Overview of 5G New Radio and Carrier Aggregation: 5G and Beyond Networks

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Abstract—Recent pandemic has affected the telecom industries with the need for connectivity more than before. It has accelerated the research and innovation activities towards 5G and beyond networks. The purpose of the presented work is to provide the urgency of the situation and state the development with the 5G NR (New Radio). 3GPP launched the standardization activity for 5G system in Release 15, 5G New Radio (NR). This paper presents a comprehensive overview of the development of NR, including deployment scenarios, numerologies, frame structure, new waveform and enhanced carrier aggregation (CA). Since coverage and capacity are the key elements of an optimal 5G user experience. Carrier aggregation is visualized as critical for 5G and upcoming networks. It enhances data capacity by aggregating carriers from same/different spectrum bands. Release 10 introduced carrier aggregation and in LTE-Advance, up to five component carriers can be aggregated but commercial solutions use up to three component carriers providing a maximum downlink speed of up to 450Mbps. This paper provides an overview of carrier aggregation, its needs and set of potential solutions and research scope to mitigate the foreseen challenges with CA.

Keywords— 5G NR, Carrier Aggregation, LTE-Advance

I. INTRODUCTION

A. Societal Impact on Telecom Industry

The year 2020 has affected every genre of lives. Drastic transitions have been observed at the personal and professional levels. The demand for ubiquitous connectivity has witnessed a quantitative transition, as people tend to be online more than before. There is a shift of mobile data traffic from commercial areas, offices, etc. to residential areas by virtue of lockdowns. New pandemic lifestyle has triggered work-from-home culture in the majority of sectors including education, trading, software industries, conferences, webinars, etc. resulting in intensified demand for connectivity in both fixed and mobile networks.

The intensified data usage is directly proportional to the rise in services like work-based applications, virtual networks, video conferencing, entertainment apps, social media uptime, etc. These services also demand a high quality of service with minimum latency. Ericsson's Mobility Report 2020 [2] suggested that the mobile data traffic displayed an uneven distribution pattern and an increase ranging from 20-70 per cent in the voice calls activities during the initial lockdown phase. The fixed residential networks are experiencing high mobile data traffic while the usual hotspots have shown decreased or negative mobile traffic records.

This extensive transition worldwide has created a huge growth in mobile network traffic. Measures are taken to support the unusual growth and it has accelerated the need for

5G and beyond network deployment. Ensuring connectivity while maintaining QoS are the main aim of the telecom industries. To have a control of the situation, it has become utmost priority to connect health cares, hospitals, running businesses, education, etc. As per the survey made by [2], 83% asserted the Information and Communication Technologies (ICT) have been essential to cope up with daily activities.

Figure 1 Transition in Mobile Network Traffic in central Paris two weeks before (a) and after (b) lockdown [2]

Most of the consumers have raised concerns in the degraded service and performance. Many telecom giants have already responded to the new societal standards like Vodafone, Proximus, Telenor, Telefonica, Orange, etc. [3].

Therefore, telecom giants have escalated the initiatives to bridge the gaps in connectivity. The research and innovation activities are getting intense towards 5G deployment and technologies to support beyond 5G era.

B. 5G Network Expectations

The need for 5G Network is more now than before to match up the demand to maintain the new lifestyles. [2] Suggests that consumers rely on the upcoming solutions for better network coverage, reduced latency and higher speeds compared to current 4G networks. New use cases evolved where 5G enabled robots can serve as medical assistants. The constructive consequence of this pandemic is demand for 5G to replace the legacy broadband infrastructure.

5G system was designed to meet IMT-2020 requirements set by the ITU-R [5]. 5G will provide more advanced and enhanced capabilities compared to 4G LTE (IMT-Advanced). Table 1, summarizes the 5G requirements. 5G targets a 20x peak data rate, 10x lower latency and 3x spectral efficiency than existing 4G LTE systems. The full-fledged 5G network rollout is awaited to exploit undisrupted services. Some of the 5G expectations are [2]; Autonomous Vehicles (such as AR/VR assistance, Infotainment, AR Dashboards), Resilient Networks, Remote healthcare (such as Ambulance Drones,

Smart Equipment), Enhanced Augmented and virtual reality (AR/VR) applications (Technical Assistants), Green and Cost-Efficient Network [4], Financial Services, Agricultural Innovations (such as Predictive Maintenance, Autonomous Harvesting), Media and Entertainment (such as High-quality streaming, 3D broadcast), Manufacturing (such as Cloud Robotics, Goods Tracking), etc.

To have a mature 5G connectivity, we are still lagging on the technology and the required 5G hardware. In this paper, we are presenting an overview of Carrier Aggregation as one of the prominent technologies to achieve high network throughput and spectral efficiency. This paper is organized into the following sections; Section I is the introduction, which comprehensively explains the current scenario and 5G requirements. Section II defines the 5G New Radio and Spectrum. Section III describes briefly Carrier Aggregation and its benefits. It also describes LTE-CA. Section IV drafts the scope of CA for 5G and beyond networks and Open challenges.

Table 1: Key performance requirements of IMT-2020

Requirement		Value
Data Rate	Peak	DL: 20Gbps UL: 10Gbps
	User Experienced	DL: 100Mbps UL: 50Mbps
Spectral Efficiency	Peak	DL: 30bit/s/Hz UL: 15bit/s/Hz
	Average	DL: 3.3 ~ 9 bit/s/Hz UL: 1.6 ~ 6.75 bit/s/Hz
Area Traffic Capacity		10 Mbps/m ²
Latency	User Plane	1 -4ms
	Control Plane	20ms
Connection Density		1,000,000 device/km ²
Reliability		1-10 ⁻⁵ success probability
Mobility		0km/hr ~ 500 km/hr
Mobility Interruption Time		0ms
Bandwidth		100 MHz

II. 5G NEW RADIO AND SPECTRUM

3GPP is responsible for defining a new 5G core network (5GC) and a new radio access technology (5G “New Radio”). 3GPP Release 15 [6] introduced 5G New Radio (NR) in 2018 as the global standard for the air interface. 5G NR has following deployment modes [7];

- **Standalone Mode:** In this deployment, User Equipment (UE) operated by 5G Radio Access Technology without any requirement 4G LTE RAT. NR gNB acts as the master node and offers service in both control and user planes.
- **Non-Standalone Mode:** It combines multiple RAT. In this mode, both LTE and 5G cell connections are required. LTE/LTE-A eNB will be the master node and act as the anchor carrier i.e. all the control plane will be with eNB and gNB will serve the user plane.

3GPP Releases 16 [8] and 17 [9] demonstrated new enhancements of 5G NR which includes existing features and new deployment verticals. The carrier frequencies are increased to achieve higher data rates and to accommodate more spectrum needs. [10] For 5G NR deployment with existing LTE/LTE-Advance networks with same or different coverage, it is important to consider backward compatibility. The feasible deployment scenarios are considered based on the Master Node selection.

A. 5G NR Design Specifications

5G NR is designed specifically to co-exist with the LTE to utilize existing cellular structure and enhances overall network performance by reduced interference, low latency, usage of beamforming and multiple antennae.

The significant enhancements in 5G NR features are [8] as follows:

- Multiple-Input, Multiple-Output (MIMO) and Beamforming Enhancements
- Dynamic Spectrum Sharing (DSS)
- Dual Connectivity (DC) and Carrier Aggregation (CA)
- User Equipment (UE) Power Saving

The new verticals and deployment scenarios from Release 16 are mostly as follows:

- Integrated Access and Backhaul (IAB)
- NR in Unlicensed Spectrum
- Industrial Internet of Things (IIoT)
- Ultra-Reliable Low Latency Communication (URLLC)
- Intelligent Transportation Systems (ITS)
- Vehicle-to-Anything Communications Positioning. (V2X)

3GPP releases [7][8][9] eventually introduced the new features called, enhanced mobile broadband (eMBB), URLLC and massive machine-type communications (mMTC). These new services offer urgent data delivery with ultra-low latency and massive packet transmissions are of crucial importance for NR. eMBB describes the category for bandwidth-keen applications. such as high-definition telepresence, telemedicine and remote surgery and supports high capacity and high mobility radio access. URLLC describes mission-critical services such as autonomous vehicles, healthcare, and industrial automation. These applications strikes for Low-Latency, String-Security and Ultra-Reliability. mMTC

describes the fast-growing, high-volume, dense IoT nodes/applications. Smart Metering, Smart Buildings, Smart Cities and Asset Tracking are some of them. These are mainly applications with Low-Power, Low-Cost, and Low-Complexity.

Integration of the above mentioned features and to optimize network performance, an efficient Resource Management algorithm is required [10]. This also requires a ready model with concrete deployment scenario, frame structure, access technologies and enhanced Carrier Aggregation schemes (discussed in following sections).

B. 5G NR Frequency Bands

5G NR frequency bands are categorized into two different ranges, namely Frequency Range 1 (FR1) and Frequency Range 2 (FR2). The 5G frequency bands are mainly sub 6GHz and mmWave bands. Sub 6 GHz is used for long-range while mmWave bands are suitable for short-range. 3GPP TS 38.101 [8] provides a list of frequencies of the 5G NR standard. FR1 includes sub-6GHz frequency bands has been extended to cover potential new spectrum offerings from 410 MHz to 7125 MHz. FR2 includes frequency bands from 24.25 GHz to 52.6 GHz.

Since we know, the spectrum is the scarce resource so have available spectrum, unlicensed frequency bands are being exploited [8]. The NR operations in unlicensed spectrum target the 5GHz and 6GHz unlicensed bands. It supports both standalone operation and licensed-assisted operation in NR Standalone.

C. NR Numerology, Waveforms and Frame Structure

In comparison with LTE subcarrier spacing, 15kHz, NR supports multiple subcarrier spacing summarized in table 2 [11]. This support to multiple types of sub-carrier spacing in NR distinguishes it from LTE.

In 5G NR, each numerology is labelled as a μ and $\mu = 0$ represents 15 kHz similar to that in LTE. And in the second column, the subcarrier spacing of other μ is derived from ($\mu = 0$ and scales up to the power of 2).

Table 2 Types of NR Numerology

μ	$\Delta f = 2^\mu \cdot 15[\text{kHz}]$	Cyclic Prefix (CP)
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

The slot length inversely proportional to the numerology, wider the subcarrier spacing- shorter the slot length as explained in Table 3[11] [12].

Table 3 NR Slot Lengths

μ	$N_{\text{slot}}^{\text{sym}}$	$N_{\text{slot}}^{\text{frame}, \mu}$	$N_{\text{slot}}^{\text{subframe}, \mu}$
0	14	10	1
1	14	20	2
2	14	40	4

3	14	80	8
4	14	160	16

According to TR 38.802 [12] and TR 38.804 [13], the maximum channel bandwidth per NR carrier is 400 Mhz in Release 15 [7]. In NR, transmitters and receivers have a wider bandwidth at high-frequency bands. The high carrier frequencies and a large subcarrier spacing are exposed to the Doppler Effect and inter-carrier interference (ICI) respectively.

The sub-frame length of NT is 1ms, which consist of 14 OFDM symbols, each 15kHz subcarrier spacing and normal Cyclic Prefix (CP). Each slot can carry control signals at the start and/or end OFDM symbol and enable gNB to allocate resources for emergency services under URLLC applications. The TDD scheme in NR is more flexible than that in LTE. NR adopts mini-slots to support small size packet transmissions with similar features.

The frame length is composed of 12 subcarriers in frequency domain capable of basic scheduling supporting same subcarrier spacing and prefix.

For considering waveforms for NR, many schemes were investigated like filterbank multicarrier (FBMC), generalized frequency-division multiplexing (GFDM), etc. over key characteristics like enhanced bandwidth, increased efficiency in terms of power and spectrum, reduced interference, etc. OFDM based new waveform makes one of the potentials for NR because of its easy and flexible design.

III. CARRIER AGGREGATION AND 5G NR

Carrier Aggregation is the technology to enhance the data capacity, throughput, data rates and improved network performance in the uplink, downlink, or both. It allows efficient spectrum utilization by combining two or more carriers in the same or different frequency bands, into a single aggregated channel [13][15]. It enables aggregation of FDD and TDD and licensed and unlicensed carrier spectrums. Carriers can be aggregated in three ways as illustrated in Figure 2:

- Intra Band Contiguous CA: It is a rare scenario with given frequency allocations today but can be possible with new spectrum bands like 3.5 GHz and so. This aggregation is the simplest in terms of hardware implementation. The contiguous channels are of the same size and in the same spectrum band.
- Intra Band Non- Contiguous CA: It is expected in countries where spectrum allocation is noncontiguous within a single band, when the middle carriers are loaded with other users, or when network sharing is

Figure 2 Carrier Aggregation

considered. The non-contiguous channels are of different sizes within the same spectrum bands.

- **Inter Band Non- Contiguous CA:** It is the most realistic scenario since there is no contiguous wide spectrum to achieve the IMT-Advanced peak data rate. The channels are of the same size in different spectrum bands.

Carrier aggregation was introduced in Release 10 as a new feature to combine different component carriers to increase overall bandwidth and throughput. It played an important role to provide operators flexibility for making the best use of available spectrum. 44 frequency bands are available providing 700 MHz -2.7 GHz theoretically that can be aggregated, but commercial solutions can use up to three component carriers with an achieved downlink speed of up to 450Mbps.

Carrier aggregation technology is critical to allow coexistence of 4G and 5G by allowing operators to combine different 4G carriers with 4G carriers or with 5G carriers. The LTE-A standard specifies that each of the component carriers (CCs) is limited to 20 MHz of bandwidth and aggregation of up to five allows a maximum of 100 MHz of total signal bandwidth which gives a fivefold increase in channel capacity and data speed [14].

A. Cross Carrier Scheduling

Cross-carrier scheduling is an important feature in HetNets to mitigate the issues of inter-cell interference at cell-edge. It can be used to balance the traffic loads and scheduling across different component carriers [15][16][17].

B. Dynamic Spectrum Sharing

DSS provides a cost-effective and efficient solution for enabling a smooth transition from 4G to 5G by allowing LTE and NR to share the same carrier. 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 [15].

C. Dual Connectivity and Carrier Aggregation

Release 16 reduces latency for setup and activation of CA/DC, thereby leading to improved system capacity and the ability to achieve higher data rates. Unlike release 15, where measurement configuration and reporting does not take place until the UE enters 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 [1][7]. According to TR 38.802 [12], the following points are the highlights:

- Maximum number of Carrier Aggregation / Dual Carrier is 16
- Maximum aggregated bandwidth in phase 1 is around 1 GHz (contiguous or non-contiguous)
- Cross-carrier scheduling and joint UCI feedback is supported
- Per-carrier TB mapping is supported

D. Benefits of Carrier Aggregation

- Efficient use of available spectrum and leveraging of the underutilized spectrum.

- It allows MNOs to efficiently utilize the fragmented frequency resource.
- **Network carrier load balancing:** Enables intelligent and dynamic load balancing with real-time network load data.
- CA helps in the aggregation of frequencies irrespective of spectrum regulations. It can aggregate licensed, unlicensed as well as perform aggregation in shared spectrum scenario.
- Increased uplink and downlink data rates with better network performance and higher throughput.
- The expanded coverage allows carriers to scale the networks resulting in enhanced scalability.

IV. CHALLENGES

A. Downlink CA challenges include:

- **Downlink sensitivity:** For designing a duplexer for each CC, interference between uplink and downlink at the reception at downlink needs to be considered. With large frequency separations between two bands, either a separate duplexer/duplexer or a multiplexers/hexiplexers can be used. However, a multiplexer is more challenging to develop as increases PC board area while simplifying the RF frontend.
- **Harmonic generation:** Non-linear components like transceiver output stages, power amplifiers (PAs), duplexers, etc. results in Harmonics. Design developments should consider device performance against the reduced harmonic generation.
- **De-sense challenges in CA radio design:** Limited filter attenuation causes Multiband radio signals to interfere with each other resulting into a higher probability of desense in CA applications if isolation or cross-isolation between the transmit and receive paths.

B. Uplink Challenges

To reduce maximum power as the Intra-band uplink CA signals uses more bandwidth and have higher peak-to-average-power ratios (PAPRs) than standard LTE signals. 3GPP allows for different Maximum Power Reductions (MPRs) to be applied based on different configurations of RBs. Because of higher peaks, more signal bandwidth, and new RB configurations, a Power Amplifier design needs proper tuning for very high linearity.

C. Implementation Challenges

The hardware implementation along with resource allocation is critical in CA [18]. There are crucial requirements like signal processing capabilities, Radio Frequency (RF) chains, oscillators, strong battery life, etc. From the RF context, CA-FDD implementation is more challenging.

The mobile network operators (MNOs) have fragmented frequency resource and with CA implementation this will result in coexistence of multi-operator networks placed closely [19]. The transmitter and receiver design considerations are critical to reducing the interference caused due to the undesired transmitter emissions and the cross-

isolation issues as UEs communicate on multiple bands simultaneously.

V. POTENTIAL SOLUTIONS AND OPEN RESEARCH AREAS

A. Receiver and Transmitter Design Considerations

Multiplexers and RF Filters: To provide faster data rates using available spectrum chunks, the number of aggregated carriers will increase and so the simultaneous transmission within UEs. The consequences with the increased transmission in UEs leads to critical issues concerning the number of antennae, RF filtering techniques, multiplexers, quadplexers, etc. [18] [19] Multiplexers provide isolation to the aggregated carriers, simultaneous with low insertion loss and low current consumption. It also provides in-band and cross-isolation. RF filter design consideration needs to be mapped accordingly to meet the required quality of performance. The bulk acoustic wave (BAW) and temperature compensated-surface acoustic wave (TC-SAW) filters [18] needs proper matching.

Guard Band Setting: Even though in non-contiguous CA, sufficient amount of frequencies are used as a guard band to avoid interference but it still remain open to interference caused by adjacent carriers of other systems. In the case of high mobility, orthogonality of adjacent carriers will be affected by a large Doppler shift [20]. Therefore, the guard band setting for a component carrier is critical for CA irrespective of the type to have high spectral efficiency.

B. Resource Allocation and Scheduling Techniques

Sleep Time: Sleep Control is elementary in HetNets in terms of having reduced power consumption and high QoS. It has been investigated as a mean for QoS provision but limited research is done so far for CA operations [23]. Sleep awareness management for CA Operations can benefit from developing energy-efficient networks with improved performance.

Power Allocation: Optimization through joint resource allocation and relay-based component carrier selection can boost system performance and interference mitigation [20] [23]. For Uplink (UL) communication, the main constraint is the transmission power. Bandwidth enhancement is not effective if the user device reaches its maximum transmission power. Increase in peak-to-average power ratio (PAPR) is critical with multiple simultaneous transmissions as it reduces UE transmission power. This makes it challenging for users to allocate multiple component carriers with a power limitation, especially in unfavourable channel conditions. Adequate component carrier selection schemes in uplink can enhance system performance.

Cross Carrier Scheduling: Cross carrier scheduling techniques are effective in handling intercell interference (ICI). ICI is a major issue with users at cell-edge [22]. Physical Downlink Carrier Channel (PDCCH) requires more transmit power than the traffic channel. With this scheduling technique, the component carriers are divided into primary and secondary to offer service to the primary cell and the secondary cell respectively.

Packet Scheduling: Packet scheduling and component carrier assignment are significant CA functionality for downlink transmission. A large amount of overhead is caused because of uplink signalling transmissions which make packet scheduling and channel awareness characteristics important.

This scheduling prioritises user with good channel state for allocating resources. It uses the multiuser frequency domain scheduling diversity. The prominent requirement for packet scheduler design is to handle multiple component carrier environments.

VI. CONCLUSIONS

CA is significantly used to achieve high spectral efficiency by utilizing the fragmented frequency resources by MNOs. The enhancements in the 3GPP's releases 16 and 17, CA is an eminent technology for upcoming networks. It contributes to a wide range of applications and use-cases. With recent enhancements, CA can aggregate up to sixteen component carriers can be aggregated to achieve a bandwidth up to 1GHz because of the latest enhancement in 5G NR specifications. CA comes as a solution scarcity of available spectrum, it has its critical implementation challenges. The complex filter designs, the importance of Multiplexers to different crucial considerations from RRM perspective like power allocation and resource block scheduling will open a new research area and the market for future networks.

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