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A Study on Cross-Carrier Scheduler for Carrier Aggregation in Beyond 5G Networks

Nidhi(1), Bahram Khan(2), Albena Mihovska(1), Ramjee Prasad(1) and Fernando J. Velez(2)
(1) Department of Business Development and Technology, Aarhus University, Herning, Denmark,
(2) Instituto de Telecomunicações and Universidade da Beira Interior, Covilla, Portugal

1. Abstract

Carrier Aggregation (CA) allows the network and User Equipment (UE) to aggregate carrier frequencies in licensed, unlicensed, or Shared Access (SA) bands of the same or different spectrum bands to boost the achieved data rates. This work aims to provide a detailed study on CA techniques for 5G New Radio (5G NR) networks while elaborating on CA deployment scenarios, CA-enabled 5G networks, and radio resource management and scheduling techniques. We analyze cross-carrier scheduling schemes in CA-enabled 5G networks for Downlink (DL) resource allocation. The requirements, challenges, and opportunities in allocating Resource Blocks (RBs) and Component Carriers (CCs) are addressed. The study and analysis of various multi-band scheduling techniques are made while maintaining that high throughput and reduced power usage must be achieved at the UE. Finally, we present CA as the critical enabler to advanced systems while discussing how it meets the demands and holds the potential to support beyond 5G networks, followed by discussing open issues in resource allocation and scheduling techniques.

Keywords:
5G New Radio (5G NR), Carrier Aggregation (CA), Component Carrier (CC), Cross-Scheduling Schemes, Radio Resource Management (RRM).

2. Introduction

Coverage and capacity for the 5G user experience are the essential elements. Carrier Aggregation (CA) is the foundation key for 5G. It will extend the coverage by considering the mid, low, and high bands. It will lead to increased capacity also. CA and the coordination of Radio Access Network (RAN) are possible solutions for low latency, high capacity, and optimized coverage for 5G mid-band and high-band deployment. To overcome the demands of wireless data and applications, the service providers need to research a new spectrum source that can use the existing spectrum efficiently. 5G enables a new spectrum source, both the mid-band and high-band radio frequencies, to allow the latest applications and provide better data speeds. Getting more benefits from these new spectrum bands, solutions are needed to extend cell coverage. CA is one of the solutions that use the spectrum efficiently. Third Generation Partnership Project (3GPP) Release 15 [1] introduced 5G New Radio (NR) in 2018 as the global standard for the air interface and explained CA in licensed and unlicensed bands, and considered aggregation in shared spectrum scenarios as well. A solution that allows expanding the spectrum assets when deploying 5G is Inter-band NR CA. This type of CA can extend the cell coverage area of mid-band Time Division Duplex (TDD) by a factor of 2.5 [2]. On the other hand, carrier aggregation with NR in the highest frequency bands (i.e., millimetre wavebands) allows coverage area extension by four.

In Release 16, the number of rate-matching patterns available in NR has been increased to allow spectrum sharing when CA is used for LTE. Besides, Release 16 reduces latency for setup and activation of CA/Dual Connectivity (DC), leading to improved system capacity and the aptitude to achieve higher data rates. Unlike Release 15, where measurement configuration and reporting do not take place until the UE comes into the fully connected state, in Release 16, the connection can be resumed after periods of inactivity without the need for extensive signalling for configuration and reporting [3]. Additionally, Release 16 introduces a periodic triggering of Channel State Information (CSI) reference signal transmissions in case of the aggregation of carriers with different numerology. In the Release 17 Enhanced Mobile Broadband (eMBB) trend, the NR frequency range will be extended to allow for exploiting more spectrum (above 52.6 GHz), including the 60 GHz unlicensed band, while defining new Orthogonal Frequency Division Multiplexing (OFDM) numerology and channel access mechanism to comply with regulatory requirements applicable to unlicensed spectrum.

The rest of the paper is structured as follows. Section III addresses the CA-enabled 5G networks. Section IV describes various resource management and scheduling techniques. In Section V, we discuss the research challenges. Finally, conclusions are drawn in Section VI. Figure 1 shows the overall structure of the paper.

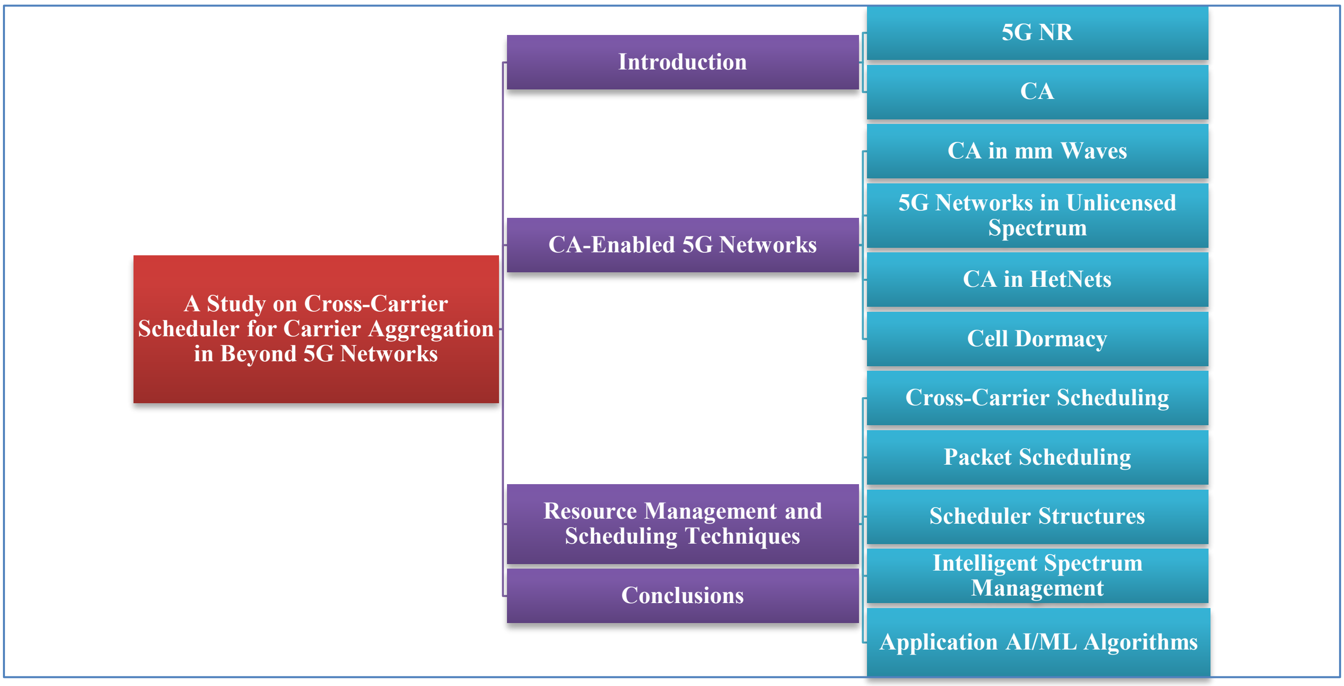

Figure 1. Paper Structure.

3. Carrier Aggregation Enabled 5G Networks

3GPP has parted the band into three parts for 5G services [2]. The frequency band of less than 1 GHz is considered a low band, while the 2.4 GHz - 40 GHz is a high band and 1GHz - 2.6 GHz and then 3.5 GHz- 6 GHz is regarded as a mid-band. With the combination of these bands, the deployment of 5G and beyond will support a high data rate and less resource utilization. The range of a single low band (below 7 GHz, with Frequency Division Duplex, FDD) can cover hundreds of square miles considering 5G services whose speed range is from 30 to 250 megabits per second (Mbps). These are the most common services to deploy, providing a wide area coverage. The mid-band (below 7 GHz, with Time Division Duplex, TDD) can provide up to a several-mile radius with currently goodput ranging from 100 to 900 Mbps. At the same time, the high band (above 2.4 GHz) is just covering the shortest cell radius with a goodput range from 1 up to 3 Gbps. By deploying 5G networks in these combinations of frequency bands/ranges and speeds, the networks not only support a high data rate but also provides the best solution for 5G spectrum requirements. The comparison of frequency bands is shown in Figure 2.

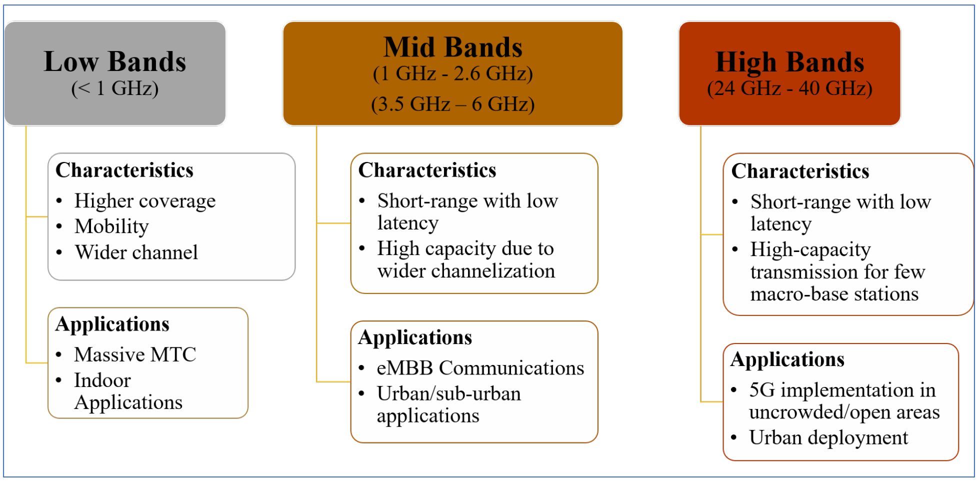

Figure 2. Comparison of 5G Low, Mid and High-Frequency Bands.

Carrier Aggregation with Millimetre Wavebands

Millimetre Wavevands (mmWaves) are one of the promising opportunities to address the shortage of spectrum in a wireless network. It became the redeemer of 4G/5G mobile operators. It will suit its coexistence with the LTE network [4]. CA and mmWave bands scenarios are extensively investigated in [5, 6]. These papers consider the channel state information and low computational complexity to improve carrier aggregation technique and reduce energy consumption in 5G scenarios. The aggregation of the mmWave and sub-6 GHz frequencies is the need of the network. It can deliver the massive capacity and multi-Gigabit speeds desired for consumers and enterprise applications. Combining the different combinations of spectrum resources will make it possible for 5G devices to achieve wired broadband-class speeds wirelessly.

5G Networks in Unlicensed Spectrum

5G's essential design model intends to support diversified spectrum bands. 3GPP introduced unlicensed spectrum bands for 5G NR as Unlicensed 5G NR (5G NR-U) to enhance the LTE's Licensed Assisted Access (LAA) with Release 16 [7]. It also marked 5G NR-U deployments in the license-exempted 5 GHz and 6 GHz bands. The supported deployment modes for 5G NR-U are (i) Carrier Aggregation, (ii) Dual Connectivity (DC), and (iii) Standalone. In both CA and DC deployment modes, the unlicensed bands support the amplification of the user-plane capacity in DL. In dual connectivity mode, NR-U supports Uplink (UL) in addition to the DL. CA deployment mode is built on LTE-LAA, whereas the DC deployment mode is based on the extended LAA (eLAA) [8]. In either deployment mode, the control-plane data resides over the licensed bands. The standalone mode relies independently on the unlicensed spectrum for control and user plane operations. It will lead to an open 5G network to eliminate dependencies on the licensed mobile network operators (MNOs). NR-U is foreseen to bring new opportunities to enhance spectral efficiency with its underlying enhancements. Table I shows globally available and under-review unlicensed spectrum bands based on Release 16 [7, 9].

Table 1. Unlicensed Spectrum Bands in 3GPP [9]

Countries	1-7 GHz Mid-Bands (sub 7GHz)	Status	24+ GHz High-Bands (mmWave)	Status
United States	5.2 – 5.8 GHz	Available Now	57 – 71 GHz	Under Study/ Review
	5.9 – 7.1 GHz	Available Now		
Canada	5.2 – 5.8 GHz	Available Now	57 – 71 GHz	Under Study/ Review
European Union (except Germany, France & Italy)	5.2 – 5.9 GHz	Available Now	57 – 71 GHz	Under Study/ Review
	5.9 – 6.4 GHz	Under Study/ Review		
United Kingdom	5.2 – 5.9 GHz	Available Now	57 – 71 GHz	Under Study/ Review
	5.9 – 6.4 GHz	Available Now		
Germany	5.2 – 5.7 GHz	Available Now	57 – 71 GHz	Under Study/ Review
France	5.2 – 5.7 GHz	Available Now	57 – 71 GHz	Under Study/ Review
Italy	5.2 – 5.7 GHz	Available Now	57 – 71 GHz	Under Study/ Review
China	5.2 – 5.3 GHz	Available Now	59 – 71 GHz	Under Study/ Review
	5.7 – 5.8 GHz	Available Now		
South Korea	5.7 – 5.8 GHz	Available Now	57 – 64 GHz	Under Study/ Review
	5.9 – 7.1 GHz	Under Study/ Review		
Japan	5.7 – 5.8 GHz	Available Now	57 – 64 GHz	Under Study/ Review
India	5.2 – 5.5 GHz	Available Now	57 – 66 GHz	Under Study/ Review
	5.7 – 5.9 GHz	Available Now		
Australia	5.2 – 5.8 GHz	Available Now	57 – 66 GHz	Under Study/ Review

Carrier Aggregation in Heterogeneous Networks

CA and Heterogeneous networks (HetNets) are two distinct features of the beyond 5G cellular networks [10]. The Small Cell (SC) deployment in HetNets is advantageous for data offloading, coverage, and improved cell edge spectral efficiency. CA facilitates increased transmission bandwidth and capacity by scheduling the multiple Component Carriers (CC) on the physical layer [11]. The general realization of CA is facilitated by the addition and removal of a secondary CC without interrupting resource allocation. The resources are available to the users from SCs within the macrocell topology. Fronthaul network connects the Remote Radio Heads (RRHs) to the Baseband Unit (BBU), the same as the Macro and Small Cell. Figure 3 illustrates the conventional CA deployment in the same macrocell site.

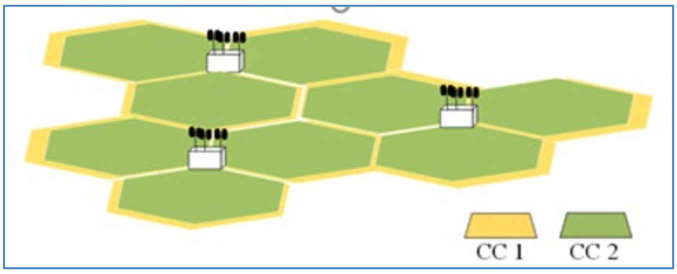

Figure 3. Carrier Aggregation Deployment in the same Macrocell

Enormous traffic and connection requests are eminent in dense heterogeneous networks with SCs, making the establishment of multimedia sessions critical. CA offers a great solution in such scenarios by facilitating SC deployments inside macrocells. The evolved NodeB (eNBs) offloaded high traffic on the small cells with CA. Figure 4 illustrates the CA deployment between macro and small cells.

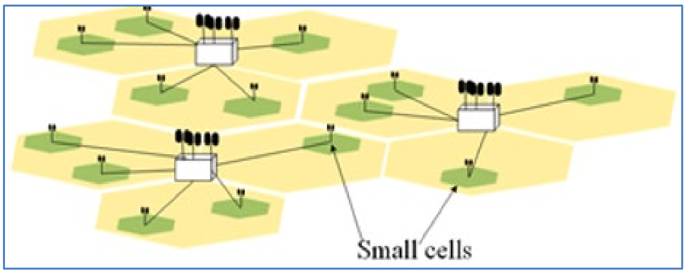

Figure 4. Carrier Aggregation Deployment between Macrocell and Small Cell.

Next Generation NodeB (gNBs) deployments by the Mobile Network Operators (MNOs) ensure better services by increasing the system capacity. Small cells enable flexible deployments while ensuring affordability in price and enhanced energy and spectral efficiency. SC technologies integrate multiple radio access (CA) technologies to increase the coverage capacity and service availability. CA-enabled SC deployments exploit lesser physical space than the macro cell deployments [12]. The deployment of small cells with carrier aggregation within the macro cell becomes a viable and economical solution to improve the performance of the entire 5G NR network.

Cell Dormancy

3GPP Release 16 introduced the concept of small cell dormancy, which improves the power consumption in CA-enabled scenarios. The considered dormant cell device stops monitoring the physical downlink control channel while keeping the channel state information measurements and beam management [13]. This method did not consider the dormant cell deactivated, but comparatively, fewer activities save power. For power saving, deactivation is also another possibility. With deactivation, it does not provide the channel state information reports. Also, the small cell reactivation takes longer than returning from dormancy [14].

4. Resource Management and Scheduling Techniques

Cross-Carrier Scheduling

In CA-enabled scenarios, the UE is served by more than one CCs either from the same or different macro/small cells. The resources are scheduled based on the Scheduling Grants (SG) and the Scheduling Assignments (SA) corresponding to the data. The scheduler decides for each carrier and transmits individual SAs. Thus, a device receives multiple Physical Downlink Control Channels (PDCCHs). Scheduling is called “Self-Scheduling” when the SG and SA are transmitted on the same cell as the data, and it is known as Cross-Carrier Scheduling (CCS) when SG and SA are transmitted on different cells than the data. For CCS, the Downlink Control Information (DCI) accommodating the SG for a carrier is received on a different carrier [15]. CCS was initially introduced in 3GPP Release 10 [16] with a carrier indicator field (CIF) limited to 3 bits to support aggregation of up to 5 CCs. When a UE is in search mode, the CIF value affects the DL control channel and defines the carrier for SG. In the primary cell (PC) configuration, CIF-Presence-r10 indicates the availability of CIF in PDCCH DCI. A CIF value of 0 indicates PC, while another indicates the secondary cells (SCs). To support 32 CCs enhancements for CA with the latest 3GPP releases [1], the CIF length increased from 3 to 5 bits.

Packet Scheduling Schemes

Packet Scheduling Algorithms (PCA) hold utmost importance in Radio Resource Management as they indicate how transmission occurs. Figure 5 illustrates the classification taxonomy of packet scheduling schemes. An efficient PCA in a CA environment has the following requirements [17];

- Tolerant to the multi-CCs environment,
- High QoS,
- High system throughput,
- Optimized fairness,
- Low complexity.

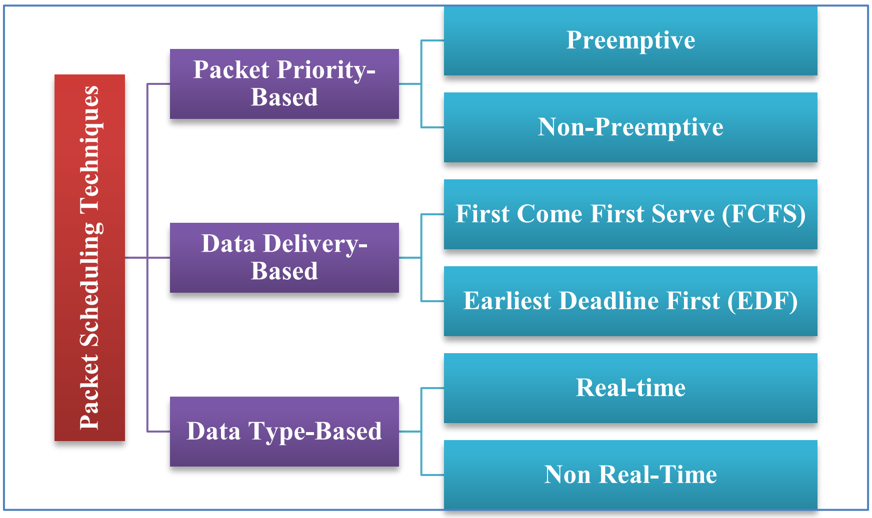

Figure 5. Classification Taxonomy for Packet Scheduling Schemes.

In [18], the authors have proposed an improved Proportional Fair (PF) scheduling algorithm for a multi-carrier system. A novel Carrier Weight Factor (CWF) is used to limit the usage accessibility of the CCs. CWF defines the carrier coverage weight factor and the user category weight factor. In [19], the authors have addressed the resource scheduling with CA and demonstrated enhanced spectral efficiency and reduced energy consumption. They used a discontinuous reception mechanism from LTE-LAA, allowing UEs to go to sleep when inactive and addressed CCs scheduling mechanisms to minimize the wake-up time. In [20], authors have proposed multi-band scheduling strategies to optimize RBs distribution in the multiple CCs environment with strict QoS constraints. The implementation is demonstrated using the LTE-Simframework and proposed migration to the 5G framework (5G-Air-simulator).

Scheduler Structure for CA

To allocate resource blocks (RBs) in CA, the eNB requests UE for the carrier specifications, including QoS. eNB takes calls for carrier activators and PC assignments for the UE and indicates through the PDCCH signals for fixed time slots. Delay is observed in the case of larger time slots. Thus, the scheduler response time is critical in CA systems to manage delay and throughput trade-offs with the UE [21]. In [21, 22], the authors have explained the following two structures for the schedulers to optimize the time slot to enhance the QoS at the UE.

a) *Disjoint Queue Scheduler*: In DQS, individual users have independent traffic queues on each CCs. Therefore, this scheduler operates in a two-step model to allocate the RBs. At the first level, the scheduler allocates the traffic packets on each CC and waits for their turn to transmit. Then, at the second level, schedulers present at each CC allocate the RBs and map the packets to the user. The schedulers at both levels can use the same or separate scheduling algorithms. However, this approach offers little efficiency and high complexity with large packets as the user packet, CC, and the associated RBs are mapped one-to-one.

b) *Joint Queue Scheduler*: In JQS, the users have a shared/joint queue to access the CCs, resulting in a single-layer scheduling platform. The scheduler allocates the traffic packets to all the CCs with the RBs. Thus, the user packet uses all the available RBs on different CCs. This scheduling structure offers higher efficiency and a higher frequency selective gain than the DQS, as the mapping is one-to-many but not successful with high traffic densities. In addition, together with a priority-based scheduling scheme, JQS can mitigate long waiting queues.

Intelligent Spectrum Management

Spectrum sharing allows for cooperative use or the simultaneous use of the radio under-utilized statically assigned frequency spectrum resource [23] by several independent entities in a particular geographical area. Multi-tier spectrum sharing by using Licensed Shared Access (LSA) [24] can help in the effective utilization of the white spaces or the under-utilized parts of the spectrum. To achieve a scaling effect for these techniques, it has been shown by the Spectrum Collaboration Challenge (SC2), in [10], that Collaborative Intelligent Radio Networks (CIRNs) and Artificial Intelligence (Al)-based autonomous wireless radio technologies that exchange explicit information to solve joint problems, via collaboration, can efficiently share and reuse spectrum without coordination and with the guarantee of incumbent protection [23].

Application Machine Learning and Artificial Intelligence

The exponentially growing demand for connectivity is raising concerns about massive operations and maintenance requirements. Machine Learning (ML) and Artificial Intelligence (AI) applications at various levels of the network can provide scalable and flexible solutions to manage complex generations of communication. For instance, AI can identify patterns in enormous datasets and thus can significantly reduce the prediction and decision time for processing tasks. In addition, AI can administer MNOs in determining demand and reconfiguring the network. In CA-enabled networks application of ML algorithms can determine the CCs to select based on the available spectrums. Moreover, it guarantees fairness in selecting the carriers from both available licensed and unlicensed spectrums [25].

5. Open Research Issues

Efficient and intelligent future frequency spectrum usage will need to be addressed far beyond 5G [26]. The mobile communication sector is requesting more and more spectrum to accommodate higher traffic volumes and more demanding quality of service requirements. Traditionally, greater throughput was mainly obtained by increasing the available spectrum bandwidth and deploying more infrastructure. Providing greater throughput without wasting precious spectrum requires more complex radio spectrum management. AI-based spectrum management solutions have not been fully exploited since [27]. Future mobile and wireless networks will comprise heterogeneous, small cells overlaid with macro and microcells. Flying UAVs acting as relays are also of great interest beyond 5G ecosystems and studies on the resulting cost/revenue trade-off and business plans [28]. The cost-benefit trade-off of considering different splits, making Remote Radio Heads cheaper while moving high PHY layer software functionalities to the edge of the Cloud-RAN and considering different types of heterogeneous networks with small cells (or even cell-free mobile networks) needs to be analyzed. One relevant approach is proposed in [29], where the authors compare the results for the cost reduction versus coverage-QoS trade-off in a heterogeneous deployment with Macro-RRHs (MRRHs) and Small-RRHs (SRRHs) between the 3.6 GHz and 28 GHz, i.e., they explore energy and cost reduction through variation of the number of active Remote Radio Heads or Units (RRHs) needed according to traffic demands. Different solutions based on intelligent interference management (or avoidance), evolved multi-band scheduling (on top of packet scheduling to manage radio resources), big data and machine learning strategies may be investigated. Both sub-6 GHz bands and the future use of mmWaves needed to be investigated [29], [30].

6. Conclusions

In this paper, we have presented CA techniques and enhancements concerning the latest 3GPP releases on enhancements. Different scheduling techniques have been discussed. CA enabled 5G networks have been discussed in detail with various opportunities in licensed, unlicensed spectrum bands, mmWave bands, and HetNets. The structure for the schedulers has been discussed in detail as well. Finally, we have presented an overview of the CA scheduling techniques and introduced the scope of AI/ML in-network sensing and management aspects. Extensive simulations will be performed in the near future to evaluate the basic limits for system capacity and service quality bounds in heterogeneous networks with indoor and outdoor picocells. Further, we intend to focus on various access schemes like CP-OFDM and DFT-Spread (DFT-S) OFDM for both UL and DL and analyze resource allocation concerning CA.

7. Acknowledgements

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