulators does not have CIF in the DCI transmitted on the PDCCH. For extra optimizing control and data channel functioning through multiple CCs the cross-CC scheduling functionality deals with extra system flexibility. Furthermore, to enhance the dynamic Layer-2 packet method of scheduling, the LTE Release-8 similarly supporting the Semi-Persistent-Scheduling (SPS) for the deterministic traffic flows as like VoIP that maintains control channel resources [9]. SPS also supporting for LTE-Advanced with CA, while its limitation is, can be configured through users PCell only through RRC signalling.

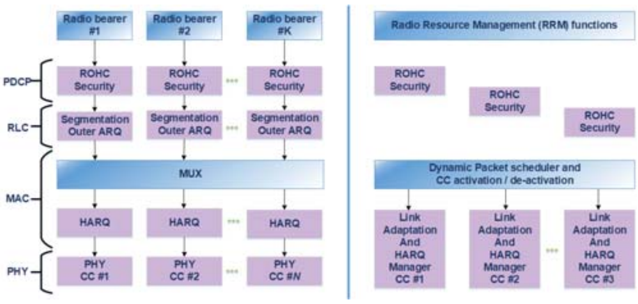

Fig. 7 From left to right the overview of DL user plane architecture and RRM algorithms, adapted from [10]

c) Primary Cell and Secondary Cell Management

PCell and SCell are the control techniques that manage the network to add/remove SCell or switch the user equipment PCell. RRC idle user equipment unit establishes an RRC connection toward a serving cell that automatically considers as PCell. With the RRC connection on the PCell, for UE traffic demand the network can further configure SCell according to the UE capability of performing CA. The RRC connection is used to convey the necessary information of an SCell to the UE, also the functionality of reconfiguration, addition, and removal of SCell to UE are accomplished through RRC connection. To advance the quality of the link the PCell of UE can be further changed to provide the balancing between different SSC. PCell variation does not essentially require UE to switch to single-carrier operation. Intra-LTE handover in LTE-Advanced permits the focus of PCell to configure one or more SCell for UE to utilize instantly when handover occurred.

d) eNB Implementation

For contiguous CA the DL transmitter chain block diagram is shown in Fig. 8.

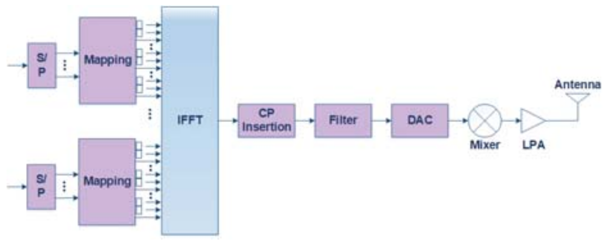

Fig. 8 Block diagram for DL transmitter CA, adapted from [20]

Fig. 8 shows that it required a single transmitter chain with one IFFT because the carrier is considered contiguous. For efficiently supporting the wide bandwidth essential for LTE-Advanced, Linear Power Amplifier (LPA) mixing methods are necessary to be considered, it is capable of accompanying 20-30 MHz modulation bandwidth. For combining LPA resources, distinctive techniques are frequently considered that are cavity, hybrid, coherent combining, and combining by means of Fourier Transform matrix. Selection between these methods is dependent on the design criteria like the cost, LPA bandwidth, complexity, whole transmission bandwidth, also the main important band whose combining is contiguous or non-contiguous. Considering non-contiguous aggregation, LPA must not be apprehensive as like multiple transmitter chains, containing IFFTs is necessary. For this type CA, the transmitter should be prudently designed, which can be separate to block the mixing of signals that be able to lead to false emissions.

e) UE Implementation

Single-Carrier Frequency Division Multiple Access (SC-FDMA) using DFT-Spread OFDM in LTE uplink is physical layer approach system. OFDM and SC-FDMA have several resemblances, among them, the main one is frequency domain orthogonality between users. SC-FDMA has lower power amplifier de-rating obligations, that improve the battery life and prolong the range [21]. Using N x SC-FDMA in UL the CA is supported, for the value of N equal to two the block diagram for UL indicating is presented in Fig. 9. Meanwhile, aggregated carriers are contiguous for DL a distinct transmitter chain that can be cast-off. While for the implementation of CA in UL N DFT-IFFT sets are essential [20]. When the transmitter is on multiple carriers at that instant the single carrier stuff in the uplink is no lengthier treating. Because of this the cubic metric rises that needs higher back-off in power amplifier, thus lessening extreme transmit power at the UE. Detailed evaluation of the cubic metric for the diverse figure of SC-FDMA carriers is shown in Fig. 10. As clearly shown, it has considerable expansion in cubic metric while they consider transmitting using multiple UL carriers. Though, in suitable channel conditions the multi-carrier transmission drive is usually limited to UEs, it will have no harm of coverage for those users. Apart from this, the advanced transmission power drive is mandatory and can influence battery life. On the other side, at the cell edge, the users would be scheduled just on a single carrier. As a consequence, coverage might be enhanced, since the eNB can be dynamically allocating the users to the best UL carrier.

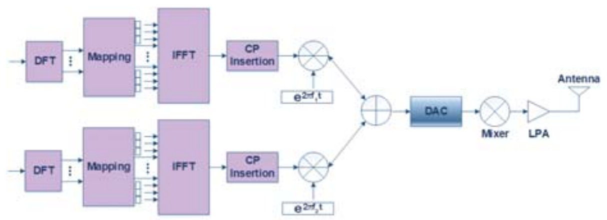

Fig. 9 Transmitter block diagram for UL CA, adapted from [20]

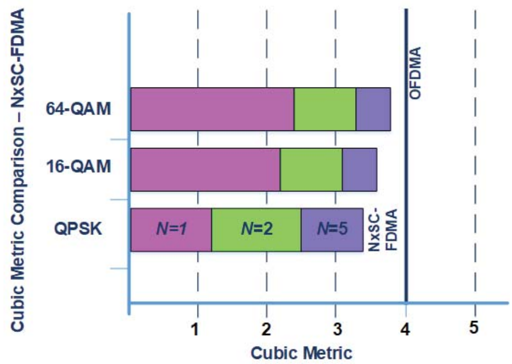

Fig. 10 Cubic metric comparison for N x SC-FDMA

III. Performance Evaluation of Macro-cellular Scenarios

LTE-Sim is an open-source framework proposed to perform the verification of LTE-based systems and to simulate LTE networks [7]. It includes several aspects of LTE technical specifications, such as Evolved Packet System (EPS) and Evolved Universal Terrestrial Radio Access (E-UTRA), allowing for the use of single-cell and multi-cell environments and handover procedures alongside traffic generators and scheduling procedures.

A. LTE-Sim Packet Level Simulator

The ecosystem of LTE-Sim was built using the $C++$ programming language and the objected-oriented paradigm to ensure modularity, being composed of 90 classes. The protocol stack of LTE-Sim is shown in Fig. 11.

The four main components of the project are:

- The simulator;
- Network Manager;
- Flows Manager;
- Frame Manager.

Radio resource allocation is made in the time-frequency domain with the time domain resources being allocated according to each TTI with a duration of 1 ms. The frequency

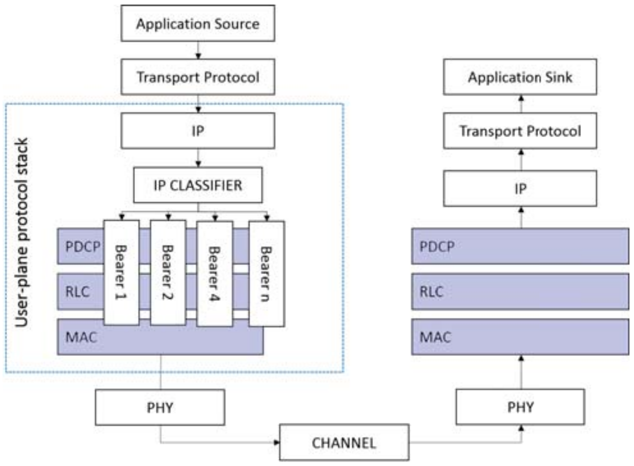

Fig. 11 Protocol stack of LTE-Sim, adapted from [7]

domain, on the other hand, considers the division of the bandwidth into sub-channels of 18 kHz. For every TTI, there are 14 OFDM symbols divided into 0.5 ms, with each consecutive TTI forming an LTE frame.

Regarding the application layer, the simulator offers four different traffic generators:

- Trace-based;
- Voice over IP (VoIP);
- Constant Bit Rate (CBR);
- Infinite Buffer.

The trace-based application uses trace files extracted from [22], that provides video traces created by the encoding of uncompressed video files [23] that allow the simulation of realistic video files transmissions.

VoIP applications operate by coding voice messages and sending them as data packets over IP-based networks and are common on telephony systems [24]. In LTE-Sim, these applications use flows based on G.729 which is a coder consisting of nano-rate that uses fixed-point arithmetic operations and works at 8 kbits/s [25]. The simulator uses a Markov chain with the VoIP applications being divided into ON/OFF periods where the source sends packets of 20 bytes during the ON period and within intervals of 20 ms and keeps a 0 rate of transmission during the OFF period.

CBR refers to an encoding technique which allows for the use of applications that keep the bit rate the same throughout the transmission [26]. One of the disadvantages of these types of applications is the lack of optimization in the relation quality versus storage. The simulator allows the configuration of packet size and packet time interval for this kind of applications.

The infinite Buffer generator works by creating applications that always have packets to be sent by the source.

At the level of channel structure, the simulator works with all the bandwidths for LTE-based systems i.e., 1.4, 3, 5, 10, 15, and 20 MHz, offering a bandwidth manager that allows for each device under a simulated scenario to know the bandwidth being used, using a PHY object defined to each device. Furthermore, two types of frame structures are available i.e., FDD and TDD following the specifications for E-UTRA.

The FDD frame structure, referred to as frame structure type 1, is composed of 10 subframes available for DL and also 10 subframes for UL with transmissions at each 10 ms interval in the latter case [27], being applicable to full-duplex and half-duplex. Each radio frame is composed of 20 slots and each subframe comprises two consecutive slots, as shown in Fig. 12.

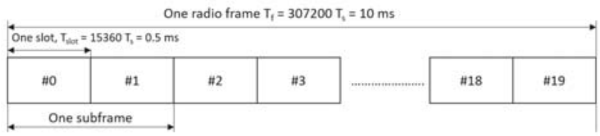

Fig. 12 FDD Frame Structure, adapted from [27]

The TDD frame structure is represented in Fig. 13, where each radio frame is divided in two halves that in turn are composed of subframes corresponding to every TTI.

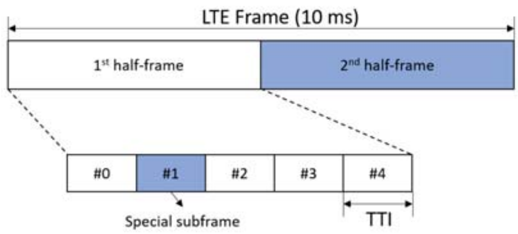

Fig. 13 TDD Frame Structure, adapted from [27]

The simulator computes the SINR for each sub-channel as follows:

$$SINR_{i,j} = \frac{P_{RX,i,j}}{(FN_0B) + I} \quad (1)$$

where F is the noise figure, N_0 is the noise spectral density, B is the bandwidth for a resource block, and I is the interference computed for the eNBs sharing the same frequency resources.

For the transmit power $P_{RX,i,j}$, in this study one considers a normalized transmit power computed to ensure the delivery of SINR for all cell radius, for the 800 MHz and 2.6 GHz frequency bands. Exponential Effective SNIR Mapping (EESM) computations are then extracted from these formulations for SINR.

Regarding mobility, LTE-Sim offers two implementations, i.e., random direction and random walk. In the random direction mobility model, an entity chooses a random direction in which to travel and moves towards the pre-defined border following that direction. When the entity achieves the border, it pauses its movement and chooses a new direction to follow [28]. For the random walk model, an entity chooses randomly a direction and a speed and moves from its current location to a new location using the variables assigned. For the results presented in the following sections, the random direction mobility model is used to perform the movements of the UEs.

B. Carrier Aggregation with LTE-Sim

For the analysis proposed in this work, one considers the ITU radio propagation model for macrocell scenarios in urban and suburban areas proposed in [29] and described as follows:

$$PL = 40(1 - 4 \times 10^{-3})log_{10}(R_{km}) - 18log(D_{hb}) + +21log10(f) + 80dB \quad (2)$$

where R is the distance between UE and eNB in kilometers, D_{hb} is the height of the BS which is assumed to be 15 m, f is the carrier frequency in MHz. Following the definitions from (2), the path loss models for the 800 and 2600 MHz frequency bands are given in Table 1 from [5].

The inter-band carrier aggregation deployment scenario from Fig. 14 considers the existence of two collocated CCs hexagonal coverage zones operating at the frequency band 7 (2.6 GHz) and frequency band 20 (800 MHz), while also considering the existence of the first tier of interferes, as illustrated in Fig. 14. The allocation of UEs at each CC is decided in every TTI, following the metrics of three packet schedulers, namely, the Enhance Multi-Band Scheduler (EMBS), General Multi-Band Scheduler and Basic Multi-Band Scheduler (BMBS).

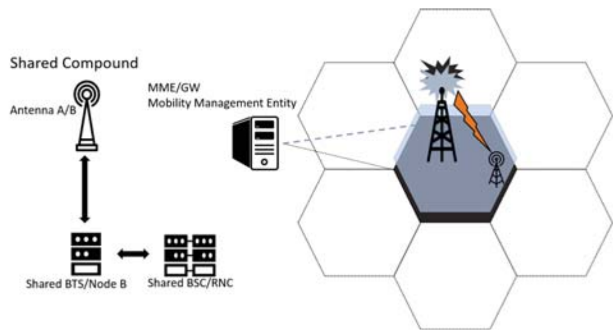

Fig. 14 Inter-band carrier aggregation deployment scenario, adapted from [6]

In the implementation of each multi-band scheduler, while optimizing the allocation of resources, an allocation matrix, $X = [x_{b,u}]$ is considered to help to allocating RBs to the UEs. After this allocation matrix is created, the Modified Largest Weighted Delay First (M-LWDF) DL packet scheduler is used to compute metrics to the assigned CC. This algorithm is designed to support multiple data users while considering different QoS parameters [30], by computing a metric $W_{i,j,b}$ as follows:

$$W_{i,j,b} = \alpha_i D_{HOL,i} \times \frac{r_{i,j}}{R_{i,j}} \quad (3)$$

where $D_{HOL,i}$ is the $i-th$ flow head of line packet delay, $\bar{R}_i$ is the flow average transmission rate, given by (4) and $r_{i,j}$ is the instantaneous available rate for each sub channel in each flow:

$$\bar{R}_i(k) = 0.8\bar{R}_i(k-1) + 0.2\bar{R}_i(k) \quad (4)$$

In (4), $R_i(k)$ is the throughput achieved in each flow and $R_i(k-1)$ is the throughput for the previous TTI. Furthermore, in (3), the parameter α_i is used to ensure precedence to users with strongest requirements in terms of acceptable loss rate in cases of flows with equal HOL. The variable α_i is computed as follows:

$$\alpha_i = \frac{log(\delta_i)}{\tau_i} \quad (5)$$

where δ_i is the probability that the delay will exceed the established threshold of τ_i.

The description of the applied multi-band schedulers is as follows, adapted from [5]:

1) General Multi-band Scheduler: The proposed General Multi-band Scheduler as well as the following scheduler described in this section were proposed in [31], [6] and [4] as a way to offer CA as resource to improving network capacity adding an extra dimension of scheduling at the TTI level. The authors proposed the scheduling solution by using Integer Programing (IGP) establishing a Profit Function (PF) which considers the ratio between the requested application rate and the available rate on the DL channel, as described in (6):

$$(PF) = \sum_{b=1}^{m}\sum_{u=1}^{n} W_{\text{B,U}} \cdot X_{\text{B,U}} \quad (6)$$

where $X_{\text{B,U}}$ indicates whether the UE is allocated in band u or not. Also, in (6), $W_{\text{B,U}}$ is a normalized metric whose values are given by:

$$W_{\text{B,U}} = \frac{[1 - BER(CQI_{\text{B,U}})] \cdot R(CQI_{\text{B,U}})}{S_{\text{RATE}}} \quad (7)$$

where $BER(CQI_{\text{B,U}})$ is the Bit Error Rate (BER), in taken from the previous DL transmission, $R(CQI_{\text{B,U}})$ is the throughput as function of the MCS and S_{RATE} is the bit rate of the video encoding service.

For the purposes of the proposed work, one considers that each UE in the network can only transmit and receive over a single frequency band at a time. This constraint is specified by (8):

$$(ACt)\sum_{b=1}^{m} X_{\text{B,U}} \leq 1, X_{\text{B,U}} \in \{0,1\}\, \forall u \in \{0,...,n\} \quad (8)$$

Furthermore, a constraint is established to control the number of UEs allocated at each band at each given time. The constraint considers the maximum normalized load that a band can handle, as shown in (9):

$$(BC)\sum_{b=1}^{n} \frac{S_{rate} \cdot (1 + R_{Tx} \cdot BER(CQI_{b,u}))}{RCQI_{b,u}} \cdot X_{\text{B,U}} \leq L_b^{MAX} \forall u \in \{0,...,n\} \quad (9)$$

where S_{rate} is the throughput of the requested service, which is normalized by the maximum throughput that the network can offer, $RCQI_{b,u}$. After the process of maximization is performed, an allocation matrix, $X = [x_{b,u}]$ is created to help to allocate RBs to the UEs.

2) Enhanced Multi-band Scheduler: The Enhanced Multi-Band Scheduler (EMBS) uses a scheduling metric to perform decisions about the allocation of each RB in each CC, according to (10):

$$W_{i,j,b} = D_{HOL,i} \cdot \frac{R(CQI_{i,j,b})^2}{\bar{R} \cdot S_{rate}} \quad (10)$$

where $R(CQI_{i,j,b})$ is the throughput for in the $i-th$ flow for band b and $j-th$ sub channel as a function of MCS, $D_{HOL,i}$, $\bar{R}$, and S_{rate} stands for the same parameters as in the GMBS.

3) Basic Multi-band Scheduler: The Basic Multi-Band Scheduler (BMBS - also simply referred as CRRM) algorithm is also studied in the context of this work. This algorithm works by allocating UEs to a preselected frequency band, until a threshold, L_b^{MAX}, is reached. Once the threshold is reached, the remaining UEs are allocated to the next frequency band. Equation (11) describes the allocation process for this scheduler:

$$x_{bu} = \begin{Bmatrix} 1, & \text{if } L_b \leq L_b^{MAX} \\ 0, & \text{if } L_b > L_b^{MAX} \end{Bmatrix} \quad (11)$$

The GMBS is more complex when compared to EMBS and BMBS (i.e., CRRM) but it only allows for UEs to be allocated at one CC at the time, while EMBS uses a metric that allows for the allocation of a user in more than one CC. Also, the use of IGP makes the computation process in GMBS more demanding, which reduces its performance when the number of UEs is higher.

Further details on the extension of LTE-Sim to support carrier aggregation and multi-band scheduling are given in [4] and [5], where previous research with non-uniform distribution of users within the cells is addressed.

C. Simulation Results

With the CA schedulers implemented upon the LTE-Sim stack, it was possible to evaluate the performance by computing the average Packet Loss Ratio, throughput, and delay. We compare the scenario of two separated LTE-A networks operating at the 2.6 GHz and 800 MHz frequency bands and the scenarios with aggregation between the two bands that are managed by the BMBS (also labelled as CRRM), GMBS and EMBS multi-band schedulers.

To perform the underlying simulations, one first considers a cell radius of 1 km, with the number of UEs from 8 to 80. The simulations are executed a total of 50 times and the results for the measured parameters are the average of the total number of simulations. The simulations were performed with transmissions based on video traces of 128 kbps video bit rate, considering a maximum delay of 0.1 s, with flow durations of 40 s assuming that the UE distributed are moving with a speed of 3 kmph.

Fig. 15 shows the variation of the average cell PLR with the number of UEs, where the yellow line highlights the points corresponding to a PLR 2%. As one would expect, GMBS and EMBS schedulers perform better, with EMBS presenting a lower value of average PLR in most of the cases, when compared to the remaining schedulers.

The average delay is evaluated considering the previous parameters. Fig. 16 shows the variation of the delay, in seconds, with the nuber of UEs, for a number of users up to 80. It is possible to see that, while CRRM and GMBS show values of delay that are relatively close, EMBS shows lower values, specially on the range after 50 UEs.

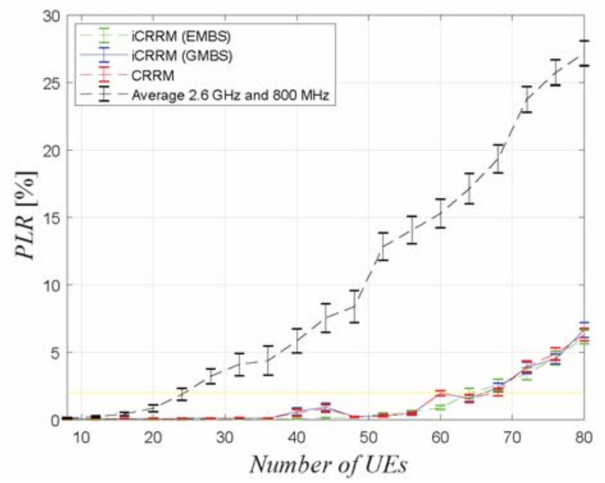

Fig. 15 Average cell PLR as a function of UEs for $R = 1000$ m

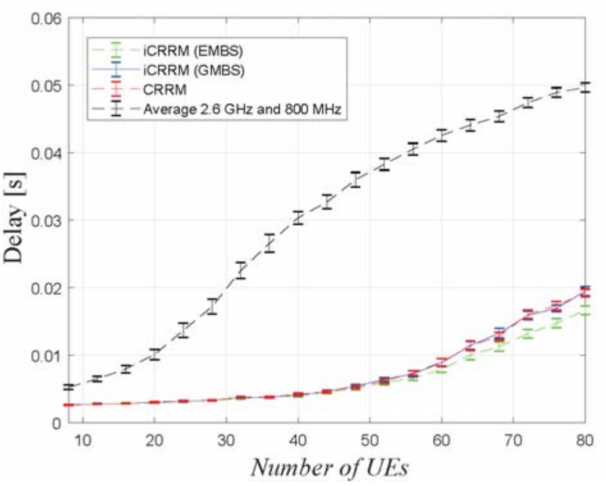

Fig. 16 Average cell delay as a function of UEs for $R = 1000$ m

Fig. 17 presents the variation of the supported goodput with the cell radius (for radii up to 1000 m). In this case, although the difference of performance among the schedulers seems less apparent, Fig. 17 shows that as the number of UEs increases, EMBS tends to perform better when compared to CRRM and GMBS.

In order to further evaluate the system capacity one also considers the maximum goodput achieved with each scheduler, considering a PLR threshold of 2%. The results of this analysis are presented in Fig. 18, where it is possible to see that the performance of the three schedulers is very close for most cases considered, with the EMBS performing better for cell radius higher than 1800 m.

By considering CA, mobile operators and service providers are able to deliver services to mobile subscribers ensuring satisfactory levels of Quality of Service, reducing the levels of Packet Loss Ratio, and thus increasing the throughput achieved in communication. It is shown that the use of CA reduces the levels of PLR considerably, with the case of no CA achieving 27% of PLR against a maximum of 7% achieved by GMBS.

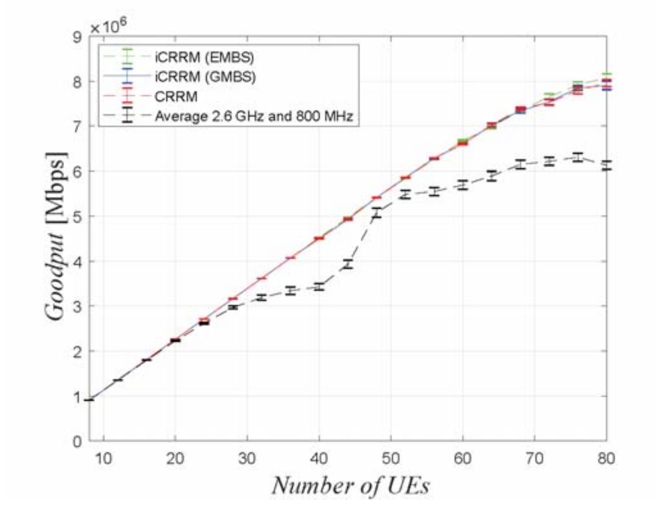

Fig. 17 Average cell supported goodput as a function of UEs for $R = 1000$ m

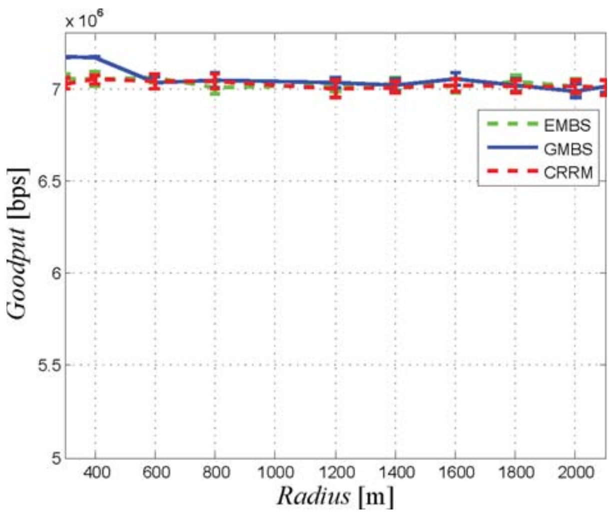

Fig. 18 Average cell goodput for a threshold of 2% for the PLR

Values of 7.5 Mbps for a cell radius of 300 m and of 7 Mbps for 2100 m of cell radius are achievable. The PLR threshold of 2% is exceeded at a total of 67 UEs, for the latter case for cell the cell radius. In [6], [5] a techno-economic benefit of using CA was analyzed by investigating the cost-revenue trade-off of such 4G cellular network deployments.

IV. Conclusion

The paper provides a detailed overview of LTE-advanced CA. According to the literature review when the resource of the spectrum becomes scarcer the carrier aggregation will become a very important scheme in the upcoming communications system. We have explained the basic carrier aggregation and system capacity optimization concepts for LTE-Advanced. By using wide bandwidth CA provides higher data rates and enables flexible and optimal utilization of frequency resources. Mainly the carrier aggregation between non-contiguous frequency bands offers novel opportunities to get more benefit from frequency assets for LTE-Advanced in different bands. Furthermore, the allocation of multiple carrier components resource, and modification of transmission parameters as like coding schemes, transmission power, modulation for different carrier components are still open research topics.

Real-world application of Carrier Aggregation has been explored within the context of LTE-Advanced, via the use of an integrated CRRM entity that performs inter-band CA via the scheduling of two Carrier Components (i.e., band 7 and band 20). The main motivation behind this work is to have a framework that is able to deliver services to mobile subscribers ensuring satisfactory levels of Quality of Service, reducing the levels of Packet Loss Ratio, and thus increasing the throughput achieved in communication. For the simulations presented in this chapter the LTE-Sim packet-level simulator was considered, where the three proposed multi-band schedulers were tested for applications based on traces of videos of 128 kbps.

To evaluate system capacity, scenarios have been considered where the different cell radius and number of uniformly distributed User Equipments were used in simulations obtained data to evaluate the performance of the system. First, a scenario has been considered where the cell radius was 1000 and the number of UEs changed from 8 to 80. In this first case, the three proposed schedulers have been tested and their performance has been compared to results obtained for a scenario without CA, for the same cell radius and number of UEs. The analysis for the first case scenario demonstrates that the use of CA considerably reduces the levels of PLR, with the case of absence CA achieving 27% of PLR against a maximum of 7% achieved by GMBS.

In a second analysis, the dependence on cell radius was evaluated for values in the range between 300 and 2100 m, with the number of UEs going from 8 to 80. Again the use of CA proved to be capable of surpassing for the cell radii and number of UEs. Values obtained in this study have also been used to estimate system capacity by considering a threshold of 2% for PLR. Under these assumptions, one is able to obtain values for the goodput of 7.5 Mbps for a cell radius of 300 m and of 7 Mbps for a cell radius of 2100 m, with the PLR threshold being exceeded at a total of 67 UEs, for the latter case. Compared to the case of non-uniform distribution of users from [4] and [5], when the uniform distribution of users is considered within the cell, there will be more users near the cell edge, i.e., further away from the cell centre. As a consequence, the average SINR for these users is lower, and there is a reduction from circa 7.5 Mbps (as presented in [5] for EMBS) to circa 7 Mbps in the average cell supported goodput.

Future research will include the consideration of carrier aggregation and multi-band scheduling in Cloud RAN based heterogeneous network with small cells deployments. The approach is two-fold and will include not only the conceptual/simulation framework but also exploring an experimental setup with 4G (and beyond) small cells operating at sub-6 GHz frequency bands.

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