Extending the LTE-Sim Simulator with Multi-band Scheduling Algorithms for Carrier Aggregation in LTE-Advanced Scenarios

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***Abstract*—Carrier Aggregation (CA) has been proposed by 3GPP LTE-Advanced to meet or even exceed IMT-Advanced systems enhanced peak data rates requirements. In its rationale, multiple Component Carriers (CC) can be flexibly aggregated so that user equipment can access a total bandwidth of up to 100 MHz. As each CC has the same structure as the one from LTE R8, CA does not require notable changes in the LTE physical layer structure. Nevertheless, the way radio resources are allocated to mobile users in CA scenarios is still an hot research topic and the availability of an open source tool modelling such kind of feature is highly demanded in both academia and industry contexts. The present contribution is three-folded. First, it presents an open source and freeware extension of the well-known LTE-Sim simulator, which implements CA functionalities. Second, it also proposes an implementation of multi-band scheduling strategies able to optimally distribute radio resource among mobile users in the presence of multiple CCs and strict Quality of Service (QoS) constraints. Third, computer simulations have been also carried out to demonstrate the effectiveness of the aforementioned contributions. In particular, simulation results show the capacity improvements achieved by the proposed Enhanced Multi Scheduler against systems without CA, considering values of the bandwidth per component carrier of 5 and 20 MHz, in terms of average cell packet loss, delay, goodput and spectral efficiency.**

I. Introduction

To meet the increasing demand for wireless broadband services from fast-growing mobile users, aggregating small portions of the frequency spectrum is one of the viable techniques to enhance data rates, reduce latency and optimize packet transmission. The concept of carrier aggregation is introduced by the 3rd Generation Partnership Project (3GPP) in its Long Term Evolution-Advanced (LTE-A), e.g., LTE R10.

Carrier Aggregation (CA) is employed as a solution to bandwidth extension and is considered as a key enabler for LTE-A [1], which can meet or even exceed the IMT-Advanced requirement for large transmission bandwidth (40 MHz-100 MHz) and high peak data rate (500 Mbps in the uplink and 1 Gbps in the downlink) [2]. Each aggregated carrier is referred to as a Component Carrier (CC). Individual CCs can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz. A maximum of five equal or different bandwidths CCs can be aggregated. Besides, LTE-A User Equipment (UE) may simultaneously receive or transmit data on one or more CCs.

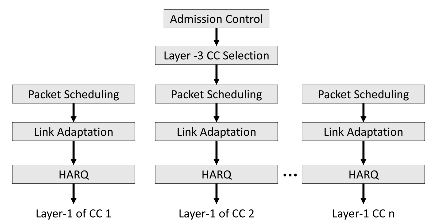

Fig. 1. Multi-component carrier LTE-A system RRM, extracted from [5].

Carrier aggregation requires some changes from the baseline LTE R8, although each component carrier in LTE-A remains backward compatible with LTE R8 as described in [3]. The Radio Resource Management (RRM) framework for LTE-A retains many similarities with that from LTE. With the use of CA, however, it becomes possible to schedule a user on multiple non-contiguous CCs simultaneously, each of which may exhibit different radio channel characteristics. Besides, supporting multi-CC operation introduces some new challenging issues in RRM framework from LTE-A [4]. Authors from [4], [5], [6] addressed low complexity solutions for such resource allocation problem in multi-carrier systems.

Figure 1 illustrates the RRM structure for a multi-component carrier LTE-A system. The eNB first performs admission control to decide which users to serve. Then, it employs layer-3 CC Selection to allocate the users on different CCs [5]. Once the users are assigned onto certain CC(s), layer-2 Packet Scheduling is performed. In order to allow for backward compatibility, so that LTE and LTE-A users can co-exist, independent layer-1 transmissions are considered, which contain Link Adaptation and Hybrid Automatic Repeat Request (HARQ) per CC, following LTE assumptions [3].

In terms of network architecture, the main layers impacted by CA are the Radio Resource Control (RRC), MAC and PHY layers. The core network, Packet Data Convergence Protocol (PDCP) and Radio Link Control (RLC) are not considerably impacted by CA. On the one hand, from the perspective of the user plane, the aggregated carrier is a single bearer just like any other. On the other, from the device point of view, the user plane and layers above RRC are not impacted by CA [7].

Undoubtedly, due to the presence of an higher amount of

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radio resources, and underlying statistical multiplexing gain, CA may significantly improve the overall network performances. However, some new challenging issues arise at the RRM domain: the way radio resources belonging to multiple CCs can be assigned to each user, according to its carrier capability, experienced channel quality, and Quality of Service (QoS) requirements, still represents a key aspect in the design of resource management schemes for CA-based systems. In this context, a modular and freely available simulation platform can be really useful to enable research activities to converge towards such common goal.

At the present, the LTE-Sim simulator (developed and presented by G. Piro et al. in [8], [9], [10] and [11]) is one of the most diffused open source project implementing several features related to both LTE and LTE-A technologies. At the time of this writing, it supports single and heterogeneous multi-cell environments, urban scenarios with femtocells, multi users scenarios, user mobility, handover procedures, frequency reuse techniques, several features belonging to both control and user plane protocol stack, QoS management, well-known scheduling strategies for both downlink and uplink, several urban and rural channel models, adaptive modulation and coding scheme, channel quality indicator feedbacks, block error rate models for the physical layer, four kinds of network nodes (i.e., UE, eNB, HeNB, and MME/GW), and five traffic generators at the application layer (infinite buffer, VoIP, video, CBR, and WEB). The effectiveness of LTE-Sim is demonstrated by the presence of more than 230[1] citations get by its reference paper and the interest of more than 600 worldwide members subscribed to the official mailing list[2]. Nevertheless, despite the huge number of features LTE-Sim provides, it had not yet supported CA.

With the aim of enlarging the scope of the aforementioned simulator, we present herein an open source and freely available LTE-Sim extension modelling CA functionalities. Moreover, multi-band scheduling strategies, able to optimally distribute radio resource among mobile users in the presence of multiple CCs and strict Quality of Service (QoS) constraints, have been also implemented. In addition, computer simulations have been carried out to demonstrate the effectiveness of all the implemented features, thus showing he capacity improvements achieved by enhanced CA-based scheduling algorithms against systems without CA, in terms of average cell packet loss, delay and goodput. Given the recognized role that LTE-Sim covers in worldwide research activities, the relevant added value offered by the CA, the enormous attention to RRM related aspects, and the need of valid simulation tools supporting research activities in this context, we believe that this work promises relevant future impact in academia and industrial sectors.

The remainder of this paper is organized as follows. Section II introduces the LTE-Sim simulator framework. Section III discusses multi-band scheduling algorithms implemented in LTE-Sim. In particular Section III proposes the Enhanced Multi-band Scheduling (EMBS) algorithm whilst describing the enhancements introduced to the LTE-Sim simulator at both physical (CA) and MAC layers (multi-band scheduling strategies). Section IV addresses simulations and performance evaluation for the EMBS, in comparison with a scenario without CA. Finally, Section V draws some conclusions.

[1]Source: google scholar (December 2014)

[2]https://groups.google.com/forum/\#!forum/lte-sim

II. The LTE-Sim simulator in a nutshell

LTE-Sim is an open source tool developed for simulating LTE and LTE-A networks, as described in [12] and [8]. In order to ensure modularity, polymorphism, flexibility, and high performance, LTE-Sim has been written in C++, as an event-driven simulator, considering the object-oriented paradigm. At the present, the software is approximately composed by 100 classes, 450 files, and 67,000 lines of code. Moreover, at the present, it is one of the most diffused open source project studying and developing innovative system level solutions for both LTE and LTE-A technologies. To provide an overall discussion of the aforementioned tool, this section covers its main features through a top-down approach. Additional details can be found in [8], [9], [10] and [11].

A. Network topologies and user mobility

In LTE-Sim, the network topology is composed by a set of cells (i.e., macro, pico, and femtocells) where mobile users are served, and network nodes (including *UserEqupment*, *ENodeB*, *HomeEnodeB*, and *MME-GW*). Both of them, are characterized by an unique ID and a position in a Cartesian system.

In general, the simulator can be used to evaluate the performance of networks composed by one or more cell properly deployed onto the scenario. Due to the availability of a number of channel models (described in the following sub-sections), it is possible to study the performance of LTE and LTE-A networks in urban, sub-urban, and rural environments. To better simulate urban conditions, it is possible to integrate a number of femtocells within the cell. To this end, two specific femtocell structures, i.e., *Building* and *Street*, have been implemented. The former is composed by a number of apartments, each one delimiting the area of a given femtocell. As defined in [13], two different types of building have been developed: (a) Dual Stripe blocks, which consists in two buildings composed of two rows of 10 apartments each, and (b) 5x5 apartment grid, which is composed of 25 apartments located over a 5x5 grid. The latter models two rows of buildings located along a wide road. Each apartment contains up to one active femtocell (i.e., an active *HeNodeB* is working in the femtocell), meaning that, for instance, a 5x5 grid building can contain up to 25 femtocells. The presence of an active femtocell in a single apartment can be randomly decided through the definition of an activity ratio [13], that is the probability that an active home base station is present within an apartment.

Furthermore, user mobility is also supported. On the one hand, Random Direction, Random Walk, and Manhattan [14] mobility models are implemented. On the other, two system level inter-cell handover procedures have been defined. The first is the position-based one, and allows the user to select the nearest base station. The second one, namely the power-based, allows the user to select the node from which it receives the highest power level.

B. LTE protocol stack

At the application layer, four different traffic generators have been implemented, as follows:

- *Trace-based* video application: it generates/sends packets based on realistic video trace files, which are available on [15]. Depending on the structure of the trace file, it may model both real-time and on demand video applications.

- *VoIP* application: it generates G.729 voice flows, which is modeled by an ON/OFF Markov chain [16].
- *CBR* application: it generates packets with a constant bit rate. In particular, packet size and inter-arrival packet time can be defined for this kind of traffic.
- *Infinite-Buffer* application: it models an ideal greedy source that always has packets to be sent.

When a downlink (uplink) flow starts, it activates a dedicated radio bearer between eNB and UE and vice versa (UE and eNB). When a network device receives a packet from the application layer, it forwards the packet through the user plane protocol stack in order to add protocol headers. Then, the packet is enqueued at MAC layer and associated to a particular bearer, using the *IP packet classifier*. Now, the packet can be sent over the channel and received by another network device, according to the scheduling decisions. When a network device receives packets from the channel, it forwards them to the upper layer through the same user plane protocol stack. Then, it delivers them to the proper application sink.

LTE-Sim implements several functionalities of both user-plane and control-plane LTE protocol stacks [17]. The Radio Resource Control (RRC) Entity manages downlink and uplink dedicated radio bearers for a given device and interacts with the classifier in order to classify a packet into a proper radio bearer. The Packet Data Convergence Protocol (PDCP) Entity provides the header compression of packets coming from the upper layer and will be enqueued into a proper MAC queue. The Radio Link Control (RLC) Entity models transparent, unacknowledged, and acknowledged data transmissions at the RLC layer. The MAC Entity provides, for both UE and eNB devices, an interface between the device and the PHY layer designed to delivery packets coming from upper down to PHY layer, and vice versa. At the base station side, it integrates downlink and uplink packet scheduling algorithms as well as Adaptive Modulation and Coding (AMC) schemes. At the mobile user side it implements the generation of CQI feedbacks and uplink buffer status report.

Additionally, it is worthwhile to note that one of the main impacts introduced by CA at the MAC sub-layer is the introduction of scheduling over multiple carriers [7]. This topic will be further addressed in Section III-B.

C. Physical interface and channel models

At the physical layer, LTE-Sim models the time-frequency structure of LTE radio resources, as described in [18]. Both frequency division duplex (FDD) and time-division duplex (TDD) multiple access techniques, as well as all six channel bandwidth configurations (i.e., 1.4, 3, 5, 10, 15, and 20 MHz) are supported, too.

All devices within the same cell should know the operative bandwidth and available sub-channels for both uplink and downlink. This information is stored into the *BandwidthManager* object. An instance of the *BandwidthManager* class is defined for each PHY object. Instances of devices belonging to the same cell store the same information.

The *Channel* object has been developed to handle packet transmission, taking into account the propagation loss model. When a PHY instance has to send packets on a set of sub-channels, it sends to the channel a list of packet to send and the transmission power. The packet transmission is handled in two consecutive steps. For each attached physical device, the channel first calculates the propagation losses according to the propagation loss model and updates the value of the power of the transmitted signal. Then, it forwards packets to all physical devices attached to it and calls the reception procedure.

According to [19], the propagation loss model considers four different phenomena: (i) path loss, (ii) penetration loss, (iii) shadowing, and (iv) effect of fast fading due to multipath. To support various cell scenarios, five path loss realizations have been implemented: macro-cell channel realization for urban and suburban areas, macro-cell channel realization for the rural area, micro-cell channel realization, Winner II [20], and 3GPP indoor propagation [13]. As default, the large scale shadowing fading has been modeled trough a log-normal distribution with 0 mean and 8 dB of standard deviation. The penetration loss, instead, is set to default value of 10 dB [19]. Finally, fast fading is implemented through both Jakes [21] and Roza Zheng models.

When the user receives packets, it estimates, at the physical layer, the Signal-to-Interference-plus-Noise-Ratio (SINR) corresponding to the received signal for each sub-channel (by considering the received power, noise, and interference), computes the corresponding Block Error Rate (BLER) and determines if packets have been correctly received.

In LTE networks, the Transport Block (TB) is the quota of data transmitted at the physical layer during one time slot [22]. It depends on the MCS chosen by the AMC module, the number of antenna ports, the duration of the prefix code used at physical layer, the number of symbols used by the control channel, and the number of resource blocks assigned to a given user. Figure 2 shows the range of TB values, integrated into the simulator, as a function of both MCS index and number of physical resources. Such data have been tandem from [22] and it is assumed to have a normal prefix code, two antenna ports, three OFDM symbols for Physical Downlink Control Channel (PDCCH), no synchronization signals, and the absence of Physical Broadcast Channel (PBCH).

III. Proposed LTE-Sim extensions

A. CA features

With the introduction of CA, if cross-carrier scheduling is enabled, the PDCCH may not be transmitted on the second CC or cell. This means that the Downlink Control Information (DCI) header includes a Carrier Indicator Field that identifies the intended carrier. Thus, the primary cell performs all scheduling and the second cell is reserved for user's data. On the one hand, this enables coordinated scheduling of data across multiple carriers. On the other, it also enables efficient network planning as discussed in [7]. To extend LTE-Sim with CA, several modifications are foremost addressed on the physical interface and channel models. On the one hand,

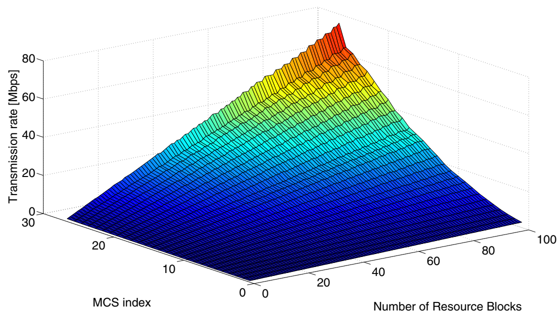

Fig. 2. Behaviour of the values of the TBs by varying the number of resource blocks adopted for the transmission and the MCS index.

at the current stage of development, two symmetrical CC may be employed in the simulator, e.g., with 5 or 20 MHz bandwidth, at the 800 MHz and 2.6 GHz frequency bands. The *BandwidthManager* has been extended for implementing specialized classes to support multi-band operative bandwidths and sub-channels for all devices. Besides, the *Channel* class has also been extended and is now able to take into account the losses from each sub-channel according to the corresponding CC propagation loss model (only for macro-cell propagation at the moment). On the one hand, 5 MHz CCs have been chosen according to the available bandwidth in some countries, such as Portugal [23]. On the other, 20 MHz CCs have been selected, following the trend LTE-A bandwidth in some countries, e.g., South Korea [24], United kingdom [25] or Germany [26].

When the user receives packets it estimates the SINR for the received signal and estimates channel quality and converts it in a set of CQI feedbacks reported to the eNB for each CC, following the convention shown in Fig. 1. During the simulation, each eNB maintains the list of UEs associated to it, storing, for each of them, the ID and the latest CQI feedbacks.

B. Downlink multi-band schedulers

Scheduling decisions are strictly related to the channel quality. With the extensions addressed in the physical layer, UEs are able to periodically measure the experienced channel quality of both CCs, create CQI feedbacks and transmit them to the eNB during the UL. These feedbacks on each CC is of fundamental importance for proper allocation and of distribution of resources among users. Hence, the *DownlinkPacketScheduler* class as also been extended to implement three multi-band scheduling strategies in the context of CA.

Two downlink multi-band schedulers have been implemented so far. The General Multi-Band Scheduling (GMBS) problem (proposed in [27]) is solved with Integer Programming (IP), using binary variables. On the one hand, the GMBS aims at maximizing the cell goodput, considering the video service bit rate, Bit Error Rate and achievable DL throughput according to the supported Modulation and Coding Scheme (MCS). On the other, GMBS only allows to allocate UEs to one of the available CC at a time, i.e., TTI. Further details on GMBS are available in [27].

For comparison purposes, a Basic Multi-Band Scheduling (BMBS) that implements basic Common RRM functionalities has also been included in LTE-Sim. BMBS aims at allocating UEs to a preselected/primary CC, say band 20 (800 MHz), until the maximum load that can be handled in the band, L_b^{max}, is reached. Beyond this capacity threshold, the remaining UEs are allocated to the second CC, say band 7 (2.6 GHz). Similarly to GMBS, UEs can only be allocated to one band at each TTI. The performance and average cell capacity (Packet Loss Ratio, delay and goodput) of both GMBS (integer programming approach) and BMBS have been thoroughly addressed in [27] within the framework of simulations performed with LTE-Sim.

Due to the limitations of the previous schedulers, Enhanced Multi-Band Scheduling (EMBS) has been proposed. One of the main drawbacks of GMBS is the complexity of the optimization process, specifically as the number of UEs in the network growth [27]. Besides, this scheduler does not allow that UEs use more than one CC at the same time (i.e, TTI). In EMBS strategies, on the one hand, a scheduling metric for each RB of each CC is computed. In return, the allocation of RBs is performed according to the highest value obtained. On the other hand, UEs may be allocated in either or both bands simultaneously. The metric is computed has:

$$w_{i,j,b} = D_{HOL,i} \times \frac{R(CQI_{i,j,b})^2}{\bar{R}_i \times S_{rate}} \qquad (1)$$

where $D_{HOL,i}$ is the *i-th* flow head of line (HOL) packet delay, $\bar{R}_i$ is *i-th* flow average transmission rate, and S_{rate} stand for the video bit rate. $R(CQI_{i,j,b})$ is the DL throughput of band/CC for the *i-th* flow in the *j-th* sub-channel as a function of the supported MCS. Hence, the channel diversity of both CCs is also accounted for during the scheduling (RBs allocation) process. $D_{HOL,i}$ insures that video flows with higher delay obtain higher metric value. $R(CQI_{i,j,b})$ is squared to guarantee that RBs with higher CQIs, i.e., higher achievable data rates, also obtain higher metric values.

IV. Simulation and Performance Evaluation

CA has been evaluated in two scenarios with a frequency reuse pattern equal to three. The first with two 5 MHz bandwidth CCs (at 800 MHz and 2.6 GHz). The second addresses two 20 MHz bandwidth CCs (also at 800 MHz and 2.6 GHz). UEs consider the random direction mobility model at 3 kmph. Each UE uses one video flow, the H.264 128 kbps coding rate foreman video clip has been considered for 5 MHz CCs, whereas an H.264 3.1 Mbps coding rate video clip was used for 20 MHz CCs. Additionally, a maximum delay of 100 ms is considered for the performed simulations. Two simulation scenarios were considered. The first addresses two LTE system operating separately at 800 MHz and 2.6 GHz, i.e., without CA, for both values of the bandwidth, i.e., 5 and 20 MHz. The second addressed the EMBS, also for both 5 and 20 MHz CCs. Simulations have been run twenty times in these scenarios and results have been averaged whereas 95 % confidence intervals were computed. Three performance metrics have been considered. The average cell Packet Loss Ratio (PLR), delay and goodput (application lever throughput). It is important to note that the PLR and delay in the scenario without CA have been averaged whereas the two different values for system goodput were summed.

Figure 3 shows the average cell PLR as a function of the number of UEs for cell radius *R* = 1500 m. According to the ITU-T G.1010 [28] and 3GPP TS 22.105 [29], the PLR

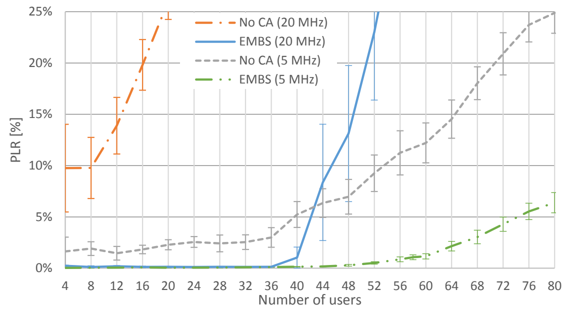

Fig. 3. Comparison of the average cell PLR, as a function of the number of UEs, for CA between scenarios with 5 and 20 MHz CCs (the case with the separate use of two bands, without CA is considered as a reference).

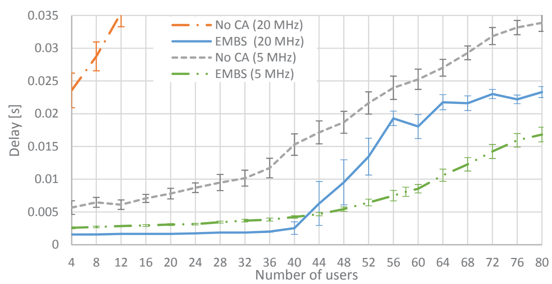

Fig. 4. Comparison of the average delay in a cell as a function of the number of UEs for CA between scenarios with 5 and 20 MHz CCs.

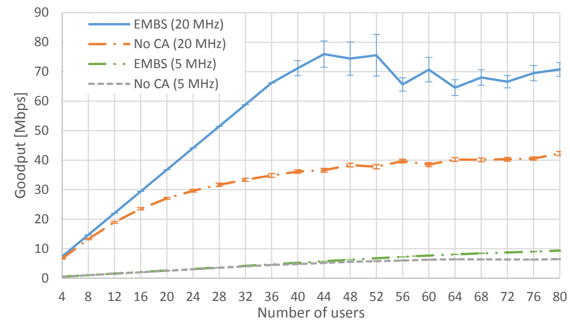

Fig. 5. Average cell supported goodput as a function of the number of UEs.

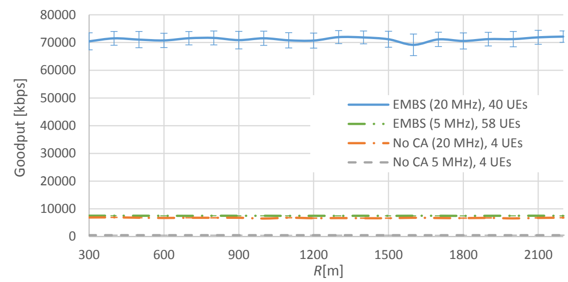

Fig. 6. Average supported cell goodput as a function of the cell radius with PLR ≤ 1 %.

performance target is 1 %. By analysing the scenarios with EMBS for bandwidths of 5 MHz (128 kbps video clip) and 20 MHz (3.1 Mbps video clip), with EMBS, this PLR threshold is only exceeded above approximately 58 UEs (PLR = 0.94 %) and 40 UEs (PLR = 1.04 %), respectively.

The average cell delay for R = 1500 m is shown in Fig. 4. The delay performance targets defined by [28] and [29] are 150 ms (preferred) and 400 ms (limit). From the simulations results it is shown that neither of these targets is exceeded. Nonetheless, when the previous 1 % PLR performance target is exceed, i.e., for 54 and 40 UEs with EMBS, using the 5 MHz and 20 MHz CCs, respectively, the achieved delay is approximately 8 and 2.5 ms (128 kbps and 3.1 Mbps video clips, respectively). Without CA the average cell delay is always considerably superior to the ones from the previous cases.

The supported cell average goodput is shown in Fig. 5, for R = 1500 m. With EMBS and 5 MHz bandwidth, a maximum value of 9.4 Mbps is obtained for the average cell goodput, whereas with 20 MHz bandwidth 76 Mbps are achieved. Without CA, only 6.47 and 42 Mbps are achieved, respectively.

It is worthwhile to analyse the value for the goodput which corresponds to number of users supported under the 1 % PLR performance target (since the 150 ms threshold has not been reached). In this context, with EMBS, the corresponding values for the average supported cell goodput are approximately 7.48 and 71.2 Mbps, for the 5 and 20 MHz (58 and 40 UEs), respectively. Results without CA are not considered since the PLR performance target is always exceeded.

Figure 6 shows the average supported cell goodput as a function of the cell radius, R, for the number of users supported under the 1 % PLR threshold. In this case, the formulation to compute the transmitter power required to guarantee a similar average SINR for different values of the cell radius is the one from [27]. The transmitter power has been normalized so that comparable results between CCs are assured and eNBs from lower cell radius have reduced energy consumption.

The average cell spectral efficiency has been computed as the ratio between the goodput and the CCs bandwidth, i.e., 5 and 20 MHz (128 kbps and 3.1 Mbps video clips). Figure 7 shows the average cell spectral efficiency and corresponding percentage of gain (between EMBS and without CA). Considering the number of UEs, supported under the PLR threshold, with EMBS, the value for the spectral efficiency is 1.78 b/Hz/cell (for 40 UEs), in the 20 MHz case, whereas for bandwidth of 5 MHz, the spectral efficiency is only 0.75 b/Hz/cell. The corresponding percentage of gain is 97 % and 22.7 %, respectively.

V. CONCLUSION

In this paper, the implementation of CA functionalities in the LTE-Sim open source framework has been addressed. A brief overview of LTE-Sim features has been presented, whereas more detailed class extensions to accommodate LTE-A CA features have been given. Moreover, the Enhanced Multi-band Scheduling strategy has been proposed, the innovative contribution from this research, whereas the basic and general multi-band schedulers, already proposed in previous works, have been reviewed. Considering two 5 MHz and 20 MHz CCs operating at 800 MHz and 2.6 GHz, with 128 kbps and 3.1 Mbps video clips, respectively (in two operation scenarios), the performance and capacity gain of CA has been shown. Extensive simulations have been performed with LTE-Sim. The performance analysis was ad-

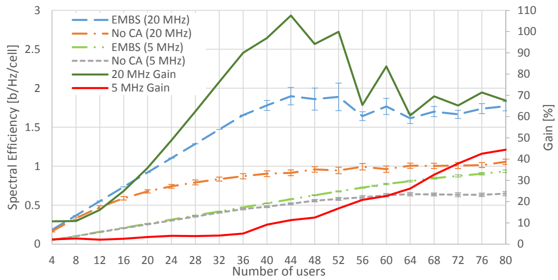

Fig. 7. Average spectral efficiency and corresponding percentage of gain for bandwidths of 5 and 20 MHz with PLR $\leq$ 1 %.

dressed considering ITU-T G.1010 and 3GPP TS 22.105 PLR and delay performance targets, as well as the corresponding supported goodputs. Results have shown that, with EMBS, PLR considerably decreases, and the 1 % PLR threshold is only exceeded above 58 and 40 active UEs for 5 and 20 MHz CCs, and traffic from 128 kbps and 3.1 Mbps video clips, respectively. Considering this 1 % PLR threshold, the average supported cell goodputs are approximately 7.48 and 71.2 Mbps, with EMBS for 5 and 20 MHz CCs, respectively. Additionally, one verifies that the ITU-T G.1010 and 3GPP TS 22.105 150 ms preferred delay performance target has not been exceeded in the performed simulations. By comparing the spectral efficiency and percentage of gain between the use of EMBS and the case without CA, percentage gains of 97 % (for 40 UEs) and 22.7 % (for 58 UEs) have been obtained for scenarios with 5 and 20 MHz bandwidths, respectively.

Further extensions, in the context of CA, of LTE-Sim will address the inclusion of channel models for small cells, e.g., pico and femto, radio resource management and capacity evaluation for future heterogeneous network scenarios. A provisional version of the simulator is available in [30].

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