Integration of Carrier Aggregation and Dual Connectivity for the ns-3 mmWave Module

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ABSTRACT

Thanks to the wide availability of bandwidth, the millimeter wave (mmWave) frequencies will potentially provide very high data rates to mobile users in next generation 5G cellular networks. However, mmWave links suffer from high isotropic pathloss and blockage from common materials, and are subject to an intermittent channel quality. Therefore, protocols and solutions at different layers in the cellular network and for the TCP/IP protocol stack have been proposed and studied. A valuable tool for the end-to-end performance analysis of mmWave cellular networks is the ns-3 mmWave module, which already models in detail the channel, Physical and Medium Access Control layers, and extends the Long Term Evolution stack for the higher layers. In this paper we present an implementation for the ns-3 mmWave module of multi connectivity techniques for 3GPP New Radio at mmWave frequencies, namely Carrier Aggregation and Dual Connectivity, and discuss how they can be integrated to increase the functionalities offered by the ns-3 mmWave module.

CCS CONCEPTS

• **Networks** → **Network simulations**; **Mobile networks**;

KEYWORDS

mmWave, 5G, Cellular, Carrier Aggregation, Multi Connectivity

ACM Reference Format:

Tommaso Zugno, Michele Polese, Michele Zorzi. 2018. Integration of Carrier Aggregation and Dual Connectivity for the ns-3 mmWave Module. In *Proceedings of the 2018 Workshop on ns-3 (WNS3 2018)*, June 2018, Surathkal, India. ACM, New York, NY, USA, 8 pages. <https://doi.org/10.1145/3199902.3199909>

1 INTRODUCTION

Communication at mmWave frequencies will be one of the key features of the fifth generation of cellular networks (5G), given that the wide available bandwidth at these frequencies [32] can potentially enable multi-gigabit-per-second data rates [9, 24] and satisfy the Enhanced Mobility Broadband 5G use case [36]. 3GPP New Radio (NR), the 5G standard for cellular networks, will support communication at frequencies up to 52.6 GHz [3], and the first trials have confirmed the potential for ultra-high achievable throughput [36].

However, there are several challenges to be addressed for a successful deployment of mobile mmWave networks, mainly related to

the harsh propagation environment at such high frequencies, and in the recent years there have been several efforts focused on solving these issues. The first challenge is the high isotropic propagation loss, which increases with the square of the carrier frequency. This is addressed by using highly directional communications, that increase the link budget and hence the range at which communication is still feasible, and are enabled by the fact that, thanks to the small mmWave wavelength, it is possible to pack many antenna elements in small areas [33, 39]. The second challenge is related to blockage, which prevents direct Line of Sight (LOS) communication in the presence of obstacles, buildings and even the human body [31]. Nonetheless, as shown in [32], in an urban environment with a rich scattering environment, it is possible to communicate also in Non Line of Sight (NLOS) using reflections, but with a Signal to Noise Ratio (SNR) which is approximately 30 dB smaller. This problem can be solved with network densification, i.e., the increment in the density of the deployment of mmWave base stations, with inter-site distance in the order of a few hundreds of meters to decrease the outage probability [24, 31].

The characteristics of the communications at mmWave frequencies, however, also introduce challenges in the whole network stack. For example, the usage of directional transmissions requires new protocols for initial access and tracking at the Medium Access Control (MAC) layer [37], while the network densification and the sensitivity to blockage events call for fast network procedures to timely update the serving base station [26]. The performance of transport protocols is also affected by the intermittency of the mmWave channel, which causes the emergence of bufferbloat and low utilization of the available resources [27].

The need for the design of cross-layer solutions and the analysis of the performance of mmWave cellular networks in an end-to-end environment has motivated the introduction of a mmWave module for ns-3 [14], which is publicly available and extensively described in [21]. It features the implementation of mmWave channel models (including the 3GPP model [42]), and custom Physical (PHY) and MAC layers with a dynamic frame structure that adapts to the large bandwidth available at mmWaves [12], and extends the higher layers of the Long Term Evolution (LTE) module implementation (e.g., by using queueing techniques in the Radio Link Control (RLC) buffers, or by modeling also the connection to the control elements of the core network). The module has been already used to study the performance of frame structures, schedulers, mobility management techniques and transport protocols in end-to-end mmWave cellular networks [21].

In this paper, we describe the implementation of two multi connectivity techniques that are included in the latest 3GPP specifications for NR [6] and the internetworking between LTE and NR [5], which can be used to improve the connection reliability and/or the throughput. In particular, we will focus on Carrier Aggregation (CA)

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WNS3 2018, June 2018, Surathkal, India

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ACM ISBN 978-1-4503-6413-3/18/06...\$15.00

<https://doi.org/10.1145/3199902.3199909>

Table 1: Multi connectivity solutions for mmWave cellular networks, at different layers and across a single or multiple Radio Access Technologies (RATs)

Multi connectivity technique	Relevant specifications for NR at mmWave frequencies	Single or multi-RAT	Main features
Coordinated Multi-Point	CoMP is not included in 3GPP NR specifications. Studied in [18, 19, 41]	Single	Increases the received SNR by combining multiple identical transmission
Carrier Aggregation (available in ns-3 mmWave)	3GPP TS 38.300 [6], TR 38.802 [3]	Single	Increases the data rate or the diversity using multiple carriers with a common MAC layer
Dual Connectivity (available in ns-3 mmWave)	3GPP TS 38.300 [6], TS 37.340 [5]	Both	Uses different cells to increase the data rate or the reliability, and to improve the mobility management. Used for LTE-NR internet-working
Multipath TCP (available in ns-3 with DCE [28, 40])	RFC 6824 [13] (independent from 3GPP NR specifications)	Multi	Combines multiple TCP subflows on different network interfaces to increase the throughput
Application layer solutions (available in ns-3 with custom implementations [11])	Independent of specification bodies. Studied in [11]	Multi	Use different RATs to increase the diversity and improve the Quality of Experience

for mmWave frequencies, and describe how it can be integrated with multi-Radio Access Technology (RAT) Dual Connectivity (DC) in a combined LTE-mmWave scenario. The inclusion of these features increases the realism and the capabilities of the ns-3 mmWave module, and enables the simulation of more complex scenarios with advanced multi-RAT solutions, agile spectrum management and higher throughput.

The remainder of the paper is organized as follows. In Sec. 2 we describe the main multi connectivity solutions for mmWave cellular networks, with a focus on CA and DC and the related 3GPP specifications. In Sec. 3 we present the implementation of CA, and in Sec. 4 we discuss that of the DC and the integration between the two. In Sec. 5 we report some examples and results, and we conclude the paper and provide insights on future works in Sec. 6.

2 MULTI CONNECTIVITY FOR MMWAVE CELLULAR NETWORKS

Given the harsh propagation environment at mmWave frequencies, and the probability of link disruption given by self-blockage or external obstacles, it is important to design and deploy mechanisms that provide communication diversity. Beside diversity in time, which can be achieved using retransmissions and improves the overall end-to-end performance by hiding the channel losses to the higher layers [28], another important kind of diversity is introduced by multi connectivity over different base stations and/or with links at different frequencies (also called macro diversity) [31]. The multi connectivity for user and control planes can be implemented in multiple ways, which mainly differ for the layer at which the integration among the available links happens (i.e., PHY, MAC or higher layers) and the heterogeneity of the links (i.e., whether they belong to the same RAT or not), as shown in Table 1.

Multi connectivity techniques for the same RAT. At the physical layer, the same signals, transmitted from different synchronized access points of the same RAT, can be combined at the User Equipment (UE) side to increase the Signal to Interference plus Noise Ratio (SINR) with the Coordinated Multi-Point (CoMP) technique.

At mmWave frequencies, papers [18, 19] analyze the gain in terms of coverage when using CoMP, while the authors of [41] study the throughput and Radio Link Failure (RLF) performance in a Cloud Radio Access Network (C-RAN) setup with CoMP. Nonetheless, CoMP is not included in the latest 3GPP NR specifications, therefore we will not consider it for implementation in ns-3 in this paper.

At the MAC layer, instead, multi connectivity is usually achieved with CA, which is already widely used in LTE-Advanced networks [4, 23]. While with CoMP the data transmitted by each base station is the same and in the same time and frequency resources, in order to increase the SINR, with CA different data streams can be transmitted in each link (also called Carrier Component (CC)). Moreover, different CCs can use different frequencies, and can be adapted to the channel independently (i.e., they can use different Modulation and Coding Schemes (MCSs), and/or retransmission processes), but are usually transmitted by the same base station. CA increases the available data rate for the user, since it aggregates the spectrum across multiple bands, but can also be used for agile interference management [23] and spectrum sharing with unlicensed bands with the LTE-U extension [43]. CA will be supported also by the 3GPP NR standard, which also considers mmWave frequencies for the access, with a maximum of 16 CCs [3, 6]. At mmWave frequencies, carrier aggregation techniques can be used to combine carriers with very different propagation properties (e.g., 28 and 73 GHz) or in licensed and unlicensed bands [16] in order to improve the reliability of transmission and/or increase the throughput [31]. However, to the best of our knowledge, there are no studies on the application of this technique to mmWaves.

Finally, another single-RAT multi-connectivity technique is DC, introduced in 3GPP LTE-Advanced networks [4] and extended in NR [6]. In this case, the user is connected to multiple base stations, with one cell acting as primary and the other as secondary. The integration happens at the Packet Data Convergence Protocol (PDCP) layer [7], which is located in the primary cell, and the lower layers (i.e., RLC, MAC and PHY) of the different cells are independent.

Figure 1: Protocol stack for the integration of multi-RAT dual connectivity and carrier aggregation at the Radio Access Network (RAN) side. The layers in gray are those affected by the CA implementation

The main difference between DC and CA is in how the cellular network stack is set up for each bearer, i.e., for each end-to-end traffic flow. With DC, each bearer is configured with a different and independent RLC instance per cell, which forwards and receives data from a common PDCP instance, while CA has a single RLC for each bearer (independently of the number of CCs) and can support joint scheduling at the MAC layer across the different carriers. Therefore, while DC can be deployed in different non-colocated cells (which could also use different multiplexing techniques and frame structures in the air interface), CA is usually applied to carriers belonging to the same cell. However, CA enables a tighter level of integration and balancing between the different links. With DC, once the data is forwarded from the PDCP to the primary or secondary RLC, it will be transmitted in the selected cell and, if the channel quality of that link worsens, there is no possibility of changing the selected cell on the fly (the data would need to be forwarded from one RLC to the other). With CA, instead, there is a single RLC layer for each bearer, thus, until the bearer data is actually scheduled on one of the available carriers, in principle it could be transmitted on any of them. Notice that DC and CA can be combined, i.e., a primary or a secondary cell can use multiple CCs per user.

Multi connectivity across different RATs. Dual Connectivity plays an important role also in multi connectivity across different RATs: for example, papers [26, 38] proposed DC as a promising technique for the inter-networking between 4G (i.e., LTE) and 5G cellular networks, and the 3GPP recently announced the support of LTE and NR integration with DC [5, 6]. In particular, DC between LTE and NR is seen as a promising enabler of early NR deployments, which would piggyback on the already deployed LTE core network (i.e., Evolved Packet Core (EPC)), thus initially avoiding a costly deployment of the new 5G core network. Given that the integration is at the PDCP layer, this option also allows a different design for the RLC, MAC and physical layer in 5G NR with respect to LTE.

The performance of the combination of different RATs at sub-6 GHz and mmWave frequencies with dual connectivity has been studied in [26, 29], showing that it can improve both throughput stability and latency while reducing the control signaling and simplifying the mobility management. Moreover, multi connectivity across different RATs can also improve the control plane reliability, for example by reducing the signaling overhead and the latency for the directional initial access needed at mmWave frequencies [17].

Finally, multi connectivity at the transport or application layer recently emerged as a possible enabler of simultaneous communication over different and completely independent RATs, such as cellular networks managed by different operators and/or cellular and Wi-Fi networks. In particular, in [28, 34] the performance of Multipath Transmission Control Protocol (TCP) [13] has been studied over a combination of sub-6 GHz (LTE or Wi-Fi) and mmWave links, while in [11] multi connectivity on LTE and mmWave is used at the application layer to improve the quality of video streaming.

Given the importance of multi connectivity for mmWave networks, we believe that integrating and enabling multi connectivity techniques in the mmWave module for ns-3 improves the realism and the validity of the performance evaluation of mmWave cellular networks. In the following sections we will present the multi connectivity solutions (i.e., multi RAT Dual Connectivity, and Carrier Aggregation) available in ns-3 mmWave¹, as shown by the protocol stack represented for the RAN in Figure 1 and the UE in Figure 2.

3 CARRIER AGGREGATION IN NS-3 MMWAVE

The modeling of the CA feature in the mmWave module for ns-3 follows the 3GPP specifications for NR [6], and aligns the PHY and MAC design to the ns-3 LTE module implementation [8], for which the CA capability was introduced in [10]. In this section, we will describe the main characteristics of our implementation, and the differences with respect to CA in the LTE module.

As shown in Figure 1 and Figure 2, the implementation for the data plane involves the lower layers of the protocol stack (i.e., MAC and PHY), i.e., it is transparent with respect to the functionalities offered by the RLC and PDCP layers. The control functionalities are performed by the Radio Resource Control (RRC) layer, which is in charge of sharing the information for the carrier setup between the base station and the UE. In particular, the base station broadcasts information on the primary CC, and the UE connects to it. Then, when it enters the RRC_CONNECTED state, the base station RRC can instruct the UE to add and/or remove additional carriers with different parameters [6].

In our CA model, and as generally done in the ns-3 mmWave module [21], we inherit and extend the inter-layer interfaces of the LTE module (i.e., the Service Access Points (SAPs)) [8] and the classes that implement them, in order to increase the flexibility

¹ Multipath TCP can also be on top of different RATs, e.g., mmWave and LTE, or Wi-Fi, using Direct Code Execution (DCE) as described in [21, 28].

Figure 2: UE protocol stack for the integration of multi-RAT dual connectivity and carrier aggregation. The layers in gray are those affected by the CA implementation

and account for different channel and propagation conditions for the different carriers, as well as possibly different numerologies, as specified in [6].

CC Configuration. Similarly to the LTE implementation [10], the basic class of the CA implementation is the `MmWaveComponentCarrier` class and its `MmWaveEnbComponentCarrier` and `MmWaveUeComponentCarrier` extensions. An instance of this class represents a single carrier, and contains pointers to the associated protocol stack layers and relevant configurations, as shown in Figure 3. In particular, in our implementation, a `MmWaveComponentCarrier` object contains a reference to a `MmWavePhyMacCommon` object, which is used to specify the numerology, frequency and bandwidth information for the carrier. The `MmWavePhyMacCommon` class was introduced in [20], and prior to the CA implementation, a single `MmWavePhyMacCommon` was created by `MmWaveHelper` during the configuration of the simulation. This object was shared by all the evolved Node Base (eNB) and UE PHY and MAC layer classes, as well as by the channel model classes, to provide access to a set of common parameters. With the CA implementation, instead, an instance of `MmWavePhyMacCommon` is created for each possible carrier, and is associated to the unambiguous identifier of the carrier (i.e., carrier ID stored in the `m_componentCarrierId` private variable of `MmWavePhyMacCommon`). Each of these objects is shared by all classes of the layers at the base station and UE side that are related to the same carrier. The carrier-specific `MmWavePhyMacCommon` instance then defines the carrier frequency (with the attribute `CenterFreq`), the bandwidth (for which it is possible to control the size of the resource blocks and their number) and the frame structure (i.e., the number of symbols per subframe, their duration, and the number of subframes per frame).

CC Managers. The different `MmWaveComponentCarrier` objects in the UEs and base stations are managed by a single CC manager, i.e., an object that implements respectively the `LteUeComponentCarrierManager` or the `LteEnbComponentCarrierManager` interfaces. The CC manager, together with the `MmWaveUeMac` or `MmWaveEnbMac` classes, models the functionalities of the MAC layer as show in Figure 1 and Figure 2 for the mmWave protocol stack. In particular, at the base station side, it receives the Buffer Status Reports (BSRs) from the RLC layers, and forwards them to the `MmWaveScheduler` instances following different policies according to the particular implementation of the CC manager. The schedulers then allocate the available resources and generate Downlink Control Information for the different carriers. In the current implementation, the scheduling on the different carriers is independent, but we plan to extend it in order to model joint cross-carrier scheduling. The CC manager at the UE side is a simplified version of that at the base station, since it does not need to split the BSRs between

Figure 3: Information represented by instances of `MmWaveComponentCarrier` (and extensions)

the carriers, but limits itself to forwarding them to the base station CC manager. In particular, only the primary CC is used to report the BSRs and the exchange of control information², since it is the only CC in which the Service Radio Bearers are set up.

In the mmWave CA implementation, we provide different implementations of the CC manager at the base station side. As for LTE, there is a `MmWaveNoOpMacComponentCarrierManager` which is used for single-carrier simulations, and a `MmWaveRrMacComponentCarrierManager`, which applies a round robin policy and splits the BSRs equally across the carriers, with the result that they reach a similar throughput. In addition, we include also a bandwidth-aware CC manager. It is likely that different carriers over different frequency bands will use different bandwidths, given that the higher the carrier frequency the larger the bandwidth that can be allocated to mobile network operators³. Therefore, a typical use case for CA in the mmWave band would be the aggregation of a CC at relatively low carrier frequency, with a smaller bandwidth, but with better propagation properties (i.e., lower pathloss), and other CCs at much higher frequencies with larger bandwidths. In this case, a round robin CC manager that evenly splits the packets to be transmitted across the different carriers would not yield an optimal performance, given the different data rates that can be supported by the CCs. Therefore, the CC manager implemented in the `MmWaveBaRrMacComponentCarrierManager` class is made aware of the bandwidth available to the different carriers during the simulation setup, and then, when it receives the BSRs from the RLC layer instances in the base station or the UE, it divides the reports according to the bandwidth ratio across the carriers.

Another difference with respect to the LTE implementation is the usage of different channel model objects for the different carriers. In the mmWave module, indeed, the joint modeling of the propagation loss, the small and large scale fading and the beamforming has a fundamental importance for the accuracy of the simulation results. In our previous paper [42] we introduced the implementation of the 3GPP channel model for frequencies above 6 GHz [2], which has features that depend on some carrier-specific parameters, such as the bandwidth and the carrier frequency. Therefore, we decided to use

²While implementing the CA feature for the mmWave module, we discovered a bug that prevents the CA implementation of the LTE module in ns-3.27 and ns-3.28 to use the resources allocated for the uplink. This bug is fixed in our implementation, and we proposed a patch for LTE, see https://www.nsnam.org/bugzilla/show_bug.cgi?id=2861.

³For example, the International Telecommunication Union is considering the allocation to mobile operators of bands of approximately 3 GHz in the 20–30 GHz spectrum, and of 10 GHz in the 60–80 GHz spectrum [15].

different `MmWave3gppChannel` objects⁴ for each carrier, and use the `MmWavePhyMacCommon` of the carrier to set up the necessary parameters. Finally, we extended the `MmWaveSpectrumValueHelper` class in order to support the configuration (i.e., bandwidth, numerology and carrier frequency) of the different carriers.

CA configuration in ns-3 mmWave simulations. Thanks to the adoption of a `MmWavePhyMacCommon` object per carrier, the user of the ns-3 mmWave module has a lot of flexibility in configuring the parameters of the simulation. We provide two comprehensive simulation examples in the `mmwave-ca-same-bandwidth.cc` and `mmwave-ca-diff-bandwidth.cc` files in the examples folder of the mmWave module. The first step in the simulation configuration is the initialization of a `MmWavePhyMacCommon` per CC. The method `SetAttribute` can be used to set the relevant parameters for the carrier. Then, a map that associates the carrier ID to the `MmWaveComponentCarrier` is created, and passed as a parameter to the `MmWaveHelper` with the method `SetCcPhyParams`. The user then deploys the nodes, installs the relevant `NetDevices`, mobility models and applications as in a non-CA simulation script. It is the `MmWaveHelper`, indeed, that transparently takes care of the initialization of the channel objects and the association to the correct carrier, and of the setup of the mmWave base stations and UEs with the carriers information.

4 DUAL CONNECTIVITY IN NS-3 MMWAVE

The ns-3 mmWave module can also simulate UEs that can connect to two different RATs (i.e., LTE and mmWave base stations) at any given time. The modeling and the implementation of this functionality has been described in our previous works [25, 26, 29]. For the sake of completeness, we recall here the main features, and describe the changes needed to support CA.

The DC feature can be used to enhance the quality of the connection in two different ways, i.e., by increasing the reliability or the throughput. The reliability can be improved by using just the mmWave RAT and performing a seamless fallback to LTE when all the mmWave base stations are in outage. The throughput, instead, is increased by actively transmitting data on both links. The implementation follows the 3GPP specifications for multi-RAT DC [5], and involves the higher layers of the protocol stack shown in Figure 1 and Figure 2, i.e., from the RLC layer up. The core of the implementation is a new `NetDevice`, i.e., the `McUeNetDevice`, which models a dual-stack (i.e., LTE and mmWave) UE with a single `EpcUeNas` class as the interface between the higher layers and the cellular protocol stack in the data plane.

In order to simulate a Non Stand Alone deployment (i.e., a deployment of an LTE and of an NR RAN with a common LTE-EPC core network), the LTE eNB acts as the primary cell, i.e., as the mobility anchor towards the core network, and the NR Next Generation Node Base (gNB) at mmWave frequencies as the secondary cell. The `MmWaveHelper` class supports the installation of both LTE and mmWave base stations with the same EPC. The downlink packets for the UE are routed from the Packet Gateway to the LTE eNB,

Figure 4: SAP interfaces for DC between the `McEnbPdcP`, `LteRlc` (or subclasses) and `EpcX2` classes

and the integration happens at the PDCP layer: a single PDCP instance is created for each bearer, and controls two instances of the RLC layer, one in each cell. The X2 interface connects the different base stations, and is used to forward downlink PDCP Packet Data Units (PDUs) from the primary to the secondary, and vice versa for the uplink. In order to support this functionality, we introduced two classes that extend `LtePdcP`, i.e., `McEnbPdcP` at the RAN and `McUePdcP` at the UE. We also defined new SAP interfaces, between the PDCP, the RLC layer and X2, which are configured during the bearer setup process in the RAN, to enable the packet forwarding to and from the remote RLC/PDCP as shown in Figure 4.

The control plane was also extended in order to support DC. Contrary to the intra-RAT DC for LTE [1], in the latest LTE-NR internetworking specifications [5] and in our implementation [29] both the LTE and NR mmWave stacks feature a complete implementation of the RRC layer. It performs control functionalities on the link such as initial access, collection and reporting of link measurements, bearer setup and management, mobility. The RRC layer in the LTE stack manages both the local link and the setup of the dual connectivity with the selected mmWave cell. We extended the implementation of the `LteEnbRrc` and `LteUeRrc` classes to support the DC functionalities, in particular for the new network procedures and the support of the split bearers.

The ns-3 mmWave DC also includes a fast handover procedure for the secondary cell (i.e., the one at mmWave), extensively described in [26], that avoids the interaction with the core network during secondary cell updates and improves the performance of the mmWave RAN with mobile UEs by reducing the handover interruption time and the latency during handover events. Moreover, during the handover procedure, we support two different RLC buffer management policies. If RLC Acknowledged Mode (AM) is used, the handover is lossless, i.e., the PDUs in all the RLC buffers are forwarded from the source to the target cell. Instead, when Unacknowledged Mode (UM) is adopted, the handover is seamless, i.e., the source forwards to the target cell only the RLC PDUs which have not yet been transmitted [22, 35].

With respect to the implementation described in [29], we extended the `McUeNetDevice` class in order to support carrier aggregation. Figure 5 shows a simplified UML diagram of the integration of the DC and CA implementation for an `McUeNetDevice`

⁴The `MmWave3gppChannel` class implements the `SpectrumPropagationLossModel` interface, and in particular the `DoCalcrxPowerSpectralDensity` method which applies fading and beamforming to the received power spectral density according to the 3GPP channel model and different beamforming techniques [42]. Moreover, in this current iteration, we support only the 3GPP channel model, but we plan to extend the implementation to all the channel models available in ns-3 mmWave.

Figure 5: Simplified UML diagram of a dual-connected device, an LTE eNB and a MmWave eNB that also support carrier aggregation. We only report the main classes of the DC-CA integration implementation, i.e., the SAP interfaces are omitted

and an LTE and a mmWave base stations. It can be seen that the mmWave and the LTE CA implementations are used respectively in the MmWaveEnbNetDevice and LteEnbNetDevice classes, while they coexist in the McUeNetDevice. The example in Figure 5 shows two CCs per RAT, but it is actually possible to configure independently the number of CCs in the LTE and mmWave RATs. Then, given that different RRCs are in control of the LTE and mmWave links, it is possible to set the CCs after the UE has attached to either of the two RATs, using RRC connection reconfiguration messages.

5 EXAMPLES

In this section we describe two examples related to the application of CA to mmWave frequencies and report some relevant results that illustrate the flexibility of the CA implementation in configuring carrier-specific parameters and of the CC manager. They can be found in the files mmwave-ca-same-bandwidth.cc and mmwave-ca-diff-bandwidth.cc.

In the following examples, we always consider a total bandwidth of 1 GHz. However, we compare different scenarios in which one CC (with a fraction of the bandwidth) or the whole 1 GHz bandwidth is affected by additional blockage. The 3GPP channel model [2, 42], indeed, models different kinds of blockage phenomena. The main distinction is between the NLOS and LOS conditions, which differ

because the main cluster of rays⁵ is blocked or not, respectively. However, it is possible to model additional blockage events on the other clusters. This feature represents the attenuation that can be caused by (i) the human body of the user holding the device (self-blockage), or (ii) other external obstacles (non-self-blockage). The blockage is randomly applied in certain angular directions, and thus on the clusters whose angle of arrival or departure belongs to those regions. The per-cluster attenuation specified in the 3GPP model and in our implementation is of 30 dB [2], even though some recent papers proposed measurement-based models with a smaller attenuation (i.e., 15 dB) [30]. The additional blockage can be set using the Blockage attribute of the MmWave3gppChannel class, and there is the possibility of selectively setting it carrier by carrier with the method SetBlockageMap of the MmWaveHelper class. In our performance evaluation, we consider that, if multiple carriers are used with different antenna arrays in the mobile device, then the user may just block one of them with his/her hand or body, while, if the whole bandwidth is allocated to a single carrier, then the link is either completely blocked or not.

In the first example, we consider a single user in a NLOS condition with respect to the serving mmWave base station. They exchange data in both downlink and uplink, using a full buffer condition at the RLC layer that saturates the capacity of the link (i.e., the RLC instance belongs to the class LteRlcSm). The user is placed at a 2D distance $d \in [50, 100, 150]$ m from the base station, with an urban macro fading condition [2]. In this example, we consider one or two CCs using the same total amount of bandwidth. Therefore, if a single carrier is selected, it is configured with a bandwidth $B = 1$ GHz, whereas, if two carriers are set up, each of them will use a bandwidth $B = 500$ MHz. We also compare two CC deployment strategies. The first is a contiguous allocation in the 37 – 40.5 GHz band, around a carrier frequency of 40 GHz. The second, instead, is a non-contiguous deployment with a CC at 32.5 GHz, in the 31.8 – 33.4 GHz band, and the other at 73 GHz, in the 66 – 76 GHz band [15]. The same number of antenna elements for both configurations is used at the base station (64) and at the UE (16).

The results are shown in Figure 6a for the contiguous allocation, and in Figure 6b for the other one. We only report the downlink throughput S_{RLC} , since the results in uplink are similar given the frame structure adopted. It can be immediately seen that the usage of CA improves the RLC throughput in both cases. If CA is not used, and the whole 1 GHz bandwidth is controlled by a single scheduler, then it is not possible to properly adapt to different channel conditions that may be present in different chunks of the allocated bandwidth. The metric that is used to allocate the MCS, and consequently the transmission opportunities, is indeed based on the average SINR, and does not take into account frequency selective fading. With CA, instead, it is possible to assign different MCSs to each CC, that maximize the throughput while preventing packet loss, and different retransmission processes [6], so that each CC can optimally adjust to the different channel conditions. This can be observed also when comparing the contiguous allocation case in Figure 6a with the non-contiguous one in Figure 6b. In

⁵The 3GPP 3D Spatial Channel Model (SCM) considers the received signal as a combination of different *clusters*, composed of multiple *rays*. Each cluster has its own angles of arrival and departure, delay with respect to the first cluster, and phase, and the total power is given by the aggregation of the power in the different clusters [2].

(a) Contiguous allocation: 2 carriers with a bandwidth of 500 MHz each, at 39.75 and 40.25 GHz, the second with and without blockage, or 1 carrier with a bandwidth of 1 GHz at 40 GHz with and without blockage.

(b) Non contiguous allocation: 2 carriers with a bandwidth of 500 MHz each, at 32.5 and 73 GHz, the second with and without blockage, or 1 carrier with a bandwidth of 1 GHz at 73 GHz with and without blockage.

Figure 6: Throughput at the RLC layer for different configurations of the carrier aggregation in the mmwave-ca-same-bandwidth.cc example

Figure 7: Comparison (in the mmwave-ca-diff-bandwidth.cc example) among different bandwidth splits for the two CCs, i.e., for $R_{CC} = B_{CC1}/B_{CC0} \in [0.5, 0.25, 0.125]$, with a constant total bandwidth $B = B_{CC0} + B_{CC1} = 1$ GHz in the 39.5 – 40.5 GHz spectrum

the first configuration, the spectrum band of the scenarios with and without CA is the same (from 39.5 to 40.5 GHz), therefore the pathloss and fading parameters are similar. In the non-contiguous one, instead, one of the CCs or the only carrier if CA is not used are at 73 GHz. It can be seen that CA manages to make up for the throughput loss given by the higher pathloss at 73 GHz, and that the gap between the scenarios with and without CA is larger in the non-contiguous configuration than in the contiguous one. Finally, especially in the contiguous deployment scenario, the CA throughput is similar when the secondary CC is in blockage or not, corroborating the performance gain that can be achieved with a more agile resource allocation and channel adaptation mechanism.

The second example, instead, uses the bandwidth-aware scheduler, and compares the performance of different ratios $R_{CC} = B_{CC1}/B_{CC0} \in [0.5, 0.25, 0.125]$ between the bandwidth allocated to the different carrier components CC0 and CC1. The CA deployment is in a contiguous spectrum band around the 40 GHz carrier. The user is randomly placed at a distance $d \in \mathcal{U}[0, 150]$ m and moves in the scenario with a random walk mobility model. Figure 7 reports the downlink MAC-layer throughput of each carrier and the downlink RLC throughput. It can be seen that the performance

worsens as the ratio R_{CC} decreases, and one of the two carriers occupies a much larger bandwidth than the other. For the secondary CC, whose bandwidth decreases with R_{CC} , the ratio between the throughput and the allocated bandwidth remains constant, while for the primary, whose bandwidth increases with R_{CC} , the same ratio decreases. A configuration with a small R_{CC} is indeed similar to a configuration without CA for the primary CC, and does not provide the same channel adaptation capabilities as a configuration with a more even split of the bandwidth between the two CCs.

6 CONCLUSIONS

In this paper, we presented the first implementation of carrier aggregation for the ns-3 mmWave module, and the integration of CA with the LTE-NR dual connectivity feature. Multi connectivity is an important feature in mmWave cellular networks, since it helps increase the reliability of the mmWave link by providing macro diversity (i.e., the possibility of using multiple mmWave links with different frequencies and spatial characteristics) and a ready fall-back to legacy networks at sub-6 GHz features. Therefore, modeling both CA and DC in the ns-3 mmWave module is an important contribution to the module, that makes it possible to simulate more complex, advanced and realistic scenarios⁶.

After an overview on the multi connectivity options for mmWave in the literature and in the 3GPP or IETF specifications, we described the implementation of CA, focusing on the flexibility of the configuration of the parameters in the different carriers and on the implementation of a bandwidth-aware carrier manager. Then, we illustrated the DC implementation, with additional details on the integration with CA. Finally, we provided some examples and preliminary results for CA at mmWave frequencies, showing how CA improves the throughput of the network even if the same total bandwidth is considered, given the higher efficiency in performing the per-carrier scheduling and the macro diversity.

As future work, we plan to investigate additional CC manager policies, which could benefit from PHY-MAC cross-layer approaches, with additional channel information considered in the allocation

⁶The code of the CA-DC implementation can be found at <https://github.com/nyuwireless-unipd/ns3-mmwave/tree/ca-dc-integration>

of resources to the different carriers. Moreover, we will implement joint-carrier schedulers, to increase the efficiency of CA, and complete our implementation with a test suite.

ACKNOWLEDGMENTS

This work was partially supported by the US Department of Commerce – National Institute of Standards and Technology (NIST) through the project “An End-to-End Research Platform for Public Safety Communications above 6 GHz.”

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