Multi-Carrier Waveforms and Multiple Access Strategies in Wireless Networks: Performance, Applications, and Challenges

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ABSTRACT Current generation mobile communications require high-quality services. Adopting multiple access (MA) and multi-carrier waveforms potentially enhances the quality of services offered to end-users. However, in the majority of literature, the integration of multi-carrier and multiple-access approaches have not been extensively examined. One possible solution is to review multiple access and multi-carrier waveforms simultaneously to create a favorable foundation for the integration of these schemes. Thus, we consider a comprehensive review of multiple-access systems and multi-carrier waveforms jointly from 1st to 5th-generation (1G-5G) cellular networks. Initially, we present orthogonal MA (OMA) schemes called: frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency division multiple access (OFDMA) that have been utilized in 1G, 2G, 3G, and 4G, respectively. In addition, 5G wireless non-orthogonal multiple access (NOMA) techniques such as power domain NOMA (PD-NOMA), code domain NOMA (CD-NOMA), and other NOMA multiplexing methods are addressed in detail. On the other hand, we glanced at 5G cellular multi-carrier waveforms such as filter bank multi-carrier (FBMC), universal filtered multi-carrier (UFMC), generalized frequency division multiplexing (GFDM), and filtered orthogonal frequency division multiplexing (f-OFDM) waveforms. The assessment and comparison between different OMA, NOMA, and multi-carrier waveforms are carried out with the parameters: modulation schemes, bit error rate (BER), signal to noise ration (SNR), sum rate, peak-to-average power ratio (PAPR), latency, out of band emission (OOBE), and complexity. The analytical formulas of OMA, NOMA, and multi-carrier waveform schemes are also derived and verified using simulation data. Each multiple access strategy's merits, shortcomings, applications, and factors influencing its performance are also addressed. Eventually, possible recommendations for the integration of multiple-access and modulation technologies for next-generation mobile networks are also included.

INDEX TERMS Waveforms, modulation, multi-carrier, multiple access, orthogonal, non-orthogonal.

I. INTRODUCTION

Wireless networks set the stage for innovative features such as smart cities, homes, and vehicles with enhanced security [1]. In addition, mobile data applications such as Internet-of-things (IoT), high definition video, social networking, machine-to-machine (M2M) communication require fast broadband connectivity. To achieve these ambitious demands

and requirements, different generations of wireless networks have evolved. Similarly, modulation and multiple access methods have evolved from generation to generation to meet the demands of each of the mobile eras. Currently, these modulation and multiple access (MA) approaches are being integrated to suit these increased needs in 5G wireless network.

Waveforms are classified as single-carrier or multi-carrier. Single carrier waveforms have a lower peak to average power ratio (PAPR) than their multi-carrier counterparts.

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Furthermore, block transmission with a cyclic prefix reduces equalization complexity. However, a single carrier does not allow for user frequency multiplexing, reducing spectral efficiency and scheduling flexibility in multiple access scenarios. Furthermore, the PAPR of single-carrier waveforms increases with pulse shaping and transmit beamforming.

Multi-carrier modulation aims to split the bandwidth of the signals into parallel sub-carriers of the total bandwidth [2]. In this regard, different multi-carrier waveforms have evolved in the generations of wireless networks (1G-5G). Therefore, the choice of suitable and acceptable waveforms has long been a question of significant interest in a wide range of physical layers specified in the design wireless network standards. In this regard, we aim to present the performance, limitations, challenges, and comparisons of multi-carrier waveforms of OFDM with FBMC, UFMC, GFDM, and F-OFDM.

For 5G wireless network transmission, multi-carrier waveforms are logical choices. Furthermore, novel 5G multi-carrier-based waveforms, such as FBMC, UFMC, GFDM, or f-OFDM, necessitate a lot more research [3]. The primary goal of these multi-carrier waveforms is to maximize spectral efficiency and flexibility by shaping the spectrum via filtering. Filtering improves the frequency localization of the signal, allowing guard bands to be reduced. Because ICI is considerably reduced and per-sub-carrier or block equalization is possible, filtering may also eliminate the cyclic prefix (CP). In comparison to single-carrier signals, multi-carrier signals are more complicated [4].

Multiple access strategies allow several users to share limited network resources in telecommunication networks optimally. They are implemented to manage bandwidth among multiple users when more than one user needs to access such resources. This allows everyone to benefit from the services of the network by ensuring that no single user consumes all of the network's resources [5].

Researchers have been working on discovering the best MA scheme to obey simple concept of resource sharing among several users since the dawn of modern communications. The commencement of MA generation intends to be very evident and crucial in techniques of sharing bandwidth, frequency, time, and code separation. As a result, FDMA is used as a fundamental multiple access mechanism in analog first-generation cellular communication. TDMA is the most common mode of communication in digital 2G systems. For 3G networks, CDMA is the most widely used kind of multiple access. In the fourth generation of mobile systems, OFDMA and SC-OFDMA are utilized for the downlink and uplink, respectively [6].

Multiple access systems are classified as either orthogonal multiple access (OMA) or non-orthogonal multiple access (NOMA). Wireless resources are orthogonally allotted to various users in OMA according to their combinations of time, frequency, and code-domain. However, the number of supported users is restricted by the number of orthogonal resources accessible in OMA. Another issue is that channel-induced impairments almost always destroy orthogonality, even when orthogonal time, frequency, or code-domain resources are used. Hence, high-complexity "orthogonality restoration methods," like multi-user equalizers, must be used. As a result, OMA's ability to meet 5G's radical spectral efficiency and massive connectivity demands continues to be a challenge.

NOMA is being recommended for the 5G wireless system to support more users. Unlike standard orthogonal transmission techniques, NOMA employs non-orthogonal transmission on the transmitter side to induce intra-cell and/or inter-cell interference deliberately. Multi-user signal separation is performed on the receiver side via sequential interference cancellation (SIC). NOMA techniques allow multiple users to use non-orthogonal radio resources concurrently [7]. Table 1 shows the different multiple access methods from 1G to 5G.

Different from other research works that consider only the study of one, two, or three types of multi-carrier or multiple access strategies, this review considers a range of waveforms and multiple access schemes from 1G - 5G. The research gaps found in previous researches are also included in each waveform and MA technique before dealing with to the next method. The drawbacks of each of the predecessors and successors are not documented and reviewed in a single scientific work. Thus, we jointly consider waveforms and multiple access working principles, architectures, analysis, merits, and limitations from the first-fifth generations, which were treated independently and scattered.

Current generation mobile communications require high-quality services. Adopting multiple access (MA) and multi-carrier waveforms potentially enhances the quality of services offered to end-users. However, in most literature, the integration of multi-carrier and multiple-access approaches have not been extensively examined [18]. As a result, the review of multiple access and multi-carrier waveforms concurrently lays a solid foundation for integrating these schemes.

Therefore, to the best of the author's knowledge, this is a different review to consider the multi-carrier waveforms and multiple access strategies from 1st to 5th generations. In addition, the advantages, disadvantages, research gaps, and recommended solutions are included. Thus, the contributions of this work to the current research works are:

1) A Comprehensive study of multiple access standards and multi-carrier waveforms for the different generations of wireless networks (1G - 5G).
2) Review of OMA, NOMA, and multi-carrier waveforms with the focus of 5G wireless network.
3) Review of OMA schemes (FDMA, TDMA, CDMA, OFDMA and SC-OFDMA).
4) Review of 5G NOMA schemes called power-domain NOMA, code-domain NOMA, and NOMA techniques.
5) Comparison of OMA and NOMA schemes with respect to the parameters capacity, SNR, BER and PAPR.

6) Performance comparison of 4G OFDM and 5G wireless multi-carrier waveforms called: FBMC, UFMC, GFDM and f-OFDM.
7) Finally, a detailed survey of the benefits of multiple access and multi-carrier waveforms, research challenges, and their summery 5G wireless networks are addressed.

The remainder of the article is organized as follows. Section II gives the evolution of wireless networks from 1G-5G. The basic aspects of multiple access strategies from 1G-4G are described in Section III. This section addresses the fundamental concepts underlying multiple access systems and then demonstrates their applications. The review is then extended to $1^{st} - 4^{th}$ generation multiple access techniques. A more in-depth discussion of multiple access techniques in 4G, specifically OFDMA and SC-FDMA, is also available. Section IV provides detailed explanations of non-orthogonal multiple access schemes. Section V also thoroughly examines the current multi-carrier waveforms for 5G. Finally, Section VI presents the conclusion and research directions.

II. EVOLUTION OF WIRELESS NETWORKS
Our future is a networked society with unrestricted access to information and data sharing for everyone, everywhere, and at all times. To achieve these lofty goals, new technological components must be investigated to supplement existing wireless technologies. Furthermore, the exponential increase in mobile data traffic, combined with ongoing demands, puts increased pressure on mobile network operators to provide end-users with higher data rates and lower latency services. As a result, the transition from 1G to 5G is required.

A. FIRST GENERATION (1G)
This was the 1st mobile system deployed in the 1980s. It was completely analog, supporting only voice service with a data rate of about 2.4 kbps [8]. In this regard, the first multiple access communication systems were FDMA. The 1G standards were: advanced mobile phone system (AMPS), Nordic mobile telephone (NMT), and total access communication system (TACS) [1], [8], [9]. As it is the first generation, it has many disadvantages, like a frequent interruption of the voice, poor handoff, and no security at all.

B. SECOND GENERATION (2G)
It is the first digital cellular system. The 2G system offers a fixed data rate of 64 kbps while attempting to keep a certain level of service quality. It also starts services like short message service (SMS) and e-mail. The main 2G standards are the global system for mobile communications (GSM), interim standard 95 (IS-95), and interim standard 136 (IS-136) [10]. The significant advantage of 2G cellular phones is the extended battery life, which is achieved by low power radio signals with data rates of up to 144 kbps. 2G is also evolved to 2.5G that uses the 2G system framework but applies packet switching along with circuit switching.

General packet radio service (GPRS) and enhanced data rate for GSM evolution (EDGE) are the two leading 2.5G technologies, with data rates of 50 kbps and 200 kbps, respectively [1], [8]. The MA employed in this generation is TDMA.

C. THIRD GENERATION (3G)
This is launched in late 2000 with transmission rate of up to 2 Mbps with improved QoS. The 3G systems combine high-speed mobile access with Internet protocol (IP) services. Extra features such as global roaming and enhanced voice quality makes 3G a remarkable generation. Wideband code division multiple access (WCDMA), universal mobile telecommunications systems (UMTS), and code division multiple access (CDMA) 2000 technologies are used in 3G. In addition, high-speed uplink/downlink packet access (HSUPA/HSDPA) and evolution-data optimized (EVDO) have created an intermediate wireless generation between 3G and 4G with an improved data rate of 5-30 Mbps [9], [10]. A 3G cellular system requires more power than most 2G models, making it more expensive than its predecessor.

D. FOURTH GENERATION (4G)
A 4G wireless network standard system enhances existing communication networks by providing a comprehensive and dependable IP-based solution. Compared to previous generations, services such as voice, data, and multimedia are delivered to subscribers ''at any time and from any location'' at high data rates. Users can also access multimedia messaging services, digital video broadcasting and video chat, high definition TV content, and mobile TV [11].

An advanced radio interface, as well as technologies such as multiple-input multiple-output (MIMO), orthogonal frequency-division multiple access (OFDMA), and link adaptation, are used in 4G systems. For high mobility, 4G systems can support data rates of up to 100 Mbps, and for low mobility, data rates of up to 1 gigabit per second (Gbps) [12]. Because the networks have reached their theoretical limits, the 4G network cannot presently accommodate the anticipated future traffic. In LTE-A standard, the concept of multihop in-band and out-band relays has been introduced, which helps in increasing the coverage area. The main limitations of 4G systems is the use of cell-specific reference signals (CRS), which decrease the energy efficiency of the network by causing excessive overhead [13]. Because of the massive energy consumption and scarcity of spectrum, a new mobile communication standard known as 5G is required.

E. FIFTH GENERATION (5G)
With the explosive growth in end-user demand, 4G is being replaced by 5G advanced access technologies of non-orthogonal multiple access (NOMA). The main reason for the shift to 5G is to resolve the needs that 4G does not effectively address. Those are, increased data rate, decreased end-to-end latency, massive device connectivity, lower cost, and consistent quality of experience provisioning. Device densities, extreme eNBs with a large number of antennas, and

TABLE 1. Comparison of wireless network evolution [1], [8]–[14].

Generation	1G	2G	3G	4G	5G
Deployment	1980	1990	2000	2010	2020
Technology	AMPS, NMT TACS	GSM	WCDMA	LTE,WI-Max	Multi-RATs, Wi-Gig
Modulations or Waveforms	FDM	TDM	CDM	OFDM	FBMC, UFMC, GFDM, f-OFDM
Multiple Access	AMPS, FDMA	GSM, TDMA, GPRS, EDGE	(W)CDMA,HSUPA /HSDPA, EVDO	OFDMA, SC-FDMA	NOMA
Switching	Circuit	Circuit/Packet	Circuit/Packet	Packet	Packet
Bandwidth	30kHz	200kHz	5MHz	20MHz	60GHz
Frequency Band	800MHz	850/900/ 1800/1900MHz	800/850/900/ 1800/1900/2100MHz	1.8GHz, 2.6GHz	30 - 300GHZ
Data Rate	2 kbps	64 kbps	2 Mbps	1 Gbps	> 1 Gbps
Latency	N/A	629 ms	212 ms	60- 98 ms	< 1 ms
Core Network	PSTN	PSTN	Packet Network	Internet	Internet
Application	Voice	Voice + Data	Voice + Data + Video Calling	Online Gaming + HDTV	UHD Video + Virtual Reality
Unique Feature	Mobility	SMS, E-mail	Better Internet	Faster BB Internet	Ultra Fast BB Internet

ultra-high carrier frequencies with massive bandwidths are all features of 5G wireless networks. The objective is to guarantee complete connectivity and achieve pervasive and uninterrupted communications between people and machines, at anytime, anywhere, and with any service. The ultimate requirements of 5G are summarized in Table 2 [13], [14].

F. WIRELESS NETWORKS PERFORMANCE REQUIREMENT
The various performance requirements for 5G cellular network standards identified by academicians, vendors, or researchers to achieve optimum performance are mentioned here under [1], [13], [14].

1) DATA RATE
In 5G wireless networks, peak data rates of 10 Gbps (uplink) and 20 Gbps (downlink) are required, which is a ten-fold increase over the existing LTE cellular network's peak data rate of 150 Mbps [1].

2) LATENCY
In 5G wireless systems, a latency of less than 1 ms is required, which is also a ten-fold improvement over the current 4G wireless networks' 10 ms round-trip time.

3) BANDWIDTH
In order to support a large number of connected devices and ultra high bandwidths for more extended periods, a thousand-fold higher bandwidth per unit area is required.

4) ENERGY USAGE
Hundred-fold energy efficiency is anticipated in 5G [1]. Standardization bodies are already contemplating implementing green technology to reduce the energy consumption of devices substantially. To meet the subscribers' demand, improvement in energy efficiency is a mandatory criterion of green communication. The power requirement of the network increases with the frequency of use. To maximize the efficiency of upcoming systems, scheduling of time and frequency resources needs to be coordinated with the power optimization techniques.

5) BATTERY LIFE
Compared to 4G wireless networks, 5G wireless networks have a long-lasting battery life (up to ten years) to endorse a broader range of applications.

6) MASSIVE CONNECTIVITY
It is critical for emerging 5G wireless networks to connect billions of devices to realize the vision of D2D (device-to-device) and IoT technologies.

7) NETWORK AVAILABILITY
The 5G wireless standard anticipates a network that is always accessible everywhere and all the time. In a 5G wireless network, complete coverage is expected regardless of the location of the users.

8) QUALITY OF EXPERIENCE (QoE)

Characterizes each user's subjective perception of how well an application or service works. QoE is highly application and user-specific, with a satisfactory degree of reliability. Therefore, 5G must provide end-users with a better wireless network experience and satisfaction.

9) SECURITY

Higher security is yet another requirement for 5G standardization in authentication, authorization, and accounting.

Table 2 summarizes the ultimate requirements of 5G [13], [14].

TABLE 2. 5G performance requirements [1], [15].

Performance Requirements	Value
Peak Data Rate	> 10 Gbps
User Experienced Data Rate	> 0.1 Gbps
Connectivity Density	10^6 connections/Km^2
Service Density	10 Gbps/Km^2
End-to-end Latency	$<$ a millisecond level
Traffic volume density	Tens of Gbps per Km^2
Mobility	> 500 km per hour
Energy Efficiency	10 times 4G
Spectral Efficiency	3 - 4 times 4G
Battery Life	10 times 4G

III. ORTHOGONAL MULTIPLE ACCESS TECHNIQUES

A telecommunications network has limited resources, which are typically measured in bandwidth. When multiple users attempt to access such limited bandwidth, a multiple access scheme is used to control the share of bandwidth among multiple users. This allows everyone to access network services while also ensuring that no single user consumes all available resources. Since the dawn of modern communications, researchers have been trying to discover the best MA scheme to follow the simple rule of resource sharing among multiple users. Thus, multiple access in communication networks is a method that enables multiple users to share limited network resources effectively. The basic ways of sharing bandwidth, frequency, and time separation were chosen as the starting point for multiple access era [5].

Mobile radio networks are distinguished by their operational modes, services, applications, and multiple-access schemes. The scarcity of available radio spectrum has a significant impact on the growth of commercial radio communication technologies. Thus, the goal is to assign as many users to each available radio frequency segment as possible. This is accomplished by using various multiple-access schemes, which multiplex users and share resources in terms of time, frequency, or code. This indicates that users share the same resource by mitigating interference with other users. Basically, multiple access technologies can be classified as

TABLE 3. Modulation and multiple access in different generations of cellular networks [3], [16]–[19].

Gene ration	Modulation	Multiple Access	Duplex	Resources	Examples
1G	FDM	FDMA	FDD / FDD	Frequency / Frequency	AMPS, NMT
2G	TDM	TDMA	FDD	Time Slots	GSM, IS-54
3G	CDM	CDMA	FDD/ TDD	Time Slots /PN Codes	WCDMA
4G	OFDM	[SC]-OFDMA	FDD/ TDD	Time/ Frequency	LTE, LTE-A
5G	FBMC, UFMC GFDM, f-OFDM	PD, CD-NOMA Other NOMA	FDD/ TDD	Time/ Frequency	5G-NR

orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA).

The traditional multiple access method called OMA allows multiple users to share resources orthogonally with respect to time, frequency, or code [16]. Thus, depending on how the resources are shared, the most common OMA techniques are divided into frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA) and orthogonal frequency division multiple access (OFDMA). The summary of basic OMA, NOMA, and modulation schemes for the evolved generations of mobile communication are shown in Table 3.

A. FREQUENCY DIVISION MULTIPLE ACCESS

Researchers have been looking for multiple access schemes to allow resource sharing between multiple users since the beginning of modern communication systems. The emergence of multiple access was chosen as a transparent and fundamental way of sharing bandwidth, frequency, and time separation. Frequency modulation (FM) was used in the first MA wireless communication networks to divide the available frequency spectrum for a given system into some frequency channels. Each channel is assigned to a single user and covers a portion of the total bandwidth utilization (Figure 1. a) [16], [20].

Multiple users accessing the same system via different frequency channels could do so without experiencing substantial interference from other users accessing the system simultaneously. This is known as frequency division MA (FDMA). In an FDMA system, the bandwidth per user is entirely determined by the data rate and modulation scheme used. The system's total bandwidth is $B_s = K * B$ where K is the number of channels and $B = \alpha(\frac{R_b}{k})$ is the bandwidth per channel disregarding guard bands. When the guard bands are taken into account, we get the following expression.

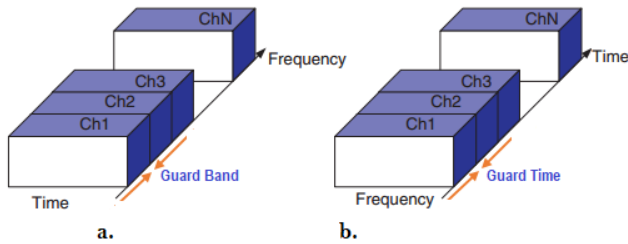$$B_s = K(B + B_g) \tag{1}$$

where B_g, denotes guard band size.

FIGURE 1. Multiple access schemes a. FDMA b. TDMA [16].

Limitations of Frequency Division Multiple Access
- It is challenging to assign multiple carriers in the same channel.
- Narrowband channels (less than the wireless channel's coherence bandwidth) are preferential.
- To reduce spectral emissions into adjacent frequency bands, guard bands in the frequency domain are required.
- There are a limited number of orthogonal resources [17].

B. TIME DIVISION MULTIPLE ACCESS

TDMA systems start in the digital communications period by subdividing the time axis into time slots designated to a single user for data transmission. The TDMA scheme's operational principles are frame and multi-frame, which means that a user can send a large data file within time slots of periodic frames. Figure 1. b shows data from a single user always remains in the same time slot position of a frame, all information from that portion is collected and aggregated at the receiver to shape the original transmitted packet.

When transmitting in a TDMA system, each transmitter uses the whole bandwidth. The system bit rate R_b^s is the rate at which each user transmits when accessing the channel. Neglecting guard times, the data rate per user is $R_b = \frac{R_b^s}{K}$, where K denotes the number of time slots per frame. If guard times are considered, the time allocated per channel is $T = \frac{T_f}{K} - T_g$ where T_f, K and T_g express the frame duration, number of time slots, and the guard time, respectively. The data rate per channel is calculated by dividing the number of bits transmitted per user by the frame duration [21].

$$R_b = \frac{\left(\frac{T_f}{K} - T_g\right) R_b^s}{T_f} \quad (2)$$

Obviously, a short guard time is required to improve the system's efficiency. Practical considerations, however, limit the minimum size of T_g. Thus, the system bandwidth is directly proportional to the system data rate:

$$B_s \propto \frac{R_b^s}{k} \alpha \quad (3)$$

where k represents the number of bits per symbol and α shows a constant related to the filtering, pulse shape and modulation order.

Many cellular standards, such as the 2G GSM and the 2.5G GPRS, adopted TDMA as their MA scheme.

Advantages of TDMA
1. The TDMA system's bit capacity is independent of the number of accesses.
2. The transponder's power amplifiers in a TDMA system operate in saturation mode, increasing the capacity of multiple accesses.
3. Because of the use of high-speed logic circuits and processors with high data rates, TDMA systems provide greater flexibility.
4. TDMA systems are less expensive than FDMA systems because they are easier to multiplex, are distance independent, and can be easily interfaced with terrestrial services.
5. Higher levels of interference noise can be tolerated by TDMA systems.

C. CODE DIVISION MULTIPLE ACCESS

The number of channels or time slots for a given system is fixed in FDMA and TDMA strategies, and a single channel is allotted to a single user for the duration of the communications period. A dedicated channel or time slot ensures service quality for real-time and constant-bit-rate voice telephony. However, as the number of services continues to expand from simple voice to more burst data transmissions, fixed channel assignment demonstrates a lack of effectiveness in utilizing the scarce spectrum, particularly as the number of users grows exponentially. This demonstrates that a much more dynamic channel assignment form of TDMA and FDMA could allocate a channel only when the user requests it. With this in mind, CDMA schemes based on spread spectrum schemes are launched in 3G. Using a high clock chip rate, the comparatively narrowband user's information is spread across a much broader spectrum in CDMA. As shown in Figure 2. a, it is possible to send multiple users' information on the same frequency spectrum without considerable complexity in sensing the desired signal at the receiver side if each user uses different uncorrelated codes and the correct spreading code is known to the receiver. With spread spectrum techniques, CDMA has evolved into a dynamic channel allocation MA scheme with no rigid channel allocation limitations for individual users. Unlike TDMA and FDMA, the number of users in CDMA is not fixed, allowing for the addition of new users to the system at any time. The maximum number of concurrent users in the system using the same frequency spectrum is determined by the total power of multi-user interference. CDMA is identified as the main MA scheme for 3G mobile cellular systems due to its demonstrated capacity improvement over TDMA and FDMA.

In CDMA, multiple users, possibly using different orthogonal codes, are multiplexed onto the same carrier. When received at the mobile station, transmissions on different codes in the downlink are orthogonal. The signal is transmitted from a fixed BS on the downlink, and all codes are received synchronized. As a result, in the absence of multipath, different code transmissions do not interfere with
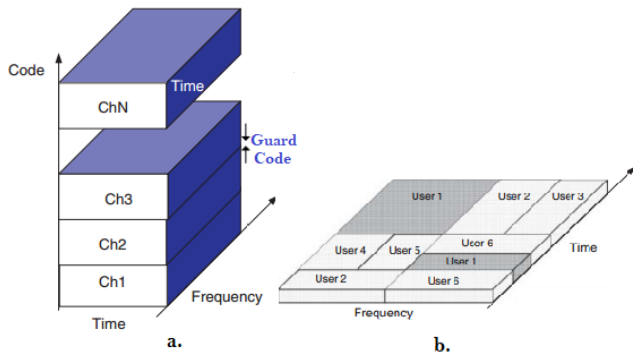
FIGURE 2. Multiple access schemes a. CDMA b. OFDMA [16].

each other [22]. Nevertheless, when multipath propagation is present, the codes are no longer orthogonal and interfere with each other, resulting in IUI or ISI. The issue is aggravated on the uplink because propagation times from mobiles in various locations to the BS fluctuate. When the received codes arrive at the BS, the codes are not synchronized, and orthogonality is not guaranteed.

D. ORTHOGONAL FREQUENCY DIVISION MULTIPLE ACCESS

OFDMA is a multiple access method used in the LTE wireless downlink channel. It divides the data into parallel sub-streams rather than transmitting data as a single stream. OFDM is a type of frequency division multiplexing (FDM) and multi-carrier modulation (MCM) strategy. The core principle behind multi-carrier modulation is to split the signal's bandwidth into parallel sub-carriers or narrow bands of the total bandwidth, as shown in Figure 2. b.

To address CDMA constraints, 4G employs MA techniques known as OFDMA and single-carrier carrier FDMA (SC-FDMA) for the downlink and uplink, respectively. Unlike CDMA, OFDMA has distinguishing characteristics like high flexibility, robustness to channel fading, ease of equalization, and high spectral efficiency [23]. Because of these appealing characteristics, OFDMA has become more valuable for high-speed data transmission. Furthermore, the entire frequency band is subdivided into orthogonal subcarriers.

For 4G wireless downlink transmission requirements, OFDM has been deemed the best solution. However, like any other technology, it has limitations as well, including high peak to average power ratio (PAPR), inter-carrier-interference (ICI) between sub-carriers, and high sensitivity to frequency errors [24]. Because the OFDM signal in the time domain is a sum of parallel random signals, this easily resulted in a high PAPR. Of course, high PAPR in the downlink is not a significant challenge as long as power is not an issue. However, an inexpensive power amplifier is required for the uplink since battery life is limited. To decrease the PAPR, the techniques employed are selective mapping, clipping, filtering, etc. As a result, an uplink mechanism has a trade-off between low computation complexity and system performance.

SC-FDMA, which is similar to OFDM but has an additional DFT pre-coding before OFDM modulation, is developed to address PAPR constraints. It is a technique for high-data-rate uplink communication with comparable throughput, performance, and complexity. SC-FDMA has the extra benefit of having a lower PAPR than OFDM, making it suitable for the uplink transmission by user terminals [25].

The transmitted signal of a user with M allocated sub-carriers is expressed as [6]

$$\mathbf{D} = [d_0, d_1, \ldots, d_{M-1}]^T \qquad (4)$$

where $[\cdot]^T$, and d_i denotes transpose operation, and modulated symbol respectively. After IFFT modulator, the signal vector $\mathbf{S}$ is

$$\mathbf{S} = \mathbf{F}_N^* \mathbf{T}_{N,M} \mathbf{D} \qquad (5)$$

where $T_{N,M}$ represents the subcarrier assignment mapping matrix, and its component attributes are determined by either distributed or localized sub-carrier allocation. $\mathbf{F}_N^*$ describes the N point IFFT matrix and $[\cdot]^*$ is conjugate operation. The $\mathbf{F}_N^*$ is the N point IFFT matrix is $\mathbf{F}_N = [\mathrm{f}_1^T, \mathrm{f}_2^T, \ldots, \mathrm{f}_N^T]^T$ and $\mathbf{f}_i = \frac{1}{N}\left[0, e^{-j\frac{2\pi}{N}l}, e^{-j\frac{2\pi}{N}2l}, \ldots, e^{-j\frac{2\pi}{N}(N-1)l}\right]$. The received signal in frequency domain after fading channel and FFT process, can be expressed as

$$\mathbf{h} = \mathbf{H}\mathbf{T}_{N,M}\mathbf{D} + \mathbf{n} \qquad (6)$$

where $\mathbf{H} = diag(H_K)$ and H_K is the frequency channel response at sub-carrier k. $\mathbf{n}$ is the *AWGN* noise vector and $\mathbf{r} = \left[r(0), r(1), \ldots, r(N-1)\right]^T$, in which $r(k)$ is the received signal at subcarrier k.

When analyzing the performance of OFDMA, the following parameters are taken into account:

1. **Bit Error Rate (BER)**: It is expressed as the ratio of bits in error with the total number of bits transmitted over a given time interval. It occurs when bits are altered due to interference, noise, distortion, or synchronization errors. BER is measured by comparing the transmitted and received signals and computing the error counts over the total number of bits transmitted.

2. **Signal to Noise Ratio (SNR)**: It is the ratio of bit energy (E_b) to the noise power spectral density (N_o) ($SNR = \frac{E_b}{N_o}$). SNR also refers to the ratio of useful information to false or irrelevant data. There exists an inverse relation between BER and SNR ($SNR \propto \frac{1}{BER}$). High BER causes packet loss, which minimizes throughput, and raises latency. Therefore, the BER is described in terms of SNR for any modulation technique. The graph in Figure 3 depicts the relationship between BER and SNR for OFDMA and SC-FDMA systems. The result confirms that the SC-FDMA system has a lower BER than the OFDMA system.

3. **Error Probability (P_e)**: The probability of error represents the rate of errors in the received signal. In the AWGN channel, for example, the error probability of
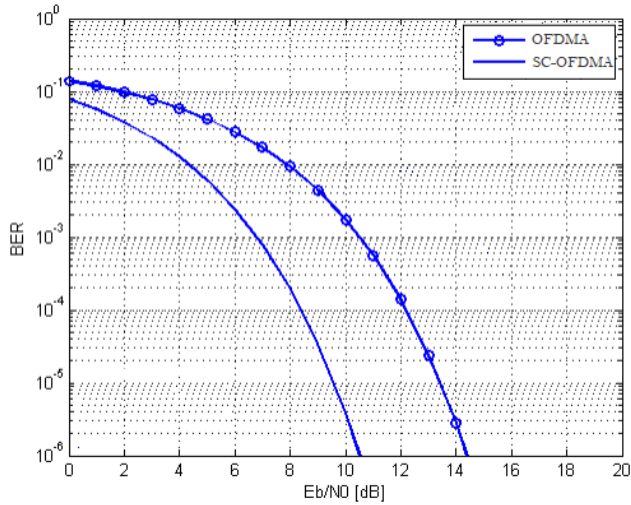
FIGURE 3. BER versus SNR (Eb/No) for OFDMA and SC-FDMA [26].

FIGURE 4. Channel capacity with fixed transmit power [22].

M-ary PSK and M-ary QAM is expressed as

$$P_e \cong 2\left(1 - \frac{1}{\sqrt{M}}\right) erfc\left[\sqrt{\frac{3E_{av}}{2(M-1)N_o}}\,\right] \quad (7)$$

where, N_o and E_{av} represent the noise density in AWGN and average value of transmitted symbol energy in M-ary QAM respectively.

4. **Power Spectral Density** (*PSD*): It defines a signal's power distribution with respect to frequency. The PSD is critical in making the correct radio resource management decisions at the BS in a wireless communication system, particularly for transmission format allocation, such as modulation and bandwidth.

5. **Power Limited Capacity**: A wireless channel's capacity with constant transmit power could be described as follows:

$$C = W \log\left(1 + \frac{SNR}{W}\right) \quad [Mb/S] \quad (8)$$

where W is the bandwidth in *MHz* with the constant transmit power P. When the transmit power is held constant, increasing bandwidth does not result in a linear increase in capacity. Figure 4 depicts the channel capacity as a function of bandwidth for different values of *SNR* at 1*MHz*. In order to achieve a linear increase in capacity, the transmit power must be scaled with bandwidth, necessitating the use of expensive high-power power broadband power amplifiers. However, this allows multiple concurrent transmissions on the uplink to maximize total transmitted power and capacity.

6. **Peak-to-Average Power Ratio (PAPR)**: The OFDM signal generated from the input information symbols, $X(k)$ for $0 \leq k \leq N-1$ is [26]

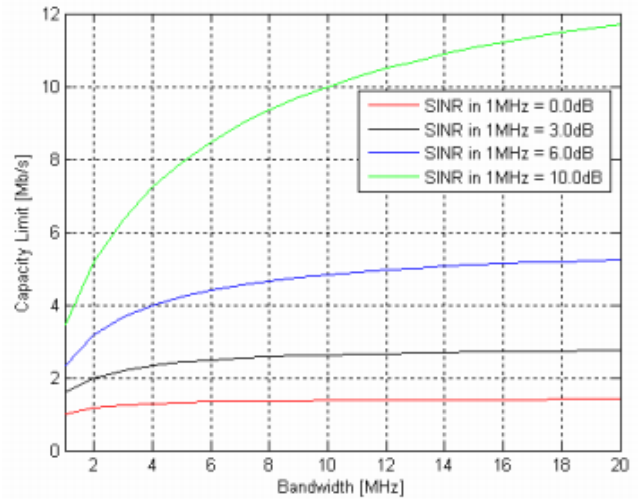$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k)e^{j(2\pi f_k t)} \quad (9)$$

where, $t = 0 \leq t \leq NT$, N is number of subcarrier, T is symbol period, $f_k = k\Delta f$, $\Delta f = \frac{1}{NT}$. As shown in (10), PAPR is the maximum instantaneous power divided by the average power of the OFDM symbol. High PAPR causes distortion and orthogonality loss among OFDM subcarriers.

$$PAPR = \frac{\text{Peak power of x(t)}}{\text{Average power of x(t)}} \quad (10)$$

where P_{peak} describes the maximum power of an OFDM frame and P_{avg} is the average power in each frame. The PAPR for a continuous time signal, $x(t)$ could be expressed as

$$PAPR = \frac{\max\{|x(t)|^2\}}{E\{|x(t)|^2\}} \quad (11)$$

where t is $0 \leq t \leq NT$ and $E\{\ldots\}$ is an expectation operator, $E\{|x(t)|^2\}$ describes average power of $x(t)$ and $\max\{|x(t)|^2\}$ is the peak power of $x(t)$.

The total system resources in OFDMA are shared among multiple users accessing the system by allocating only a fraction of the total bandwidth to each user. As a result, multiple users transmit on orthogonal subcarriers concurrently. Transmissions from multiple users are orthogonal if the relative delay between the received transmissions is less than the length of the cyclic prefix. The CP length is typically several microseconds to account for the multipath delay. As a result, timing synchronization within the CP is possible.

To achieve orthogonal transmissions in a CDMA-based uplink, sub-chip level synchronization with a small fraction of a microsecond depending on the chip rate is required, which makes it difficult in practice. The uplink capacity for an OFDMA system is [22]:

$$C_{OFDMA} = \sum_{i=1}^{K} \beta_i \log_2\left(1 + \frac{P}{fP + \beta_i N_O}\right) \quad (12)$$

where the capacity is in [$B/s/Hz$], β_i is the fraction of bandwidth allocated to user i. K, P, and f describe the number of users transmitting simultaneously, the received power for a user, and the ratio between other-cell and own-cell signal, respectfully. Because of the orthogonal sub-carriers used by different users and 1-tap OFDM sub-carrier equalization, there is no intra-cell interference or ISI in the case of OFDMA. However, for the OFDM case, cyclic prefix overhead (typically around 10 %) must be considered. As a result, the capacity of an OFDMA system could be reduced to account for CP overhead as

$$C_{OFDMA} = \left(\frac{T_S}{T_S + T_C} \right) \log_2 \left(1 + \frac{KP}{fKP + N_O} \right) \quad (13)$$

where T_s denotes the OFDM symbol duration and T_C describes the cyclic prefix duration.

Multiple users transmitting at the same time in a CDMA system interfere with each other due to the asynchronous nature of the received transmissions. Of course, in 3G systems based on CDMA, the same codes scrambled with different PN sequences are assigned to multiple users accessing the system, resulting in non-orthogonal uplink transmissions. A CDMA system's uplink capacity limit is defined as

$$C_{CDMA} = K \log_2 \left(1 + \frac{P}{(1+f)KP + (\alpha - 1)P + N_O} \right) \quad (14)$$

where K shows the number of users transmitting concurrently, P is the received power for a user, f is the ratio between other-cell and own-cell signal, α is the fraction of the own-user signal considered as interference, and finally N_0 is the background noise.

IV. NON-ORTHOGONAL MULTIPLE ACCESS

Multiple access schemes, classified as orthogonal multiple access (OMA) or non-orthogonal multiple access (NOMA), are methods for sharing radio resources across multiple users in a cell. OMA technologies include FDMA, TDMA, CDMA, and OFDMA, used in 1G, 2G, 3G, and 4G wireless communication systems, respectively. Multiple users are assigned to orthogonal radio resources in the time, frequency, code-domain, or their combinations in traditional OMA schemes such as FDMA, TDMA, CDMA, and OFDMA.

In FDMA, each user transmits a unique, user-specific signal over their unique frequency resource, so the receiver detects all users' data in their respective frequency bands. Likewise, in TDMA, each user is assigned an exclusive time slot, making it easy to distinguish the different users' signals at the receivers in the time domain. Multiple users can share the same time-frequency resources in CDMA, and their transmitted symbols can be mapped to orthogonal spreading sequences such as Walsh-Hadamard codes. Thus, a decorrelation receiver with a low level of complexity is used for multi-user detection (MUD). OFDMA is a combination of FDMA and TDMA in which radio resources are orthogonally separated in the time-frequency grid.

In theory, due to orthogonal resource allocation, there is no user interference in OMA systems. The number of supported users, however, is limited by the number of orthogonal resources available in OMA. One more issue is that channel-induced impairments almost always destroy their orthogonality even when orthogonal time, frequency, or code-domain resources are used. As a result, high-complexity "orthogonality restoring measures" such as multi-user equalizers should be used, which becomes a hard limit when massive connectivity is needed for 5G. Furthermore, it has been demonstrated theoretically that OMA cannot consistently achieve the maximum achievable sum-rate of multi-user cellular communication systems. As a result, meeting the extreme spectral efficiency and massive connectivity prerequisites of 5G remains a challenge for OMA.

To overcome the limitations of OMA, NOMA is currently being investigated as a design option for 5G wireless networks. The prominent characteristic of NOMA is that it can support more users than the number of orthogonal resource slots, thanks to non-orthogonal resource allocation.

Backward compatibility with conventional OFDM systems must also be considered when developing a new modulation scheme for 5G technology. Thus, it should also have the following main characteristics to resolve the challenges [18].

1) High Spectral Efficiency: New modulation techniques should greatly enhance system SE by reducing the guard band or guard time resources by mitigating OOB leakage among adjacent users.
2) Loose Synchronization Requirements: Many users are anticipated to be supported, particularly for the Internet of things (IoT), making synchronization challenging. As a result, new modulation schemes should handle asynchronous scenarios.
3) Flexibility: To support users with varying data rate requirements, modulation parameters (sub-carrier width and symbol period) are configured separately and conveniently for each user.

Thus, the 5G system requires introducing a new multiple access system to offer improved spectral efficiency and enhance the system's access capability and capacity. Inspired by such objectives, the newly proposed 5G multiple access strategy is non-orthogonal multiple access schemes (NOMA) [27]. Figure 5 depicts the various waveforms and multiple access approaches.

In comparison to conventional orthogonal transmission methods, NOMA employs non-orthogonal transmission on the transmitter side to deliberately introduce intra-cell and/or inter-cell interference. Based on successive interference cancellations (SIC), multi-user signal separation is carried out. NOMA techniques enable multiple users to use non-orthogonal radio resources at the same time. Each user signal is multiplexed in NOMA systems by various power allocation coefficients or signatures, such as codeword, sequence, interleaver, and preamble. Multi-user grouping (deciding which users should be grouped
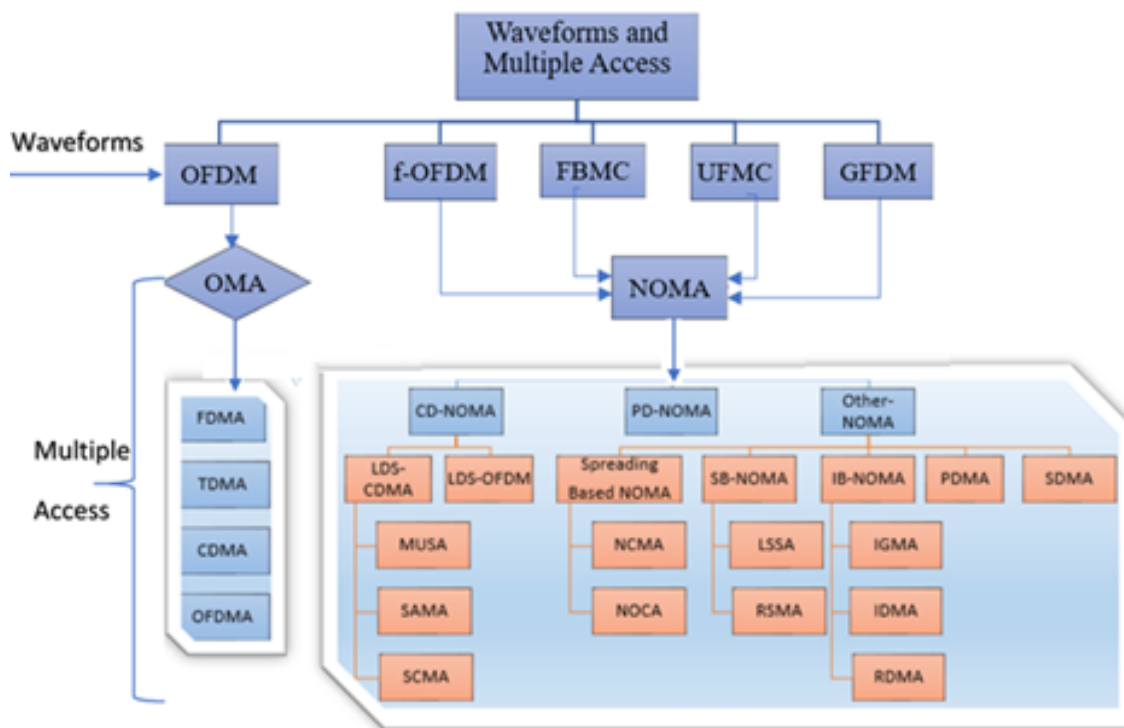
OMA	Orthogonal Multiple Access	CDMA	Code Division MA
IGMA	Interleaver-grid MA	PD-NOMA	Power Domain NOMA
TDMA	Time Division Multiple Access	PDMA	Partition Division MA
NOMA	Non-Orthogonal Multiple Access	SDMA	Spatial Division MA
OFDMA	Orthogonal Frequency Division Multiple Access	LSSA	Low Code Rate & Signature Based Shared Access
CD-NOMA	Code Division NOMA	SB-NOMA	Signature Based NOMA
LDS-CDMA	Low Density Spreading CDMA	RSMA	Resource Spread MA
MUSA	Multi-user Shared Access	IB-NOMA	Interleaver-Based NOMA
SCMA	Sparse Code Multiple Access	IDMA	Interleave Division MA
LDS-OFDM	Low Density Spreading OFDM	RDMA	Repetition Division MA
NOCA	None Orthogonal Coded Access	NCMA	Non-orthogonal Coded MA
SAMA	Successive Interference Cancellation Aided MA	FDMA	Frequency Division Multiple Access

FIGURE 5. Multiple access techniques (1G - 5G).

to deploy NOMA), resource allocation (power, code, etc.), users with significant power differences are preferred, and SIC or MUD (multi-user detection) interference cancellation techniques are used to eliminate the controlled NOMA modifications [7]. This can be accomplished by employing advanced IUI cancellation but at the expense of increased receiver complexity. As a result, the key characteristics of NOMA are [17], [18], [28]:

- Massive Connectivity: OMA is limited by the number of orthogonal resources available, but NOMA is not. NOMA theoretically supports an infinite number of users. NOMA's ability to support multiple users within a single resource block means that it has the potential to support massive connectivity for billions of devices. This feature is crucial for IoT networks with a large number of users that just require low data rates.

- Lower Latency: There is no need to schedule requests from users to the BS in the NOMA uplink, which is usually necessary for OMA schemes. As a result, flexible scheduling and grant-free uplink transmission are developed in NOMA, reducing transmission latency significantly.
- Improved Spectral Efficiency: Each NOMA user consumes the entire bandwidth, whereas each OMA user utilizes only a portion of it. As a result, NOMA has a high SE because multiple users use each resource block (time/frequency/code).
- Improved Cell-edge Throughput: NOMA endorses more equitable user fairness. Furthermore, in the downlink of AWGN channels, NOMA has a higher capacity bound than OMA.
- Relaxed Channel Feedback: Perfect uplink CSI is not compelled at the basestation in NOMA. In channel feedback, only the received signal strength is required.

NOMA techniques can be classified as power domain NOMA (PD-NOMA), code domain NOMA (CD-NOMA), and other multiple access NOMA [18], [28].

1) POWER-DOMAIN NOMA

NOMA is implemented in a relatively new domain, notably the power domain. It assigns multiple users to various power coefficients in terms of channel conditions [29]. After classic channel coding and modulation, various signals generated by multiple users at the transmitter are directly superimposed on each other. Multiple users share the same time-frequency resources detected by MUD algorithms such as SIC at the receivers. As a result, spectral efficiency improves at the expense of increased receiver complexity compared to traditional OMA. Non-orthogonal multiplexing with superposition coding at the transmitter and SIC at the receiver outperforms traditional orthogonal multiplexing. It is also optimal from accomplishing the capacity region of the downlink broadcast channels. Multiple users within the same time/frequency/code resource block support power-domain NOMA by differentiating them with various power levels. Unlike multi-user detection systems such as CDMA, which have multiple observations at the receiver, power-domain NOMA typically has only one observation. In particular, during NOMA uplink transmission, the signal received at the basestation is

$$Y = \sum_{a=1}^{A} h_a \sqrt{p_a} x_a + n \qquad (15)$$

where p_a and x_a denotes the transmit power and transmit symbols from the ath user, respectively, n is AWGN with variance σ^2, and the number of users sharing similar resource block is A. The transmit power, pa, is adjusted for each user to promote SIC at the receiver and guarantee that users with higher powers are detected with high precision. When SIC is invoked at the receiver, the user with the strongest CSI is decoded first. The corresponding signal element is
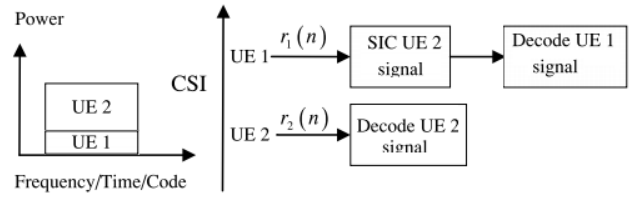

FIGURE 6. Downlink power-domain NOMA for the achievable rate of user equipment 1 and user equipment 2 $r_1(n)$ and $r_2(2)$ respectively [18].

then subtracted from the received signal. The SIC receiver processes signal in decreasing order of strength. It should also be noted that the transmit power levels of various NOMA users are usually different because they are exposed to different channel conditions. If the first detected symbols are all accurate, the NOMA user's received SINR is given by

$$SINR_a = \frac{p_a |h_a|^2}{\sum_{b=a+1}^{A} p_b |h_b|^2 \sigma^2} \qquad (16)$$

Figure 6 depicts the downlink transmission of NOMA for the two-user case, where different power levels differentiate the users sharing the same resource block with a total power constraint. The basestation, in particular, sends a superimposed signal involving two signals for the two users. In contrast to traditional power allocation schemes, such as water filling, NOMA designates less power to users with improved downlink CSI to ensure fairness and utilize diversity in time/frequency/code domains. At the receiver, SIC is used for signal detection. The user with the higher transmit power, the lower downlink channel gain, is decoded first, while the other user's signal is treated as noise. When the signal corresponding to the user with the highest transmit power is detected and decoded, its signal component is subtracted from the received signal to detect successive users. It should also be noted that the first detected user experiences the most IUI, and the detection error in the first user is passed on to the other users. That is why we must assign enough power to detect the first user. When PD-NOMA is combined with various communication methods (massive MIMO, coordinated multi-point (CoMP), cognitive radio, and so on), NOMA's performance improves.

When NOMA is used, two users are served by the same basestation, as shown in Fig. 7. This graph depicts the outage probability of NOMA and OMA with varying cell radius. The NOMA scheme supports two users, with the far user located at the cell's edge and the other user supported by the OMA scheme positioned randomly within the cell. The path loss exponent is 2. The transmit power SNR is 40 dB. The power allocation coefficients in NOMA are 4/5 and 1/5 for two users, respectively. According to the graph, the NOMA scheme has a lower outage probability. However, to mitigate interference, NOMA requires a more complex transmitter and receiver. Furthermore, power-domain NOMA is typically effective when only two or a few users share the same resource block. However, as the number of users

multiplexing in the power domain grows, multiple access interference worsens, and NOMA performance suffers [18].

2) CODE-DOMAIN NOMA

By allocating different codes to different users, code-domain NOMA allows multiple transmissions in the same time-frequency resource block. Compared to power-domain NOMA, CD-NOMA has inevitable spreading and shaping gain at the expense of additional signal bandwidth. The most widely used code-domain NOMAs are low-density spreading CDMA (LDS-CDMA) and low-density spreading OFDM (LDS-OFDM) [29].

LDS-CDMA is an innovative CDMA technology. Its distinguishing characteristic is using a low-density signature, equivalent to the low-density parity-check (LDPC) matrix, for codebook construction. When the number of users exceeds the number of samples per symbol period in traditional CDMA, MA is unavoidable, and optimal multiuser detection is challenging. However, because of the sparse structure of the signature in LDS-CDMA, a low-complexity near-optimal multiuser detection scheme based on a message-passing algorithm (MPA) is used in LDS-CDMA detection, effectively improving performance. Multi-User shared access (MUSA), successive interference cancellation aided multiple access (SAMA), and sparse code multiple access are all improved mechanisms and distinct forms of CDMA (SCMA).

LDS-OFDM is comparable to LDS-CDMA, except that the signature output is mapped into OFDM sub-carriers rather than CDMA time samples. As a result, a low-complexity MPA detector is used. In addition, unlike LDS-CDMA, LDS-OFDM employs multi-carrier transmission, making it suitable for wideband channels. Furthermore, because of its robust compatibility with OFDM, it is flexible in resource allocation.

3) OTHER NOMA SCHEMES

Aside from the well-known PD-NOMA and CD-NOMA solutions, a variety of additional NOMA systems, such as spatial division multiple access (SDMA) [28], pattern division multiple access (PDMA) [64], signature-based NOMA [65], interleaver-based NOMA (IB-NOMA) [28], and spreading-based NOMA [28], have recently been explored.

V. MULTI-CARRIER MODULATION TECHNIQUES

Single-carrier (SC) and multi-carrier (MC) waveforms are the two most common waveform formats [30]. A high data rate stream takes up a considerable percentage of the available spectrum in SC modulation techniques. Because of the narrow coherence bandwidth of the channel in high-rate transmission circumstances, SC systems need complicated equalization algorithms to interact with ISI. Therefore, SC modulation sends the whole data on a single carrier. GSM and CDMA both employ this method. The main reasons for choosing SC are battery power usage, and coverage expansion [31].
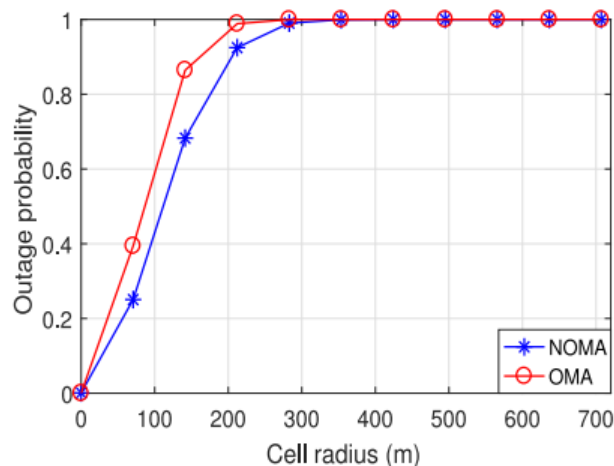

FIGURE 7. Outage probability of NOMA and OMA with different cell radius [18].

In MC systems, on the other hand, a high data rate data stream is split into different lower-rate streams, each of which is modulated on various sub-channels and multiplexed in the frequency domain. Multi-carrier modulation works by dividing the signal's bandwidth into parallel sub-carriers or narrow bands of the entire bandwidth [2].

OFDM is a multi-carrier modulation technology used in 4G wireless networks such as LTE and LTE advanced. Although OFDM has a simple implementation and is resistant to channel delays, it has a high PAPR. Furthermore, OFDM has large out-of-band side lobes, resulting in low spectral efficiency. That is, 4G communication technologies are constrained and will not be able to meet all 5G requirements [40]. In fact, various research projects have been conducted to develop waveforms for 5G wireless networks since 5G communication systems demand more data throughput, reduced latency, and more efficient spectrum utilization than ever before. Thus, the competent multi-carrier waveforms for 5G wireless standard approaches to overcome the identified limitations of the OFDM system are: universal filtered multi-carrier (UFMC), filter bank multi-carrier (FBMC), generalized frequency division multiplexing (GFDM), and filtered orthogonal frequency division multiplexing (f-OFDM) [33], [34], [36], [38], [40], [41].

A. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

An OFDM is a kind of modulation that uses multiple carriers. By inserting guard bands, it divides the spectrum into sub-carriers. These carriers overlap but are orthogonal because of the sensitivity of the pulse shaping. A cyclic prefix is used to remove ISI. On the receiver side, a one-tap equalizer is employed. OFDM has several advantages, including interference mitigation, barrier to fading, channel equalization simplicity, and computational efficiency [33].

The available bandwidth in MC transmission is split up into various parallel sub-channels known as sub-carriers. An OFDM signal is made up of N orthogonal and contiguous sub-carriers that are spaced in the frequency domain.
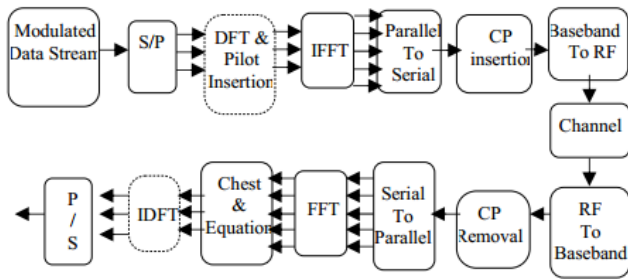
FIGURE 8. OFDM transmitter and receiver [43].

Radio-channel frequency selectivity, rate of channel fluctuations, phase noise, and the Doppler effect all influence sub-carrier spacing [42]. Multiplexing in both the frequency and time domains is feasible. The Δf range between these subcarriers is chosen so that they are non-frequency selective and have a flat gain in the frequency domain. For OFDM, different sub-carriers are spaced at $\Delta f = \frac{1}{T_{symbols}}$, which is known as orthogonality. The Figure in 8 shows the implementation block diagram for the transmitter and receiver of OFDM. It is realized with the parameters: number of sub-carriers, sub-carrier spacing, and CP length.

In OFDM system, a set of symbols upcoming from QAM modulation $X_{(m,k)}$, k = 0, 1, ..., N-1 and then this complex data symbols are modulated with IDFT on N parallel sub-carriers. Finally, CP is added to each OFDM symbol. That is, the last number of CP (N_{cp}) elements of an OFDM symbol at its beginning is copied. Thus, the OFDM transmitted signal takes the following form:

$$x(t) = \sum_{m=0}^{M-1} x_m(n + m(N - N_{cp})) \qquad (17)$$

with

$$x_m(n) = \sum_{k=0}^{N-1} X_{m,k} e^{j2\pi kn/N} \qquad (18)$$

where $X_{m,k}$ is denotes data symbol while K and M describe the number of sub-carriers and OFDM symbols, respectively. On the other hand, the inverse transmitter operations are applied so as to recover the original signal. That is

$$\begin{aligned} y_n &= h_n * x_n + w_n \\ &= \sum_{m=0}^{L} h_n x_m(n - m + N_{cp}) + w_n \end{aligned} \qquad (19)$$

w_n is a white Gaussian noise in time domain, x_n is transmitted over a channel h_n, provided that impulse response length L is shorter than N_{cp}.

OFDM also has limitations, which are mentioned as follows.

a) *Cyclic Prefix Overhead:* A cyclic prefix continues to add overhead redundancy to the transmission. Because a cyclic prefix is a copy of the tail of a symbol repeated

in its beginning, the same content is transmitted twice. Thus, the cyclic prefix is

$$\beta_{overhead} = \frac{T_{CP}}{T_{CP} + T_{symbol}} \qquad (20)$$

b) *Peak to Average Power Ratio (PAPR):* The addition of many sub-carriers with a variety of phases results in high power. When the summation of the different sub-carriers increases in OFDM, the power consumption reaches its peak. The use of IFFT creates high PAPR in the OFDM system.

c) *Sensitivity to Timing Offset and Frequency:* The transmitter and receiver use the same reference frequency to keep orthogonality. It loses the property of orthogonality because of ISI, which occurs due to sub-carrier leakage [37].

d) *Signaling Overhead*: due to the irregular timing of massive machine communication, the strict synchronization and orthogonal mechanisms required by OFDM brings intolerable signaling overhead.

e) *Out-Of-Band Emission*: OFDM with a large OOB emission is difficult to fully exploit the fragmentation resources between the used frequency bands [44].

f) *Synchronization*: When frequency-time quasi-synchronization is used, the performance of an OFDM-based system suffers highly. OFDM's high-spectrum side lobes cause problems, such as the need for precise synchronization. Of course, OFDM is indeed a perfect multi-carrier modulator scheme in the downlink. Synchronization is simple because all sub-carriers in the downlink are transmitted from the same BS. On the other hand, synchronization is more difficult in the uplink because each node transmits separately. As a result, precise synchronization in the uplink of an OFDM network is not attainable. Moreover, with CP-OFDM, the usage of CP affects overall spectral efficiency. In this regard, windowing and filtering are well-established techniques that suppress side lobes in CP-OFDM. Windowing is generally accomplished in the time domain, while filtering is applied in the frequency domain. Windowing smooths the transition between neighboring symbols by adding an additional window to both the edges of the generated symbols. The advantages of windowed OFDM (W-OFDM) include its simplicity [44], while the drawback is limited OOB emission improvement is attained. Another method to reduce the OOB emission of CP-OFDM is to use filtering. The 5G waveform filtering approaches that are used to reduce OOB emission and other limiting factors of OFDM are FBMC, UFMC, GFDM, and f-OFDM. These multi-carrier waveforms support 5G wireless communication standards.

B. FILTER BANK MULTI-CARRIER
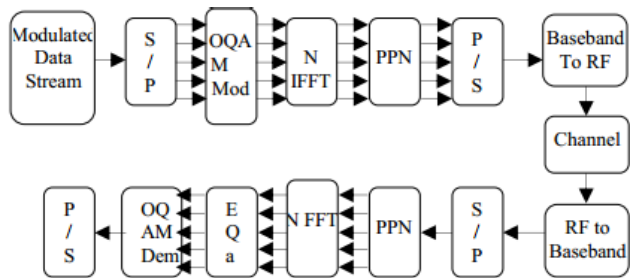FBMC is a more sophisticated OFDM approach that provides more extraordinary performance and efficiency when

FIGURE 9. FBMC transmitter and receiver [43].

FIGURE 10. Filter bank multi-carrier transceiver [50].

compared to OFDM. It was created to address the disadvantages of OFDM in terms of spectral efficiency deterioration and synchronization constraints. Sub-carrier filtering is used in FBMC to solve the ISI problem. In this regard, the block diagrams of OFDM and FBMC are identical, except for the CP in OFDM is replaced with filtering in FBMC as shown in Figure (9). FBMC also enables 5G applications to simultaneously sense the available spectrum and undertake transmission activities with the same device, opening up a plethora of new possibilities [45].

In comparison to OFDM, FBMC has the following fundamental distinctions:

1) Uses OQAM mapping in place of QAM mapping to reduce ICI using effective filtering [36].
2) To minimize ISI and ICI, polyphase network filtering is used after the IFFT process to obtain enhanced frequency and/or time localization based on the shape and length of the prototype filter [46].
3) It does not require CP because it uses frequency and temporal localization with filtering and QAM modulation [47]. This can reduce side lobes to a minimum [48].
4) The low delay-spread guarantees optimal performance with simple one-tap equalizers [49].
5) Suitable for a high-mobility environment with a fragmented spectrum for multi-point coordination.

FBMC implements a filtering operation at a sub-carrier level, which requires a long filter length. The requirement for these long filters poses difficulties in terms of actual implementation [26]. In addition, FBMC does not employ the cyclic prefix. As a result, interference occurs in the multi-path channel, which should be addressed using an equalizer. Another drawback of FBMC is that it is incapable of handling MIMO channels. Furthermore, due to the long filter tails of FBMC, it is not used in 5G applications, including IoT and M2M, where extremely short messages with very low latency are exchanged.

The general FBMC transceiver is shown in Figure 10 where P_T and P_R are the synthesis and analysis prototype filters, respectively. Its input signal equation is [50]:

$$\mathbf{s}_i(t) = \sum_n \mathbf{s}_i[n]\delta(t - nT) \qquad (21)$$

where $s_i[n]$ represents the data symbols, i being the sub-carrier index. T denotes the time spacing between the symbols. In FBMC, T is always equal to T_{FFT}, but the duration of
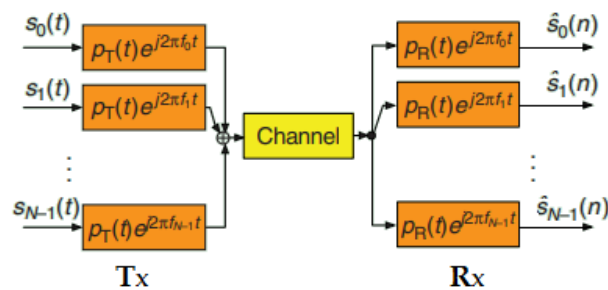
the P_T and P_R may be greater than T, making the successive symbols overlap each other. Thus, the overall transmitting signal is

$$\mathbf{x}(t) = \sum_n \sum_{i=0}^{N_c-1} \mathbf{s}_i[n]\mathbf{P}_{Tx}(t - nT)e^{j2\pi(t-nT)f_i} \qquad (22)$$

where $\mathbf{x}(t)$ is a group of time-limited sub-carriers consists of complex-valued tones and their magnitudes scaled by $\mathbf{s}_i[n]$. In addition, each sub-carrier is passed through a filter bank denoted by $\mathbf{P}_{Tx}$ to generate the transmitting signal. Thus, with the assumption of ideal channel conditions, the received signal $\mathbf{y}(t)$ is similar to the transmitted signal $\mathbf{x}(t)$.

Each sub-carrier of multi-carrier signals is filtered in the frequency domain in FBMC to lower side-lobe levels [50], [51]. As a result, the FBMC is a "synthesis" filter bank at the transmitter and a "analysis" filter bank at the receiver, with an IFFT as a modulator and an FFT as a demodulator, respectively.

C. UNIVERSAL FILTERED MULTI-CARRIER

UFMC, like f-OFDM and FBMC, is a filtered multi-carrier modulation scheme that uses specially designed filters to reduce OOBE. It inherits all of the benefits of FBMC and OFDM while eliminating the disadvantages [52]. Instead of single sub-carriers as in FBMC or the entire band as in f-OFDM, UFMC filters chunks of continuous sub-carriers [44]. The UFMC employs the sub-band filtering approach, in which frequency domain filtering is done with a defined granularity. The OOB emissions are reduced as a result of the filtering process. When comparing UFMC to OFDM, the side lobes are significantly lower in UFMC. As a result, when it comes to interference between sub-carriers caused by frequency shifts in the channel, UFMC is more resilient than OFDM.

The use of CP in UFMC is determined by the desired ISI. The ISI decreases when CP is used and vice versa. Cyclic prefix is typically not required in typical UFMC systems because the transition areas offer ISI protection. The signals are transmitted one after the other in the time domain to produce orthogonality in the frequency domain. Furthermore, the UFMC waveform's usage of sub-bands allows for better time localization. In comparison to the CP-OFDM waveform,
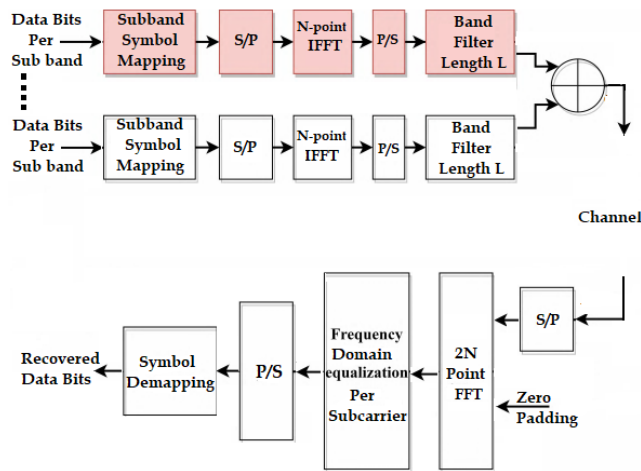
FIGURE 11. UFMC transceiver [54].

the absence of CP in the UFMC waveform necessitates more complicated receiver designs [53].

The benefits of UFMC are better spectral efficiency, requiring less overhead, emitting less OOB, being suitable for short burst transmissions, and allowing for low latency modes. Like any other technology, UFMC also has drawbacks. They are being unsuitable for high data rates, having a wider delay spread, requiring multi-tap equalizers, and increasing the implementation complexity by introducing filters and using FFTs for the sub-band [28]. However, if the UFMC is based on a finite impulse response filter rather than the traditional method, the computational complexity is reduced and the OOBE impact is very low [44].

The block diagram of a UFMC transceiver is shown in Figure 11, where N is the size of the IFFT at the transmitter. UFMC only uses transmit filters, unlike other filter-based waveforms that also use receive filters. The signal is filtered using a Dolph-Chebyshev filter of length L. The length of the received signal is $N + L - 1$ given the lengths of the sent signal N and the channel impulse response L. The data symbols are generated by performing a 2N-point FFT followed by a decimation with factor two by padding $N - L - 1$ zeros at the end of the received signal [28], [33]. The N sub-carriers are divided into sub-bands B. The number of sub-carriers in each sub-band is fixed, and they cannot be used for transmission. Zero padding is used to compute the N-point IFFT for the unallocated carrier. The sub-band replies are added together. The receiver employs a 2N-length FFT. A 2N-point FFT is used in the receiver to demodulate the signal. A key characteristic of UFMC is the use of a 2N-point FFT in the receiver, which allows the data symbols to be recovered without the need for CP. The symbol information is in the N even bins, and the ICI is in the N odd bins. Although the 2N-point FFT can perform effective demodulation without CP, the UFMC suffers from noise augmentation. Due to the noise enhancement, the SNR of UFMC is degraded by [28]

$$10 \log(1 + L/N), [dB] \tag{23}$$

At the transmitter, the base-band modulation used is Q-PSK. The output of the modulator is designated as D, where $D = [d_0, d_1, \ldots, d_{M-1}]^T$, where d_j is the modulated data with the sub-carrier index, $j = [0, 1, \ldots, M - 1]$. The modulated data vector D is multiplied with a precoding matrix A and is shown as in [40]:

$$\mathbf{X} = \mathbf{AD} \tag{24}$$

where $\mathbf{A}$ is the precoding matrix of size MXM. The kth sub-carrier of X is

$$X(k) = \sum_{m=0}^{M-1} a(k, m)d(m) \tag{25}$$

where $k = 0, 1, \ldots, M - 1$

The $MX1$ precoded data vector $X = [X(0), X(1), \ldots, X(K), \ldots, X(M - 1)]^T$ is divided into B sub-bands and each sub-band consists of M_B sub-carriers such that $M = BM_B$. As seen in (26), the signal of every sub-band is given to the various N-point IDFTs to obtain the time-domain signal. However, before performing the IDFT execution, each unoccupied frequency block is zero-padded to form an N-symbol block. Each zero-padded symbol stream is then processed by the N-point IDFT block to produce a time-domain vector $x_{Bi}(n)$.

$$x_{Bi}(n) = IDFT[X_{Bi}]$$
$$= \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_{Bi}e^{j2\pi nk/N} \tag{26}$$

The time-domain signals in equation (26) then pass through a Dolph-Chebyshev filter f_i of length L. The filter length is crucial since it affects the UFMC system's parameters, such as OOB emissions and overall performance. Long filter lengths may result in capacity loss due to overhead, whereas excessively short filter lengths may result in performance loss due to multipath fading channels. The filtered signal as a result is expressed by y_{Bi} is

$$y_{Bi} = x_{Bi} * f_i \tag{27}$$

The filter output has a length of $N + L - 1$ due to the linear convolution operation. The time-domain output signals from the various sub-bands join to form a UFMC waveform y as

$$y = \sum_{i=0}^{B-1} y_{Bi} \tag{28}$$

D. GENERALIZED FREQUENCY DIVISION MULTIPLEXING
Although OFDM has several favorable properties, such as immunity to frequency selective fading and ease of implementation, it misses the mark in meeting the needs of 5G wireless networks. By lowering the symbols, the addition of CP in OFDM lowers spectral efficiency and prohibits getting low latency. Additionally, OFDM is particularly susceptible to time and frequency synchronization issues because of its rectangular pulse shape and has significant OOB emission.
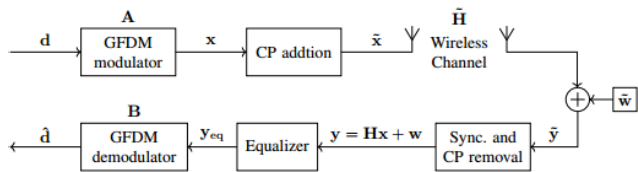
FIGURE 12. GFDM transceiver diagram [19].

To address the issues, researchers' approaches are divided into two categories: CP-OFDM-based and non-CP-OFDM-based [55]. The filtered OFDM (f-OFDM) and windowed OFDM (WOFDM) proposals in the CP-OFDM-based class attempt to address these concerns while maintaining orthogonality. In order to achieve better temporal and spectral features, the proposals in the non-CP-OFDM-based class initially disregard orthogonality. This leads to a significant paradigm shift in waveform design, which may cause some backward compatibility concerns. GFDM is a well-known non-CP-OFDM-based waveform that is an extended form of OFDM [57]. It is a promising non-orthogonal multi-carrier transmission system that's gotten much interest recently in the context of 5G cellular systems [56].

GFDM symbol has a block structure that contains KM samples where K sub-carriers carry M time slots, each composed of a group of OFDM symbols. Because GFDM utilizes only one cyclic prefix per symbol, its spectral efficiency is more significant than OFDM. The presence of CP allows for low-complexity frequency domain equalization. For each sub-carrier in GFDM, circular pulse shaping is used. This considerably minimizes OOB emission, allowing GFDM to be used for fragmented and opportunistic spectrum allocation. Furthermore, GFDM tolerates time and frequency synchronization errors because it is a non-orthogonal multi-carrier scheme. GFDM's block structure also allows for a variable time and frequency segmentation. Thus, as far as modulation is concerned, GFDM appears to be a viable option for meeting the demands and limitations of the 5G system.

The GFDM transceiver block diagram is shown in Fig. 12. It has a block structure of K sub-carriers, each with M time slots. The overall samples in a GFDM block are denoted by the symbol $N = KM$. The general GFDM transmit signal $x(n)$ of one block's baseband model is given by [57]

$$x(n) = \sum_{k=0}^{K-1} \sum_{m-0}^{M-1} d_{k,m} g_{k,m}(n), \quad n = 0, \ldots, N-1 \quad (29)$$

where n is sampling index, $d_{k.m}$, represents the complex valued data symbol, which is mapped from a Q-QAM constellation, of the kth sub-carrier and m^{th} time slot. The transmit filter $g_{k,m}$ circularly shifted to the mth time slot and modulated to the kth sub-carrier is expressed as

$$g_{k,m} = g((n - mK)_{modN}) exp(j2\pi \frac{kn}{K}) \quad (30)$$

After collecting the filter samples in a vector $g_{m,k} = [g_{k,m}(0), \ldots, g_{k,m}(N-1)]^T$, the expression

in (29) is written as

$$x = \mathbf{A}d \quad (31)$$

where d is a KM X 1 column vector containing $d_{k,m}$ as its $(mK + k)^{th}$ element and $\mathbf{A}$ is a KM X KM transmitter matrix with structure

$$\mathbf{A} = [g_{0,0}, \ldots, g_{K-1,0}, g_{0,1}, \ldots, g_{K-1,1}, \ldots, g_{K-1,M-1}] \quad (32)$$

The last step at the transmission is the addition of a CP with length N_{CP} to remove ISI. If the channel impulse response is assumed to be shorter than the CP and the transmitter and receiver are fully synced, then the received signal after the removal of CP can be:

$$\begin{aligned} y &= \mathbf{H}x + w \\ &= \mathbf{H}\mathbf{A}d + w \end{aligned} \quad (33)$$

where $\mathbf{H}$ is an N X N circular convolution matrix made from the channel impulse response, w is the vector of AWGN samples with elements having zero mean and δ_w^2 variance.

E. FILTERED ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

OFDM has a number of shortcomings, including drift sensitivity and carrier frequency offset, PAPR, and strong OOB emission. It is one of the alternatives to be employed in 5G waveforms in order to attain the expectations of 5G and overcome the constraints of OFDM [58].

A band in f-OFDM is divided into a distinct number of sub-bands, with sub-band filtering applied to each sub-band. Each sub-band has a different number of sub-carriers, sub-carrier spacing, and bandwidth. In addition, the CP, transmission time interval, IFFT size, and FFT size vary within each sub-band (Figure13). The main difference between the structures of UFMC and f-OFDM is the filter length and CP, which usually allow residual ISI [18], [37].

In f-OFDM, first, bit sequences are mapped into BPSK/QAM symbols, as shown in Fig. 13. Symbols are then mapped on orthogonal sub-carriers using IFFT, and CP is added to avoid ICI and ISI. After that, it goes via a pulse shaping filter before being broadcasted over a multi-path fading channel. QAM is employed with different modulation orders in this system. The modulated signal is subjected to IFFT to convert it to an OFDM symbol, with N denoting the size of the IFFT/FFT. The cyclic prefix prevents ISI induced by wireless channel delay spread. The filter $f(n)$ is an FIR digital filter that can achieve f-OFDM using a variety of window functions. The channel is AWGN, a multi-path of wireless channels or combining these two channels. Finally, the receiver follows the inverse process of the transmitter. The prototype filter $p(t)$ used in this waveform is a rectangular pulse mask of the OFDM symbol and a CP. Besides, the filter $f(t)$ is cautiously proposed to eliminate OOB interference. The length of the filter is set to 1/2 of the OFDM symbol,
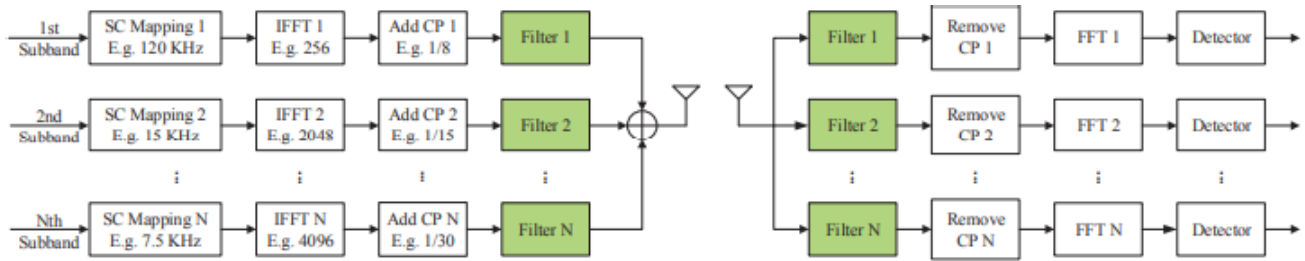
FIGURE 13. Downlink transceiver architecture of f-OFDM [59].

as well as the bandpass filter $p_i(n)$ which depends on time-domain [54] is

$$f(n) = p_i \cdot w(n) \qquad (34)$$

where $p_i(n)$, is ideal band pass filter and $w(n)$ is the Hanning window.

The large filter length of f-OFDM is its fundamental problem. The second constraint is that the filters should be generated dynamically based on the tone allocation. Due to the filter length, this is also difficult for low-latency service.

Filtered-OFDM shares much of the same properties as UFMC, with the exception of the following specific qualities [36]. i. Based on the user's needs, the whole band is subdivided into smaller sub-bands, each with a distinctive bandwidth. ii. Sub-carrier spacing varies by sub-band based on the user's need to effectively utilize spectrum. iii. To mitigate ISI, a CP is introduced in each sub-band, and the length of the CP is added as required to prevent additional spectrum utilization.

F. COMPARISON OF WAVEFORMS

So far, we have been investigating the different types of 5G waveforms (FBMC, UFMC, GFDM, and f-OFDM) compared to the 4G OFDM waveform. In this section, we compare them with respect to the different types of waveform performance indicators like computational complexity, spectral efficiency, PAPR, and filter length as summarized in Table 4. It is also shown in the simulation of the waveforms shown in Figure 14 with respect to the BER and SNR. As shown in Figure 14, FBMC outperforms all other waveforms in terms of BER performance. On the other hand, GFDM has the worst system performance, whereas UFMC has a stronger BER performance than OFDM.

Because all synthesis and analysis filters are frequency-shifted types of the corresponding low-pass prototype filter frequency response, the prototype filter is a critical component in multi-carrier modulation schemes. According to the concept of selecting the prototype filter, the most commonly used prototype filter is preferred in the investigation of various waveforms. For FBMC, the prototype filter evaluated in [60] is used, efficiently reducing the side-lobe of FBMC. The rectangular filter, one of the most popular proto-type filters in the OFDM theory model, is designated as the prototype filter for OFDM. For GFDM, we choose an RRC
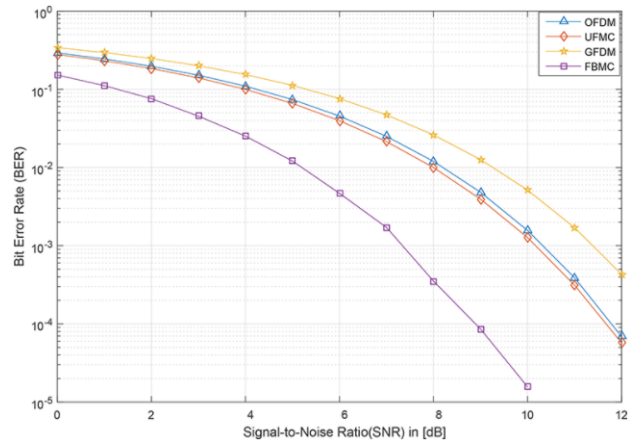

FIGURE 14. BER versus SNR comparison (FBMC, OFDM, GFDM and UFMC) [52].

filter, which has lower frequency domain spectrum leakage as the roll-off coefficient increases. When studying the GFDM system, the RRC filter [61] is commonly used as the prototype filter. In addition, we use the Dolph-Chebyshev filter [62] for UFMC, which suggests an approach for designing UFMC. Another reason for choosing these prototype filters is that they illustrate their benefits in various modulation structures. The use of the RRC filter, for instance, allows the GFDM to be flexible, which would be difficult to achieve with other prototype filters.

So far, the waveforms OFDM, FBMC, UFMC, GFDM, and f-OFDM have been discussed. OFDM is basically used for 4G wireless systems, while FBMC, UFMC, GFDM, and f-OFDM are 5G waveforms.

Although all types of filter-based OFDM ensure low OOBEs than standard OFDM, the OOBE reduction in FBMC is superior to all other waveforms. FBMC does not use a cyclic prefix, which enhances spectral efficiency. However, due to the long filter tails of FBMC, it is not used in 5G applications where IoT and M2M allow the exchange of very short messages with very low latency. The requirement for extremely long filters causes problems, particularly when considering practical system aspects. Furthermore, FBMC is incompatible with MIMO applications. With its high spectral efficiency, GFDM is one of the top contenders for 5G. GFDM employs a single CP for each packet. This improves bandwidth efficiency, but it may cause interference in adjacent subcarriers. To avoid this interference, GFDM necessitates

TABLE 4. Comparison of waveforms [19], [36]–[39], [53], [59].

Characteristics	Multi-carrier Waveforms				
	OFDM	FBMC	GFDM	UFMC	f-OFDM
Filter Length	$\leq$ CP Length	$= (3, 4, 5)X$ Symbol Duration	$\gg$ Symbol Duration	= Zero Padding Length	$\leq 1/2X$ Symbol Duration
Filter Granularity	Whole Band	Whole Band	Sub-carrier	Sub-band	Sub-band
Time Orthogonality	Orthogonal	Orthogonal in Real Domain	Non-orthogonal	Orthogonal	Non-orthogonal
Frequency Orthogonality	Orthogonal	Orthogonal in Real Domain	Non-orthogonal	Qasi-orthogonal	Quasi-orthogonal
OOBE	Bad	Best	Good	Good	Good
Latency	Low	High	High	Low	Low
PAPR	High	High	Moderate	High	High
CFO Robustness	Good	Better	Good	Good	Good
Mapping Scheme	QAM	OQAM	QAM and OQAM	QAM	QAM
Filter Convolution	Cyclic	Linear	Cyclic	Cyclic	Cyclic
Cyclic Prefix	Yes	No	Yes	No	Yes
Complexity	Low	High	High	Very High	Moderate

the use of complex receivers. When compared to CP-OFDM, both FBMC and GFDM achieve less OOBE. However, the transceiver structure used in FBMC and GFDM differs from that used in CP-OFDM, making FBMC and GFDM incompatible with existing 4G LTE systems. Although UFMC does not require complex equalization procedures, the length of the transmit filter in UFMC is comparatively smaller when compared to FBMC and GFDM. The disadvantage of UFMC is that it is more sensitive to time differences, so it may not be appropriate for applications requiring loose time synchronization. Because f-OFDM employs a longer filter length than UFMC, it effectively balances the frequency band and time localization. In addition, F-OFDM is less challenging than UFMC because it uses cyclic prefix channel equalization methods. Another benefit of f-OFDM is that the sub-carrier spacing and cyclic prefix length are different for each user. Finally, because f-OFDM is more adaptable, it is more compatible with existing systems.

A detailed comparison among these waveforms is found in Table 4.

VI. CONCLUSION AND RESEARCH DIRECTIONS
A. CONCLUSION
This paper looks at the multi-carrier waveforms and multiple access schemes emphasizing 5G wireless networks. Our goal for multiple access is to discuss the various multiple access approaches, such as OMA and NOMA. Despite our focus on NOMA, we also address the classic multiple access mechanisms that have existed throughout the history of wireless communications, from the first to the fourth generation (1G-4G). Each OMA technology (FDMA, TDMA, CDMA, and OFDMA) is outlined in its operations, advantages, and limitations. The novel orthogonal MA approaches are used to reduce out-of-band leakage while satisfying the different demands of 5G networks. NOMA is another interesting technique that differs from previous generations of wireless

networks, and it is extensively discussed in this paper. The evaluations, comparisons, and challenges of NOMA and OMA are also discussed. We also discussed a variety of critical hurdles, opportunities, and research directions in NOMA design, such as the conceptual design and analysis of power-domain, code-domain, and other domain NOMAs. Finally, the key multiple access techniques used from 1G to 5G with different modulation schemes (BPSK, QPSK, 16-QAM) are evaluated using the parameters BER, SNR, capacity, and PAPR.

On the other hand, this review conducts a thorough investigation of 5G multi-carrier waveforms. It begins with a detailed explanation of waveform structure and description. Then, 5G multi-carrier waveforms called: OFDM, f-OFDM, FBMC, UFMC, and GFDM are discussed and compared. This review examines the roles of 5G waveforms in relation to OFDM. Compared to FBMC and GFDM, f-OFDM and UFMC are more flexible in lowering complexity, as illustrated in the discussion. The study also discovered that PAPR is lower for OFDM than for the other waveforms. This is due to windowing and filtering strategies. Although the per-sub-carrier filtering feature makes FBMC the most resistant to carrier frequency offset, it also makes challenging to obtain Doppler diversity since the channel's temporal variation is averaged out by the long tail of the filter's impulse response. Our findings also show that, as compared to normal OFDM, the filter-based waveform achieves significantly lower OOB emission with minimal performance compromise. Based on the findings, multi-carrier waveforms and NOMA technologies are projected to play a crucial role in future 5G wireless communication systems with high connectivity and low latency. Finally, from the results of our discussion, it is worth mentioning that the joint consideration and design of new modulation and NOMA schemes are an essential direction to be explored in 5G networks.

B. RESEARCH DIRECTIONS

There are many problems and open issues in multi-carrier waveforms and multiple access schemes that must be addressed to achieve the goals set by the 5G wireless network.

1) JOINT DESIGN OF MULTI-CARRIER AND NOMA SCHEMES

The output of the sparse spreading matrix is mapped into orthogonal sub-carriers in some NOMA schemes, which are based on OFDM. In general, researchers are looking into effectively merging modulation and the NOMA scheme. When SCMA and f-OFDM are used together, the short CP of f-OFDM might introduce ISI and ICI when the sub-band is small, lowering SCMA's detection performance [18].

2) RESOURCE ALLOCATION

In comparison, NOMA has been brought to the attention of academics by creating resource allocation algorithms to NOMA as a potential radio access technology in next-generation communication systems, despite significant practical challenges that must be overcome. Multi-cell, interference scalability, carrier aggregation integration, resource allocation, and inter-cell communications are among them.

3) DESIGN OF WAVEFORMS AND MULTIPLE ACCESS FOR HIGH FREQUENCY BANDS

For high-frequency bands (mmWave and Teraherz), the development of modulation and multiple access approaches is gaining traction. Due to current circuit design limits, these bands appear to be great candidates for minimizing spectrum scarcity. However, the mmWave and THz bands have been shown to have poor propagation properties, providing substantial challenges in the design of 5G wireless networks. Noise and path loss, for example, are significant limitations in the mmWave and THz bands. In addition, high-level impairments such as carrier frequency offset and phase noise must also be considered because the mmWave and THz bands are noise-limited.

4) MULTI-USER CHANNEL ESTIMATION

The usage of mmWave communications in cellular systems necessitates the consideration of multi-user communication. This demands the use of a multiple access strategy, such as OFDMA or NOMA [28]. Unfortunately, most research studies assume single-user or multi-users with a single antenna per user, which is unrealistic. As a result, when designing channel estimation algorithms for multiple users, the implemented multiple access mechanism must be considered.

5) FREQUENCY-SELECTIVE CHANNELS

Because the individual frequency components experience independent fading, the vast bandwidth accessible in the mmWave bands unavoidably leads to frequency-selective channels. Traditionally, this problem has been overcome by using multi-carrier waveforms such as OFDM, FBMC, or UFMC [63]. The channel estimation for the wide-band

problem has primarily been researched in the context of hybrid architectures with OFDM. This field has to be further investigated in order to cover all architectures and multi-carrier waveforms.

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