Enhanced Multi-Band Scheduling for Carrier Aggregation in LTE-Advanced Scenarios

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Abstract—This work updates and proposes an integrated Common Radio Resource Management (iCRRM) for inter-band Carrier Aggregation (CA) between band 7 (2.6 GHz) and band 20 (800 MHz), in the context of Long Term Evolution-Advanced (LTE-A) scenarios. The iCRRM entity performs Component Carrier (CC) scheduling and increases user’s quality of service and experience. Two multi-band schedulers are implemented, an updated General Multi-Band Scheduling (GMBS) algorithm which performs User Equipment (UE) allocation to only one of the CCs at a time by using integer programming optimization, and a new Enhanced MBS (EMBS), which allocates UEs to one or both CCs simultaneously with reduced optimization scheduling complexity. Following the current and upcoming trend of growth from mobile applications usage, video traffic is addressed. The performance of iCRRM is compared with the one from a simpler CRRM, where scheduling is performed by first allocating UEs in one of the two CCs until it is fully loaded and the case of the summed capacity of two bands system without CA. Simulation results have shown that, for a cell radius equal to 1000 m, with EMBS and GMBS, 3GPP and ITU-T’s 1 % Packet Loss Ratio (PLR) threshold is only exceeded above 58 UEs while CRRM 54 UEs are supported, with PLRs of 0.88 %, 1.03 % and 0.99, respectively. Without CA the minimum obtained PLR is approximately 2 %. The corresponding values for the average cell goodput are 7500, 7400 and 6900 kbps for EMBS, GMBS and CRRM, respectively. It has been found that a minimum value of 2.5 for the Quality of Experience can only be supported up to approximately 70, 68, 64 and 36 UEs, with a corresponding supported cell goodput of 8800, 8450, 7950 and 3500 kbps with EMBS, GMBS, CRRM and without CA, respectively. Finally, costs and revenues are analysed from the operator/service provider’s point of view, for two fixed MByte prices, i.e., equal to 0.005 and 0.01 €/MByte. An optimal operating point that maximizes expected profits is sought. Results have shown substantial improvements by using CA. For R = 1000 m and MByte price of 0.01 €/MByte profits of 440, 416, 385 and 173 % have been obtained for the EMBS, GMBS, CRRM and without CA, respectively.

I. INTRODUCTION

To meet the increasing demand for wireless broadband services from fast-growing mobile users, aggregating frequency spectrum is one of the viable techniques to enhance data rates. The concept of spectrum aggregation is introduced by 3GPP in its LTE-Advanced (LTE-A), e.g. LTE R10, a candidate radio interface technology for IMT-Advanced systems standards. However, the introduction of spectrum aggregation or carrier aggregation (CA), as referred to in LTE R10, has required some changes from the baseline LTE R8, although each component carrier (frequency band) in LTE-A remains backward compatible with LTE R8 as described in [1].

CA is considered as a key enabler for LTE-A [2], 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) [3]. Each aggregated carrier is referred to as a Component Carrier (CC). The CC can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz and a maximum of five CCs can be aggregated and can also be of different bandwidths. Therefore the maximum aggregated bandwidth is 100 MHz. In this context, user equipment (UE) may simultaneously receive or transmit data on one or multiple CCs, whereas in the 3GPP R8 specifications [4], each UE uses only one CC to communicate at one time. Moreover, since it is important to keep backward compatibility with R8 and R9 UEs, the aggregation is based on R8/R9 carriers and can be used for both FDD and TDD.

The easiest way to arrange aggregation would be to use contiguous component carriers within the same operating frequency band (as defined for LTE), so called intra-band contiguous. However, in practice, such a large portion of continuous spectrum is rarely available. CA, where multiple CCs of smaller bandwidth are aggregated, is an attractive alternative to increase data rate. Additional advantages are offered by CA in terms of spectrum efficiency, deployment flexibility, backward compatibility, and more. By aggregating non-contiguous carriers, fragmented spectrum can be more efficiently utilized [5]. For non-contiguous allocation it could either be intra-band, i.e. the CCs belong to the same operating frequency band, but have a gap, or gaps, in between, or it could be inter-band, in which case the CCs belong to different operating frequency bands [6]. In [7], [8] and [9] the authors addressed the problem of how to optimize the resource allocation process in a multi-carrier system, while maintaining low complexity. Both simple theoretical and simulation results were obtained, which show that with low number of users and low percentage of LTE-A users, the load balancing method of Round Robin (RR) achieves better performance than the Mobile Hashing (MH) balancing. It was also found that using independent packet scheduling per CC suffers from poor coverage performance. In this context, the authors proposed a cross CC packet scheduler algorithm, which is a simple extension of the existing PF scheduler. The cross CC algorithm is aware of the user throughput over all the aggregated CCs. As a result, it was shown that the cross CC algorithm maximizes the network utility even if users are provided with different number of CCs. This approach however only accounts for
the cell throughput and disregards QoS parameters, e.g., delay and loss. Besides full buffer traffic is addressed which is not representative of nowadays and future cellular networks traffic. In [10] a scheduling strategy for CA using pre-organized Resource Blocks (RB) sets was presented. Besides, an analytical evaluation framework was performed to determine the expected number of RBs required by users, based on a mapping of Channel Quality Indicator (CQI) values to data rates per RB and the statistical behaviour of the CQI. RBs can be grouped into sets based on the predefined maximum number of RBs and spectrum availability. By scheduling these RBs this scheme can help reduce the scheduling delay. Nevertheless this adds further scheduling complexity due to the RB pre-organization functionality.

In this context, this work addresses LTE-A CA and proposes an updated integrated Common Radio Resource Management (iCRRM), from [11], that performs CCs scheduling to satisfy user’s Quality of Service (QoS) and experience (QoE) requirements and to maximize spectral efficiency. Two inter-band CA, Band 7 (2.6 GHz) and Band 20 (800 MHz) are considered. As stated above, large portions of continuous spectrum are rarely available and the aggregation of smaller bandwidths is an attractive solution to reduce spectrum under-utilization. Besides, the Portuguese communication regulator, Anacom, auctioned in 2011 LTE’s bands 7 and 20, during this event only 5 MHz bandwidths (“lots”) were available for the considered CCs [12]. In this context, 5 MHz bandwidth CCs are considered for this research. Additionally, following the forecast from [13], video traffic is addressed under the premise that in 2013 it represented more than half (53%) and will reach 69% of all worldwide mobile data traffic by 2018. Additionally, a normalised transmitter power formulation is proposed. One the one hand, this formulation allows for computing the required eNB power to maintain a constant average cell SINR for all cell radii, hence have comparable CA results for different cell radii. On the other hand, the formulation guarantees lower energy consumptions, e.g., small cell radii require lower transmitter power than their counterpart with larger radii to achieve similar SINR and coverage.

Considering extensive simulations results the iCRRM performance metrics, i.e., packet loss, delay, goodput, and user’s expected Quality of Experience are analysed and compared with a simple CRRM, which performs basic multi-band scheduling, and the summed capacity of two CCs LTE systems, i.e., without CA.

The remainder of this paper is structured as follows. Section II addresses CA common radio resource management, objective and system model. Section III presents the proposed Multi-Band Scheduling strategies. Section IV introduces simulations parameters. Section V analyses the obtained results in terms of packet loss ratio, delay, quality of experience, and goodput. Section VI addresses the cost/revenue analysis from the operator point of view. Finally, Section VIII draws some conclusions and further work.

II. COMMON RADIO RESOURCE MANAGEMENT FOR CARRIER AGGREGATION, OBJECTIVE AND SYSTEM MODEL

The RRM framework for LTE-A retains many similarities with that from LTE. With CA, however, it becomes possible to schedule a user on multiple CCs simultaneously, each of which may exhibit different radio channel characteristics. Supporting multi-CC operations introduces some new challenging issues in RRM framework for LTE-A systems [14].

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, and then employs layer-3 CC Selection to allocate the users on different CCs [7]. Once the users are assigned onto certain CC(s), the layer-2 Packet Scheduling (PS) is performed. In order to allow for backward compatibility so LTE and LTE-A users can co-exist, it has been decided to use independent layer-1 transmissions, which contain Link Adaptation (LA) and Hybrid Automatic Repeat Request (HARQ) etc, per CC, in line with the LTE assumptions [1].

The use of an independent link adaptation for each CC may help to optimize transmission according to radio conditions. Different levels of coverage can be provided by setting each CC with its own transmission power. This is especially the case of inter-band CA, since the radio channel characteristics such as propagation, path loss and building penetration loss, may vary according to the operating radio frequency bands, i.e., selecting different transmission parameters, such as modulation scheme, code rate, and transmit power per CC, it is expected to be useful to further improve user QoS.

In the context of this research, one investigates a non-contiguous CA from an upper layer point of view and proposes an integrated CRRM (iCRRM) entity where CRRM and CA functionalities are performed together. First, by using an Integer Programming (IP) based algorithm, the inter-frequency handovers are achieved in an optimised way, performing the scheduling via the optimal solution of a General Multi-Band Scheduling (GMBS) problem. Additionally, due to the complexity and the impossibility of allocating UEs to more than one CC an Enhanced Multi-Band Scheduling (EMBS) is incorporated into the iCRRM entity. This EMBS performs the scheduling functionalities differently from of the GMBS with reduced complexity and allows allocating UEs to multiple CCs.

The employed Resource Allocation (RA) allocates the user packets to the available radio resources in order to satisfy the user requirements, and to ensure efficient packet transport, e.g., minimise loss, to maximize spectral efficiency. The RA is envisioned to have an inherent tuning flexibility to maximise the spectral efficiency of the system for any type of traffic QoS requirements. The RA adopted here maps packets of variable...
size into CCs for transmission over the Physical (PHY) layer depending on the channel quality.

The novelty of the approach is that the proposed iCRRM enables the integration of spectrum and network resource management functionalities leading to higher performance and system capacity gains. The key to such integration is the pooling of the resources together; the integration allows for mapping of the service requirements onto an available spectrum amount and translates the latter into network load. As stated above, the iCRRM uses inter-band CA to achieve lower delays and higher user throughput by exploiting the channel diversity. These bands show independent Channel Quality Indicators (CQIs) over time and space, which becomes a source of diversity at the PHY layer, with an important chance to achieve higher spectrum efficiency. Information from the network about the system state (e.g., received signal strength, transmitted power, UEs velocity, etc.) are used in RRM and procedures such as load, admission and congestion control can successfully be combined with dynamic spectrum use.

In the context of CA in a LTE-A scenario, two frequency bands, e.g., two CCs are available to the operator, band 7 and band 20, i.e., 2.6 GHz and 800 MHz. The addressed scenario resembles 3GPP scenario 2 [4] and, although propagation loss is higher at 2.6 GHz, through transmitter power tuning a constant average Signal to Interference plus Noise Ratio (SINR) is guaranteed in this study. Thus, comparable results between CCs are assured. The network is deployed with two collocated omnidirectional hexagonal cells with radio frequency band 7 and 20, and the corresponding first tier of interferers. For future reference, it is worthwhile to note that a full Radio Access Network (RAN) infrastructure sharing configuration [15] is assumed, e.g., the mast, eNB and Radio Network Controllers (RNC) are share by both CCs, the addressed scenario and infrastructure sharing configuration are shown in Fig. 2.

The radio channel follows the ITU radio propagation COST-231 Hata model, for macro cell propagation scenarios in urban and suburban areas outside the high rise core where the buildings are of nearly uniform height [16]. The channel loss between the UE and the eNB is modelled by using a shadowing loss with log-normal distribution and by considering fast fading with Jakes model.

III. Multi-Band Scheduling

A. General Multi-Band Scheduling

The following General Multi-Band Scheduling (GMBS) is an adaptation to LTE of the work proposed in [11] where the authors implemented an iCRRM, able to schedule users between the 2 GHz and 5 GHz High-Speed Downlink Packet Access (HSDPA) frequency bands. CA offers an added dimension for user scheduling at the Transmission Time Interval (TTI) level and poses an optimization problem for improving network resource exploitation. The scheduling problem can be formulated as a General Assignment Problem (GAP) [17]. In this specific scenario, the user allocation problem is referred to as GMBS. The proposed Profit Function (PF) maximises the total throughput of the operator via a single objective problem.

In the context of this research, the GMBS problem is solved with Integer Programming (IP), using binary variables. The PF is defined considering the ratio between the rate available on the DL channel and the requested rate by the service flow, and is expressed as follows:

\[
(PF) \sum_{b=1}^{m} \sum_{u=1}^{n} W_{b,u} \cdot x_{b,u} 
\]

where \( x_{b,u} \) is the allocation variable, i.e., a Boolean variable that indicates if UE \( u \) is allocated on band \( b \). The normalised metric \( W_{b,u} \) is given by:

\[
W_{b,u} = \frac{[1 - BER(CQI_{b,u})] \cdot R(CQI_{b,u})}{S_{rate}}
\]

where \( S_{rate} \) is the video service bit rate, \( BER(CQI_{b,u}) \) is the average Bit Error Rate (BER) occurred in previous DL transmissions for user \( u \) on band \( b \) for the Modulation and Coding Scheme (MCS) supported, and \( R(CQI_{b,u}) \) is the DL throughput for user \( u \) on band \( b \), also as a function of the supported MCS.

The constraints for GMBS vary, depending on the ability of the UEs to simultaneously transmit and receive in multiple frequencies (multiple transceivers at the UEs), or just over a single band at the time. The LTE standard allows allocating multiple RBs for each UE and each UE may have multiple flows. However, in this work it is assumed that UEs only use a single video flow with \( S_{rate} = 128 \) kbps. In this context the GMBS constraints are twofold:

1) **Allocation Constraint (ACt)**, each user can be allocated only to a single frequency band:

\[
(ACt) \sum_{b=1}^{n} x_{b,u} \leq 1, x_{b,u} \in \{0, 1\} \quad \forall u \in \{0, \ldots, n\}
\]

2) **Bandwidth Constraint (BC)**, the total number of users on each band is upper bounded by the maximum normalised load that can be handled in the band, \( L_{b}^{max} \in \{0, 1\} \), as follows:

\[
(BC) \sum_{u=1}^{m} \frac{S_{rate} \cdot (1 + R_{Tx} \cdot BER(CQI_{ba}))}{R(CQI_{ba})} \cdot x_{ba} \leq L_{b}^{max} 
\]

\( \forall b \in \{0, \ldots, m\} \) (4)

Fig. 2. Inter-band CA infrastructure sharing configuration and deployment scenario.
where the first term is the requested service data rate for user $u$, including bit loss, normalized with the maximum data rate that the network can offer to the user $u$ on band $b$ which is $R(CQI_{b,u})$. The BC accounts for the user traffic requirement, DL capacity and overhead caused by losses.

Upon the maximization of the PF, a Boolean multi-band allocation matrix is created, $X = [x_{b,u}]$. This matrix is used, in conjunction with available downlink packet schedulers, to allocate RBs to the network users. The allocation matrix returns 1 to allocate $u$ to $b$ or 0 for no allocation.

Finally, one of the simulator implemented DL packet schedulers computes metrics for the allocated CC/band RBs, and assigns them according to the highest metric value. Through extensive simulations it has been found that for video applications the M-LWDF scheduler presents the best results, including bit loss, normalized with the maximum data rate. Therefore, the computation complexity of resource scheduling (optimization) would become unacceptable. Besides, both of these downsides have already been identified in the literature [1]. Hence, in the context of this research an Enhanced Multi-Band Scheduling (EMBS) has been developed. On the one hand, IP optimization is no longer employed, instead a more traditional scheduling approach is used, i.e., a scheduling metric for each RB of each CC is computed. In return, the RBs allocation is performed according to the highest value obtained. On the other hand, this approach allows to allocate UE in either or both bands simultaneously, e.g., according to the metric value. The scheduling metric is computed has fallows:

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

where $D_{HOL,i}$, $R_i$ and $S_{rate}$ stand for the same as above (for the GMBS), and $R(CQI_{i,j,b})$ 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. In this case $D_{HOL,i}$ insures that video flows/UEs with the higher delay, i.e., the difference between the time in which the transmission was requested and the current simulation time, obtains an higher metric value. $R(CQI_{i,j,b})$ is squared to guarantee that RBs with higher CQIs achieve an higher metric value, and as a consequence higher data rates should be obtained.

### C. Basic Multi-Band Scheduling

Finally, for comparison purposes, another multi-band scheduler was implemented in a CRRM and considered for CA evaluation. This scheduler is rather simpler than the ones proposed above and implements basic CRRM functionalities. Its aim is to allocate UEs to a preselected frequency band, say band 20, until $L_b^{\text{max}}$ is reached. Beyond this capacity threshold, the remaining UEs are allocated to the second available frequency band, say band 7. Similarly to the GMBS, UEs can only be allocated to one band at the time. Given this considerations the allocation variable $x_{b,u}$ is given by:

$$x_{b,u} = \begin{cases} 1, & \text{if } L_b \leq L_b^{\text{max}} \\ 0, & \text{if } L_b > L_b^{\text{max}} \end{cases}$$

### IV. SIMULATION ENVIRONMENT

In this work, the CA gain is evaluated for several inter-cell distances with a frequency reuse pattern equal to three. In order to have comparable results and to reduce energy consumption by reducing the transmitter power for low cell radii CA is analysed at constant average cell SINR. The method to compute a normalised transmitter power required to maintain such average SINR, i.e., the transmitted power for each cell radii so they all have a similar average cell SINR, was described in our previous work [11] and [20], and used within the simulation framework of this research, but will not be discussed here, as it is beyond the scope of this paper.

To study the performance of the proposed iCRRM several LTE system level simulations have been performed within a LTE-A scenario, shown in Fig. 2. The comparison parameters include the average cell supported goodput, delay, Packet Loss Ratio (PLR) and QoE. Simulations have been performed with LTE-Sim [18], developed at University of Bari, which is an event-driven simulator written in C++ using the object-oriented
paradigm. Several traffic generators at the application layer have been implemented and the management of data radio bearer is supported. In particular, the video traffic addressed in this research is a trace-based application which sends packets based on realistic video trace files. UEs are constantly moving at 3 kmph using LTE-Sim random direction mobility model, each UEs only use one H.264 128 kbps video bit rate flow, and maximum delay of 1 ms is considered. LTE-Sim [18] provides a support for radio resource allocation in a time-frequency domain and, in this configuration, the duration of one LTE radio frame is 10 ms. One frame is divided into 10 sub-frames of 1 ms each, and each sub-frame is divided into two slots of 0.5 ms each. Each slot contains either six or seven OFDM symbols, depending on the Cyclic Prefix (CP) length [21]. The normal CP is used in urban cells and high data rate applications while the extended CP is used in special cases like multi-cell broadcast and in very large cells (e.g. rural areas, low data rate applications).

Furthermore, LTE radio resources are allocated in units of RBs or Physical RBs (PRBs). Each PRB contains 12 subcarriers and one slot. If the normal CP is used, a PRB will contain 12 subcarriers over 7 symbols. If the extended CP is used, the PRB contains only six symbols. In the context of CA, normal CP frames is assumed, each carrier band has a 5 MHz bandwidth and thus a total of 25 + 25 = 50 PRBs are available for scheduling. An overview of the simulation parameters are presented in Tab. I.

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame structure</td>
<td>FDD</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 MHz per CC</td>
</tr>
<tr>
<td>Slot duration</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Scheduling time (TTI)</td>
<td>1 ms</td>
</tr>
<tr>
<td>Number of RBs</td>
<td>25 RB per CC</td>
</tr>
<tr>
<td>Max delay</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Video bitrate</td>
<td>128 kbps</td>
</tr>
<tr>
<td>UE mobility</td>
<td>random direction, 3 kmph</td>
</tr>
</tbody>
</table>

V. Simulation Results

The evaluation of the proposed iCRRM entity involved performing several simulation scenarios:

1) Two LTE system operating separately at 800 MHz and 2.6 GHz, i.e., without CA;
2) One LTE-A scenario with both frequency bands managed with basic CRRM functionalities (basic multi-band scheduling);
3) One LTE-A scenario with both frequency bands managed with the proposed iCRRM entity:
   a) One set performed with GMBS;
   b) One set performed with EMBS.

Each scenario was simulated twenty times, these results were averaged and the confidence intervals were computed. The average cell Packet Loss Ratio (PLR), and delay analyses are performed by averaging the results from 1) while comparing them with the ones from 2) and 3). In terms of average cell supported goodput analyses, the system capacity obtained in 1) is summed and compared with the results from 2) and 3).

Additionally, it is worthwhile to note that the following results obtained without CA were compared and are well within the range of ones obtained in packet scheduling algorithms studies performed in [18], [21] and [19].

A. Packet Loss Ratio

Figure 3 shows the average cell PLR as a function of the number of UEs for a cell with \( R = 1000 \) m. As expected, both CRRM and iCRRM outperform the scenario without CA. However, according to the ITU-T G.1010 [22] and 3GPP TS 22.105 [23] recommendations the PLR should not exceed 1 %. In this context, the 1 % PLR threshold is only exceeded above approximately 58 UEs with iCRRM general (GMBS) and enhanced (EMBS) multi-band scheduler (1.03 % and 0.88 %, respectively), whereas CRRM only supports up to 54 UEs (0.99 %), without CA the minimum obtained PLR is approximately 2 %. Besides, it is also verified that overall the EMBS enables to obtained lower PLR values than the ones with the GMBS.

B. Delay

The average cell delay for \( R = 1000 \) m is shown in Fig. 4. As in the previous case both CRRM and iCRRM present better results than the ones without CA, i.e., lower delay. Moreover, iCRRM’s EMBS outperforms again the GMBS. Similarly to the PLR, ITU-T G.1010 [22] and 3GPP TS 22.105 [23] also define delay performance targets, i.e., 150 ms preferred and 400 ms limit delay. For the considered number of UE neither of these targets is exceeded. Nonetheless, when the previous 1 % performance target is exceed, i.e., 54 and 58 UEs with CRRM and iCRRM, respectively, the achieved delay is approximately 11.22, 11.44 and 7.68 ms with CRRM and iCRRM’s GMBS and EMBS scheduler, respectively. Without CA the average cell delay is always superior to the ones from the above cases.

C. Quality of Experience

The permanent evolution of wireless network technologies allows for improved data rates and coverage areas while facilitating new multimedia and mobile services. Considering this evolution of services and applications, operator’s success does not only depend on their QoS, but also if it meets the end user’s expectations. With the increasing competition, improving the quality of the offered services, as perceived by the users (QoE), becomes important as well as a significant challenge to service
providers with a goal to minimize the customer churn yet maintaining their competitive edge [24]. However, QoS is generally defined in terms of network delivery capacity and resource availability but not in terms of the satisfaction to the end-user. In this context, besides assessing the network service level parameters the QoE can also be evaluated by employing the model for the mapping between QoS and QoE proposed in [25]. This model addresses multimedia applications, e.g., gaming, video, web-browsing and audio. The video sub-model is based on the Mean Opinion Score (MOS) measurements which were mathematically fitted to obtain an equation that characterizes the QoE as a function of the PLR, delay and video bit rate as shown in [25]. Considering this model and previous average cell PLR and delay simulation results (with $b_{rate} = 128$ kbps), Fig. 5 shows the predicted average cell QoE as a function of the number of active UEs in a cell with $R = 1000$ m. From Fig. 5 it is clear that employing CA improves the average cell QoE. Without CA an average QoE of 2.7 is obtained below 28 UEs, beyond this values the quality substantially decreases and reaches its lower value with the maximum considered UEs. With CA, as expected by the obtained PLR and delay the EMBS provides the better results followed by the GMBS and the CRRM. Moreover, it is interesting to note that as expected by ITU-T G.1010 [22] and 3GPP TS 22.105 [23], the higher decline of the estimated QoE value occurs approximately with the same number of UEs from which the 1 % PLR is exceeded, i.e., 54 and 58 UEs with CRRM and iCRRM, respectively.

D. Goodput

The supported average goodput is shown in Fig. 6 considering $R = 1000$ m. In this case, the performance gap between iCRRM, CRRM and no CA is less apparent. With the exception of the case without CA all the remaining scenarios can support the cell traffic requirement up to approximately 52, 56 and 58 UEs with CRRM, iCRRM GMBS and iCRRM EMBS, respectively. However, it is clear that as the number of UEs within the cell increases so thus the iCRRM performance gain, in comparison with both CRRM and no CA results. In the context of the iCRRM it has also been shown that above 58 UEs the goodput obtained with the EMBS is higher than the one obtained with the GMBS.

Additionally, it is also important to consider the supported goodput within ITU-T G.1010 [22] and 3GPP TS 22.105 [23] performance target. Considering the number of UE supported within the 0.1 % PLR margin, i.e., 58 and 54 UEs with iCRRM and CRRM, the supported goodput improvement between both RRM is evident, as shown in Fig. 7 for different cell radii. With iCRRM an average of 7500 and 7400 kbps are supported, with the EMBS and GMBS, respectively, whereas only 6900 kbps are supported with CRRM. The case without CA is not considered since the lowest PLR is approximately 2 %.}

Similarly to the above ITU-T and 3GPP target performance considerations and bearing in mind the ITU-T ACR scale [26] which lower QoE value is 1 and highest is 5, a value equal to 2.5 is henceforward considered as a threshold below which the QoE is not acceptable. In this context, and considering Fig. 5, without CA the average cell QoE is no longer considered
sufficient above 36 UEs. With CA the 2.5 threshold is no longer achieved above 64, 68 and approximately 70 UEs with CRRM, iCRRM GMBS and iCRRM EMBS, respectively. Finally, the number of UEs supported by the cell below this QoE threshold can also be reflected in terms of average supported cell goodput, as shown in Fig. 8. Given these considerations, the average supported goodput is approximately 8800, 8450, 7950 and 3500 kbps with iCRRM EMBS, iCRRM GMBS, CRRM and without CA, respectively.

VI. COST/REVENUE ANALYSIS

From the economic analysis point of view, the different entities from cellular systems, such as subscribers, network operators, service providers, regulators, and equipment vendors, should be taken into account [27]. In this research, one considers operator’s/service provider’s point of view, whose main goal is to obtain the maximum profit from his business, i.e., to increase revenue, decreasing costs as much as possible. In this paper, costs and revenues are analysed on an annual basis, although project duration of five years is assumed. Moreover, the analysis is performed under the assumption of a null discount rate. Nevertheless, this section does not intend to perform a complete economic study, but aims at simply present initial contributions to facilitate cellular planning optimisation. Appropriate enhancements would be required, in order to perform a complete economic analysis based on discounted cash flows (e.g., to compute the net present value). From a cellular planning and radio resource management perspective, the objective of the operator is to determine an optimal operating point that maximizes the expected revenue. Examples of major decisions affecting this include the type of technology to be used, the size of the cell, and the number of radio resources in use in each cell. It is therefore important to identify the main components of the system’s costs and revenues, in particular those that allow a direct relationship to either the maximum cell coverage distance or the reuse pattern. In this context the cost per unit area is given by [27]:

$$C_i[\text{€/km}^2] = C_{fi}[\text{€/km}^2] + C_b[\text{€/cell} \cdot N_{[\text{cells/km}}^2]$$ (10)

where $C_{fi}$ is the fixed term of the costs (e.g. licensing and spectrum auctions or fees), and $C_b$ is the cost per BS. The number of hexagonal coverage zones per unit area is given by:

$$N_{[\text{cell/km}}^2] = \frac{2}{3\sqrt{3}R^2}$$ (11)

where $R$ represents the cell radius. Then the total cost per BS, considering every element in the infrastructure, is given by:

$$C_{[\text{€/cell}]} = \frac{C_{BS} + C_{bh} + C_{inst} + C_{M&O}}{N_{[\text{year}}}$$ (12)

where $N_{[\text{year}}] = 5$ is the project’s lifetime, $C_{BS}$ is the cost of the BS, $C_{bh}$ is the backhaul cost, $C_{inst}$ is the installation cost of the BS, and $C_{M&O}$ is the operation and maintenance cost.

The revenue in a hexagonal-shaped coverage zone per year, $(R_v)_{cov-zone}$, can be obtained as a function of the supported throughput per eNB, $R_{sup}[\text{kbps}]$, and the revenue of a channel with a data rate $R_{bl}[\text{kbps}]$, $R_{bl}[\text{MByte}]$, by:

$$(R_v)_{cov-zone} = \frac{N_{hex}[\text{km}] \cdot R_{(b-sup)}[\text{kbps}] \cdot T_{bh} \cdot R_{bl}[\text{€/min}]}{R_{b-ch}[\text{kbps}]}$$ (13)

where $N_{hex}$ is the number of hexagonal areas, $T_{bh}$ is the equivalent duration of busy hours per day, and $R_{b-ch}$ is the bit rate of the basic “channel”.

The revenue per unit area per year, $R_v[\text{€/km}^2]$, is obtained by multiplying the revenue per cell by the number of cells per unit area:

$$R_v[\text{€/km}^2] = \frac{N_{hex}[\text{km}^2] \cdot (R_v)_{cell}}{N_{hex}[\text{km}^2] \cdot R_{b-sup}[\text{kbps}] \cdot T_{bh} \cdot R_{bl}[\text{€/min}]}$$ (14)

The (absolute) profit is given by:

$$P[\text{€/km}^2] = R_v - C$$ (15)

from which, the profit in percentage terms is given by:

$$P[\%] = \frac{R_v - C}{C} \times 100$$ (16)

One considers a LTE system deployed in Portugal. The BS/eNB cost $C_{BS}$ is assumed to be the value referenced in [28], i.e., $C_{BS} = 10,000$ €. The BS installation cost, $C_{inst} = 22,500$ €, is obtained by assuming 2,500 € for the radio installation plus 20,000 € for the infrastructure cost, e.g., site acquisition, site design and site construction. The backhaul cost is considered to be $C_{bh} = 5,000$ €. Finally the operation and maintenance costs which include first-line maintenance, rental costs and preventive and corrective infra maintenance, is $C_{M&O} = 1,500$ € per year of operation. For a project duration of $N_{year} = 5$, one obtains $C_i = 9,000$ € per BS/eNB.

Bearing in mind Anacom’s auction results [12] it is known that each 2 × 5 MHz of bandwidth was sold for 45,000,000 € and 3,000,000 € for the 800 MHz and 2.6 GHz CCs, respectively. Considering $k = 3$, the total license cost for the 800 MHz and 2.6 GHz are $3 \times 45,000,000$ € = 135,000,000 € and $3 \times 3,000,000$ € = 9,000,000 €, respectively. Assuming these values and considering a total area of 91391.5 km² as the area of Portugal the fixed cost per unit area is:

$$C_{fi} 800 MHz[\text{€/km}^2] = \frac{135,000,000}{91391.5 \times 5} \approx 295$$ (17)

$$C_{fi} 2.6 MHz[\text{€/km}^2] = \frac{45,000,000}{91391.5 \times 5} \approx 19.70$$ (18)

A summary of the costs assumptions is presented in presented in Tab. II.
Although nowadays the trend is to consider flat rate/fee for data and multimedia traffic revenues, in this work, one still considers the price per megabyte, MByte, of information, \( R_{144} / MByte \). In this context, two \( R_{144} / MByte \) values are considered, i.e., 0.005 and 0.01 €/MByte. Assuming the above costs assumptions and channel price, the simulated average supported goodput results, \( R_{\sup} / \text{kbps} \), with 80 UEs (no CA), and assuming an equivalent duration of busy hours per day, \( T_{b} \), equal to 6 busy hours per day, 240 busy days per year, one computes the total cost, \( C_{\text{total}} \), and the total revenue per unit area per year, \( R_{v} \) total \( (R_{v} / \text{€/m}^2) \). Fig. 9 shows that \( C_{\text{total}} \) and \( R_{v} \) total decrease as the as the cell radius increases, the revenues are higher than the total cost and, as expected, higher revenues are obtained with higher MByte prices.

The analysis of the percentage of profit obtained by considering two simulated results of \( R_{b-\sup} / \text{kbps} \) for the \( R_{v} / \text{€/km}^2 \) computation. Initially one considers the average supported goodput for PLR \( \leq 1\% \), this also means that as the scenario without CA thus not support this performance threshold it will not be considered. Secondly, the \( R_{b-\sup} / \text{kbps} \) reached with QoE \( \geq 2.5 \) is addressed. Fig. 10 and Fig. 11 show the percentage of profit with \( R_{144} / MByte = 0.005 \) for PLR \( \leq 1\% \) and QoE \( \geq 2.5 \), respectively, whereas Fig. 12 and Fig. 13 show the percentage of profit with \( R_{144} / MByte = 0.01 \) under the same goodput constraints.

Overall it is evident that the profit increases as the price per MByte increases and that it also diminishes as a function of the cell radius, i.e., as the cell radius increases profits are lower. Considering PLR \( \leq 1\% \) the CRRM presents the lower results, whereas iCRRM’s EMBS and GMBS reach comparable profits as their respective goodputs are also similar. Under the QoE \( \geq 2.5 \) goodput constraint, as expected given their supported goodputs, i.e., higher number of supported UEs, iCRRM EMBS presents the higher profits, followed by iCRRM GMBS and CRRM, the case without CA obtains by far the lower results.

\[ \begin{array}{|c|c|} 
\hline
\text{Costs} & \text{Value} \\
\hline
C_{f1, 3000 \text{MHz}} / \text{€/km}^2 & 925.00 \\
C_{f1, 2.6 \text{GHz}} / \text{€/km}^2 & 19.70 \\
C_{f2} / \text{€} & 10,000 \\
C_{b,\sup} / \text{€} & 22,500 \\
C_{b,\sup} / \text{€} & 5000 \\
C_{\text{sup}} / \text{€} & 1500 \\
\hline
\end{array} \]

Fig. 9. Total cost and revenue for different cell radii, \( R_{144} / \text{€/MByte} \) equal to 0.005 and 0.01.

Fig. 10. Percentage of profit for different cell radii and PLR \( \leq 1\% \), \( R_{144} / \text{€/MByte} = 0.005 \).

Fig. 11. Percentage of profit for different cell radii and QoE \( \geq 2.5 \), \( R_{144} / \text{€/MByte} = 0.005 \).

Besides the obvious profit gains with higher MByte price it is interesting to note that although the scenario without CA may support the QoE \( \geq 2.5 \) constraint it has been shown that under the addressed simulations and cost assumptions with \( R_{144} / \text{€/MByte} = 0.005 \) a profit value of 0 % is obtained for \( R = 2100 \text{ m} \). Employing iCRRM’s EMBS and considering \( R = 1000 \text{ m} \) a profit of 130 and 360 % are obtained for PLR \( \leq 1\% \) with \( R_{144} / \text{€/MByte} \) equal to 0.005 and 0.01, respectively. For the QoE \( \geq 2.5 \) limitation the profit reaches 170 and 440 % for the same MByte price. With iCRRM’s GMBS and the same cell radius, profits of 129 and 357 % are achieved for PLR \( \leq 1\% \) and 158 and 416 % for QoE \( \geq 2.5 \) considering \( R_{144} / \text{€/MByte} \) equal to 0.005 and 0.01, respectively. Using the basic CRRM with \( R = 1000 \text{ m} \) profits of 113 and 326 % and 143 and 385 % are obtained for PLR \( \leq 1\% \) and QoE \( \geq 2.5 \) with MByte prices of 0.005 and 0.01 €/MByte, respectively. Finally, without CA profits of 37 and 173 % are achieved for QoE \( \geq 2.5 \) and \( R_{144} / \text{€/MByte} \) equal to 0.005 and 0.01 €/MByte, respectively.

VII. CONCLUSION

This work proposes and adaptation and update of the integrated CRRM entity proposed in [11] for HSDPA in the context of LTE-A. The iCRRM entity implements inter-band Carrier Aggregation (CA) by performing scheduling between two Component Carriers (CCs), i.e., band 7 (2.6 GHz) and band 20 (800 MHz), with the aim of increasing users’ quality of service requirements and improve spectral usage. Besides, iCRRM may operate with one of two multi-band schedulers, the general multi-band schedulers (GMBS) operates in parallel
with a classic downlink packet schedulers, i.e., iCRRM assigns users to one CC and the scheduling of Resource Blocks (RBs) of each CC (to the allocated users) is performed by the M-LWDF packet scheduler, the enhanced multi-band schedulers (EMBS) operates on its own and allocates RBs from both CCs. Moreover, with the GMBS UEs can only be allocated to one CC at a time whereas with EMBS UEs can be allocated to both CCs. Additionally, considering available bandwidths auctioned by the Portuguese communication regulator, Anacom, in 2011, CA research was addressed considering 5 MHz bandwidth CCs. Furthermore, bearing in mind CISCO’s mobile traffic forecast, e.g., video traffic embodied 53 % of all traffic in 2013 and will reach 69 % by 2018, one addressed this work considering that each users generates one video traffic flow. In simulation terms, each flow is characterize as one trace based H.264 128 kbps video bit rate flow. Additionally, through extensive simulations, it has been found that the Modified Largest Weighted Delay First (M-LWDF) scheduler provided the best results for this type of traffic and hence was selected to operate in conjunction with iCRRM’s GMBS.

To analyse the iCRRM performance with several cell radii with comparable conditions, and to reduce energy consumption by reducing the transmitter power for low cell radii, the average cell interference-plus-noise ratio (SINR) must be kept constant. In this context, a formulation proposed in [11] and [20] to compute the transmitter power needed to cover cells of different sizes whilst maintaining the average cell SINR constant, and near the maximum, considering frequency reuse pattern three was considered. The normalised transmitter power required to maintain such average cell SINR was computed and used within the simulation framework.

Extensive simulations were performed with LTE-Sim and the performance analysis was performed addressing ITU-T G.1010 [22] and 3GPP TS 22.105 [23] performance targets and the corresponding supported goodputs. Simulations results have shown that the 1 % Packet Loss Ratio (PLR) margin is only exceeded above 58 and 54 UEs with iCRRM and CRRM, respectively. Without CA the minimum obtained PLR is approximately 2 %. In this condition, the average supported cell goodput is approximately 7500 and 7400 kbps with iCRRM EMBS and GMBS, respectively, and 6900 kbps with CRRM. The ITU-T G.1010 [22] and 3GPP TS 22.105 [23] 150 ms preferred average cell delay performance target has not been reached in the performed simulations.

Considering the unified model for the mapping of Quality of Service (QoS) parameters into Quality of Experience (QoE) from [25], the perceived impact of CA has been estimated. It has been found that a minimum QoE value of 2.5 can only be supported up to 64, 68 and approximately 70 UEs with CRRM, iCRRM’s GMBS and EMBS, respectively, whereas without CA only 36 UEs can be supported. Moreover, the average cell goodput equivalent to the number of UEs supported within this QoE threshold is approximately 8800, 8450, 7950 and 3500 kbps with the EMBS, GMBS, CRRM and without CA, respectively. The analysis of the cost/revenue trade-off arising from the optimization of LTE-A system capacity is left for further study.

The cost/revenue analysis was performed using the formulation from [27] and considering two supported goodput values, i.e., the number of supported UEs, under the PLR ≤ 1% and QoE ≥ 2.5 performance targets. In addition, two MByte price have been considered, $R_{\text{144}/\text{MByte}}$ equal to 0.005 and 0.01. It has been found that without CA the profit cannot be evaluated under PLR ≤ 1% since this constraint is not satisfied and that for QoE ≥ 2.5 null profits were obtained for $R = 2100$ m. Besides, for PLR ≤ 1% iCRRM’s EMBS and GMBS profits are the highest and yet similar since the number of supported UEs is alike. For $R = 1000$ m and PLR ≤ 1% profit of 130 and 360 %, 129 and 357 %, and 113 and 326 % were obtained for the EMBS, GMBS and CRRM, for $R_{\text{144}/\text{MByte}}$ equal to 0.005 and 0.01, respectively. Considering the QoE ≥ 2.5 performance target, the EMBS shows the highest profits given its higher number of supported UEs, the GMBS comes in second place as the most profitable whereas CRRM comes in third. Using the $R = 1000$ m reference for QoE ≥ 2.5, profits equal to 170 and 440 %, 158 and 416 % and, 143 and 385 % are obtained for the EMBS, GMBS and CRRM, with $R_{\text{144}/\text{MByte}}$ equal to 0.005 and 0.01, respectively. Moreover, the global implementation of CA technology should reduce the manufacturing and implementation costs of CA enable equipment, hence future work will assess cost/revenues analysis with up to date assumptions on economic aspects. Besides, as the flat rate pricing model is being employed worldwide, upcoming work will also address the impact of CA into this business model.

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