Multi-Node Component Carrier Management for Multi-Connectivity in 5G

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From its conception, 5G has been designed to support a wide variety of service types, ranging from enhanced mobile broadband (eMBB) to ultra-reliable low-latency communications (URLLC). To overcome the disparity of their requirements, a number of radio resource management (RRM) solutions have been proposed, among which multi-connectivity (MC) may be highlighted. That is, the aggregation of radio resources in the shape of component carriers (CC) from several base stations (BS). MC allows a number of benefits to be achieved: from increased reliability due to multi-link diversity, to throughput enhancements, due to the usage of additional radio resources and load balance among the involved BSs. This paper proposes a novel RRM mechanism to jointly manage user equipment (UE)-BS association rules and CC selection, according to network operators' policies, defined over a variety of performance indicators. Simulations show that, in a scenario of load imbalance, the proposed mechanism allows the UE throughput to be increased while improving the network efficiency by means of a proper inter-CC and inter-BS load balance when compared to traditional received power-based schemes for CC management, applied in a MC environment.

1. Introduction

Nowadays cellular networks face a stage of vertiginous growth, in an attempt to jointly support a set of services, use cases and requirements, that up to now, could only be covered by a variety of wireless technologies [1]. In this sense, the aim of the Fifth-Generation (5G) is twofold. Firstly, to improve traditional mobile communication services by means of an enhanced mobile broadband (eMBB) service. And second, the provision of the necessary tools and optimizations to support novel kinds of wireless communications, such as ultra-reliable low-latency communications (URLLC) or massive machine-type communications (mMTC).

With the completion of the first phase for the standardization of 5G, the Third Generation Partnership Project (3GPP) gave response to the eMBB and URLLC services, allowing extremely high peak and average data rates in the former case, and high reliability and latencies in the order of the millisecond in the latter case.

In order to fulfil the challenging and dissimilar requirements of these kinds of services, different solutions have been proposed, ranging from enhancements at the physical layer to medium access control (MAC) layer solutions. Together with these, a promising option yet to be explored arises: multi-connectivity (MC) [2]. MC aims at taking advantage from using radio resources in the shape of component carriers (CC) from several network nodes by holding simultaneous connections between the user equipment (UE) and those nodes through the air interface. Nowadays, MC has captured researchers' attention due to the networks densification, both in a vertical way, with multi-tier deployments, and horizontally, with the ever-decreasing size of cells.

Regarding 3GPP standards, it was with Rel-10 and Rel-12 that carrier aggregation (CA) and dual connectivity (DC) appeared, paving the way for the upcoming MC. Up to now, CA and DC have brought a number of benefits to the users, like throughput boosts or higher reliability and link robustness. These benefits have mainly been achieved by means of a proper selection of the CCs to be assigned to a UE [3, 4, 5, 6], as well as the revision of the UE-BS association rules [7, 8]. This latter has also recently been addressed under a MC approach, bringing back the concept of active set management for the addition and removal of the BSs serving a UE [9]. However, there are some important challenges related to MC that should be addressed. Some of that are presented and discussed in Section 2.

Specifically, this article first presents MC-related scenarios defined by the 3GPP for 5G networks in Section 2. In that Section, a new MC scenario considered in this work is explained and the callenges to be addressed are stated. Next, in Section 3, an algorithm for MC management in the selected scenario is proposed, where its main contributions are the following:

- The joint selection of the CCs to be assigned to a UE as well as the network nodes providing them, in a MC-enabled cellular network. Unlike in [3, 4, 5, 6, 7, 8], in which these issues are addressed separately, tackling them as a whole provides a higher degree of flexibility, which eventually allows enhanced UE performance and network resource utilization.

- Besides, and unlike in [9], in which only the received signal strength is assessed to define the active set, the proposed solution allows using a variety of sources of information as inputs for the CC management, like performance data from UE measurement reports, from the network itself or from the UE context. This enables developing a user-centric approach, in line with the current trends for 5G management tasks.

Finally, in Section 4, the proposed method is assessed for eMBB service users through simulations, showing its benefits to simultaneously achieve high throughputs while integrating network operators' policies.

2. Multi-Connectivity in 5G

Given that, during its deployment, 5G will coexist with the current LTE network in a non-standalone manner, as of today, the concept of MC is described by 3GPP as an extension of the Rel-12 DC [10, 11] in the shape of a multi-RAT dual-connectivity (MR-DC) [2], in which one of the nodes is an LTE evolved Node B (eNB) and the other one is a next-generation node B (gNB), connected to the former by means of a non-ideal backhaul. In both connectivity schemes (DC and MR-DC), for a given user, one of the nodes assumes the role of the master node (MN), carrying the signaling between the UE and the core network and determining the UE RRC (radio resource control) state, and the other one assumes the role of a secondary node (SN).

Some additional concepts related to MC are the following:

- Primary cell (PCell): In MR-DC, the cell associated to the MN over which RRC signaling and NAS (Non-Access Stratum) mobility information is interchanged.
- Primary secondary cell (PSCell): In MR-DC, cell associated to the SN over which the physical uplink control channel (PUCCH) is sent.
- Secondary cell (SCell): In MR-DC, cell associated either to the MN or the SN, not being the PCell or the PScell.

Up until Rel-15 (5G phase 1), MC only considers the aggregation of radio resources from two different nodes. It will not be until future releases that the concept of MC is expected to encompass the simultaneous connection of a UE to more than two network nodes, all of which may be 5G nodes (gNBs) in a standalone deployment.

The growing interest of standardization bodies, industry and academia towards the exploitation of MC functionalities arises from its multiple benefits, extending those of DC. One of them is the improvement of the connection robustness, due to the radio link diversity. This is especially relevant in high mobility scenarios [11], in which a high number of radio link failures would imply high handover failure rates. Besides, and related to this, MC enables reliability (understood as opposed to a packet loss rate) to be noticeably improved through data duplication at the Packet Data Convergence Protocol (PDCP) layer [12] by sending packet duplicates through different logical channels. This feature is especially relevant for URLLC services, allowing both latency and packet loss rates to be reduced [13]. On the other hand, if the data flow is not duplicated but split among logical channels, managed by different network nodes, a throughput boost may be achieved from the UE side, with the additional benefit of a possible load balance among the network nodes involved in the process throughout the X2/Xn interface. In this case, the eMBB services benefit from this feature. Besides, both the reliability and throughput boosts may be further increased by making use of CA. That is, the usage of several CCs per network node, managed at the MAC layer of each node. This leads to a more general concept of MC, in which the ability of the UE to hold connections with a number of network nodes is expanded through the bandwidth aggregation provided by CA in each node, which may be seen as an additional degree of freedom from the network management point of view.

Figure 1 shows different connectivity schemes for a MC-enabled network, showing the layer 2 structure for downlink, in which a functional block for data duplication/split at the PDCP level has been added (according to [12]). As it can be seen, UE_a and UE_c are associated only to one BS. In such case, the data may be duplicated (UE_c) or not (UE_a), and the data split, in case that it takes place, must be performed within the same node via CA at the MAC layer (UE_a). On the other hand, UE_b is associated to two nodes, allowing the data flow to be either split or duplicated between the involved gNBs at the PDCP layer. In either case, UE_b has the gNB to the left as its MN and the one to the right as its SN, from which two CCs (CC_l and CC_m) are allocated.

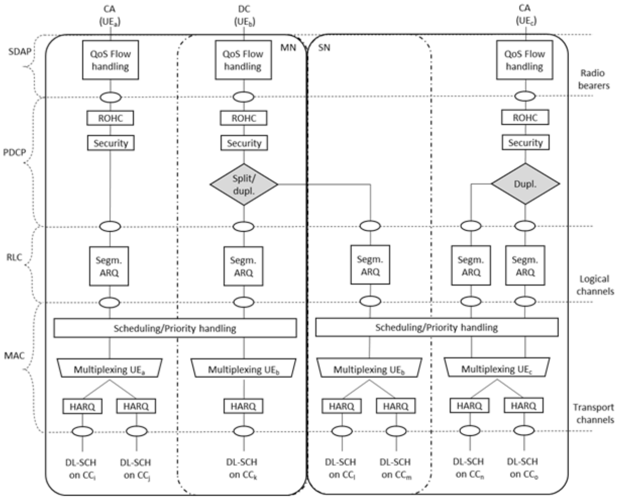


Figure 1 *Layer 2 structure for DL 5G MC, including traffic split/duplication functionalities at the PDCP layer*

In this paper, a more general scenario than the one defined in the standards is considered. This new scenario can be called multi-node connectivity or MC as well and consists in an extension of the scenarios included in 3GPP standards. In this new scenario, a UE can use CCs from more than two eNBs/gNBs. Considering this scenario, two challenges of MC are addressed. The first of them relates to the selection of the CCs to be assigned to a certain user. Given that not all the CCs managed by a node are equally loaded (in terms of the number of users being allocated) or experiment the same channel conditions, different criteria for user allocation might be followed, depending on network operators' policies. The second challenge to be addressed by MC is the UE-BS association rule, eventually derived from network operators' policies as well.

3. Component Carrier Management

This section proposes a novel functionality for radio resource management (RRM), named Component Carrier Manager (CCM), to jointly address the challenges of the CC selection within a given node and the UE-BS association rules for the SNs. In this way, assuming that a UE selected a PCell, and thus, a MN, following the cell selection/reselection criteria defined by network operators, the CCM is in charge of selecting which CCs will host its additional SCells or PSCells. The complete process between the UE activation and the CCs assignment is shown in Figure 2. Once a UE is activated, a set of metrics can be gathered including measurements of signal strength or quality such as RSRP or RSRQ. Based on one of these metrics, the RSRP in this case, the PCell is selected for this UE. Usually, the strongest cell in terms of RSRP is selected as PCell. Later on, the proposed CCM is applied. Based on metrics gathered from the UE, from the network and taking into account the selected PCell, the CCM will compute scores for all the candidate CCs to be assigned to the UE. The candidate CCs are those which provide coverage to the UE. Finally, and based on the computed scores, the CCM selects the SCells that should be assigned to the UE. More details about the CCM definition and performance can be found in the following paragraphs and in Section 4.

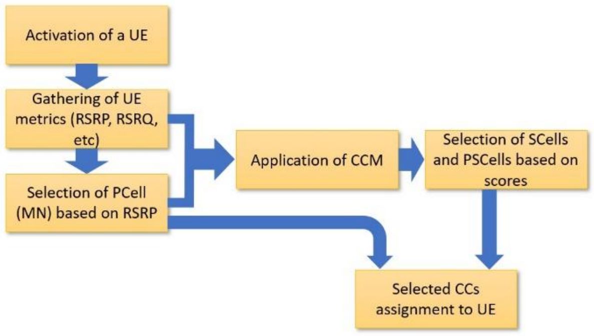


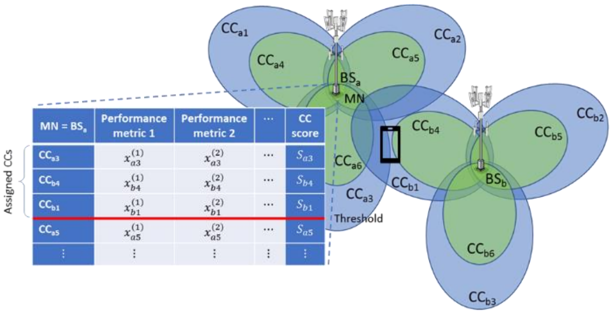
Figure 2 *Flowchart of CCs assignment process*

Specifically, the CCM aims at determining:

- The number of CCs to be assigned to a UE. In general, a higher number of CCs for a given user implies enhanced performance metrics. That is, higher throughputs or higher values of reliability.
- The carrier indices. In order to fairly share the time and frequency resources among the different users, as well as to fight time-varying fading effects, each user is assigned not only a number of CCs, but also their absolute radio frequency channel number (ARFCN).
- The specific usage of the CCs that were assigned. In principle, carriers for eMBB users will be used to increase these users' accessible bandwidth, whereas carriers for URLLC users will be used to add redundancy in the form of carriers holding a duplicated data flow.
- The source nodes providing the CCs.

To that end, a score is periodically computed for both the CCs managed by a node and those managed by its neighboring nodes, where each score stands for the suitability of a CC according to previously defined network experts' policies. For these scores to be computed, several sources of performance information are used, like performance information from the CCs themselves (e.g., their load) or metrics derived from UE measurement reports (e.g., from the reference signal received power, RSRP). For the CCM to have a more user-centric vision, service-specific quality metrics can be also taken into account; for example, the initial buffering time or the number and duration of stalls in the case of video services. Finally, metrics related to each user's context can be also considered as an input; for example, their location and speed.

Provided that the performance information has been gathered, the score for each CC may be computed. This task may be accomplished using different machine learning approaches. In order to easily integrate network operators' policies, rule-based systems might be followed; in particular, a fuzzy-logic controller (FLC) is proposed, which has been shown as a valuable tool for network management and optimization, [14]. Once every CC gets a score, both each node's and its neighbors' CCs are sorted in a descending way, and only those above a threshold defined by network experts may finally be assigned to a UE. Figure 3 shows an example of this. In this figure, BS_a (left) acts as the MN for the UE, being in charge of assigning additional SCells and PSCells to the UE. In this case, according to the performance metrics assessed and the network operators' policies, the CCs that best scored are CC_{a3}, CC_{b4} and CC_{b1}. Therefore, CC_{a3} will host a new SCell in BS_a for the UE, and CC_{b4} and CC_{b1} will host a PSCell and SCell in BS_b, respectively, setting BS_b as a new SN.



$MN = BS_a$	Performance metric 1	Performance metric 2	⋯	CC score
CC_{a3}	$x_{a3}^{(1)}$	$x_{a3}^{(2)}$	⋯	S_{a3}
CC_{b4}	$x_{b4}^{(1)}$	$x_{b4}^{(2)}$	⋯	S_{b4}
CC_{b1}	$x_{b1}^{(1)}$	$x_{b1}^{(2)}$	⋯	S_{b1}
CC_{a5}	$x_{a5}^{(1)}$	$x_{a5}^{(2)}$	⋯	S_{a5}
⋮	⋮	⋮	⋮	⋮

Figure 3 *Example of operation of the CCM. Having BS_a as the MN for a given UE, its CCs scores and those of its neighbors (BS_b) are computed and sorted, assigning those beyond a certain threshold to the UE.*

4. Proof of concept

Experiment setup

Extensive dynamic system-level simulations have been carried out to assess the benefits of the CCM in the context of a 5G network. In particular, in this proof of concept, its capability to simultaneously enhance the user experienced performance and integrate network operators' policies for load balance for eMBB services is assessed. For this test, a Matlab simulator based on [15] has been used. Table 1 shows the main simulation parameters. The simulated scenario consists of 12 tri-sectorial macrocell nodes, deployed in a realistic layout, where each sector is made up of five co-located CCs with a bandwidth of 1.4 MHz. In order to consider a more heterogeneous scenario, the antenna tilt and the transmission power of the simulated CCs have been configured with different values with the aim of simulating a situation where different CCs present different size and coverage conditions. All the UEs are MC-capable and the maximum number of CCs that may be allocated per user is five, according to an early deployment of MC-enabled UEs.

As a first approach, both the UEs and the selection of the CCs are static. That is, there are no handovers and once the CCs have been selected for a given UE, these are held throughout the duration of each UE's connection, respectively. This implies that CCs are added, but not released or changed along the simulation. At the end of this Section, some details about how to include mobility in this study are provided.

To simulate a load imbalance, part of the users is deployed in a uniform way throughout the scenario and another part of them is deployed in the shape of a hot spot (that is, a region of a high density of users; in this case, with three times the user density of the uniform deployment) along the coverage area of different nodes. A situation of load imbalance makes the affected users to experiment throughput limitations, due to the scarcity of radio resources for new connections. Moreover, information about the use of X2/Xn interface has been into account. When two or more nodes are providing CCs to a UE, the X2/Xn interfaces are used by the nodes to share control and user plane information. If this situation is repeated for a large number of users, the X2/Xn interfaces might be congested producing packet loss and an increase of latency [16].

Regarding the selection of the CCs, the PCell is the strongest cell (RSRP), [12]. However, for the selection of the PSCells and the SCells, four cases are distinguished, being two of them baseline cases:

- BaselineRSRP: PSCells and SCells are added according to the A4 event (a neighbor cell becomes better than a certain threshold), based on the received power level (RSRP), Table 1.
- BaselineRSRQ: PSCells and SCells are added according to the A4 event based on the reference signal received quality (RSRQ), Table 1.
- CCM_1: PSCells and SCells are added using the CCM. In this case, two inputs have been considered:
    - The UE-reported RSRQ.
    - The CC load (computed from the number of UEs currently allocated to that CC), given as a percentage.
- CCM_2: PSCells and SCells are added using the CCM. Apart from the inputs considered in CCM_1, an additional input is assessed:
    - In case that a CC is provided by a SN, the usage of the Xn interface between the SN and the MN due to the user plane load. This is also given as a percentage: the number of users using this interface relative to the total number of users.

Parameter	**Configuration**
Scenario	12 tri-sectorial nodes, 5 CCs per sector
Average inter-site distance	2000 m
Direction of transmission	Downlink
Band central frequency	2 GHz
Bandwidth	1.4 MHz (6 PRBs)
Frequency reuse	1
Propagation model	Okumura-Hata
	Shadowing (log-normal),
	σ_{sf}=8 dB
	Correlation distance = 50 m
Channel model	ETU model
Mobility model	Static users
Base station model	Tri-sectorial, SISO, P_{TXmax}=43 and 40 dBm
Time resolution	100 ms (1 TTI = 1 ms)
Traffic distribution	Non-uniform distribution of users
Traffic type	Finite buffer
	Packet size = 2 MB
	Poisson arrival
Antenna tilt per CC	4, 5, 6, 7 and 8º
Threshold for A4 event (baseline cases)	RSRP-based: -120 dBm RSRQ-based: -16.5 dB

Table 1 *Main configuration parameters*

The CCM is implemented as a FLC. This technique allows to easily translate the operator experience expressed in linguistic terms into several rules with an IF-THEN syntax. An FLC consists of three stages. In the first one, the numerical inputs are translated into fuzzy sets using the membership functions. Each fuzzy set is associated with a linguistic term such as high or low and the associated membership function reflects the degree of membership of an input value to a specific fuzzy set with a value between 0 and 1. Secondly, a set of IF-THEN rules are defined to relate input fuzzy sets with output fuzzy sets. These rules determine different situations that can occur, with the corresponding action that the FLC should execute (i.e. the assignment of a specific score). Finally, an output crisp value is obtained from the output fuzzy set. Each rule produces a fuzzy output that corresponds to a constant value. Depending on the input values and their membership functions, different rules can be activated with different degrees of truth. In this work, the degree of truth of a rule k (α_k) is calculated using the product operator:

$$\alpha_k = \mu(CCload) \cdot \mu(RSRQ) \cdot \mu(Xn\ usage) \quad (1)$$

Each rule will produce the corresponding fuzzy output. The method for calculating the output crisp value is the weighted average of the rules' outputs:

$$output = \frac{\sum_{i=1}^{N} \alpha_i \cdot o_i}{\sum_{i=1}^{N} \alpha_i} \qquad (2)$$

where N is the number of rules and o_i is the selected output for the rule i. The set of rules defined in the FLC are shown in Table 2 where the outputs of each rule can be *High* (meaning a score of 1), *Medium-High* (representing a score of 0.8) and *Low* (meaning a score of 0). An example rule for the proposed FLC is the following: IF (CCload is Low) AND (RSRQ is High) AND (Xn is Low) THEN (Score is High). If the CC under evaluation belongs to the MN, the usage of the Xn interface is considered as low. For CCM_1, only the antecedents concerning RSRQ and CC load are assessed; for CCM_2, the Xn usage is assessed as well. The threshold for CCs to be considered for their assignment is *Medium* (related to a score value of 0.5). That is, only those CCs scoring *High* down to *Medium* will be considered for its assignment to a UE, whenever the total amount per user is equal or lower than 5. For the sake of clarity, Table 3 shows a numerical example showing how the CCs are selected for a specific UE.

Rule number	CC load level	RSRQ	Xn usage	Score
1	Low	High	Low	High
2	Low	High	Medium	Medium-High
3	Medium	High	Low	Medium-High
4	-	Low	-	Low
5	High	-	-	Low
6	-	-	High	Low

Table 2 *Rules implementing network operators' policies*

CC Id	CC load (fuzzy value)	RSRQ (fuzzy value)	Xn usage (fuzzy value)	Score	Selected CC
1	3% (Low)	-11 (High)	0 (Low)	1	Yes
2	30% (Low)	-14 (High)	0 (Low)	1	Yes
3	30% (Low)	-14 (High)	70% (High)	0	No
4	60% (Medium)	-14 (High)	0 (Low)	0.8	Yes
5	90% (High)	-12 (High)	0 (Low)	0	No
6	90% (High)	-18 (High)	0 (Low)	0	No

Table 3 Numerical example of CC selection

Results and discussion

The benefits of using the CCM for the joint selection of SNs, as well as the PSCells and SCells, are shown next. Figure 4 shows the 5th, 50th and 95th percentile of the UE throughput for both the baseline and the CCM cases. In this figure, the throughput values have been grouped according to the number of CCs finally assigned to each UE. As it can be seen, an increasing number of CCs implies increasing throughputs in all the four cases. However, when these cases are compared among each other, the selection of the CCs according to the CCM_1 and CCM_2 outperforms both baseline cases. Considering both the CC load level and the UE-reported signal quality allows the throughput to be increased comparing to BaselineRSRP case, as the RSRP does not give an idea of the available radio resources in a CC. This information is considered if the baseline case is based on RSRQ measurements (as in BaselineRSRQ case), however, the proposed methods obtain better results since these methods use a more detailed information about the CCs load. In CCM_2, the additional consideration of the Xn usage provides supplementary information for load balancing, allowing further enhancing the UE throughput by means of a more proper inter-node load sharing.

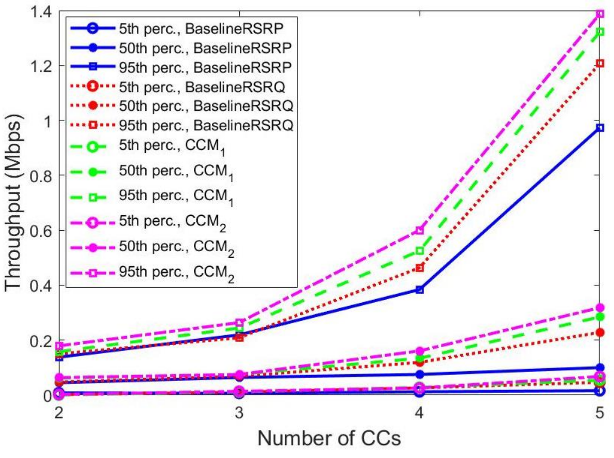


Figure 4 *Resulting 5th, 50th and 95th percentile UE throughput, grouped according to the number of CCs finally assigned for the four cases of CC selection: BaselineRSRP, BaselineRSRQ, CCM_1 and CCM_2.*

On the other hand, Figure 5 shows the usage of the Xn interface on a node basis, as the sum of the users simultaneously connected to that node and its neighbors (i.e., making use of the Xn interface between these nodes, in order to exchange information when needed). Afterwards, results have been normalized by the worst case. This figure shows the effect of the hot spot around sites 5 and 10, which is especially noticeable in the BaselineRSRP case, as the CC selection is unaware of both the intra- and the inter-node load level. Only when this information is explicitly included with CCM_1 and extended with CCM_2 the traffic load can be efficiently distributed among different nodes, thus preventing overload and increased delays in both the backhaul links and the nodes themselves.

As described before, although the scenario considered in this study is static (i.e. both the UEs in the scenario and the CCs assignment are static), this methodology can be applied in a dynamic context. In that case, users can move along the scenario and perform handovers between cells in order to select the most appropriate PCell. When the user is connected to several CCs, new methods to update these connections need to be implemented. Traditional methods based on RSRP or RSRQ can be used to evaluate which CCs should be removed from the set of CCs and which new ones should be added. In this new scenario, the proposed CCM method could be applied periodically to update the set of CCs assigned to each UE serving as an alternative for these addition/removal methods. The periodicity of CCM application could depend on different aspects such as the UE's speed, the computational cost or the variability of performance conditions.

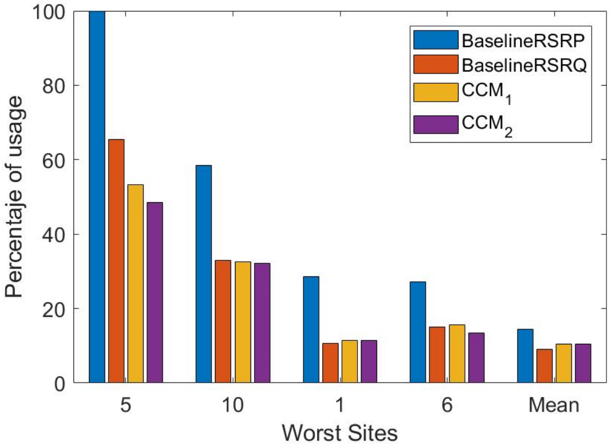


Figure 5 *Xn usage, computed as the sum of users simultaneously using each node (horizontal axis) and its neighbors, normalized to the worst case. In this figure, only the worst cases are shown. The mean case is computed over the eight remaining nodes.*

5. Conclusion

MC appears as one of the most promising features for upcoming releases of cellular communications in their purpose of encompassing a variety of service types and requirements. In this paper, the current state of MC under the scope of 3GPP has been shown, together with its expected next steps and challenges. To overcome these challenges, an RRM mechanism to jointly manage the UE-BS association and the CC selection within the chosen BSs has been proposed and assessed, allowing a variety of sources of performance information and network operators' policies to be integrated in this CC management. Results in a MC-enabled eMBB environment showed that the usage of the proposed CCM can improve both the UE perceived performance and the network efficiency by means of an increased UE throughput and better inter-node load sharing, respectively, when compared to a traditional RSRP-based and RSRQ-based CC management scheme.

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