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Injecting cognitive intelligence into beyond-5G networks: A MAC layer perspective[☆,☆☆]

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ABSTRACT

The rapid rise of heterogeneous data traffic exposes the shortcomings of fifth-generation (5G) technology, which was initially designed to form self-organizing and self-sustaining networks to facilitate the adoption of the Internet-of-Everything (IoE). This study presents the applications and service requirements of future communication networks. This study details flexible design agreements of the Medium Access Control (MAC) layer of Beyond-5G (B5G) from the current 3rd Generation Partnership (3GPP) study and highlights the current open research issues and challenges which are yet to be optimized. To ensure that the network is self-sustaining and self-organized for B5G paradigm, an intelligent network design is required. Artificial Intelligence (AI) is revolutionizing every aspect of life, therefore, this article provides an overview of how AI plays an important role in improving future-generation communication by solving MAC-related issues.

1. Introduction

The Internet-of-Everything (IoE) is shifting the focus from high-data rate services like the enhanced mobile broadband (eMBB) and massive machine-type-communication (mMTC) to delay-centric ultra-reliable low latency communication (URLLC). With a $1000x$ increase in data rate and network capacity, the fifth-generation (5G) of mobile communications was projected to be the major enabler for IoE. Release 15 of the new radio (NR), which only utilizes millimeter wave ($(\mathrm{mm}Wave$) frequencies -a real IoE carrier that has not yet been attained, has been standardized as a result of the 3GPP's development of 5G [1]. But most 5G variants throughout the world continue to operate at sub-GHz frequencies. The goal of creating a self-sustaining and self-organized network (SSN/SON) has so far remained a mirage, and these ambitions have been transferred upward to B5G networks, even if 5G networks readily enable URLLC services.

The services of URLLC, which include anything from tele-medicine to autonomous flying cars, are all designated by the International Telecommunication Union (ITU) as having dependability requirements of at least 10^{-7} packet error rate and radio

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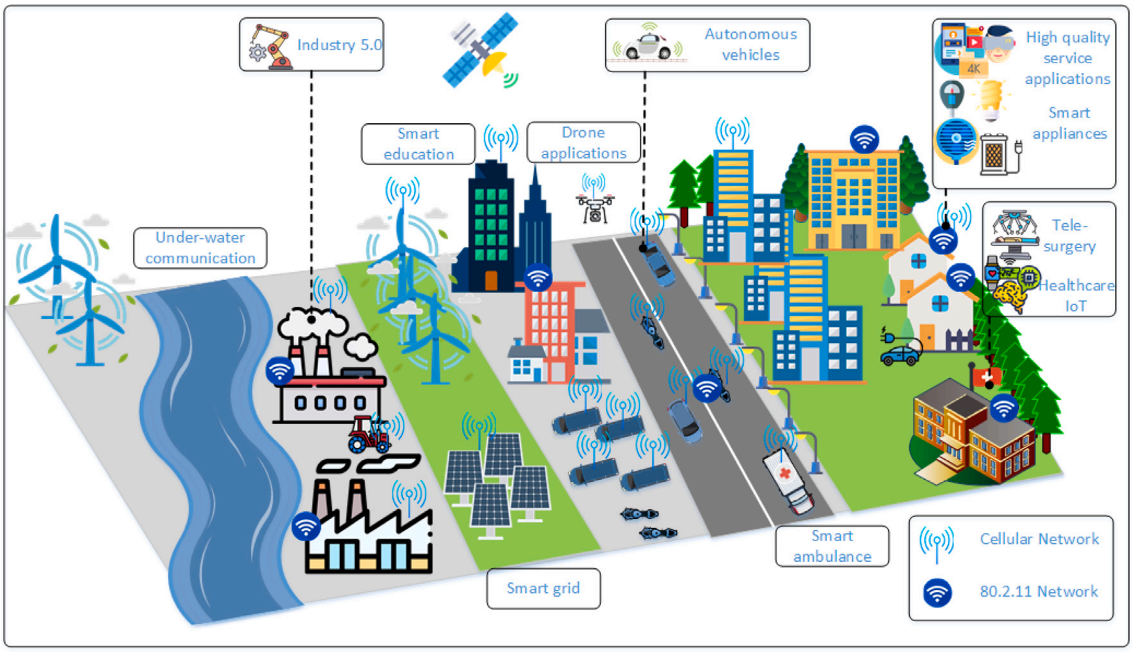


Fig. 1. Future generation communication model of a smart city.

interface delay as low as 1 ms. On the other hand, eMBB services, include high-resolution videos and extended reality (augmented, mixed, and virtual) with huge data packets that necessitate high data speeds. The mMTC services include a significant number of Internet of Things (IoT) device deployments that need increased network capacity. The purpose of 5G is to offer short-packet URLLC services, however, having various applications coexist in a network transmission causes disruptions. To support for IoE requires the 5G and B5G networks to be capable supporting data traffic from heterogeneous (Het) devices with high reliability, low-latency, and high-data rates in uplink and downlink direction. Development of SSN/SON and the coexistence of Het devices for IoEs is a developing research area. To comply with the strict delay and reliability requirements in Het data traffic, Release 15 of 3GPP specifications introduced flexible frame structure and scalable numerology. This results in transmission time interval (TTI) reduction with a variable number of orthogonal frequency-division multiplexing (OFDM) symbols. NR also provides scalable sub-carrier spacing (SCS). Increasing the SCS lowers the TTI and, as a result, increases network capacity by supporting a larger number of users simultaneously.

However, these flexibilities bring challenges and present open research issues for the research community. This article presents open research issues and challenges related to the medium access control (MAC) layer and provides insights and prospective solutions for the problems.

Machines can emulate the intelligence of the human brain thanks to artificial intelligence (AI). Natural language processing, knowledge-based judgments, and perception are examples of AI capabilities. AI is a subset of ML. Without any explicit programming, ML is the generalized AI approach that can learn from structured and unstructured data given by information technology. Recent advances in hardware processing have enabled researchers to make use of machine learning (ML) in wireless communications, particularly in 5G networks. Computer vision, image processing, parallel and distributed processing, analytics, and prediction are all made possible by ML, which imitates the functioning of the human brain. Few MAC concerns include resource allocation, channel access, and radio resource management, for which real-time network optimization based on ML algorithms may be performed with minimal complexity. The issue statement guides the selection of an ML algorithm, which is based on the problem's knowledge. As a result, it divides ML into three categories: supervised, unsupervised, and reinforcement learning. The role of AI in the transition of future communication networks will be important. Indeed, we are in the center of a perfect storm fueled by advances in hardware, storage, and software. While promising, the application of AI in wireless communication, particularly cellular communication, is still in its early phases.

Motivation: The challenges and open issues in future-generation communications are caused mainly due to the flexible MAC layer structure, operability, and scalability over a wide range of frequency bands. Furthermore, future-generation communication must support coexistence with other enabling technologies specifically IEEE 802.11 ax, ay, and upcoming future standards, operating simultaneously on the same or other frequency bands. Therefore, there exist underlying challenges. This article highlights the open research issues and challenges in the MAC layer for future-generation networks.

Article Structure: The rest of the article is organized as follows: Section 2 presents in detail the applications and service requirements in next-generation communication systems. Section 3 describes in detail the flexible frame structure and the effect of scalable

Table 1
Survey papers discussing the MAC layer of NR.

Ref.	Year	B5G Applications	B5G Service Requirements	NR Frame Structure	Open Research Issue in NR	AI based Solutions
[1]	2021	✓	x	✓	x	x
[2]	2021	x	x	x	x	x
[3]	2021	x	x	x	x	x
[4]	2021	✓	x	✓	x	x
[5]	2020	x	x	x	x	x
[6]	2020	x	✓	x	x	x
[7]	2019	x	x	x	x	x
This Work	2021	✓	✓	✓	✓	✓

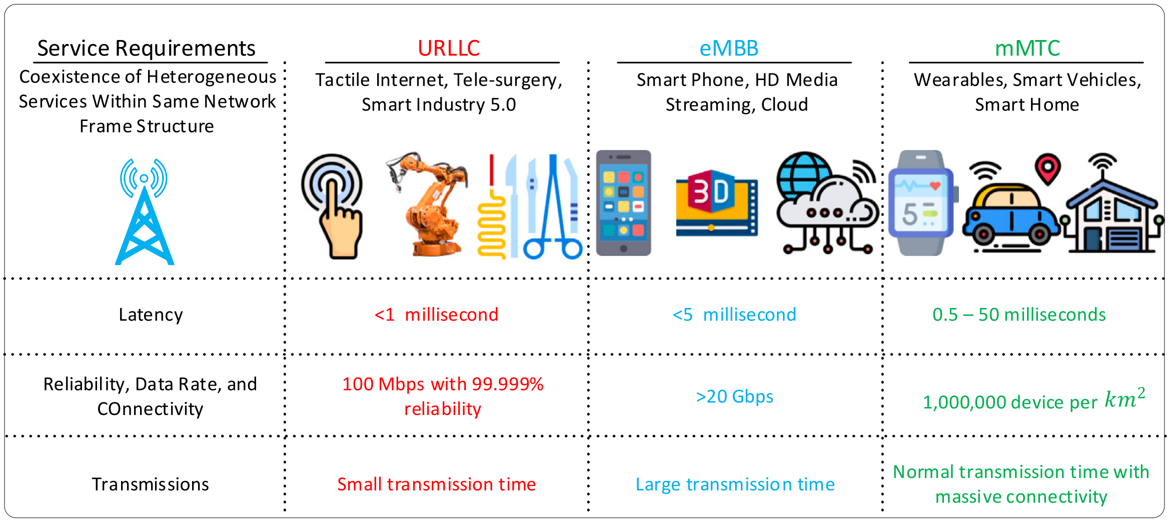


Fig. 2. Service requirements of B5G network.

numerology on the MAC layer. Section 4 provides a discussion on coexistence with other enabling technologies, specifically IEEE 802.11. Section 5 highlights the open research issues and challenges from the perspective of the MAC layer. Section 6 underlines the potential ML techniques to tackle open issues and challenges. Finally, Section 7 concludes the article. Fig. 1 illustrates the future-generation communication model of a smart city.

Comparison and Contribution: This article provides in-depth details of the NR MAC network layer. This article provides an introductory vision for the need for NR and the flexible MAC structure to enable the coexistence of Het services. Moreover, this article specifically points out the service requirements of Het applications from the B5G network and metrics to evaluate the performance. This article discusses the flexible and innovative MAC frame structure of NR in-depth. Furthermore, the article presents almost every open research issue related to MAC to the best of our knowledge. AI is the prime milestone of the B5G network to offer a self-organizable and self-sustainable fully autonomous network. Therefore, recent ML-based AI solutions for these problems are well surveyed in the article. It is of prime importance that the future generation communication network should support the exponential augmented requirements, therefore, this article presents future directions for 6th generation (6G) communication network. The cornerstone of this article is the NR MAC network layer, with a specific aim to provide readers with open research issues and challenges, and viable intelligent solutions targeting NR MAC. To depict the contribution of this article, a comparison with the most recent survey articles from 2019–2021 targeting 5G and B5G is presented in Table 1.

This article presents the exhaustive overview from the MAC layer perspective in B5G networks. To this end, Section 2 presents the 5G and B5G driving applications. Section 3, overview the NR frame structure. Section 4 presents the coexistence of B5G networks with other enabling technologies. Open research issues and challenges with the perspective of MAC layer are highlighted in Section 5. Section 6 presents the integration of artificial intelligence for the optimization of B5G MAC. Section 7 detailed the tools and simulations for NR. In Section 8, future research directions are presented and finally, conclusions are drawn in Section 9.

2. 5G and B5G driving applications

In this section, three ITU-defined application categories for 5G and B5G are briefly described: eMBB, mMTC, and URLLC. Additionally, this section identifies a few new PHY/MAC layer problems. Fig. 2 illustrates the three application categories.

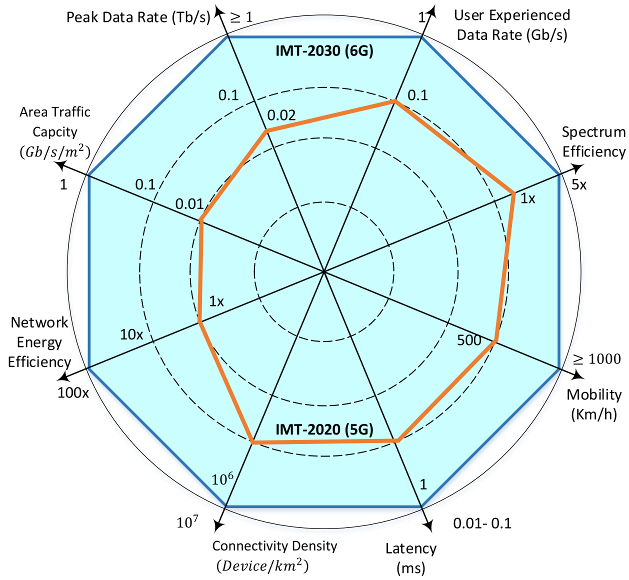


Fig. 3. Vision of B5G and 6G network.

2.1. eMBB

Virtual, Augmented, and Extended Reality (VR/AR/XR), and high-resolution video streaming are encompassed in eMBB service applications that have large packet size which is approximately four times that of the other two application types. The large packet size requires large bandwidth. The main issue that earlier generations of communication technology had to deal with was increasing system throughput with a 100-fold capacity increase, or 20 Gb/s [8]. Multiple-input–multiple-output (MIMO) transmission, high-order encoding and modulation, cell densification, and effective multiplexing are all made possible by modern PHY/MAC technology. However, to get a $100x$ high data rate, which is still untapped for the SON and SSN networks, more aggressive tactics are required. Terahertz (THz) transmission, millimeter-wave (mm-wave) communication, full-dimension MIMO, and ML-enabled networks are some feasible alternatives.

2.2. mMTC

The widespread use of machine-type devices for localization, tagging, sensing, metering, and monitoring is among the mMTC services. All of these applications require effective spectrum access and energy-saving strategies. According to the ITU, the service requirement for mMTC is 1 million per $\mathrm{km}2$. For mMTC devices with a battery expectancy of more than 10 years and a coverage area of 1–10 km, the 3GPP developed the Low Power Wide Area Network (LPWAN) radio technology known as narrowband-IoT (NB-IoT). Reduced-power wide-area network (LPWAN) solutions provide low power consumption, enhanced coverage, and low operational costs [9]. When the capacity of available resources is considerably exceeded by the number of devices, an aggressive spectrum access strategy is required to accommodate additional users.

2.3. URLLC

The delay-sensitive and high-reliability applications such as autonomous driving, tactile internet, tele-medicine, and industrial automation are covered in the URLLC service applications. In such mission-critical applications, the end-to-end packet delay should be less than 1 ms. To minimize latency, both backhaul and wireless networks must undergo significant changes. By utilizing virtual network slicing, the software-defined network (SDN) may be utilized to improve the backhaul network. Overhead in a wireless network increases delay owing to control signals, which takes around 0.3–0.4 ms per scheduling. As a result, using low latency for packet transmission is not deemed efficient since control overheads consume 60% of the resources. As a result, the PHY/MAC layer must be completely redesigned.

2.4. Service requirements

It is essential to comprehend the underlying requirements before developing workable solutions for 5G and B5G networks. This section gives a high-level overview of the requirements and issues associated with 5G Het. traffic. Figs. 3 and 4 provide insight into the service requirements of 6G.

Enabling Technologies/Requirements		5G	B5G and 6G
Service Type		eMBB, URLLC, mMTC	FeMBB, ERLLC, umMTC
Applications		• VR/AR/360° Videos • UHD Videos • V2X • IoT • Industry 4.0 • Telemedicine • Wearable Devices	• Holographic Verticals • Tactile/Haptic Internet • Digital Sensing and Reality • Industry 5.0 • Spacial communication • IoE (IIoT, IoD, IoNT, IoHT, IoT) • Intelligent Transportation System
Network Characteristics		• Cloud • Virtualization • Slicing (RAN and Core Network)	• Self sustainable and organizable • Intelligent Virtualization and slicing • Cooperative communication and network
Service Ojects		Humans and Things	Cyber Physical World (Human with everything)
KPI	Peak Data Rate	20 GB/s	≥1 Tb/s
	Experienced Data Rate	0.1 Gb/s	1 Gb/s
	Spectrum Efficiency	3x that of 4G	10x that of 5G
	Network Energy Efficiency	10-100x that of 4G	10-100x that of 5G
	Area Traffic Capacity	10 Mb/s/m^2	1 Gb/s/m^2
	Connectivity Density	10^6 Device/km^2	10^7 Device/km^2
	Latency	1 ms	10-100 μs
	Mobility	500 km/h	≥1000 km/h
Technologies		• mm-Wave Communications • Massive MIMO • Ultra Dense Network • NOMA • LDPC and Polar Codes • SDN/NFV/Network Slicing	• Sub-THz-THz Communications • SM-MIMO • NoC • AI/Machine Learning • Blockchain Spectrum Sharing • Quantum Communications and Computing

Fig. 4. B5G and 6G network enhancements.

2.4.1. *Latency requirement*

Transmission, propagation, re-transmission, and processing delay are all part of the PHY layer latency. Latency in the MAC layer includes scheduling, queuing, processing, numerous hybrid automatic repeat requests (HARQs), and decoding. The statistical multiplexing of data meant for numerous Het users causes queuing and processing delays. As the number of Het users rises, the queuing effect worsens to optimize spectral efficiency. According to 3GPP, the average latency over the radio for URLLC applications should be less than 1 ms. To decrease transmission latency, the new frame construction is necessary.

2.4.2. *Ultra-high reliability*

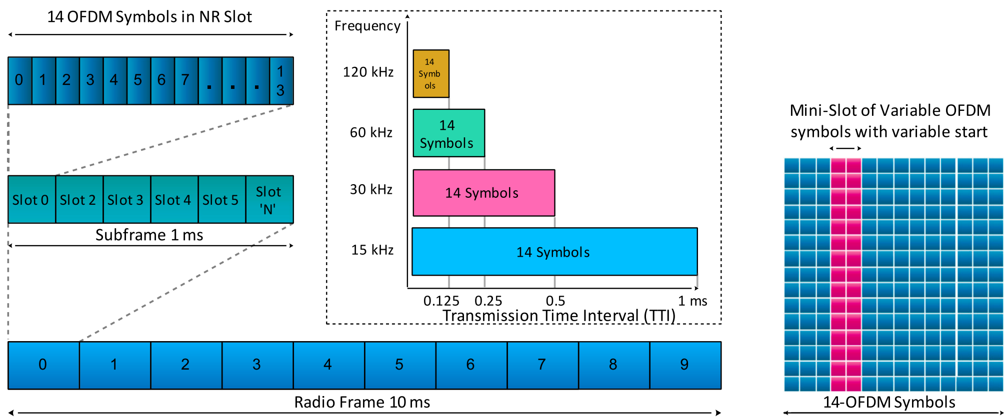
The most stringent dependability standards apply to URLLC services. The necessary dependability for URLLC services is at least 99.999% packet delivery ratio (PDR) within 1 ms of delay. Mission-critical applications, such as robotic surgery, need dependability of up to 1×10^{-7} packet error rate. The effective channel coding and re-transmission of HARQs are critical factors for achieving ultra-reliability. For brief packet transmission, advanced channel coding with an effective channel estimate approach can be used. Re-transmission systems based on time-domain resources might be a feasible choice for small slot lengths. The PDR is the KPI used to assess dependability.

2.4.3. *Coexistence of het traffic*

The 3GPP recommends that the BS give preference to URLLC whenever one is present, whether it is during scheduling, eMBB or mMTC transmission, or both. To enable URLLC, the ongoing eMBB and mMTC services should be terminated promptly and without notice. Because the interruption is not communicated to mobile users, the Quality-of-Service (QoS) of eMBB and mMTC suffers greatly. 3GPP refers to this issue as coexistence, which is related to diverse applications in 5G and B5G networks. As a result, an effective strategy for protecting all ongoing services should be implemented. Fairness is the key performance indicator for measuring the fair balance of Het traffic coexistence. Jain's fairness index is a prominent metric for measuring fairness (JFI).

3. New radio frame structure

This section presents a detailed explanation of NR frame structure, its flexibility, scalable numerology, and its effects on the frame structure.



n	SCS (kHz)	Slots/Sub-frame	Slots/Frame	Symbols/Slot	OFDM Symbol Duration including CP (μs)	Max. BW (MHz)	No. of SCs, No. of PRB	Size of PRB (kHz)
0	15	1	10	14	71.35	49.5	3300, 275	180
1	30	2	20	14	35.68	99	3300, 275	360
2	60	4	40	14	17.84	198	3300, 275	720
3	120	8	80	14	8.92	396	3300, 275	1440
4	240	16	160	14	4.46	397.4	3300, 275	2880

Fig. 5. Frame structure for NR DL/UP transmission.

3.1. NR frame structure

The NR time domain frame has a length of 10 ms and is divided into 10 subframes of 1 ms, as illustrated in Fig. 5. The subframe is further subdivided into $2n$ radio slots. The radio slot is the smallest time unit that can fit inside a single TTI. There are 14 OFDM symbols in each slot, each with the cyclic prefix (CP). The amount of radio slots is determined by the SCS. At the beginning and/or end of the OFDM symbols, each slot contains control signals. To provide a more flexible TTI size with a variable number of OFDM symbols, the mini-slot concept was adopted in NR. Any OFDM symbol with a length of two, four, or seven symbols may start a mini-slot. The time slot is $\mathrm{ms}/2n$ in duration. When $n = 1$, the time slot at 30 kHz becomes 0.5 ms, as shown in Fig. 5. The mini-slot allows URLLC traffic to be sent quickly. Because the mini-slots are individually planned with control signals, the scheduling delay is reduced. The smallest time domain unit in NR for the MAC scheduler, enabling dynamic scheduling with variable TTI, is hence the mini-slot.

3.2. Numerologies of NR

NR supports a scalable SCS which is impacted by the numerology according to the relation $2^n \times 15$ kHz, where $n = \{1, 2, 3, \dots, \}$. As the SCS tends to increase, the duration of the symbols decreases, that results in shorter radio slot duration, which in turn results in a lower end-to-end latency. Furthermore, NR also allows using multiple numerologies simultaneously on the same carrier. This is also termed as subcarrier multiplexing. As illustrated in Fig. 5, a 1 ms subframe at 15-kHz SCS equals 125 μs slot at 120-kHz SCS. Scaling up the SCS reduces the CP. Therefore, higher SCS is more susceptible to Doppler effect and inter-carrier interference (ICI). To keep OFDM symbols inside the frequency domain and encourage the use of mixed numerology with short guard bands, windowing is used to prevent transitions between OFDM symbols.

Furthermore, increasing the SCS improves the available bandwidth, as shown in Fig. 5. From 50 MHz at 15 kHz SCS, the maximum bandwidth increases to 400 MHz at 120 kHz SCS. In NR, a physical resource block (PRB) has a maximum of 12 sub-carriers (SCs). Because SCS defines the number of SCs, it also defines the total number of PRBs. As demonstrated in Fig. 5, a PRB's bandwidth varies with SCS and ranges from 180 kHz at $n = 0$ to 2.88 MHz at $n = 4$. The NR offers both time-division duplex (TDD) and frequency division duplex for Het traffic (FDD). All FDD slots are dedicated to the downlink or uplink transmission. NR allows bidirectional (uplink and downlink) transmission in all TDD slots. In order to reduce latency, Het traffic users can be allocated mini-slots of variable slots. The Het users can be scheduled for transmissions by a MAC scheduler with different SCS and therefore, TTI. The scheduled allocation is conveyed to the UEs at each time occurrence via a PHY downlink control channel. The control channel can be multiplexed with other downlink PHY channels and mapped contiguously or non-contiguously in the frequency domain. This highly adaptable architecture can minimize downlink control channel overhead to less than 1%. One of the methods suggested for URLLC application is punctured scheduling, in which the MAC scheduler overwrites the current transmission using mini-slots when a URLLC data packet arrives at the gNB. The performance of the system is reduced as a result of punctured

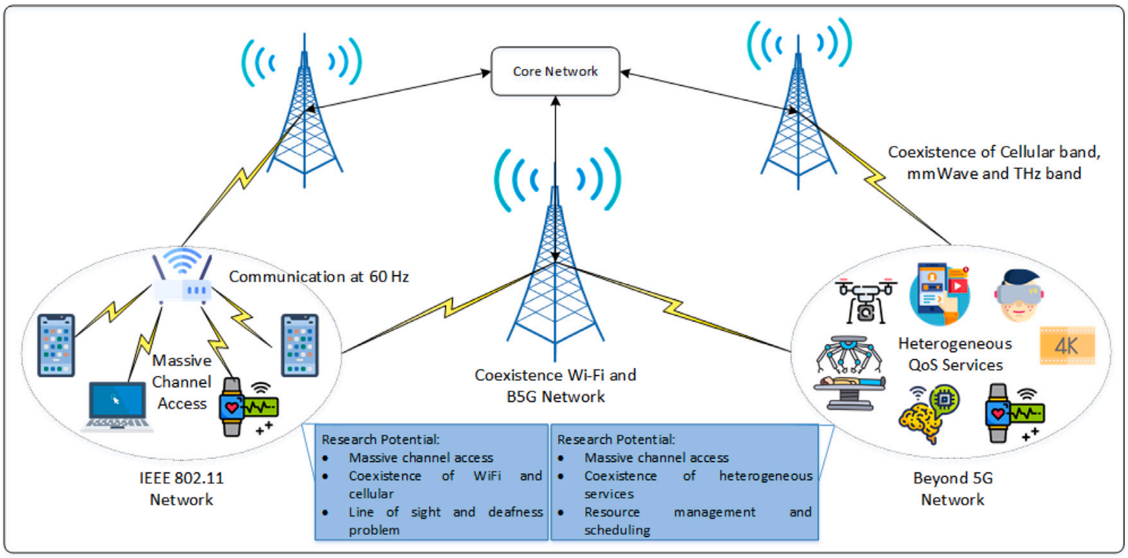


Fig. 6. Interaction of B5G cellular and WLAN networks.

scheduling, which also causes the transmission to be interrupted. To ensure that the MAC scheduling method is efficient, the size of the mini-slot and SCS should be properly chosen.

4. Coexistence of B5G network with other enabling technologies

The future communication systems would see increased interaction between cellular and WiFi technologies, and they will work in coherence with each other [10]. Fig. 6 represents the interactions between the various wireless communication technologies and what potential challenges will emerge. The B5G and 6G cellular and WiFi networks' cohabitation will be a challenge when the new mmWave standards come into effect. Most of the devices in the indoor scenario would utilize WiFi networks [11]. They can support the throughput requirements and ensure reliability in limited mobility environments such as homes and office spaces. Cellular services prove reliable in outdoor spaces where mobility is a deciding factor in network performance. The deployment scenario in the figure includes stations (STA) or User Equipment (UEs) that are connected to an Access Point (AP) and a Base Station (BS), respectively. Some devices will have the capability in terms of hardware to connect to an AP and a BS simultaneously. As the number of users (STAs + UEs) per capita increases, the allocation of channel resources while maintaining a strict QoS will become a challenging task.

- A significant challenge involves allocating the channel to a large number of users while respecting the priority and KPIs of the network.
- When two different communicating users are using similar frequency bands, there is a huge risk of interference from each other, leading to collisions between the data packets. Therefore, network designers will need to figure out a way to allow coexistence between multiple technologies.
- There may be users who wish to use different services that have different QoS requirements simultaneously on the same network.
- The mobility of some devices such as cars and drones will only increase the complexity of this challenge.
- Due to the nature of the mmWaves, they are significantly affected by obstacles and the loss of line-of-sight (LoS). mmWave are highly directional, which means that the two communicating devices should be within the LoS of each other's antenna.

For instance, a passenger in an autonomous vehicle wishes to watch high-definition video, where the car and the entertainment system utilize the same cellular network. Ensuring the passenger's safety by allowing the autonomous car to communicate with the control infrastructure while simultaneously ensuring delivery of HD multimedia content constitutes another problem of scheduling and coexistence with different services. And when this scenario is scaled up, the challenges are scaled up as well.

5. Open research issues and challenges in the perspective of the MAC layer

In this section, we outline the open research issues and challenges from the perspective of the MAC layer for next-generation cellular communication, that is, NR.

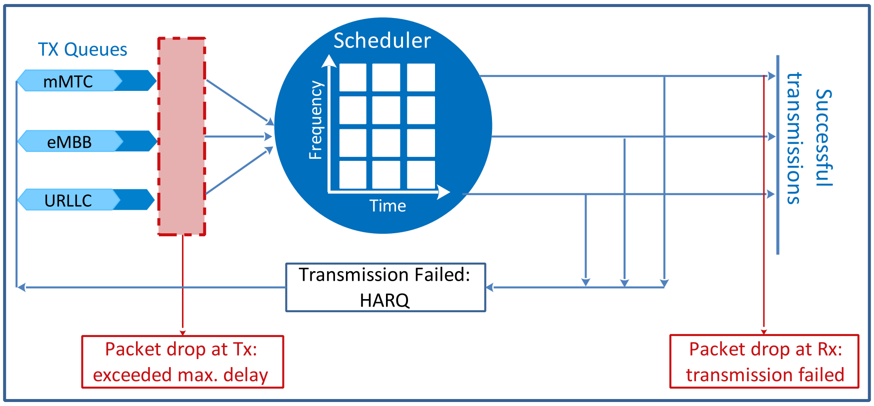


Fig. 7. Single queue model describing the PHY/MAC layer behavior at gNB for 5G and B5G applications.

5.1. Queueing model

In this section, we will go over the 5G architecture's queueing model and how it relates to the network's service requirements.

To visualize the queuing effect and QoS requirements of 5G, a simplified queuing model, shown in Fig. 7, illustrates how the MAC layer behaves when a next-generation NodeB (gNB) queues Het traffic at the downlink. While the scheduler plans the first HARQ transfer, the data packets belonging to het users are buffered at the gNB in the first transmission queue. After a round trip period, if the first HARQ transmission fails, the packet is ready for retransmission (RTT). If a packet in the gNB's buffer exceeds its transmission threshold time, it is considered to be lost, resulting a degraded reliability. A packet that cannot be decoded at the receiver after N HARQ transmissions is also considered as a failed transmission, which also degrades the reliability. The phrase "limited size of the buffer" in a queuing model denotes dropped packets at the transmitted if the queuing delay exceeds the expected latency. The scheduler at the gNB distributes time and frequency resources for transmissions and retransmissions at each time instant to meet the service needs of each user.

Furthermore, the 3GPP defined the puncturing technique in NR for URLLC communication to fulfill rigorous latency and reliability criteria, categorically interrupting ongoing eMBB transmission to transmit URLLC traffic mini-slots without informing eMBB user equipment (UE). The puncturing method reduces the eMBB user's quality of service (QoS). The degraded QoS encountered by eMBB UE is often more than the gain obtained by sending URLLC traffic. Fig. 8 depicts the mechanism of puncturing. The NR standardized scheduling in the time domain as well as frequency domain. In time domain multiple access (TDMA), the scheduling is performed at the slot level, whereas in OFDMA, scheduling is performed to physical resource blocks (PRB) in groups. In NR by default three scheduling protocols have been proposed round robin (RR), proportional fair (PF), and the maximum rate (MR) [12]:

- Round-robin: The scheduler distributes available resource block groups (RBGs) evenly across UEs connected with that beam (OFDMA), whereas the scheduler distributes available symbols uniformly in TDMA.
- Proportional fair: According to a measure that takes into account both the real rate, based on the Channel Quality Indicator (CQI)) raised to α, and the average rate that has been delivered to the various UEs in the preceding slots, the scheduler equitably distributes the available RBGs across UEs in the OFDMA mode. The measure varies when the α parameter is changed. When α is equal to zero, the scheduler chooses the UE with the lowest average rate. When $\alpha = 1$, the scheduler chooses the UE with the highest ratio of real to average rates. The resources to distribute in TDMA are whole symbols.
- Maximum rate: The scheduler allocates the available radio block group (RBG) (or the available symbols in case of TDMA) to the UE, which achieves the maximum data rate in the current transmission.

One solution is to have multiple concurrent transmissions. However, it is limited by the available system bandwidth. The 3GPP Release 15 introduced mini-slots to minimize latency by reducing the TTI from 1 ms to a few OFDM symbols while conserving the overall channel structure. Reduced TTI increases network capacity and allows for more retransmissions within latency limitations. Furthermore, it enables exact rate control. Furthermore, the 3GPP accepts scalable SCS for NR scaled by a power of 2, that is, $2^n * 15$ kHz, where $n = \{1, 2, 3, \dots, \}$. Up til now $n = 4$ has been standardized in NR. Optimal selection of the mini-slot size in terms of OFDMA symbols and SCS numerology for URLLC application can efficiently schedule the Het traffic [13].

5.2. Inter-numerology interference

Although 3GPP accepts shortening the TTI with high numerology of SCS as a feasible option for service requirements. It does, however, come at the expense of inter-numerology interference (INI). Because the CP's length scales with the SCS, increasing the SCS shortens the CP. SCs with the same SCS are orthogonal, but they interfere with one another when their SCS and CP are different. Furthermore, mix-numerologies complicate OFDM symbol alignment in the time domain, making synchronization within a frame problematic. Using set guard bands in between sub-bands is one solution, although this reduces spectral efficiency. A solution for enhanced reliability and interference reduction is provided by the INIpower-aware resource allocation based on ML.

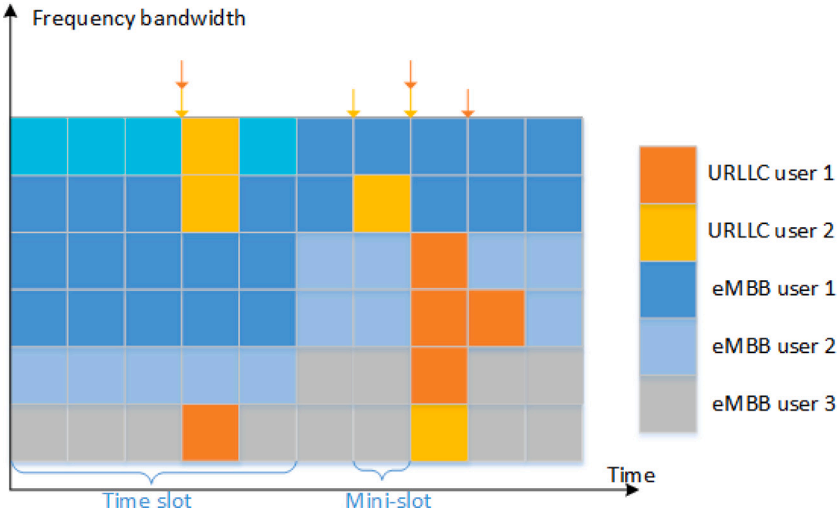


Fig. 8. Coexistence of eMBB and URLLC using puncturing mechanism.

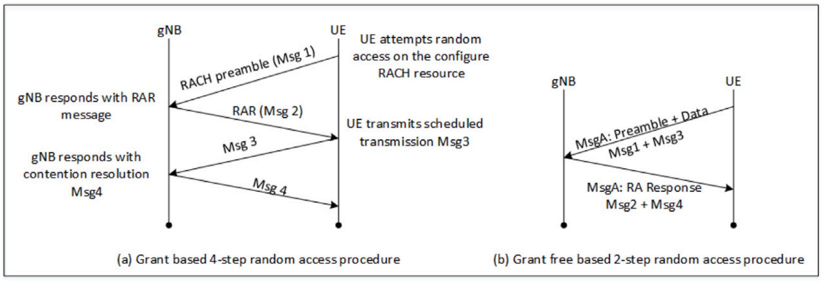


Fig. 9. Random Access Process in 5G NR.

5.3. Random access process

Uplink transmission is more constrained than downlink transmission. The user must utilize the handshaking random access (RA) technique to request resources from the gNB, which is a grant-based mechanism. The gNB allocates resources to users through dynamic scheduling to maximize system capacity. The first handshaking method must be very trustworthy to identify the existence of uplink data, which raises the overhead of the uplink control channel NR standardized grant-free also known as semi-persistent RA. Semi-persistent is one viable solution, which utilizes semi-statistical allocation [14]. Fig. 9 depicts both grant-based and grant-free RA processes. Both the random access techniques are explained as follows:

- Grant-based RA: As with Release 15, it is a four-step process, as seen in (Fig. 9a). Msg1 is a contention-based physical RA control channel (PRACH) preamble sent by the UE. The gNB or base station (BS) for 5G responds with a random-access response (RAR), also known as Msg2, after detecting the preamble. The detected preamble ID, a time-advance instruction, a temporary C-RNTI (TC-RNTI), and an uplink grant for scheduling a PUSCH broadcast from the UE known as Msg3 are all included in the RAR. In response to the RAR, the UE sends Msg3, which includes an ID for conflict resolution. When the network receives Msg3, it sends the conflict resolution message, also known as Msg4, along with the contention resolution ID. Msg4 is received by the UE, and if it discovers its contention-resolution ID, it transmits an acknowledgment on a PUCCH, completing the 4-step random access procedure.
- Grant-free RA: Two-step RACH is designed to have a single round trip cycle between the UE and the BS to decrease latency and control-signaling overhead. The preamble (Msg1) and the planned PUSCH broadcast (Msg3) are combined into a single message (MsgA) from the UE, known as MsgA. The RAR (Msg2) and contention resolution message (Msg4) are then combined into a single message (MsgB) from the gNB to the UE, as shown in (Fig. 9b). Furthermore, in the case of unlicensed spectrum, limiting the number of messages sent by the UE and gNB minimizes the number of LBT (Listen Before Talk) attempts.

When a UE transmits MsgA, it waits for the response of MsgB from gNB. There are the following three possible outcomes:

- The gNB does not receives MsgA. In this case, no response is sent back to UE and UE has to re-transmit the MsgA or opt for a four-step RA process.

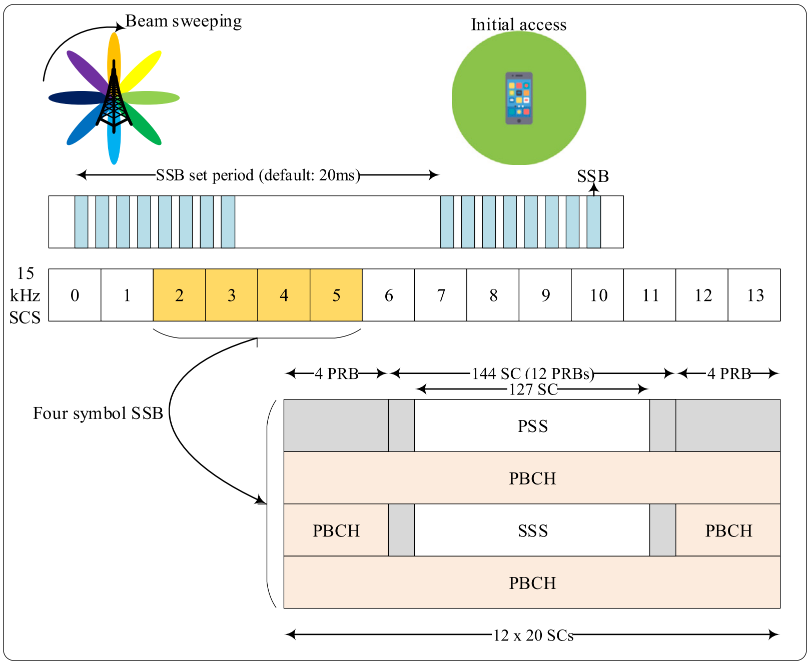


Fig. 10. SSB structure and the relation between beam sweeping and SSB set.

- The gNB receives MsgA, but fails to decode it. The gNB transmits RAR with a RA preamble ID (RAPID) and grants for MsgA re-transmission. On receiving RAR, the UE has to follow a four-step RA process by transmitting Msg3.
- The gNB receives MsgA and successfully grants access.

Users are therefore unaware of channel state information (CSI) in the grant-free technique, which raises the block error code. Non-orthogonal multiple access efficiently allocates the same resources for initial transmissions simultaneously. Moreover, packet duplication without HARQ retransmissions at the packet data convergence protocol layer to transmit multiple packets over different uncorrelated channels could achieve high reliability in minimum latency.

5.4. Synchronization

As illustrated in Fig. 10, the signal synchronization block (SSB) location is mapped to 20 PRBs (240 SCs) in the frequency domain and four continuous OFDM symbols in the time domain. The SSB in the time and frequency domains is precisely proportional to the SCS's numerology n. The SSB carries a physical broadcast control channel, primary SS (PSS), secondary SS (SSS), and a demodulation reference signal. The 127 resource elements (REs) of the first and third symbol are used for PSS and SSS respectively. The 240 REs of the second and fourth symbols along with 96 REs in the third symbol are used for PBCH and demodulation reference signal (DMRS), as illustrated in Fig. 10. Cell and sector identification, which is necessary for the initial cell search, is the responsibility of the PSS and SSS. The PSS length has been raised to 127, which is double that of LTE.

In the LTE cellular network, the SSB is placed in the center of the carrier, which makes the location of the SSB exactly known to the UE. However, the detection of the first cell search in NR is made more difficult by the scalable numerology and lengthened SS, which reduces the accuracy and latency [15]. For the blind detection of the SSB, UE tries more than one SCS value of the applied frequency range for initial cell access in NR, which complicates the process. Moreover, the NR is expected to be the enabling technology for multiple-input–multiple-output (MIMO) for large beamforming (BF) gain. In NR, gNB and UE have to determine their initial BF direction, which adds more complications for initial access. Therefore, modeling and designing an efficient initial access methodology is an open research issue for splendid research to come up with innovative yet efficient ideas.

5.5. Deafness and line-of-sight blockage

Release 15 and 16 of NR standard by 3GPP support frequency ranges up to 52.6 GHz. As the higher frequency spectrum is used, it comes along with difficult challenges. That are higher phase noise, high atmospheric and propagation losses, and more directional beams. The interest to use higher frequency is driven by the requirement of large spectrum allocation for higher data rate and throughput. Recently, the NR working group of 3GPP has decided to include sub-THz frequency bands which are beyond 52.6 GHz in Rel. 17 [16]. As NR is expected to support massive MIMO and sub-THz spectrum as well. However, for using the

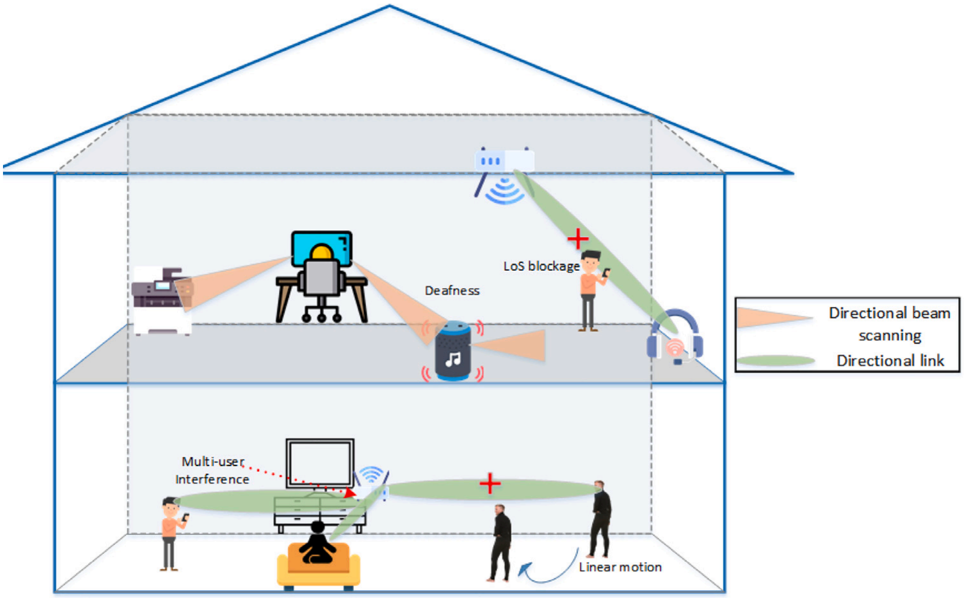


Fig. 11. Scenario illustrating deafness and LoS blockage.

sub-THz spectrum, the communication should be highly directional by forming razor-sharp beams and the MAC should support frequent handshakes between transceivers and directional beams [17]. The highly directional beams provide enhance coverage area with high radiation gain. The misalignment between transceivers causes deafness, such phenomenon is depicted in Fig. 11.

To overcome deafness, Carrier-sense multiple access with collision avoidance (CSMA/CA) either utilize an omni-/quasi-omni-directional to directional (O-to-D) antenna pairs to achieve BF and synchronization or utilize directional to directional (D-to-D) antenna pairs with caching the location information of all neighbor nodes on each sending device, the synchronization is established after sending multiple directional request-Tto-send (DRTS) packets. The line of sight (LoS) blockage can also be caused by any obstruction between transceivers. Due to LoS blockage, MAC synchronization and hand-off issues occur. To avoid LoS blockage, the MAC protocol should initiate a new handshake via an alternative to synchronize with the transceiver and resume communication. Researchers have proposed a multi-hop scheme at the mmWave and THz bands to form alternative routes to mitigate this. A careful link-level scheduling and neighbor discovery process are necessary to achieve high throughput while maintaining low interference.

5.6. Hybrid automatic repeat request (HARQ)

In C-V2X to increase the reliability of the message packet transmission blind retransmissions are carried out [18]. Since in the C-V2X broadcasting mechanism there is no feedback mechanism, the transmitting V-UE is not aware of whether the last transmission was successful or not, thus, the Tx V-UE blindly transmits up to a certain number of transmissions to increase the reliability of the message packet reception. This may increase the use of resources inefficiently as even if the last transmission was successful, the Tx V-UE will retransmit. Therefore, in C-V2X it is left to the application of vehicles to turn the HARQ ON or OFF. Since the resources are limited, when there is congestion the HARQ is turned off.

In NR-V2X, two additional modes are introduced, unicast and group cast in addition to the broadcast. In both unicast and group cast-based communications, feedback channel support is available. Therefore, NR-V2X increases transmission reliability by employing the combination of retransmission and forward error correction (FEC) technique. Utilizing the feedback channel the receiving vehicle Rx V-UE notifies the TX V-UE about the success or failure of its last transmission by sending ACK or NACK [19]. When the message is not successfully decoded at the Rx V-UE, it sends the NACK over the feedback channel to the Tx V-UE. In return the, Tx V-UE retransmit and add the parity pits to aid the successful reception of the message packet at the receiver end. If Ack is sent by the receiver then no retransmission is required by the Tx V-UE, however, if no ACK or NACK is received by the Tx V-UE, the Tx V-UE will retransmit with multiple retransmissions until the packet delay budget (PDB) associated with the generated message packet to meet the reliability.

6. Artificial intelligence to optimize B5G MAC

Artificial Intelligence (AI) enables machines to mimic human brain-like intelligence. The capabilities of AI include natural language processing, knowledge-based decisions, and perception. ML is the subset of AI. ML is the general technique of AI that can learn directly from structured and unstructured data provided by information technology without any explicit programming. The

Table 2
CR limits defined by the 3GPP corresponding to the CBR.

CBR	CR limit
$0 \leq$ CBR ≤ 0.3	No limit
0.3 <CBR ≤0.65	0.03
0.65 <CBR ≤ 0.8	0.006
0.8 <CBR ≤1	0.003

Table 3
Transmission rate corresponding to the CBR measured.

Measured CBR	Packet Tx Rate
0≤ CBR ≤ 0.3	10 Hz
0.3 <CBR ≤0.4	5 Hz
0.4 <CBR ≤0.5	2.5 Hz
0.5 <CBR ≤ 0.6	2.5 Hz
CBR > 0.6	1 Hz

ML techniques that can learn from labeled and unlabeled data sets for prediction are termed supervised and unsupervised learning. The ML techniques enable the machines to learn themselves without any prior knowledge related to the data set by interacting with the environment itself just like humans. Such ML techniques are termed Reinforcement Learning (RL) and it classifies ML into three categories that are supervised, unsupervised, and reinforcement learning. There are few techniques that learn from most of the unlabeled data, however, they also use a small amount of labeled data. Such techniques are known as semi-supervised learning. Deep Learning (DL) is a sub-class of ML with a multi-layered system to perform higher capabilities. DL techniques include Deep Belief Networks (DBNs) and Neural Networks (NNs). The association of DL and RL exploits the advantage of both techniques, which promotes high-performance algorithms such as Deep Q-Networks (DQNs) [20].

In this section, we summarize the artificial intelligence-based solutions to make the MAC scheduler efficient in V2X.

In C-V2X, the performance degrades with the increase in vehicular traffic. 3GPP does not specify the particular congestion control mechanism, however, it specifies the two metrics; channel busy ratio (CBR) and channel occupancy ratio (CR) [21]. Channel busy ratio is defined as the number of subframes occupied in the last 100 subframes/ or 100 ms. The subframe is considered occupied if the received signal strength information (RSSI) is greater than the threshold in any of the subchannels within the subframe. Wherein the CR is defined as the number of subchannels occupied by the vehicle in the last 1000 ms. To avoid channel congestion, based on the defined metrics as stated by the 3GPP, the packet transmission rate (Tx Rate) is reduced. Since the arrival time of the message, a packet cannot be controlled as it depends on the application layer, therefore, in the case of congestion the packets are buffered and not transmitted.

The 3GPP and European Telecommunication Institute (ETSI) define the corresponding CR limit against the CBR as given in Table 2. The congestion control mechanism follows the following steps.

Step: 1 In this step the vehicle will calculate the CBR and CR.

Step:2 After the vehicle derives the CBR and CR, it will look into the lookup Table 2. Against the derived CBR in step 1, the vehicle will go to the corresponding row and will check if the measured CR is greater than the CR limit defined by the 3GPP corresponding to it. If it breaches the CR limit defined the vehicle will take action as defined in Step 3.

Step:3 The vehicle will adjust its packet Tx Rate as defined in lookup Table 3 corresponding to the measured CBR value to reduce the channel congestion.

Therefore, the vehicle adjusts its TX Rate to reduce the channel congestion. However, this may increase the latency associated with the generated packets, since the packets are buffered and not transmitted.

In [22], the authors utilize deep reinforcement learning (DRL) to maximize the packet delivery ratio (PDR) while increasing the packet transmission rate. Each agent learns its policy independently. An agent takes the action based on the observations, the observation space consists of its measured CBR. The agent takes the action from the set of action space A = $\{10, 5, 3.33, 1\}$ Hz, which represents the packet transmission rate. The reward function is modeled to increase the PDR while bringing the CBR close to the target CBR i.e., increasing the packet transmission rate. Eq. (1) shows the reward function, where if the CBR is significantly less than the target CBR the reward will result in lower values. Hence, to increase the reward obtained, the action of selecting the packet transmission rate, is increased.

$$R_t = PDR - (TargetCBR - measuredCBR) \tag{1}$$

A deep reinforcement learning-based radio resource scheduling is introduced in [23]. The gNB act as an agent which schedules the resources intelligently for the UEs. The gNB assigns the radio resource blocks to the subset of the UEs which have data in their buffer to send and it is not associated with the HARQ. In [24], a distributed deep reinforcement learning-based scheme is proposed to access the spectrum dynamically. The UEs learned strategies in a distributed manner without the prior knowledge of network statistics to access the spectrum.

Table 4
Survey papers discussing machine learning to optimize MAC layer.

Ref.	Year	Approach	Technique Used
[24]	2019	Distributed	Reservoir computing and deep reinforcement learning
[23]	2020	Central	Numerology-agnostic deep reinforcement learning
[22]	2021	Distributed	Deep reinforcement learning
[25]	2022	Central	Reinforcement learning

In [25], the authors utilize reinforcement learning to select the transmission time interval (TTI) to meet the latency associated with the generated packet. 3GPP in its Rel 15 and 16 introduced the TTI of less than 1 ms. This shortening of TTI is dependent on the subcarrier spacing. 3GPP introduced the subcarrier spacing of 15 kHz, 30 kHz and 60 kHz for the sub 6 GHz band and 120 kHz and 240 kHz for the mmWave band. The corresponding slot durations are 1 ms, 0.5 ms, 0.25 ms 0.625 ms for the sub 6 GHz band and 0.3125 ms and 0.15625 ms for the mmWave band. The researchers have evaluated the sub 6 Hz band for V2X, however, the research is still ongoing for the exploitation of the mmWave band. A summary of the machine learning techniques applied to make the MAC layer efficient and intelligent is provided in Table 4.

7. Tools and simulators for NR

The 3GPP introduced NR in Release 15 and provided many papers that evaluated results along with it. However, the evaluating simulators are not made publicly available. Moreover, most private simulators are licensed and require heavy fees. The licensed simulators are very restrictive and do not allow modifications to the research community, which is a huge limitation for researchers. This section provides a brief introduction to the available NR simulators. The CTTC-Lena group has designed an NR simulator based on Network Simulator-III (NS3) named as 5G-Lena NR, which is an open-source platform [26]. The 5G-Lena NR is licensed under General Public Licensed-version 2 (GPLv2) and provides freedom of free software distribution. For real test-bed experiments, the Open Air Interface (OAI) by EURECOM provides support for NR simulations. It is licensed by Public License version 1.1 (PLv1.1).

The system-level simulation can be carried out using Vienna simulator [27]. The simulator is designed in a modular manner and is based on MATLAB to support different features. The simulator attracts researchers working in the field of Physical and MAC layers. On the other hand, MATLAB provides the 5G toolbox and supports freedom of modification as well. The OMNet++ supports discrete event-based simulation for LTE and LTC-Advanced (LTE-A). However, OMNet++ lacks support for NR.

8. Future research directions

The accomplishment of the next generation depends on meeting the aforementioned service criteria by resolving various open research difficulties. Some pressing topics that demand the research community's attention are discussed in this section [28].

8.1. Operation in multiple frequency-bands

The inclusion of mmWave and THz band in the future cellular network lays out a unique set of challenges [17]. From the perspective of hardware design, cross-compatibility in a compact form factor is a critical research issue. The considerations for massive multiple input–multiple outputs (mMIMO) to ensure a reliable wireless link is being widely explored by encompassing improvements in CMOS fabrication and novel antenna design. Additionally, from the MAC layer perspective, novel approaches toward the frame specifications are required. The different QoS requirements along with the consideration for computational and energy constraints warrant an intelligent approach to resource allocation and scheduling algorithms. Mapping the QoS requirements to the available resources is a challenge that can potentially enhance the throughput by offloading the appropriate frames to the suitable link. AI can provide tools for intelligent resource allocation as well as link selection. However, this should not cost in terms of energy and computational resources.

8.2. Secure communication

Security is without any doubt among the most critical features of the next generation cellular networks [29]. The security protocols followed should not hinder the performance of the network. Since applications like healthcare autonomous vehicles and defense are extremely vulnerable to attacks, the transfer of data over wireless links should be secured with evolving security countermeasures. The security challenges can be roughly classified into three classes based on the location, namely input, data access, and output security. The data breach at the sources such as sensors or cameras constitutes an input security threat. When the collected data in a vault is accessed without authorization, it is known as a data access breach. And if the accessed data is disseminated without permission, it constitutes an output security breach. As the attacks evolve continuously, AI can play a critical role in evolving with the new attack strategies. New lightweight protocols can be explored for securing the transmitted data. The role of blockchains is becoming increasingly significant in data security, therefore, blockchains can be integrated into the network design to mitigate data threats.

8.3. Improved channel sensing for no-line-of-sight cases

The high-frequency signals such as in the THz band are highly directional and would require additional capabilities for overcoming the no line of sight (NLoS) operation. Improved channel sounding mechanisms and tracking form the basis for mitigating this challenge. The inclusion of AI in developing instant estimates of channel conditions and topography can be explored to tackle this issue. Additionally, intelligent redundant data transmissions can be developed without overburdening the spectral resources and compromising energy efficiency.

8.4. Adaptive mobility

High QoS support for mobility is among the key goals of the next-generation cellular networks. The goals earmarked for the 6th generation cellular networks include support for devices moving at > 1000 Km/h speeds. Autonomous vehicles and service drones are the most important areas of application for 6G networks, therefore, improved sensing and localization for reliable network availability is of utmost necessity. Similar to the NLoS conditions, improved image processing algorithms along with sensor fusion can enable fast and accurate mobility models to ensure link reliability.

8.5. Energy efficiency

As smart industries, smart homes and even smart cities are turning into reality, the focus is turning on developing energy-efficient devices with long battery lifetimes. However, the 5G communication is significantly energy intensive. Therefore, the focus is now on designing energy-efficient radios as well as operational algorithms for scheduling, medium access, and encoding to extend the operational lifetime.

8.6. A joint MAC network

With the inclusion of the GHz band in both the wireless local area networks (WLANs) as well as B5G cellular networks, there is a challenge of interference between the co-existing networks. To enable this co-existence between the different radio access technologies (RATs), dedicated algorithms are designed which consume additional computational resources. Additionally, a majority of devices already support multiple RATs. Therefore, an integrated open platform can help in avoiding the deployment of multiple MAC layers for different RATs. An integrated MAC layer can be designed that uses common antenna elements which are capable of operating in the shared bands. The softwarization of the encoding and resource allocation can enable the selection of the appropriate RAT based on the QoS and device capabilities. The role of AI will be fundamental to this integrated MAC, as the decisions regarding the selection of RAT, scheduling, and security will be dynamic based on the network requirements. Fig. 12 presents an overview of this idea with mmWave and μWave RATs coordinated by a joint MAC layer.

8.6.1. Resource allocation

The vision of IoE requires every device to be connected to the Internet. The exponential increase in connected devices all over the world further stretches the scarcity of radio resources. The main two issue rises due to this is the massive radio channel access and the coexistence of Het devices in the same network. The Device-to-Device (D2D) communication provides an efficient mechanism to assist the network [30]. The D2D communication is standardized by the 3GPP in Release 12, which is termed Proximity Services (ProSe) in Release 17. The AI and D2D communication is considered to be a prime piece of the 6G communication. The AI-enabled D2D communication is proven to enhance network reliability for out-of-coverage devices.

9. Conclusion

The Internet-of-Everything (IoE) is the necessity foreseen next generation smart world. To achieve IoE, the network should be self-organizable (SON) and self-sustainable (SSN). The next generation communication standard; New Radio (NR), offers flexibility and scalability. Injecting cognitive artificial intelligence (CIA) in NR assists to achieve SON and SSN. In this article, we provided the details of the medium access layer (MAC) of NR with its flexibility and scalability. Moreover, we have put some light on the research challenges in implementing a flexible and scalable MAC structure. In this article, efficient and viable solutions offered by the CIA are also presented. The tools with simulator environments and future research direction finalize the article. This article provides a solid foundation to comprehend the problems and difficulties in the NR MAC layer and how the CIA can be used to improve it.

Declaration of competing interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to https://doi.org/10.1016/j.compeleceng.2023.108717.

Data availability

No data was used for the research described in the article.

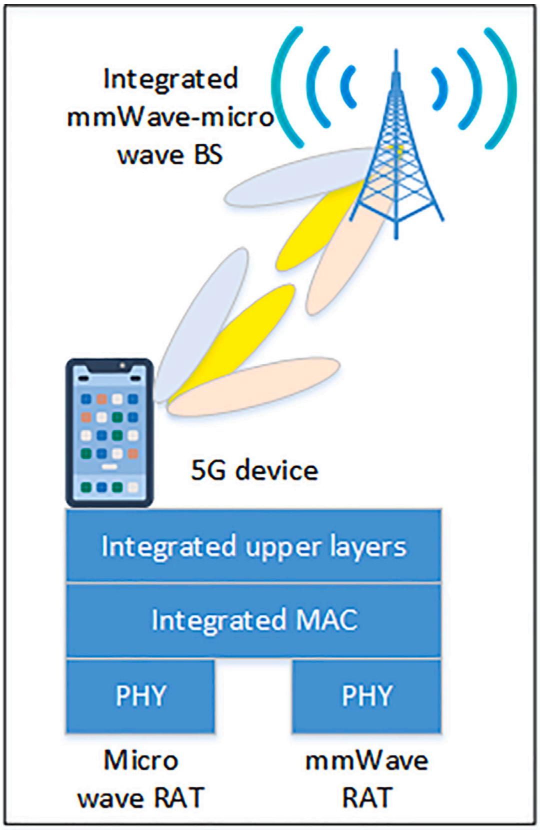


Fig. 12. MAC layer integration scheme.

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