Multi-Channel Access Solutions for 5G New Radio

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Multi-Channel Access Solutions for 5G New Radio

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Abstract

The arrival of 5G New Radio Release-15 opens the door for introducing Radio Resource Management solutions targeting enhanced mobile broadband and ultra-reliable low latency communication service classes. Multi-Channel Access is a family of such multi-service solution, which enables a user equipment to aggregate radio resources from multiple sources, either from the same or from different nodes. The objective is multi-fold; throughput enhancement through access to a larger bandwidth, reliability improvement by increasing the diversity order and/or coordinated transmission/reception, or more flexible load balance and performance increase by decoupling the downlink and the uplink access points. This paper presents a number of multi-channel solutions for the 5G New Radio multi-service scenario. In particular, we discuss throughput enhancement and latency reduction concepts like multi-node connectivity, carrier aggregation, downlink-uplink decoupled access and coordinated multi-point connectivity. A number of design challenges for these concepts are then highlighted, followed by novel solution proposals. All the proposed solutions are numerically validated, and found to result in significant performance gains over state-of-the-art solutions; for example, our proposed component carrier selection mechanism leads to an average median throughput gain of around 66% by means of an implicit load balance.

1. Introduction

The Fifth-Generation New Radio (5G NR) is the first cellular standard conceived to respond to the growing demand of multi-service mobile communication [1]. Compared to existing Long Term Evolution (LTE) networks, 5G NR requirements have expanded both vertically and horizontally. In the vertical domain, higher peak and average data rates are demanded for traditional mobile broadband services, corresponding to enhanced Mobile Broadband (eMBB) services. Horizontally, new service classes, such as Ultra-Reliable Low-Latency Communications (URLLC), are introduced.

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The first phase of 5G NR standardization focuses on eMBB and URLLC services. eMBB service class is an evolution of today's broadband traffic and targets a peak data rate of 20 Gbps, whereas URLLC services target extremely high reliability (i.e., outage probabilities of 10^{-5}) at milli-second order latency.

Solutions proposed to meet the demanding performance requirements of eMBB and URLLC services span from physical layer approaches targeting novel transceiver schemes for multi-user massive Multiple-Input-Multiple-Output (MIMO) systems [2], to Medium Access Control (MAC) layer solutions [3, 4] facilitating flexible frame structure and preemptive resource allocation for low-latency services.

Multi-Channel Access (MCA) is a promising family of Radio Resource Management (RRM) solutions being explored towards this end. MCA is the ability of a user equipment (UE) to access multiple channels in the form of different Component Carriers (CC) simultaneously. MCA connectivity can be provided from one or more nodes. Carrier Aggregation (CA) appears as an example of single-node MCA, whereas examples of multi-node MCA include the general concept of Multi-Node Connectivity (MNC). Coordinated Multi-Point (CoMP) access, multi-connectivity (MC) and downlink-uplink decoupling (DUDe) are particular use cases of MNC [5 - 8].

The aggregation of radio resources with single-node MCA allows enhancing either the throughput, or the reliability. The former requirement is achieved by splitting the data flow, whereas the latter by data duplication. By splitting the data flow among different radio resources (namely, CCs), a user has access to a larger aggregated bandwidth, resulting in a throughput enhancement. Conversely, the duplication of the data flow through different CCs allows the reception of multiple copies of the same data, thereby, improving the reliability through frequency diversity and/or repetition. However, the enhanced throughput and improved reliability with MCA are obtained at the expense of an increase in the resource usage and the signaling load. Thus, optimization of MCA operations is necessary to reap its advantages, while minimizing its detrimental effects.

This article presents MCA in 5G NR, along with its challenges and some corresponding promising solutions. We discuss MCA in 5G NR from a 3GPP point of view, describe some of its challenges, and present several promising MCA optimization schemes. Finally, the article concludes with an overview of the proposed solutions and the efforts needed for their standardization.

2. Overview of Multi-Channel Access Solutions in 5G NR

The research community has identified several MCA solutions aimed at boosting the throughput and the reliability. This article discusses four such solutions, namely MC, CA, DUDe and CoMP. An overview of these techniques, with emphasis on their implementation status in 5G NR Release-15, is presented in this section.

Multi-Connectivity

MC is an extension of the dual connectivity (DC) functionality where a UE could simultaneously connect to two distinct radio nodes, first introduced in LTE as a throughput enhancement feature [6]. Since initial 5G NR deployments will be non-standalone and complementary to LTE, 3GPP has generalized the LTE DC design to enable the support of Multi-RAT DC (MR-DC), i.e., DC between 5G NR and LTE [5].

The most prominent architecture within the MR-DC family is the E-UTRA-NR DC (EN-DC) [5], where the UE is connected to an LTE eNB as the Master Node (MN), and a NR gNB as the Secondary Node (SN). Both BSs connect to the LTE Evolved Packet Core (EPC) and are inter-connected via the X2 interface, as shown in Figure 1 (a). NR MC further extends LTE DC to consider reliability-oriented MC using packet duplication at the Packet Data Convergence Protocol (PDCP) layer. Packet duplication introduces radio link diversity, and thus increases the likelihood of successful reception. NR MC operation with data duplication in the DL direction is schematically presented in Figure 1 (b).

In NR MC setup, only the eNB (MN) establishes the control interface to the EPC (S1-C). However, all nodes have radio resource control connections to the UE, contrary to LTE DC. During MC setup, the MN requests the SN to allocate resources to the UE, along with providing the information needed to establish the connection. If the SN is able to admit the request, it allocates respective resources, and sends an acknowledgement back to the MN.

In the data plane, either node (eNB or gNB) can establish the user-plane interface (i.e., S1-U) to the EPC. The terminating node anchors the PDCP operations, such as splitting or duplicating the PDCP packets, and sends them to the other node. A data packet (which is either split or duplicated) is independently scheduled at the MAC layer of the MN and the SN.

Carrier Aggregation

CA considers MCA from a bandwidth perspective, and allows the aggregation of channels from different bands. Thus, as an example, the large spectrum availability in the millimeter wave bands can be exploited in 5G NR. In CA, the UE is assigned the Primary Cell (PCell) at the MgNB, the Primary Secondary Cell at the SgNB, and any additional CC assigned at either node is denoted as a Secondary Cell (SCell).

The CA setup is based on the same RRM measurements design as MC, where the PCell determines the suitability of potential SCell based on the UE reporting of Reference Signal Received Power/Reference Signal Received Quality (RSRP/RSRQ) measurements. However, rather than at the PDCP layer, in CA, multiple carriers can be aggregated at the MAC layer, which controls the multiplexing of data and its transmission on the available CCs. It is noteworthy that the introduced PDCP packet duplication mechanism is also supported in conjunction with CA with the restriction that the MAC layer should guarantee that two duplicated packets are not transmitted on the same CC, with the aim of preserving the duplication benefits.

Downlink/Uplink Decoupling

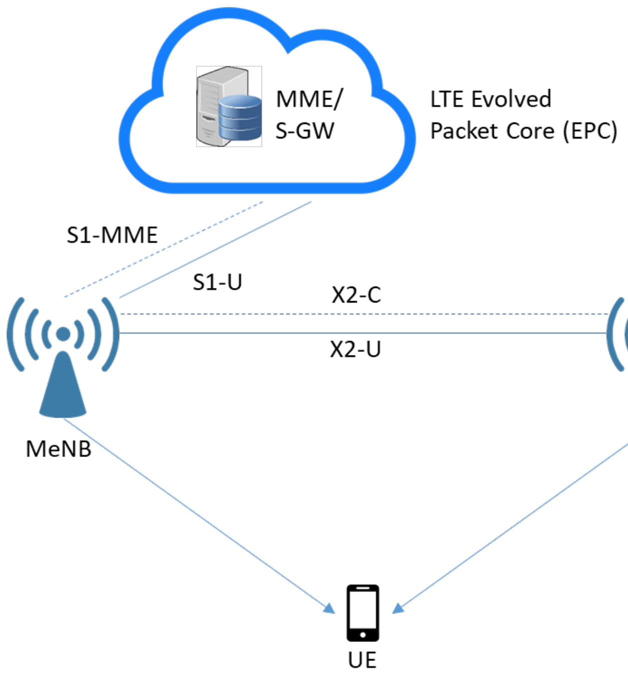
Another dimension of MCA in 5G NR refers to the possible applicability of different UE-cell association schemes for the downlink and uplink transmission directions, jointly driven by network deployment particularities and service demands. Cell densification, a promising solution to meet the stringent requirements of 5G NR (e.g., high rates in hot spots), leads to an imbalance in the DL/UL traffic [7]. This requires reconsidering the performance optimality of the conventional RSRP based UE-cell association rule.

Downlink/Uplink decoupling [8, 9] is considered a paradigm shift, in which a UE has the flexibility to be served in downlink and uplink by different distinct schedulers, located at two different nodes. Additionally, DUDe has proven to provide a higher achievable throughput compared to the Cell Range Extension solution proposed in 3GPP Release 12 [8]. Moreover, DC is considered a key-enabler for DUDe realization in NR, whether the two cells utilize the same or different frequency bands (i.e., intra-frequency and inter-frequency deployments, respectively). 3GPP has included DL/UL split results for co-channel deployments in [5], whereas DUDe discussions are expected to be relevant for Release-16.

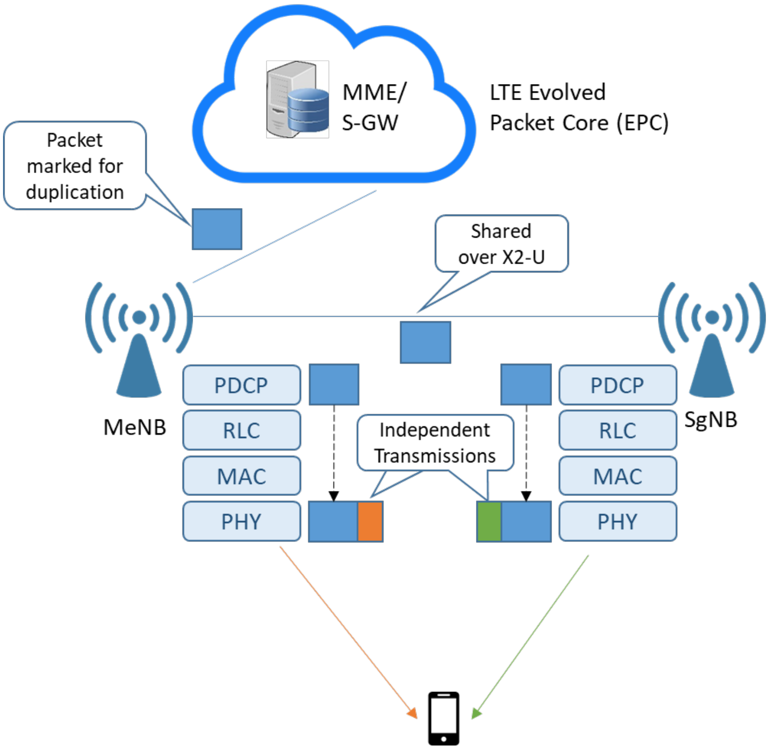
Coordinated Multi-Point Access

CoMP comprises multiple techniques that exploit different cooperation strategies among cells (or a subset of their antennas, i.e., transmission points). Relying on fast network interfaces to exchange cooperation information, CoMP could entail Joint Transmission (JT), i.e., the simultaneous transmission (or reception) of the *same data* to a UE via multiple nodes applying joint processing (and reception), thus improving reliability. Non-coherent JT-CoMP (i.e., the less complex fashion that allows the cooperating nodes to use different resources in time and frequency for the UE transmission) is expected to be supported as part of the Release-16 of NR.

Alternatively, CoMP could also restrict the transmission to a UE to one cell at a time, while leveraging coordination among the cells to increase the SINR of the scheduled transmission. To this end, CoMP entails techniques such as Coordinated Scheduling, Coordinated Beamforming, and Dynamic Point Selection. In addition, in the special application of CoMP for Interference Cancellation (IC-CoMP), the network assistance in terms of interference feedback could be exploited to eliminate inter-cell interference.



(a)



(b)

Figure 1 a) MR-DC architecture with EPC, as specified in 3GPP Rel-15 [5]. b) Schematic of reliability-oriented DC in the DL direction.

3. Challenges in Multi-Channel Access

MCA provides opportunities to improve the throughput and/or reliability experienced by a UE. However, such performance gains are challenged by a number of issues related to configuration and operation of the MCA solution. This section provides an overview of these challenges, most of which will be addressed by promising solutions proposed in the next section.

Throughput-Oriented MCA Challenges

Carrier aggregation expands the accessible bandwidth for a given UE by allowing simultaneous transmissions across multiple CCs. However, the allocation of CCs among the serving nodes is not straightforward. If additional requirements derived from operators' policies are set over an optimal throughput boost, a proper CC assignment should be made on a per-UE basis. For example, efficient algorithm design for CC allocation is needed to apply load balancing methods and to avoid redundant transmissions with low signal processing complexity while increasing the UE throughput.

Also importantly, to successfully implement any throughput-oriented MCA solution, accurate and up-to-date information broadcast has to be carried out jointly among the multiple gNBs, either through over-the-air or via the Xn/X2 interface. As an example, the throughput performance of data split MC for downlink communication is foreseen to be sensitive to the quality, capacity and delay of the Xn/X2 interface.

In what follows, we also provide some additional challenges of throughput-oriented MCA, the addressing of which is outside the scope of this article. In order to ensure an efficient uplink radio resource allocation, information regarding the available power budget, namely Power Headroom Report, needs to be provided as it impacts the SgNB selection [10]. Furthermore, energy efficiency-related issues are raised, since the UE would need to concurrently receive and process system information/data streams from two different entities in the inter-site case, consequently bringing up an energy efficiency/throughput trade-off in Heterogeneous Networks (HetNet) deployments [11]. Finally, further challenges may appear regarding, for example, the needed level of interoperability to perform data splitting between multiple nodes belonging to different operators.

Reliability-Oriented MCA Challenges

In reliability-oriented MC, a packet arriving at the PDCP-anchor node is duplicated at the PDCP layer and forwarded to the duplicating node(s) over the Xn interface. Hence, the same data packet is transmitted to the same UE through multiple links independently. The UE keeps the first successfully received packet, while discarding all subsequent copies of it.

The acknowledgement (ACK/NACK) for each transmission is fed back to the respective transmitting node. However, a NACK triggers a Hybrid Automatic Repeat Request (HARQ) retransmission, even when the packet is successfully received from the other nodes. This leads to unnecessary resource utilization stemming from redundant transmissions, and results in network traffic overheads in the affected cells, as well as to additional interference to the neighboring cells.

In further detail, doubling the resource usage leads to an increased network load. Moreover, increased transmission due to DC operation leads to higher levels of interference in the network. This decreases the experienced Signal-to-Interference-plus-Noise Ratio (SINR), which, in turn, results in requiring more Resource Blocks for a given transmission, more HARQ repetitions and an overall performance degradation. To overcome this limitation, since the same data packet is being transmitted from multiple nodes, subsequent retransmissions from other node(s) should be avoided as soon as the packet is successfully received at the UE.

Apart from inefficient utilization of network resources, reliability-oriented MCA imposes challenges relevant to the experienced communication delay. As an example, applications requiring reliable low-latency communications, such as vehicular communications and industry 4.0 applications, are the most promising use cases to be accommodated by 5G NR. To this end, a major challenge for the hyper densification of the network with multi-tier components (e.g. macro, micro, pico, etc.), is the large load imbalance among those tiers stemming from inter-tier resource availability dissimilarities. As an example, for latency-intolerant applications, where the UEs have the option to offload demanding tasks to be executed to a Multi-access Edge Computing (MEC) server, physically co-located with an eNB/gNB, the application of conventional cell association rules is non-optimal. As a result, choosing the serving node/ MEC server for task offloading is a challenging task, especially when exploiting the option of DUDe-based UE-cell association.

In relevance to the above explained challenge on the experienced communication delay, CoMP solutions devising packet duplication may be proven problematic when coordination among the various transmitting nodes is performed via utilizing interfaces of low capacity and, possibly increased delay, depending on the deployment. In other words, a trade-off between coordination efficiency (e.g., in the sense of interference mitigation effectiveness) and packet transmission timeliness needs to be addressed for CoMP access, in the existence of imperfect fronthauling connections.

4. Multi-Channel Access Solutions and Performance Evaluation

This section presents four promising MCA solutions addressing some of the challenges highlighted in the previous section, along with their performance evaluation. Each of these solutions correspond to the MCA concepts of multi-connectivity, carrier aggregation, downlink/uplink decoupling and coordinated multi-point access.

Novel Duplication Status Report for Multi-Connectivity Applications

Data duplication in MC improves the reliability at the cost of having redundant transmissions. In this section, we propose a *network discard mechanism* that relies on a novel *UE duplication status report.* This report indicates to other node(s) in the duplication set that a certain PDCP packet have been successfully received, thus allowing the duplicating nodes to discard the flagged PDCP packet if it has not yet been transmitted.

Two key information is required at the UE to send the proposed *duplication status report* to the duplicating nodes, i.e., when and to which node, to send this information. When data duplication is activated for a UE, the corresponding duplication set is semi-statically configured and activated as well, such that the UE can expect to receive duplicated PDCP packets only from these selected nodes. The UE therefore can send the *duplication status report* to the nodes in the duplication set.

To reduce the reporting overhead, we propose to include a one-bit flag in the scheduling grant associated to a PDCP PDU indicating that the packet in this physical transmission is scheduled for duplication from nodes in the preconfigured duplication set.

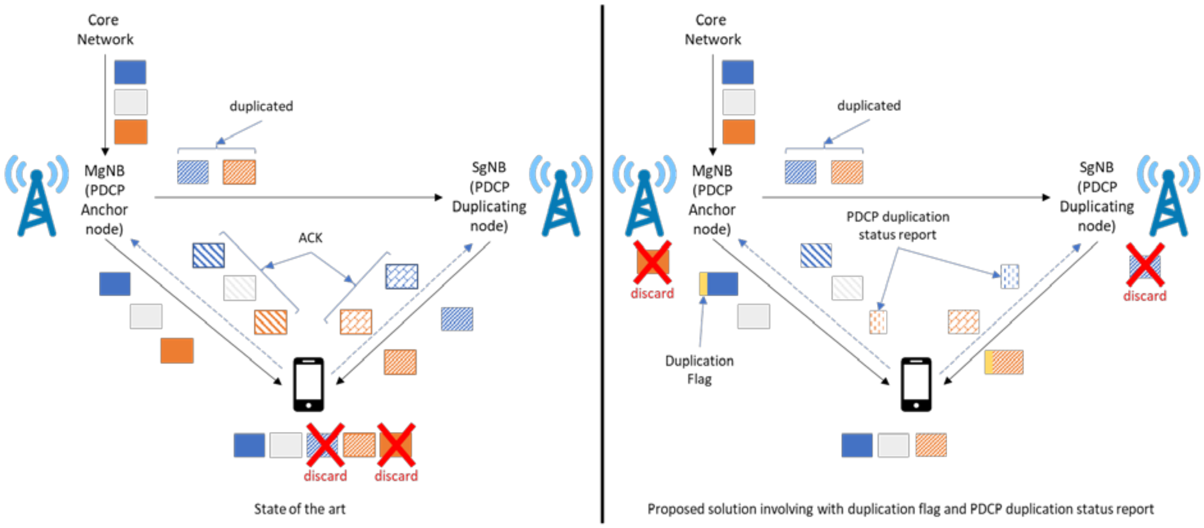
Once the UE successfully decodes a duplicated packet, it sends a normal PHY ACK to the transmitting node, along with a *duplication status report* consisting of the packet identifier (the PDCP sequence number) to the rest of the nodes in the duplication set. Upon receiving such a *duplication status report*, a node becomes aware that this particular packet is received successfully at the UE, and need not be transmitted. The node will thus be able to discard this packet from its individual buffers (if not already transmitted), thereby reducing redundant transmissions.

The key benefits of this proposal are to reduce unnecessary transmissions of duplicated PDCP packets from multiple nodes, thus reducing network resource usage and interference, and improving the overall network capacity, energy efficiency as well as latency performance.

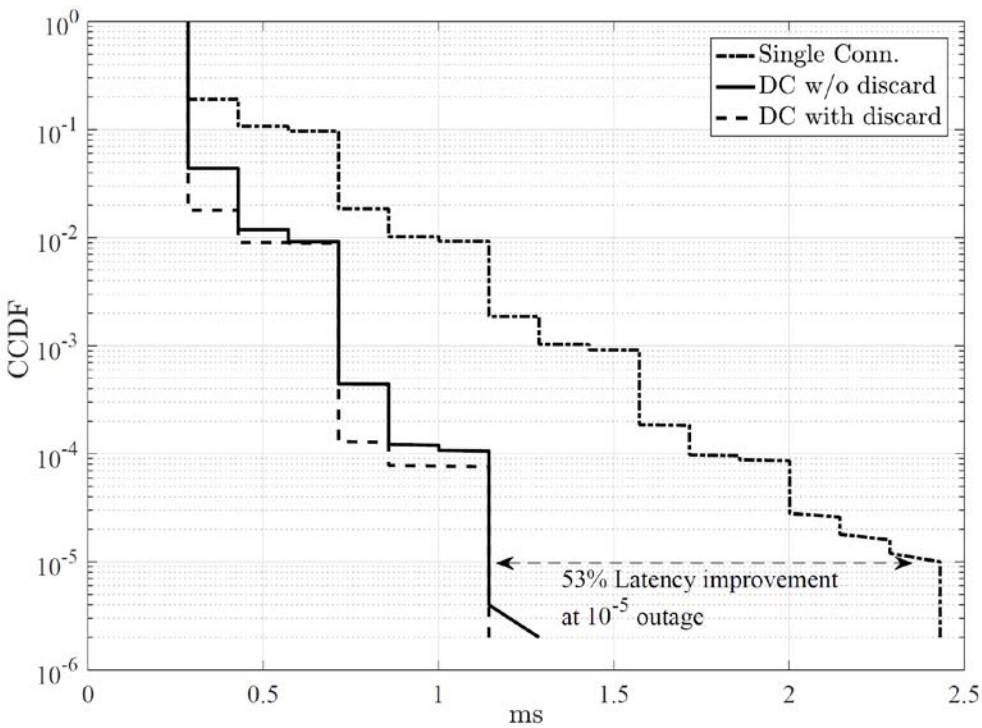
Figure 2 a) depicts the proposed discard mechanism and compares it with the state-of-the-art, where duplicated PDCP packets are discarded at the UE. In order to demonstrate its viability, the proposed discard mechanism is evaluated via Monte-Carlo simulations. In order to focus on the ideal performance gains, we consider an ideal HetNet scenario with a single macro cell and a single small cell, operating at different frequency layers. The inter-frequency DC model is thus assumed.

The macro cell is the serving cell in single connectivity mode, while both the macro and small cell serve the same UE in DC. The Complimentary Cumulative Distribution Function (CCDF) of the latency is presented in Figure 2 b). The mean SNR from both link is 10 dB, while the target SNR is 0 dB. CCDFs for both conventional DC and DC with PDCP packet discard are shown. Under ideal operating conditions, we observe a latency reduction of up to 53% at 10^{-5} outage probability with PDCP duplication via DC.

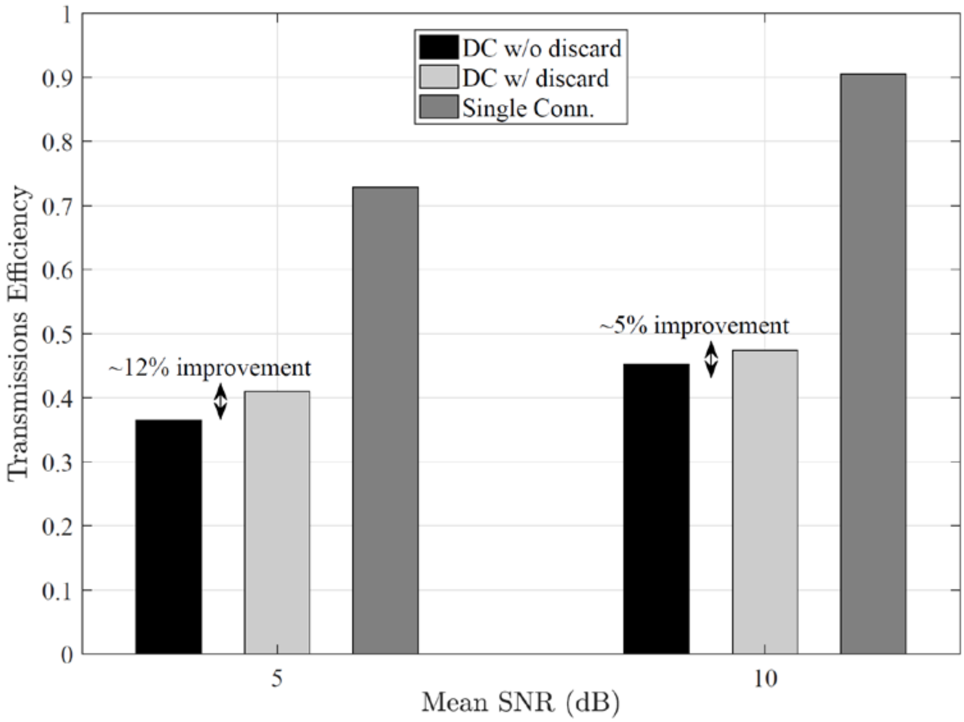
Comparing between conventional DC and DC with the proposed discard feature, we observe a slight latency reduction with the latter, as a result of the reduction in the number of duplicate transmission, which in turns leads to lowering of the queuing delay. Figure 2 c) presents the transmission efficiency for SC, DC and DC with discard corresponding to scenarios with a mean SNR of 5 and 10 dB respectively. The transmission efficiency is the number of successfully packets received per transmission attempt. A larger gain in terms of the transmission efficiency is observed under poorer channel conditions. Though not presented here, detailed system level simulations indicate higher gains with the proposed discard feature, resulting from the cumulative impact of reducing both the queuing delay and the interference.



a) Implementation schematic of the proposed solution (right) compared to the state of the art (left)



b) Latency CCDF of Single Connectivity (SC), Dual Connectivity (DC) and DC with discard for a HetNet scenario with both links at 10 dB mean SNR.



c) Transmission Efficiency of Single Connectivity (SC), Dual Connectivity (DC) and DC with discard for a HetNet scenario with both links at 5 and 10 dB mean SNR.

Figure 2: Implementation Schematic and Performance Evaluation of the proposed 'Duplication Status Report' in Multi-Connectivity Applications.

Component Carrier Selection Mechanism for MCA

This solution addresses the allocation of CCs to a UE in a generic manner, encompassing both single-node and multi-node MCA. In the case of eMBB, the user data flow would be split among the assigned CCs to maximize the throughput. In the URLLC case, the data flow would be duplicated. This solution relies on a rule-based system, which has been shown as a useful tool for optimization in the field of mobile communications [12].

This system aims at determining the number and indices of CCs to be assigned to a specific UE, as well as the gNBs providing each of them. The antecedents of the rules are made up over performance information, gathered from the UEs (e.g., RSRP or RSRQ) and the CCs themselves (e.g., load information). The consequences of the rules are scores (standing for their suitability given a certain policy), over which an aggregation method is applied. Finally, the CCs with the highest aggregated scores, whenever they are above a minimum threshold, are assigned to the users.

A proof of concept has been carried out in an environment of load imbalance. That is, a situation in which the heterogeneous distribution of the users throughout the scenario makes a reduced group of base stations support most of the offered traffic, leading to a high number of call blocks, whereas many other base stations remain almost unused. To that end, the UE-reported RSRQ and the load level of a CC, derived from the instantaneous number of UEs allocated to such CC, have been used as input performance metrics. Different rules have been defined, assigning low scores to low values of RSRQ and high-load levels and high scores in the opposite case. The final score of a CC is computed as the average of the scores provided by each rule.

The proposed solution has been tested using a system-level simulator in a macro-cell scenario, made up of 12 tri-sectorial sites, where each sector is composed, in turn, of five 1.4 MHz co-located CCs. A geographical region with a high density of users, spread throughout several sites, has been simulated to produce the load imbalance scenario. Two MCA situations have been simulated: first, as a baseline, a case in which the rules only consider the received power (RSRP) as an input, following the traditional approach for UE-gNB association; and second, the situation in which both RSRQ and CC load metrics are assessed.

Figure 3 shows the 5th, 50th and 95th percentile of the UE throughput for the first (baseline) case with dashed lines and the second case with solid lines. This figure breaks down the throughput metrics into the situations in which the number of CCs assigned to a UE ranges from one to five, depending on how many CCs scored above the minimum threshold. The proposed CC selection method results in a boost in the UE throughput, as a load balancing mechanism is implicitly carried out. For example, the proposed solution provides 66% average gain for the users experiencing the worst throughput values (5th percentile) over state of the art RSRP based solution, and up to 75% gain at the peak throughput (95 %-ile). Higher number of CCs generally imply higher UE throughputs. In cases where more than one CC is assigned to a UE, each CC may be provided by a different node. For example, for two CCs approximately half of the UEs used CCs belonging to the same node (using CA), whereas the other half used CCs provided by different nodes (using DC).

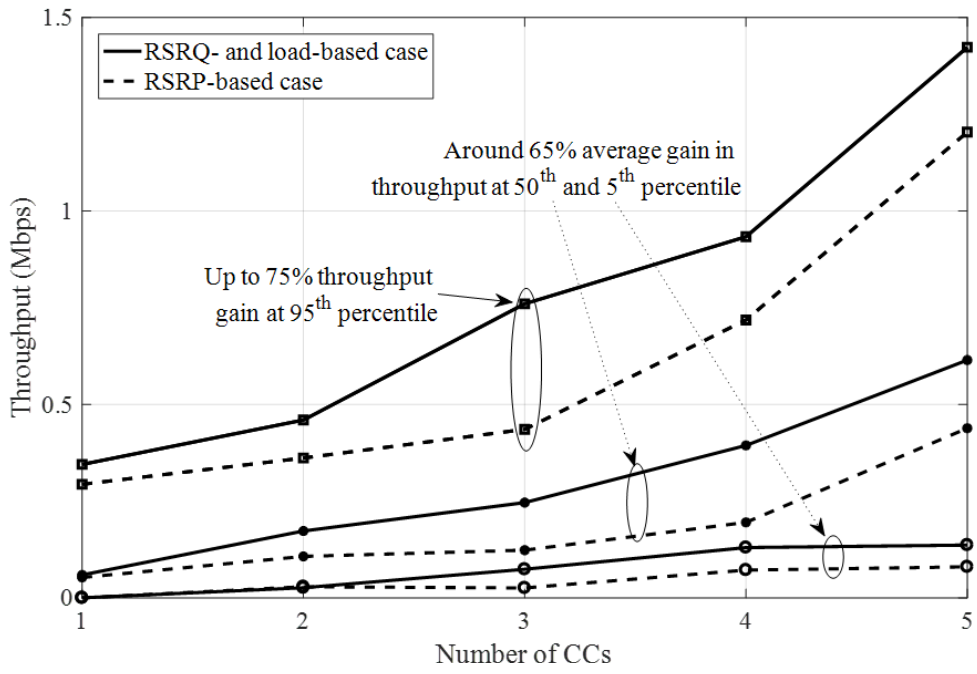


Figure 3: Per-UE achieved throughput for an increasing number of CCs, comparing the proposed solution for CC assignment with a traditional RSRP-based UE-gNB association.

Latency-Reducing Connectivity based on Processing Proximity

A new association metric in HetNets targeting latency reduction when UEs choose to offload demanding processing tasks to the network is proposed in this section. Conventionally, in homogeneous cellular systems, the downlink RSRP determines the cell to which the UE will be connected for both DL and UL communication. Nevertheless, employing such a connectivity criterion in a highly heterogeneous HetNet consisting of multi-tier BSs with diverse capabilities leads to load imbalance among the different tiers [7]. As a result, DUDe has been proposed as a disruptive solution for an enhanced network performance [8, 9], mainly giving the users the flexibility to associate with the BS that provides the minimum pathloss, when it comes to UL communication.

Latency reduction stands out as an important feature with reference to URLLC communications, including use cases such as offloading a demanding user task to the network. A key enabler for delay reduction is Multiple-access Edge Computing (MEC), which introduces computing capabilities at the edge of the network and provides an open environment targeting low packet delays due to close proximity to end users [13, 14].

An additional resource granted by MEC deployments is the available processing power at the network side, assuming that the MEC servers are physically collocated with the BSs. Considering this perspective, our proposed solution is to apply different UE-cell association rules for DL and for UL communication. Focusing on UL communication, we propose an association rule that considers the available processing power offered by MEC hosts co-located with BSs so as to best capture the *computational proximity* for low-latency UL communication, e.g., for the purpose of task offloading.

Conventionally, DUDe has been investigated in current technical literature only when the UL association is conducted based on the minimum pathloss criterion. However, in our proposed solution, a UE, as a result of applying the proposed computationally-aware association rule, will choose to connect to the closest BS with the largest available computational power. Such a connectivity metric enables user terminals to be associated to nearby BSs of considerable processing power.

To quantify the performance gain of the proposed association metric, the CCDFs of the Extended-Packet Delay Budget (E-PDB) is depicted in Figure 4. Focusing on a HetNet composed of two tiers, the E-PDB for the conventional (coupled, maximum RSRP-based) and the novel, MEC-aware association rule for UL communication (hence, decoupled association for DL/UL) are shown. For more details regarding the system model and the simulation environment, the reader is referred to [13].

The modelled E-PDB incorporates radio (i.e. UL transmission) latency along with computational (task processing) latency. The parameter ω, termed as the *inter-tier cross-domain resource disparity*, is defined as the ratio between the radio disparity (i.e. transmit power) over the computational disparity (i.e. processing power) of the two involved network tiers. One can observe that the proposed, computational proximity-based, decoupled association scheme provides a lower probability to violate a given E-PDB threshold with nearly 40% E-PDB reduction for the 50^{th}-percentile of UEs. In other words, the experienced UL latency is decreased when employing the proposed cell association rule which facilitates decoupling. This occurs due to the enhanced load balance between the different tiers along with the existence of considerable computational resources at the associated BS.

It can be stated that, by applying the proposed metric, DUDe is shown to provide latency reduction gains compared to the conventional, maximum DL RSRP-based, coupled association rule. For different values of parameter ω, an adaptive association procedure should be considered to minimize the experienced E-PDB when a UE decides to offload a demanding task to the network.

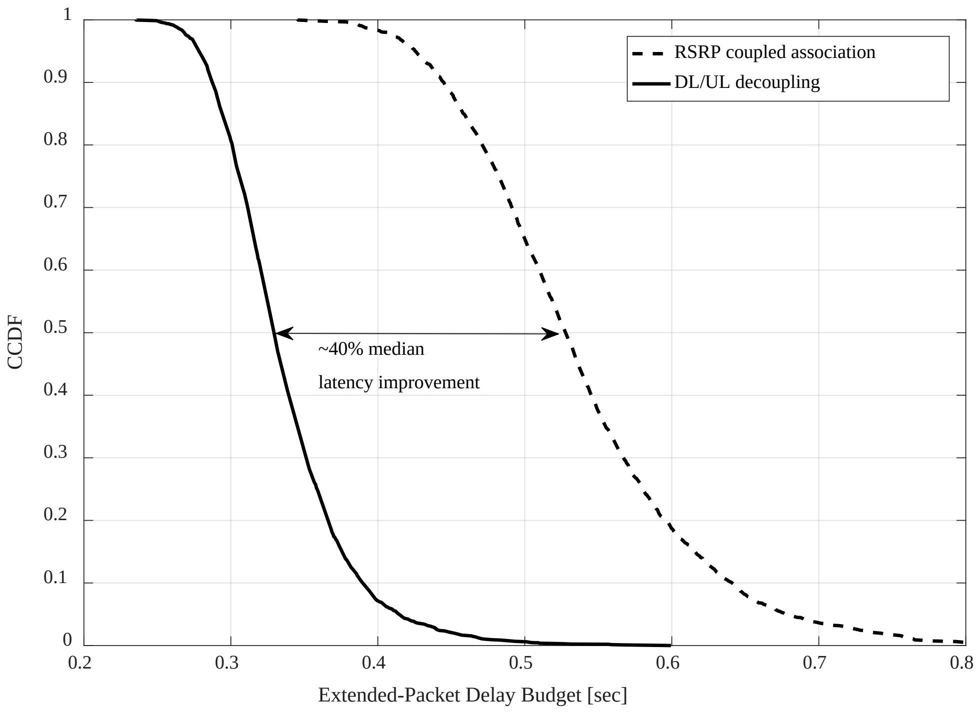


Figure 4: Extended-Packet Delay Budget CCDF comparing the (conventional) coupled and the proposed (MEC-aware) decoupled association rules for ω = 2.

Coordinated Multi-Point Connectivity for Low-Latency Applications

The network protocol must work properly for smooth data transmission, and control information must be delivered in a timely manner. For example, transmitting data in one direction can be acknowledged with the opposite direction response. These information exchanges form a two-way communication. It is important to give a fast control message response, because the sender is waiting for another action until the response comes back. To achieve this, we can adopt MNC and CoMP.

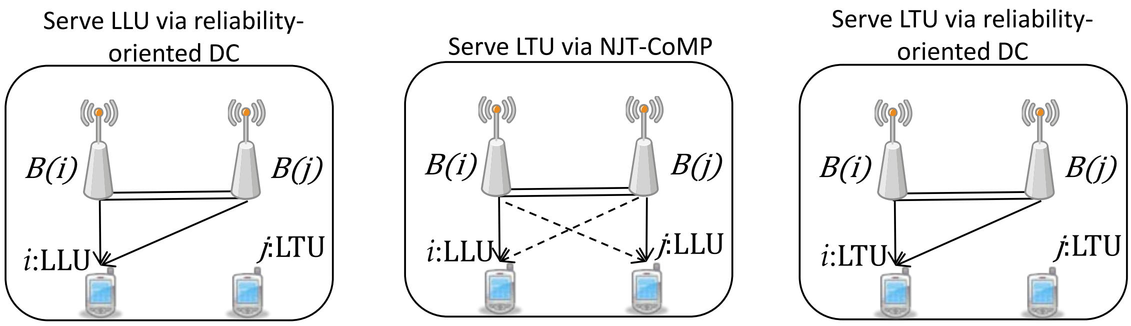
We assume that users are divided into Low Latency User (LLU) and Latency Tolerant User (LTU). Consider two neighboring BSs that are connected through an X2-like wired link. These cooperating BSs can serve their users jointly by exchanging user information. If users' Quality of Service requirements are different, they must be handled differently. For example, if LLU and LTU coexist, LLU can be processed first since transmission of LTU can tolerate delays. However, if LLU and LLU coexist, it is necessary to process both traffic types simultaneously. Therefore, it is possible to use a technique such as CoMP. Depending on the transmission direction, the following cooperation can be achieved.

Cooperation with same directional traffic: If both users have DL traffic as shown in Figure 5 a), cooperating BSs will schedule LLU using reliability-oriented DC (left of Figure 5 a)). If both users are

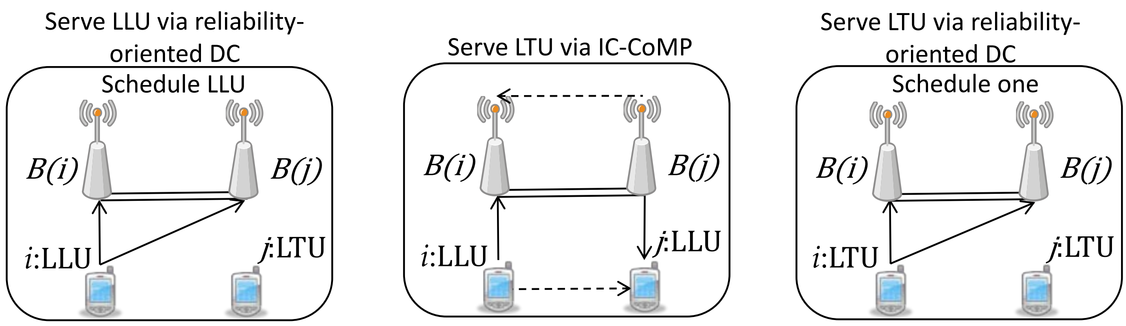
LTU, cooperating BSs schedule one user randomly via reliability-oriented DC (right of Figure 5 a)). If both are LLU, then cooperating BSs schedule them jointly using non-coherent JT-CoMP.

Cross-link cooperation: If both users have cross directional traffic (Figure 5 b)), the UL-BS can exploit information provided from the DL-BS via the wired link to execute interference cancellation to perform IC-CoMP [15]. It is assumed that UL and DL share the same frequency. However, the same technique can be applied to separate UL and DL frequencies. In this case, cross-directional traffic might be preferable because it is interference-free and will be easier to implement.

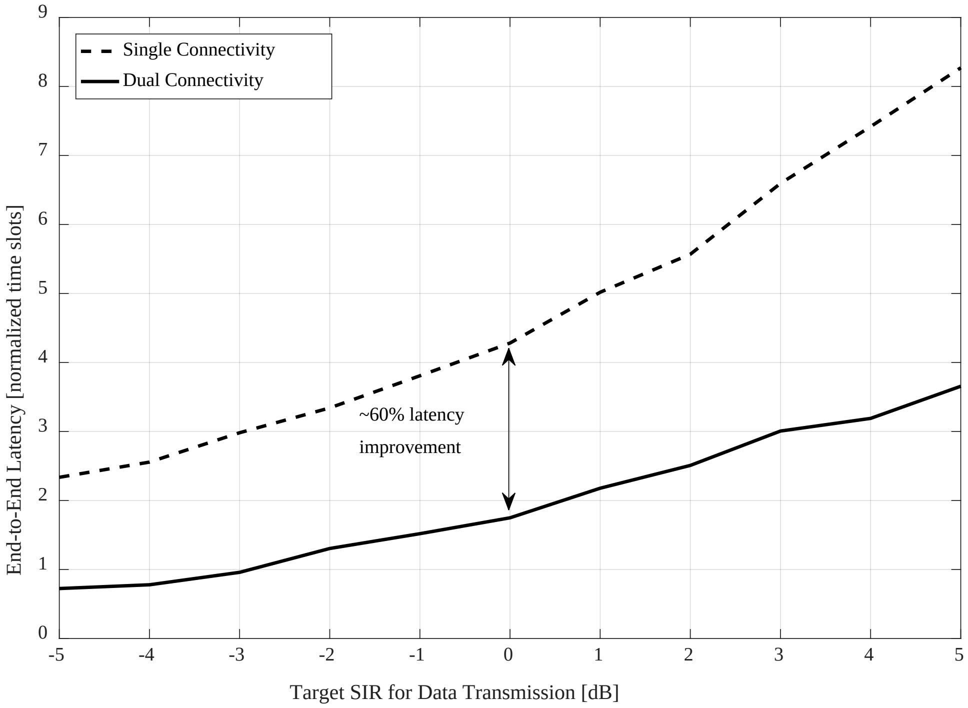
To quantify the performance, we consider a scenario where the users transmit their data and receive their acknowledgement (ACK). If a user does not receive an ACK, it retransmits the data. We assume that the UL and DL time slots have the same length. We normalize the length of time slot to one. The two-way latency is defined as the number of consumed time slots from the moment the first data was transmitted until the ACK was received. Figure 5 c) shows the latency of LLU as a function of target signal-to-interference ratio (SIR) threshold of data transmission. As the target SIR increases, the latency increases. BS cooperation by MNC reduces the latency compared to the SC scheme by around 60%.



(a) Same traffic direction. DL traffics are shown as an example.



(b) Cross directional traffic.



(c) latency as a function of target SINR threshold

Figure 5: (a) both users have the same directional traffic; (b) both users have cross directional traffic. Based on the type of the traffic, each user could be low-latency user (LLU) or latency-tolerant user (LTU); (c) simulation result.

Overview of the Proposed Multi-Channel Access Solutions

An overview of the proposed multi-connectivity solutions is shown in Table I, along with the standardization effort need to have the techniques supported in 5G NR standard (where applicable).

Table I. Overview of proposed MCA Solutions

	Scheme	Addressed Challenge / Benefits	Targeted Traffic Type(s)	Standardization Effort
Duplication Status Report for MC	A novel PDCP duplication status report is proposed to timely acknowledge reception of a PDCP packet to multiple nodes.	Increase URLLC reliability while minimizing duplication costs (interference / queueing delays).	Mainly URLLC, can also benefit eMBB	- Duplication flag - UE sending a short ACK to nodes in the duplication set
Component Carrier Selection for MCA	Rule-based system for the determination of the CCs to be assigned to a given user, according to UE- and cell-level information.	Exploiting CC management to fulfil network operators' policies. E.g., throughput increase, load balancing, etc.	Demonstrated for eMBB, however could be extended to URLLC.	Need for network interface exchanges for gathering the CC scores enabling their comparison.
Latency-Reducing Connectivity based on Processing Proximity	Design of a computationally-aware UE-connectivity framework aiming at latency minimization in HetNets	Exploiting DL/UL decoupled cell association	Mainly URLLC, can also benefit eMBB	NA
Coordinated Multi-Point Connectivity for Low-Latency Applications	Method to manage additional links for duplicated transmissions to enhanced reliability and latency	Flexibly and cooperatively decode received data, to enhance reliability	To be applied to URLLC and traffic mixes which include URLLC traffic and eMBB traffic	NA

5. Conclusion

The emerging of new services and requirements for future 5G NR demands novel radio resource management techniques. This paper provides an overview of Multi-Channel Access solutions tailored to user plane enhancements of 5G NR comprising throughput boosting, reliability improvement and latency reduction. In particular, carrier aggregation, multi-connectivity, DL/UL decoupling and coordinated multi-connectivity transmission are presented, describing their current development in 3GPP Release-15 and discussing the anticipated evolution towards Release-16. Specific solutions addressing some of the key challenges for each of the MCA concepts are proposed and numerically validated. The standardization effort needed to implement some of the proposed solutions in 5G NR are also outlined.

In all cases, the proposed solutions are found to provide promising performance benefits over state of the art solutions. For example, up to 75% peak throughput gain is observed with our proposed rule-based CC selection algorithm which jointly accounts for RSRQ and CC load, whereas up to 60% latency reduction is observed with the suggested latency-minimizing CoMP solution. Although the proposed schemes address different aspects of the challenges, they are compatible and focused towards the same goal: enabling 5G NR service requirements in a multi-service context.

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