Enabling RAN Slicing Through Carrier Aggregation in mmWave Cellular Networks

Matteo Pagin*, Francesco Agostini*, Tommaso Zugno*, Michele Polese†, Michele Zorzi*

*Department of Information Engineering, University of Padova, Italy
email:{name.surname}@dei.unipd.it
†Institute for the Wireless Internet of Things, Northeastern University, Boston, MA, USA
e-mail: m.polese@northeastern.edu

Abstract—The ever increasing number of connected devices and of new and heterogeneous mobile use cases implies that 5G cellular systems will face demanding technical challenges. For example, Ultra-Reliable Low-Latency Communication (URLLC) and enhanced Mobile Broadband (eMBB) scenarios present orthogonal Quality of Service (QoS) requirements that 5G aims to satisfy with a unified Radio Access Network (RAN) design. Network slicing and mmWave communications have been identified as possible enablers for 5G. They provide, respectively, the necessary scalability and flexibility to adapt the network to each specific use case environment, and low latency and multi-gigabit-per-second wireless links, which tap into a vast, currently unused portion of the spectrum. The optimization and integration of these technologies is still an open research challenge, which requires innovations at different layers of the protocol stack. This paper proposes to combine them in a RAN slicing framework for mmWaves, based on carrier aggregation. Notably, we introduce MilliSlice, a cross-carrier scheduling policy that exploits the diversity of the carriers and maximizes their utilization, thus simultaneously guaranteeing high throughput for the eMBB slices and low latency and high reliability for the URLLC flows.

I. INTRODUCTION

Future mobile networks will face numerous technical challenges to jointly satisfy user requirements (i.e., ultra-high throughput, availability and reliability, and low latency) and optimize the Internet Service Provider (ISP) operations (e.g., in terms of cost and energy efficiency) [1]. This upsurge of network demands results from (i) the simultaneous increase of mobile terminals; (ii) the diversity of the requested services; and (iii) the rapid evolution of new use cases, such as inter-vehicular communications and smart factory scenarios. Consequently, 5th generation (5G) networks have been designed to provide connectivity for different classes of services, with orthogonal requirements. For example, a packet error rate of $10^{-2}$ is tolerable in an eMBB system, where the focus is on high throughput; however, when it comes to industrial real-time applications, typical target values for reliability are in the order of $10^{-6}$, together with low latency [2], [3]. It follows that the design of new generations of mobile networks should be flexible enough to adapt to the different requirements.

Network slicing, defined by the Next Generation Mobile Networks Alliance (NGMN) as the concept of running multiple independent logical networks upon a common physical infrastructure, has been proposed as an enabler of flexible 5G networks [4]. Specifically, a network slice is a self-contained, virtualized and independent end-to-end network that allows operators to execute different deployments in parallel, each based on its own architecture [4]. While there have been several research efforts focused on optimizing slicing operations in wired networks (e.g., in the core of cellular networks), and in traditional, sub-6 GHz wireless networks, the state of the art lacks considerations on how this can be applied to the radio access of 5G mmWave networks.

mmWave communications are another key enabler of 5G, which will exploit the currently unused, vast portion of the radio spectrum that lies in the bands between 30 and 300 GHz to provide multi-gigabit-per-second throughput to mobile users [5]. Additionally, the small wavelength of mmWave signals and the advances in low-power CMOS RF circuits make it possible to install large antenna arrays even in a small form factor, such as that of a smartphone, hence enabling beamforming and Multiple Input, Multiple Output (MIMO) techniques. However, the harsh propagation characteristics of mmWave frequencies and the susceptibility to blockage make reliable, low latency and high throughput communications at such high frequencies very challenging [6], and call for the introduction of innovations across all layers of the protocol stack, from the physical and Medium Access Control (MAC) (e.g., beam management) to the transport and application layers [7]. In this regard, one promising strategy is multi-connectivity [8], [9], which introduces macro diversity in the RAN, increasing the robustness with respect to blockage and allowing mobile users to exploit different frequency bands. Carrier Aggregation (CA), which enables multi-connectivity at the MAC layer by providing service on multiple links (called Component Carriers (CCs)), is part of the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) and NR specifications [10], [11] and has been widely deployed to aggregate bandwidth from different portions of the spectrum [12].

This paper is one of the first contributions that studies how to effectively combine network slicing and mmWave wireless networks, satisfying heterogeneous traffic demands through flexible operations also in these frequency bands. Notably, we focus on how to serve URLLC and eMBB slices that share the same radio access resources, without compromising

This work was partially supported by the U.S. Department of Commerce/NIST (Award No. 70NANB17H166) and by the CloudVeneto initiative.
the quality of service of the users in either of the two. We tackle this problem from an intra-cell perspective, leaving the challenge of guaranteeing seamless service in the presence of user mobility as future work. The proposed slicing framework exploits carrier aggregation to (i) distribute the URLLC and eMBB flows among different carriers, which could effectively act as slices; and (ii) provide frequency diversity, e.g., slices that require high reliability could be allocated in lower portions of the spectrum, which benefit from a reduced pathloss. Additionally, we introduce MiliSlice, a cross-carrier packet scheduling policy that dynamically adapts the dispatching of packets to the different carriers with the goal to maximize the utilization of the resources available in each CC, without penalizing the performance requirements of each slice.

We evaluate the effectiveness of the proposed solution with an open-source, realistic, end-to-end, full-stack network simulator for mmWaves [13] based on ns-3, which features the 3GPP channel model for mmWave frequencies and a 3GPP-like protocol stack with carrier aggregation. The results show that, compared to a mmWave network without slicing, the proposed solution reduces the latency of URLLC flows and increases the throughput of the eMBB streams, hence enhancing the QoS achieved by both slices at the same time.

The remainder of this work is organized as follows. In Section II we provide a brief review of the state of the art regarding network slicing and CA solutions. Then, in Section III we introduce the slicing framework, focusing in particular on its novelty aspects compared to the currently available solutions in the literature. Section IV provides a simulation-based performance analysis of the presented strategy, and finally we conclude this paper and highlight possible future improvements in Section V.

II. STATE OF THE ART

This Section will review relevant research efforts for the slicing of the RAN (Sec. II-A) and carrier aggregation in sub-6 GHz and mmWave cellular networks (Sec. II-B).

A. RAN Slicing

Although introducing network slicing at the RAN is still challenging, several 5G initiatives have been pushing for new frameworks to enable network slicing in mobile networks. [14] proposes a fully programmable network architecture based on a flexible RAN to enforce network slicing, also implementing a two-level MAC scheduler to share physical resources among slices, obtaining encouraging results in terms of throughput and resource allocation adaptability. Similarly, the authors of [15] envision fully virtualized LTE base stations that can be deployed on-the-fly to serve slices with different performance requirements. Moreover, [16] analyzes the RAN slicing issue in a multi-cell network, presenting four different slicing approaches for splitting the radio resources among slices, and achieving high granularity and flexibility in the assignment of radio resources, as well as satisfactory levels of isolation. Paper [17] adapts a holistic approach to RAN slicing, proposing a framework that translates high-level service requests of the operators into a correct mapping of the physical layer resources. Finally, [18] proposes a novel latency-sensitive 5G RAN slicing solution for Industry 4.0 scenarios, where stringent latency requirements are common. This proposal, evaluated in industrial scenarios with mixed traffic types, is able to meet the latency requirements of delay-sensitive or time-critical applications, thus improving the QoS experienced by all traffic types through an efficient allocation of the resources to the slices. However, the schemes that have been proposed so far target traditional sub-6 GHz deployments, while in this work we consider the application of network slicing to mmWaves cellular systems.

B. Carrier Aggregation

Carrier aggregation is a technique that the 3GPP has first introduced in the LTE specifications [19], and extended in NR [11], which enables different CCs to operate at different frequencies, and to use different Modulation and Coding Scheme (MCS) or retransmission processes, usually within the same base station. Moreover, CA allows the aggregation of licensed and unlicensed bands with LTE-U and Licensed-Assisted Access (LAA) [20]. The advantages that this approach can bring have been profoundly studied in the literature and eventually even implemented in actual deployments, but mostly within the realm of LTE-Advanced mobile networks: the employment of CA in such scenarios provides an increase of the available per user data-rate (since it can aggregate the radio resources across the spectrum) as well as the means for an agile interference management [10].

In 5G cellular systems, the capabilities of CA have been extended with the possibility of using up to 16 [21], [11] carriers with a bandwidth of up to 400 MHz. Moreover, as NR supports mmWave communications, it will be possible to combine carriers with different propagation properties (e.g., mmWave and sub-6-GHz) or in licensed and unlicensed bands (thanks to the extension of NR-U in the 60 GHz band) [22], [23], in order to increase the throughput and improve the reliability of transmissions [5]. In our previous work [12], we analyzed the performance of different CA schemes for mmWaves using an end-to-end network simulator [13], showing that CA improves the throughput of the network, due to the higher resilience to blockage given by macro-diversity and the higher efficiency of a per-carrier scheduling and MCS selection. However, even though the preliminary analysis carried out by means of simulation in [12] shows promising results, the application of this technique to mmWaves has not been exhaustively studied so far and presents some open challenges such as the introduction of joint-CC schedulers and MAC-Physical (PHY) cross layers approaches.

III. EFFICIENT MMWAVE RAN SLICING WITH CA

In this Section, we will describe the proposed RAN slicing framework for mmWave cellular networks, providing details on how CA can be used to perform slicing, and on the cross-carrier scheduling policy that manages to guarantee to each data stream the desired QoS.

The overall goal is to satisfy the requirements in terms of latency and reliability of URLLC flows, i.e., over-the-air...
delay below 1 ms and packet loss smaller than $10^{-6}$, while maximizing the throughput of the eMBB flows that share the same radio interface. We designed the slicing framework to be robust with respect to the number of users per base station, the amount of eMBB traffic, and the configuration of the resource allocation in the access networks.

A. RAN Slicing Through CA

The CA technique involves the PHY and MAC layers, as well as the interaction between MAC and Radio Link Control (RLC). Figure 1 reports a simplified diagram of the protocol stack involved in the management of multiple carriers. During the configuration phase, the base station notifies the availability of one or multiple carrier components, to which the User Equipment (UE) could connect according to its capabilities. Once the connection setup is completed, the base station can manage the CCs by offloading users to different carriers, or by performing a cross-carrier scheduling for the users connected to multiple CCs. As described in the 3GPP specifications for NR [11], the inter-CC scheduling in CA happens in the highest portion of the MAC layer, which is interfaced with the different instances of RLC [12]. The RLC periodically sends to the MAC layer a BSR, a report with information about the occupancy of the different buffers (i.e., the size of the transmission and retransmission queues). The MAC layer then uses the BSRs to schedule the radio resources.

In this paper, we propose to adapt the CA mechanism to achieve network slicing at the RAN. As previously highlighted, most of the solutions that have been introduced to perform slicing have been considered for deployment in the core network. Those that have been implemented at the RAN are based on ad hoc scheduling at the MAC layer with a single carrier. Unlike these approaches, we propose to implement slicing at mmWaves exploiting CA, as this solution provides several advantages over the aforementioned single-carrier strategies. First of all, it allows the aggregation of multiple carriers, so that the telecom operators could use the available spectrum in a more flexible way. Additionally, CA enables isolation among the different slices by serving each one with a different carrier. Finally, it makes it possible to exploit macro diversity, i.e., to allocate flows with different requirements in portions of the spectrum with distinct propagation characteristics. For example, a CC with a lower carrier frequency exhibits a smaller pathloss, but, at the same time, may be more constrained in terms of available bandwidth with respect to a CC at a higher frequency. This provides a natural fit to serve URLLC flows in the lower CC, as they could benefit from the improved propagation conditions but have limited needs in terms of bandwidth, and the eMBB traffic in the higher portion of the spectrum, trading reliability for a larger bandwidth. In our work, we follow this principle by always scheduling URLLC flows in the CC with the lowest carrier frequency.

In the proposed slicing framework, when a telecom operator needs to allocate a new RAN slice for an end-to-end flow with a certain QoS level, it first checks if the base stations in the area where the slice should be served have CCs available to host the slice. If this is the case, it specifies at the MAC layer of each base station the QoS requirements corresponding to the specific flow (e.g., whether it is a URLLC or eMBB flow). These requirements are expressed through a Quality Class Identifier (QCI), i.e., an indicator for the QoS of each end-to-end flow standardized by the 3GPP [13], associated to the Buffer Status Reports (BSRs) generated at the RLC layer. Eventually, when the slice is operational, the MAC layer uses the QCI of the BSRs to map it to the proper CC. For example, in Figure 1 RLC3 serves an eMBB slice, and its BSRs are forwarded to CC1. Conversely, RLC1 is associated to a URLLC Data Radio Bearer (DRB), and will be scheduled on CC0. Notice that in this paper we do not focus on the admission problem, but rather on the optimization of the slice scheduling on the different CCs, as we will discuss in the next paragraphs.

B. Slice-aware Cross-Carrier Scheduling

As previously mentioned, CA enables, in principle, the orthogonal separation of the URLLC and eMBB slices in different CCs. However, as we will highlight in Sec. IV this may lead to inefficiencies in the spectrum utilization, especially in the case where the slices have heterogeneous
requirements in terms of bandwidth. In particular, even if the CC for the URLLC slices may be configured with a smaller bandwidth, the datarate difference between eMBB and URLLC flows, if not properly handled, can lead to the exhaustion of the available capacity in the eMBB slice, with idle resources in the CC for URLLC.

Therefore, as part of the proposed RAN slicing framework, we introduce MilliSlice, a cross-carrier scheduling component whose purpose is to improve the efficiency of the slicing process while avoiding detrimental effects on the QoS of whose purpose is to improve the efficiency of the slicing process while avoiding detrimental effects on the QoS of the CCs. Referring to Figure 2, this component is deployed in the CC manager, thus it does not require any modification in the per-carrier scheduling algorithm that the operator selects for each CC.

The slicing framework associates each slice to a primary carrier component, following the strategy described in the previous section, and, additionally, to one or more secondary CCs, in which the slice has a lower priority with respect to the slices that use these CCs as primary. The slices that have a low priority on a CC will be served in that CC only if the flows that use it as primary do not occupy all the available resources. This makes the cross-carrier slicing mechanism adaptive to the load of each slice. Specifically, in the aforementioned case of URLLC and eMBB sources, the proposed method distributes the data across the CCs with the following criteria. The eMBB traffic shall be partially redirected towards its secondary CC if and only if the URLLC buffers (which consider this CC as primary) contain less data to transmit than a pre-determined threshold $R_{eMBB}^\text{threshold}$; a similar principle applies to the eMBB slices.

The process is based on an adaptive forwarding of the BSRs to the different CCs, as depicted in the flow chart of Figure 3. Notably, the component carrier manager, i.e., the entity in charge of splitting the traffic among the different carriers, tracks the buffer occupancy of the RLC layers with a sliding window mechanism. Then, once the RLC sends a BSR to the MAC, the CC manager checks the associated

![Figure 2: Flow-chart of the BSR scheduling logic](image)

Algorithm 1 Cross-carrier scheduler implemented in the proposed RAN slicing framework.

**Input:** The incoming BSRs, the BufferOccupancy-Map at the CC manager, QciCcMap, associating QCIs to their primary carrier, and the set of thresholds $R$ for each QCI

**Output:** ChosenCCs, a map associating CCs and respective BSRs

1. Compute the aggregated RLC buffer occupancy (new packets + retransmissions), store it in RlcLoads
2. Consider qci, the QCI associated with the BSR BSR of a specific flow
3. if $Qci \in QciCcMap$ then
4. Add the primary CC to the list of available ones
5. ChosenCCs[QciCcMap[cci]] ← BSR
6. Check whether the RLC buffers of the various different slices contain less data than a given threshold, if so add them
7. for all entry ∈ RlcLoads do
8. $oQci ←$ QCI associated with entry
9. if $qci \neq oQci$ and $RlcLoads[oQci] \leq R_{oQci}$ then
10. ChosenCCs[QciCcMap[oQci]] ← BSR
11. end if
12. end for
13. for all $cc \in$ ChosenCCs do
14. ChosenCCs[cc] → BSR.TxQueueSize = BSR.TxQueueSize / size(ChosenCCs)
15. end for
16. end if
17. return ChosenCCs

QCI and, if the buffer occupancy of the secondary carrier is above the predefined threshold, the BSR is forwarded to the primary CC only. Otherwise, the BSR is split across the primary and secondary CCs. The pseudocode in Algorithm 1 extends this procedure for a generic number of secondary carrier components.

Furthermore, we choose the carrier operating at lower frequency to be the primary for the URLLC flow, and set the threshold $R_{eMBB} = 0$, so that the URLLC traffic is never redistributed across the CCs (i.e., it can be served only by its primary CC). This is due to the fact that URLLC packets would experience a lower average Signal-to-Interference-plus-Noise Ratio (SINR) on secondary carriers, as the primary is chosen to be the one with the lowest carrier frequency and, additionally, they would be handled with low priority in secondary CCs, thus impacting latency and reliability. Conversely, for the eMBB traffic, we set $R_{URLLC} = 1$ packet, so that these slices can be served by the secondary CC when the URLLC RLC buffers are empty.

**IV. PERFORMANCE ANALYSIS**

This Section will provide insights on the performance that can be achieved using the proposed RAN slicing framework, after a brief description of the simulator used for the performance evaluation and of the scenario of interest.
A. ns-3 mmWave Module

The performance analysis has been carried out using simulations with the open-source network simulator ns-3, which allowed us to accurately analyze the end-to-end performance of the proposed slicing framework. Specifically, the simulations are based on the ns-3 mmWave module introduced in [13], which features the 3GPP channel model for mmWaves [25], to stochastically characterize propagation loss, fading, beamforming and interference in the wireless domain, a 3GPP-like protocol stack for Next Generation Node Bases (gNBs) and UEs, and, thanks to the integration with ns-3, the possibility of simulating different mobility patterns and the details of the TCP/IP protocol stack.

To implement the slicing framework proposed in this paper, we consider the implementation of CA for the ns-3 mmWave module described in [12]. The CC manager that behaves according to the policies described in Sec. II-A is an extension of the MmWaveNoOpComponentCarrierManager class, which adaptively forwards the BSRs from the RLC instances to the MACs of the various CCs. Additionally, we implemented a complete simulation script that can be used to instantiate slicing scenarios and compare different network configurations. The open-source code base associated to this paper is publicly available [https://github.com/signetlabdei/millislice](https://github.com/signetlabdei/millislice) so that researchers interested in the area of RAN slicing can use it to further extend this work.

B. Simulation Scenario and Network Parameters

We consider a scenario that models the coverage area of a cell in an urban, densely populated area. As represented in Figure 3, the simulation scenario consists of a single cell of radius 200 m, with one gNB at the center and $N_U$ users that are uniformly dropped and move with random speed between 1 and 10 m/s. A remote host connected to the Internet holds eMBB and URLLC applications, modeled as User Datagram Protocol (UDP) sources with different data rates, each generating downlink traffic for a specific user. The system operates at 28 GHz with a total bandwidth of 500 MHz. In case CA is used, an additional carrier component operating at 10 GHz is added and the overall bandwidth is divided among the two carriers according to the parameter $\alpha_{ratio}$, which defines the ratio between the bandwidth dedicated to CC0 and that of CC1, e.g., when $\alpha_{ratio} = 0.5$, each CC is configured with a bandwidth of 250 MHz. In our solution, CC0 will act as the preferred carrier for the eMBB slice, while CC1 will be dedicated to URLLC flows. Finally, as previously mentioned, for this simulation campaign we set $R_{eMBB} = 0$ and $R_{URLLCC} = 1$. With this configuration, URLLC data is never sent to the eMBB CC, while eMBB slices can be served by their secondary CC only if the RLC buffers corresponding to the URLLC slice are empty. For a more exhaustive list of simulation parameters, please refer to Table I.

C. Network Configurations and Metrics

We consider two different baselines to benchmark the performance of the proposed slicing framework. The first ("no CA" in the plots) is a setup without CA and slicing, i.e., with a single carrier with the total system bandwidth $B$. The second ("CA, primary only" in the plots), instead, is a solution with slicing and CA, but without the adaptive cross-carrier scheduling, i.e., in which each slice has only a primary CC and cannot use the secondary CC.

We evaluated the performance of the proposed framework by analyzing the average end-to-end delay, aggregated throughput and packet loss ratio achieved at the application layer for both the eMBB and URLLC data flows. Moreover, to evaluate the per-carrier efficiency in terms of resource utilization, we defined the metric $\eta_{CCi}$, which represents the portion of the consumed resources with respect of the total available:

$$\eta_{CCi} = \frac{tx_{sym}[CC_i]}{t_{sym} \cdot f_{frame} \cdot f_{subframe} \cdot t_{sym}} \times \frac{B_{CCi}}{B} \tag{1}$$

where $tx_{sym}[CC_i]$ is the total number of Orthogonal Frequency Division Multiplexing (OFDM) symbols transmitted through CC$_i$, $t_{sym}$ is the simulation time in seconds, $f_{frame}$ is the number of frames in a second, $f_{subframe}$ is the number of subframes in a frame.
of subframes within a frame, and \( f_{\text{sym}} \) is the number of the OFDM symbols which can be transmitted in a subframe. Moreover, the weight \( B_{CC_i}/B \) represents the portion of system bandwidth dedicated to \( CC_i \), and is applied to achieve a normalized result.

### D. Results

In Figure 4, we compare the performance achieved by the three strategies over different values of the eMBB source rate. Although all the solutions are able to guarantee a reliable delivery of the URLLC traffic, it can be noticed that the introduction of RAN slicing by means of carrier aggregation is beneficial for the delay: indeed, both the primary only and MilliSlice solutions show lower URLLC delay compared with the standard approach. In particular, the lowest delay is reasonably achieved when the two flows are completely isolated, because the usage of dedicated carriers allows URLLC transmissions to be independently scheduled, without incurring additional delay due to the presence of other eMBB packets in the queue. Moreover, the possibility to employ a carrier operating at a lower frequency ensures a more reliable data delivery, making it possible to achieve the correct reception of each packet with a smaller number of MAC and RLC layer retransmissions, thus reducing the delay. However, the advantage that the complete isolation provides for URLLC traffic comes at the price of sacrificing the QoS experienced by the eMBB slice, which exhibits lower throughput (Figure 4b) and higher packet loss compared with the other solutions (Figure 4c). In this case, the carrier component dedicated to the eMBB flow does not provide enough resources to satisfy the offered traffic and becomes saturated. Instead, MilliSlice is able to achieve the best performance for the eMBB services while minimizing the URLLC delay with respect to standard systems, and thus represents a viable solution to achieve network slicing at the RAN level. Thanks to an elastic scheduling algorithm, our solution is able to efficiently exploit the available resources by allowing the congested eMBB slice to use the carrier dedicated to the URLLC flow when idle. This behavior is confirmed by Figure 5, which represents the resource utilization achieved by the three different approaches, possibly showing the portion used by either \( CC_0 \) (darker) or \( CC_1 \) (lighter) when CA is employed. It can be seen that with MilliSlice more than 80% of the system resources are exploited and the load is equally distributed among the two carriers. In contrast, with the primary only approach the carrier dedicated to URLLC is poorly utilized and about 45% of the available resources are wasted. Moreover, the more agile link adaptation provided by CA [12] enables MilliSlice to achieve a higher performance gain with respect to the single carrier approach, even using a smaller amount of resources.

If, on the other hand, we analyze the effectiveness of MilliSlice across different URLLC source data-rates, we can recognize a similar general trend of the various metrics: in Figure 6 our solution exhibits a higher throughput and lower packet loss for the eMBB flow compared with the other solutions, coupled with a reduction of the URLLC delay with respect to the single carrier approach.

However, by observing Figures 6b and 6c it can be noticed that the gain introduced by MilliSlice decreases when increasing the rate of the URLLC sources. This phenomenon can be interpreted as follows: as the amount of URLLC traffic increases, the BSR arrival occurrences indicating that the
Figure 6: Per-user performance metrics achieved for different values of the URLLC source rate; the eMBB data-rate is fixed at 100 Mbit/s.

(a) Average URLLC delay. (b) Average eMBB throughput. (c) Average eMBB packet loss ratio.

Figure 7: Average URLLC delay versus aggregated eMBB throughput.

To evaluate the robustness of the proposed scheduling algorithm to possible scenario variations, we analyzed the system behavior by varying the number of users. The results are shown in Figure 7, in which each point represents the achieved performance in terms of average URLLC delay and aggregated eMBB throughput when considering a certain number of users. One one hand, in the single carrier case, the lack of any slicing strategy makes the URLLC performance susceptible to the increase of the number of eMBB sources. On the other hand, the static carrier assignment isolates the two traffic types onto their favored carrier and lacks any degree of adaptability to the offered eMBB traffic. Instead, MilliSlice manages to scale well and sustain different numbers of eMBB sources while keeping the URLLC delay under 2 ms.

Finally, in Figure 8a we can observe how our proposed solution shows poor adaptation capabilities with respect to a variation of the $c_{ratio}$: as one of the carriers starts to gain possession of most of the bandwidth, the simplicity of our traffic redistribution strategy, coupled with the lack of ad hoc MAC layer scheduling solutions, starts to show some limitations, even though it still outperforms the other solutions. In particular, such loss in the effectiveness of our policy is driven by a sub-optimal exploitation of the system bandwidth: as depicted by Figure 8b, the CC whose dedicated resources are lower tends to be backlogged, while the other one does not absorb as much traffic as it would be capable of.

V. CONCLUSIONS AND FUTURE WORK

The variety of services that 5G networks will have to support requires both the exploitation of previously unexplored portions of the spectrum (i.e., the mmWave frequencies) and of additional flexibility in the RAN configuration. In this paper, we proposed to combine two enablers of 5G networks, i.e., network slicing and carrier aggregation, to support in the same radio interface simultaneous transmission of URLLC and eMBB traffic flows. Specifically, we proposed a simple but effective policy for the distribution of the various traffic flows among different slices, mapped across multiple carrier components, also exploiting the diversity of the different frequency bands available at mmWaves. We implemented such solution in the ns-3 mmWave module, and carried out an extensive simulation campaign, benchmarking our solution with a number of metrics against two different baseline policies. The promising results and the effectiveness of the proposed solution showed that network slicing through carrier aggregation, especially when coupled with an adaptive cross-carrier scheduling, can sustain heterogeneous 5G requirements.

Future work will focus on more refined solutions, aimed at improving the operations of the schedulers that operate at the carrier component level, to make them aware of the kind of traffic flow they need to support, and to integrate more advanced policies in the proposed slicing framework. Moreover, we will analyze more in detail the performance...
of our solution when scaling the number of flows, designing smart admission policies to efficiently exploit the available resources while ensuring the desired QoS.

REFERENCES

[1] P. Rost, C. Mannweiler, D. S. Michalopoulos, C. Sartori, V. Sciancalepore, N. Sastry, O. Holland, S. Tayade, B. Han, D. Bega et al., “Network slicing to enable scalability and flexibility in 5G mobile networks,” IEEE Communications magazine, vol. 55, no. 5, pp. 72–79, May 2017.

[2] A. Frotscher, U. Weitzker, M. Bauer, M. Rentschler, M. Beyer, S. Elspass, and H. Klessig, “Requirements and current solutions of wireless communication in industrial automation,” in International Conference on Communications Workshops (ICC). IEEE, 2014, pp. 67–72.

[3] I. Parvez, A. Rahmati, I. Guvenc, A. I. Sarwat, and H. Dai, “A Survey on Low Latency Towards 5G: RAN, Core Network and Caching Solutions,” IEEE Communications Surveys & Tutorials, vol. 20, no. 4, pp. 3098–3130, Fourth quarter 2018.

[4] NGMN Alliance, “Description of network slicing concept,” NGMN 5G P1 Requirements & Architecture Work Stream End-to-End Architecture Deliverable, 2016. [Online]. Available: https://www.ngmn.org/wp-content/uploads/Publications/2016/161010_NGMN_Network_Slicing_framework_v1.0.8.pdf

[5] S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-wave cellular wireless networks: Potentials and challenges,” Proceedings of the IEEE, vol. 102, no. 3, p. 306–355, Mar 2014. [Online]. Available: http://dx.doi.org/10.1109/PROC.2014.2299397

[6] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!,” IEEE Access, vol. 1, pp. 335–349, May 2013.

[7] M. Zhang, M. Polese, M. Mezzavilla, J. Zhu, S. Rangan, and M. Zorzi, “Will TCP Work in mmWave 5G Cellular Networks?,” IEEE Communications Magazine, vol. 57, no. 1, pp. 65–71, January 2019.

[8] M. Polese, M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, “Improved Handover Through Dual Connectivity in 5G mmWave Mobile Networks,” IEEE J. Sel. Areas Commun., vol. 35, no. 9, pp. 2069–2084, Sept 2017.

[9] M. Drago, T. Azzino, M. Polese, C. Stefanovic, and M. Zorzi, “Reliable Video Streaming over mmWave with Multi Connectivity and Networking Coding,” in International Conference on Computing, Networking and Communications (ICNC), March 2018, pp. 508–512.

[10] K. I. Pedersen, F. Frederiksen, C. Rosa, H. Nguyen, L. G. U. Garcia, and Y. Wang, “Carrier aggregation for LTE-advanced: functionality and performance aspects,” IEEE Communications Magazine, vol. 49, no. 6, pp. 89–95, June 2011.

[11] 3GPP, “NR and NG-RAN Overall Description,” TS 38.300 (Rel. 15), 2018.

[12] T. Zugno, M. Polese, and M. Zorzi, “Integration of Carrier Aggregation and Dual Connectivity for the ns-3 mmWave Module,” in Proceedings of the 10th Workshop on ns-3, ser. WNS3 ‘18, Surathkal, India: ACM, 2018, pp. 45–52. [Online]. Available: http://doi.acm.org/10.1145/3199902.3199909

[13] M. Mezzavilla, M. Zhang, M. Polese, R. Ford, S. Dutta, S. Rangan, and M. Zorzi, “End-To-End Simulation of 5G mmWave Networks,” IEEE Communications Surveys & Tutorials, vol. 20, no. 3, p. 2237–2263, Third quarter 2018.

[14] A. Ksentini and N. Nikaein, “Toward enforcing network slicing on RAN: Flexibility and resources abstraction,” IEEE Communications Magazine, vol. 60, no. 6, pp. 102–108, June 2017.

[15] X. Foukas, M. K. Marina, and K. Kontovasilis, “Orion: RAN Slicing for a Flexible and Cost-Effective Multi-Service Mobile Network Architecture,” in Proceedings of the 23rd Annual International Conference on Mobile Computing and Networking, ser. MobiCom ’17, Snowbird, Utah, USA: Association for Computing Machinery, 2017, p. 127–140. [Online]. Available: https://doi.org/10.1145/3117811.3117831

[16] O. Salient, J. Perez-Romero, R. Ferrus, and R. Agusti, “On radio access network slicing from a radio resource management perspective,” IEEE Wireless Communications, vol. 24, no. 5, pp. 166–174, October 2017.

[17] S. D’Oro, F. Restuccia, and T. Melodia, “Toward Operator-to-Waveform 5G Radio Access Network Slicing,” IEEE Communications Magazine, vol. 58, no. 4, pp. 18–23, April 2020.

[18] J. García-Morales, M. C. Lucas-Estañ, and J. Gozalvez, “Latency-Sensitive 5G RAN Slicing for Industry 4.0,” IEEE Access, vol. 7, pp. 143139–143159, September 2019.

[19] 3GPP, “Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; TS 36.300 (Rel. 15), 2018.

[20] R. Zhang, M. Wang, L. X. Cai, Z. Zheng, X. Shen, and L.-L. Xie, “LTE-unlicensed: The future of spectrum aggregation for cellular networks,” IEEE Wireless Communications, vol. 22, no. 3, pp. 150–159, July 2015.

[21] 3GPP, “Study on New Radio (NR) Access Technology - Physical Layer Aspects,” TR 38.802, V14.0.0, 2017.

[22] Z. Khan, H. Ahmad, E. Hossain, M. Coupechoux, L. A. DaSilva, and J. J. Lehtomäki, “Carrier aggregation/channel bonding in next generation cellular networks: Methods and challenges,” IEEE Network, vol. 28, no. 6, pp. 34–40, Nov.-Dec. 2014.

[23] S. Lagen, L. Giupponi, S. Goyal, N. Patriciello, B. Bojović, A. Demir, and Y. Wang, “Carrier aggregation for LTE-advanced: functionality and performance aspects,” IEEE Communications, vol. 57, no. 6, pp. 143–159, September 2019.

[24] 3GPP, “Evolved Terrestrial Radio Access Network (E-UTRAN) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; TS 36.300 (Rel. 15), 2018.

[25] K. I. Pedersen, F. Frederiksen, C. Rosa, H. Nguyen, L. G. U. Garcia, and Y. Wang, “Carrier aggregation for LTE-advanced: functionality and performance aspects,” IEEE Communications Magazine, vol. 49, no. 6, pp. 89–95, June 2011.

[26] 3GPP, “NR and NG-RAN Overall Description,” TS 38.300 (Rel. 15), 2018.