



# Comparative Analysis of Waveform Design in Fifth-Generation (5G) Wireless Communication Systems

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ARTICLE INFO	ABSTRACT
<p>Article History:            Received 10 February 2020            Received in revised form 13 May 2020            Accepted 14 June 2020            Available online 15 June 2020</p>	<p>This paper provides a comprehensive review of studies on 5G waveforms, focusing on the primary candidates and conducting a comparative analysis of their suitability for next-generation wireless communication. The research follows a structured approach to ensure clarity and coherence in the discussion. Initially, a brief introduction to waveform concepts is provided, highlighting their role in wireless communication systems and outlining the key use cases and design requirements essential for 5G networks. These requirements include spectral efficiency, latency reduction, energy efficiency, and robustness against interference. Subsequently, the characteristics of Cyclic Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM), the dominant waveform in fourth-generation (4G LTE) networks, are examined. Given that CP-OFDM serves as the benchmark for evaluating new waveforms, its strengths and limitations are critically assessed. This analysis establishes a foundation for understanding the motivations behind exploring alternative waveforms for 5G. The paper then delves into the main waveform candidates proposed for 5G, analyzing their distinct features, benefits, and trade-offs. These candidates include Filter Bank Multi-Carrier (FBMC), Universal Filtered Multi-Carrier (UFMC), Generalized Frequency Division Multiplexing (GFDM), and Orthogonal Time Frequency Space (OTFS) modulation. Each waveform is assessed in terms of its ability to meet 5G performance criteria, such as improved spectral efficiency, reduced out-of-band emissions, and enhanced performance in diverse deployment scenarios. Finally, a comparative evaluation is conducted, summarizing the key strengths and weaknesses of each waveform in relation to 5G objectives. The paper concludes by discussing the potential adoption of these waveforms in future wireless systems, considering both theoretical analyses and practical implementation challenges.</p>
<p>Keywords:            Waveform Design, 5G, Spectral Efficiency, PAPR, OOB, CP-OFDM</p>	

## 1. INTRODUCTION

The standardization activities of mobile wireless communications began with analog standards introduced in the 1980s, and new generations of mobile wireless communications have been developed approximately every 10 years to meet the increasing demand of the market and users. The transition from analog to digital in second-generation

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(2G) wireless communication systems marked the beginning of mobile data services. The digital evolution of third-generation (3G) wireless communication systems enabled video calls and Global Positioning System (GPS) services on mobile devices. Fourth-generation (4G) wireless communication systems, utilizing Orthogonal Frequency-Division Multiple Access (OFDMA) as the physical layer, further facilitated the provision of data services by making better use of time-frequency resources [1]. In recent years, the International Telecommunication Union (ITU) has set forth the expectations for the fifth generation (5G) of wireless communication systems [2], and studies for the next-generation wireless communication systems are being conducted in collaboration between universities, industry, and relevant standardization bodies to achieve the first deployment of 5G by 2020.

The vision for 5G is to significantly improve key performance indicators (KPIs) such as peak data rate, spectral efficiency, power consumption, complexity, connection density, latency, and mobility. Additionally, the new standard must support a wide range of diverse services operating within a single network [3]. The IMT-2020 vision defines 5G use cases into three main categories: Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communications (mMTC), and Ultra-Reliable Low-Latency Communications (URLLC), each with its specific characteristics, including a peak data rate of 20 Gbps for eMBB, device density of 1 million per square kilometer for mMTC, and latency less than 1 millisecond for URLLC [4]. To meet and fulfill these various requirements, a flexible air interface is necessary. Accordingly, the waveform, which is the main component of any air interface, must be appropriately designed to facilitate such flexibility [5-6].

Waveform is a fundamental component of any telecommunications technology. Generally, there are two main categories of waveforms [7]: 1) Single-Carrier Waveforms and 2) Multi-Carrier Waveforms. The 2G and 3G cellular communication systems, including GSM, UMTS, CDMA2000, as well as technologies like ZigBee and Bluetooth, are compatible with single-carrier waveforms [7]. The 4G cellular communication system (LTE) utilizes multi-carrier waveforms [7]. Multi-carrier waveforms are also employed in Asymmetric Digital Subscriber Line (ADSL), Wireless Local Area Network (WLAN), WiMAX, Digital Audio Broadcasting (DAB), and Digital Video Broadcasting-Terrestrial (DVB-T) standards. Typically, single-carrier waveforms have a low Peak-to-Average Power Ratio (PAPR) [7], making them power-efficient and suitable for scenarios with limited coverage and extended battery life for user equipment. On the other hand, multi-carrier waveforms provide high spectral efficiency, flexible resource allocation in the frequency domain, and easy integration with multi-antenna MIMO technologies, which are key items for the new 5G radio structure [6-7]. The new 5G radio structure (5G NR) supports diverse use cases with deployments across frequency ranges from below 1 GHz to 100 GHz [7].



Fig.1. Spectrum and Deployment of 5G (Source: Ericsson)

Although single-carrier waveforms can be attractive for massive IoT devices (due to increased battery life) and for high carrier frequency operations (where transmission loss is high), multi-carrier waveforms have been considered the main candidates for 5G for the aforementioned reasons. The 3rd Generation Partnership Project (3GPP), which develops protocols for mobile telecommunications, has evaluated several multi-carrier waveforms as well as single-carrier waveforms. This evaluation reveals that different waveforms have their own advantages and disadvantages, making different waveforms suitable for various scenarios. Despite recognizing that the new 5G radio interface based on multi-carrier waveforms complicates the overall system design, 3GPP concluded with an OFDM-centric approach for both uplink and downlink transmissions. Additionally, the DFT-Spread OFDM (DFTS-OFDM) waveform, which possesses single-carrier characteristics, has been considered as an option for uplink transmissions in limited coverage scenarios [7, 22].

This paper aims to provide a comprehensive overview of studies on 5G waveforms, reviewing the main candidates and performing a comparative analysis of the proposed suitable waveforms. The research scenario is presented as follows: initially, a brief description of waveform definition and the use cases and design requirements of 5G

waveforms are discussed. Subsequently, the main characteristics of CP-OFDM, currently used in fourth-generation (4G LTE) wireless communication systems, are presented. The foundation of 5G waveform discussions is CP-OFDM, as the performance of a new waveform is typically compared to it. Additionally, the fundamental features of the main waveform candidates, along with their respective advantages and disadvantages, are examined and analyzed. In conclusion, based on the research objectives, the key and essential features of the waveforms are briefly reviewed and compared.

In this research, various types of multi-carrier waveforms are presented and compared, leading to the selection of OFDM for the new 5G radio structure (5G NR). The structure of this research is as follows: initially, based on the latest available studies, OFDM-based and FBMC (Filter Bank Multi-Carrier)-based waveforms are introduced. Then, the DFTS-OFDM waveform is discussed. Another section explains the requirements and design necessities for the new 5G radio structure (5G NR). Another section of the research presents key indicators for comparing waveforms, upon which the performance of multi-carrier waveforms is compared in the concluding section.

## 2. DEFINITION OF WAVEFORM AND DESIGN REQUIREMENTS IN 5G

A waveform (Waveform) defines the physical shape of the signal that carries the modulated information. Information is mapped from the message space to the signal space at the transmitter, and an inverse operation is performed at the receiver to reconstruct and receive the message in the communication system. A waveform, defining the structure and shape of information in the signal space, can be described by its fundamental elements: symbol, pulse shape, and lattice (Figure 2). Symbols constitute the random part of a waveform, while the pulse shape and lattice form its deterministic part.

a) Symbol: A set of complex numbers in the message space is generated by grouping and aggregating several bits together. The number of bits grouped in a symbol determines the modulation order, which significantly impacts the throughput.

b) Pulse Shape: The shape of symbols in the signal space is defined by pulse shaping filters. The filter shapes determine how energy is distributed and spread in the time and frequency domains, significantly affecting the characteristics and properties of the signal.

c) Lattice: Created by sampling the time-frequency plane, the sample locations define the coordinates of the filters in the time-frequency grid. The geometry of the lattice, depending on the placement and spacing of the samples, can take various forms such as rectangular or hexagonal. Additionally, the grid can also be utilized with additional dimensions in the spatial domain.

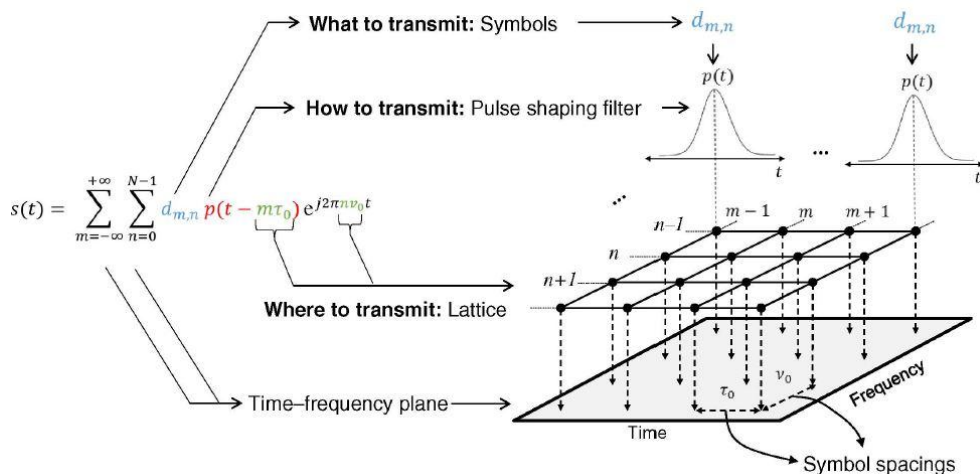


Fig.2. Definition of Waveform and Its Elements [6]

The following section will outline the requirements and design necessities of waveforms for 5G use cases. As mentioned in the introduction, the new radio structure for 5G must support a wide range of diverse services. Initially,

applications that require more bandwidth and higher spectral efficiency fall under the eMBB category, while applications that need more durability for device battery life fall under the mMTC category. For instance, industrial smart sensors [8] or medical implants [9] often operate for several years without maintenance, making low device complexity and high energy efficiency crucial for such mMTC services. Furthermore, critical applications like remote surgery [10] or autonomous vehicles [11] are presented in URLLC. The key requirements and necessities associated with each of these use cases are summarized in Table 1. The following design criteria are essential to fulfill and meet these 5G requirements:

- High Spectral Efficiency: Modulation order, type of pulse shaping filters, and lattice density play crucial roles in determining spectral efficiency. Guard units in time or frequency domains reduce spectral efficiency, which is especially important for eMBB communications. Moreover, multi-antenna techniques [12], such as beamforming and massive MIMO, are other significant aspects for efficient lattice usage. However, self-inter-symbol interference (Self-ISI) and self-inter-carrier interference (Self-ICI) of a waveform prevent the direct and effective use of MIMO techniques and significantly increase complexity [6].

- Low Latency: 5G offers a latency of less than 1 millisecond for URLLC applications. This goal can be managed by shortening the transmission time interval or increasing sub-carrier spacing. However, the latter approach increases the relative overhead of the cyclic prefix (CP) for a given transmission time interval. Additionally, localization in time is crucial, and to achieve this requirement, shorter filter/window duration is necessary [6].

High Reliability: Reliability is evaluated by Bit Error Rate (BER) or Block Error Rate (BLER) and is crucial for critical communications where errors are less tolerable. Additionally, retransmissions due to errors increase latency; hence, high-reliability links aimed at providing low latency are also desirable.

- Massive Asynchronous Transmission: It is anticipated that a large number of nodes in the 5G network will communicate for mMTC services. To maintain synchronicity for these applications, additional overhead is required. However, this significantly reduces spectral efficiency. Therefore, waveforms that demand stringent synchronization requirements are not suitable for mMTC applications. Consequently, waveforms well-established in multiplexing and localization are better suited to reduce synchronization requirements in these applications.

- Low Device Complexity: Computational complexity is another critical design criterion for waveforms and depends on the number of operations required at the transmitter or receiver. Additional algorithms for windowing, filtering, and interference cancellation significantly increase complexity, and system designers must consider this to design an energy-efficient and cost-effective transmitter and receiver.

- High Energy Efficiency: Low computational complexity and low Peak-to-Average Power Ratio (PAPR) provide high energy efficiency. PAPR is a statistical measure evaluated by the Complementary Cumulative Distribution Function (CCDF) of the signal. Low PAPR is essential for efficient performance of power amplifiers (PAs), which are among the most energy-consuming components in a transmitter and receiver.

**Table 1.** Fundamental Requirements and Necessities of 5G Use Cases

Basic requirements and requirements of	URLLC	mMTC	eMBB
	High reliability	Mass Asynchronous Transfer	High spectral efficiency
	Low latency	High energy efficiency	Low latency
Low computational complexity			

### 3. OVERVIEW OF CP-OFDM AND NECESSITY OF RESEARCH

As stated, the baseline for 5G waveform discussions is CP-OFDM. Orthogonal Frequency Division Multiplexing (OFDM) is the most common multi-carrier modulation scheme currently deployed in many standards, such as the downlink of 4G LTE and the IEEE 802.11 family of standards [13]. Its main advantage over single-carrier transmission schemes is its ability to handle frequency-selective channels for broadband communications [6]. In this modulation scheme, data is divided into parallel streams, each modulated by a set of narrow subcarriers. The

bandwidth of each subcarrier is less than the channel coherence bandwidth. Hence, each subcarrier experiences a flat fading channel, allowing frequency-domain equalization through simple multiplication. Additionally, OFDM systems efficiently use the spectrum due to overlapping orthogonal subcarriers, allowing flexible frequency allocation. A discrete baseband OFDM signal is represented as follows:

$$s_{OFDM}[k] = \sum_{n=0}^{N-1} d_n e^{j2\pi k \frac{n}{N}} \tag{1}$$

where  $d_n$  represents the complex data symbols on subcarrier  $n$  and  $N$  is the total number of subcarriers. OFDM can be easily implemented using the Inverse Fast Fourier Transform (IFFT) algorithm. Afterward, a cyclic prefix (CP) is added by copying the last part of the IFFT sequence (symbol) and appending it to the beginning of the OFDM symbol as a guard interval. The length of the CP is determined based on the maximum excess delay of the channel to mitigate inter-symbol interference (ISI).

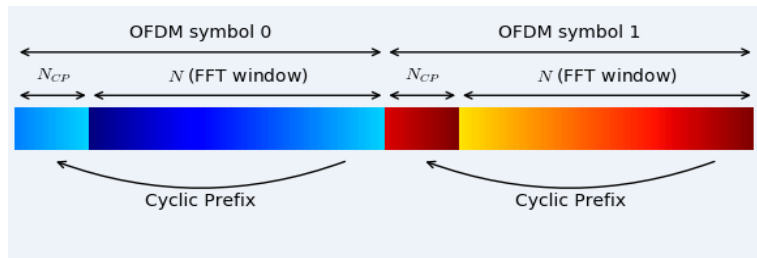


Fig.3. Insertion of CP in an OFDM Symbol [6]

On the one hand, a fixed guard interval leads to a reduction in spectral efficiency. Additionally, the CP ensures interference management in multipath environments by guaranteeing circular convolution and enabling easy frequency-domain equalization (FDE). OFDM also mitigates inter-carrier interference (ICI) to some extent by setting the subcarrier spacing according to the maximum Doppler spread [6]. The block diagrams for CP-OFDM transmitter and receiver are shown in Figure 4:

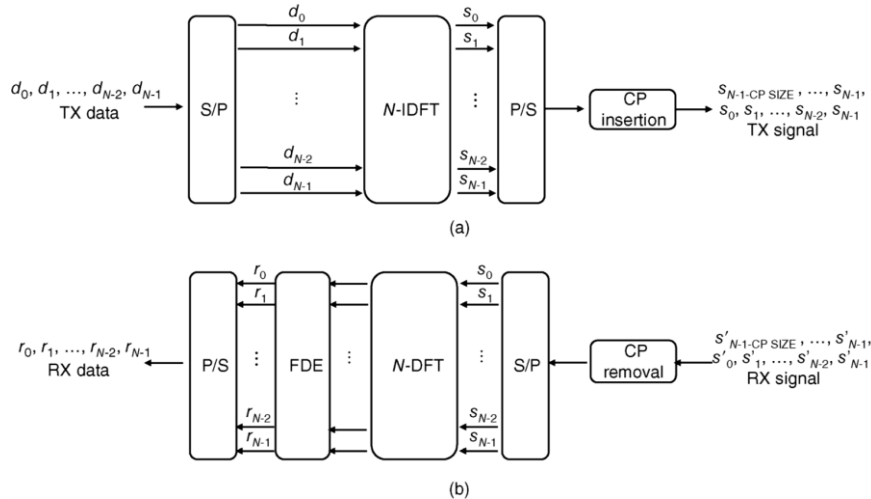


Fig.4. Block Diagram of (a) CP-OFDM Transmitter and (b) Receiver [6]

A major drawback of any multi-carrier system, including CP-OFDM, is the high Peak-to-Average Power Ratio (PAPR) caused by the random addition of subcarriers in the time domain [14]. Due to high PAPR, the power amplifier (PA) in the transmitter operates in the nonlinear region, causing distortion and spectral spreading. Moreover, the output power variance increases with the number of subcarriers. Another critical challenge for CP-

OFDM systems is the high Out-of-Band Emission (OOBE). The OFDM signal is well-represented in the time domain with a rectangular pulse shape, leading to a sinc shape in the frequency domain, as shown in Figure 5:

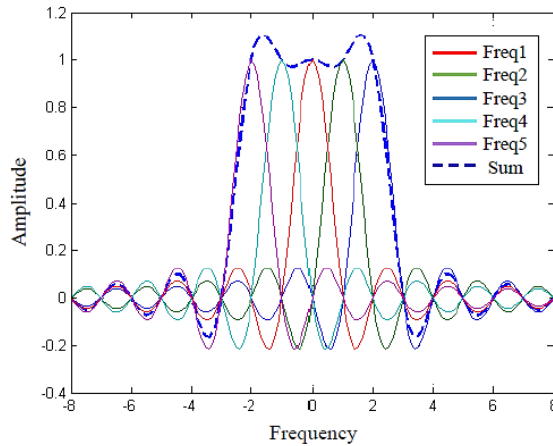


Fig.5. OOBE Problem in Multi-Carrier Schemes [6]

In particular, the sidelobes of the sinc function in edge carriers cause significant interference, which must be reduced to prevent adjacent channel interference (ACI). Typically, OOBE is reduced using various windowing and filtering techniques, along with guard band allocation [15] to meet the spectral mask requirements of different standards. The 3GPP LTE standard uses 10% of the total bandwidth as a guard band to address this issue. However, fixed guard band allocation reduces spectral efficiency. Additionally, OFDM systems are more sensitive to synchronization errors compared to single-carrier systems. For example, if orthogonality between subcarriers is lost due to frequency offset, Doppler spread, or phase noise, leakage from other subcarriers leads to inter-carrier interference (ICI). Similarly, time offset causes ISI or ICI outside the guard interval. Considering these disadvantages for the 5G standard [4, 16-19], numerous waveforms have been proposed.

Although previous compatibility, low implementation complexity, and easy integration with MIMO technology still make CP-OFDM a significant candidate for new standards, CP-OFDM suffers from limited flexibility and poor coexistence with different numerologies for various channel conditions. Additionally, 5G use cases have further challenges beyond these. The proposed waveforms, using various filtering/windowing methods and precoding strategies with certain trade-offs, provide better flexibility and time-frequency localization [6]. The main waveform candidates for 5G and beyond are classified into multi-carrier and single-carrier types, as shown in Figure 6, and are analyzed in this research. Their advantages and disadvantages are discussed and analyzed, and ultimately a general comparison is provided.

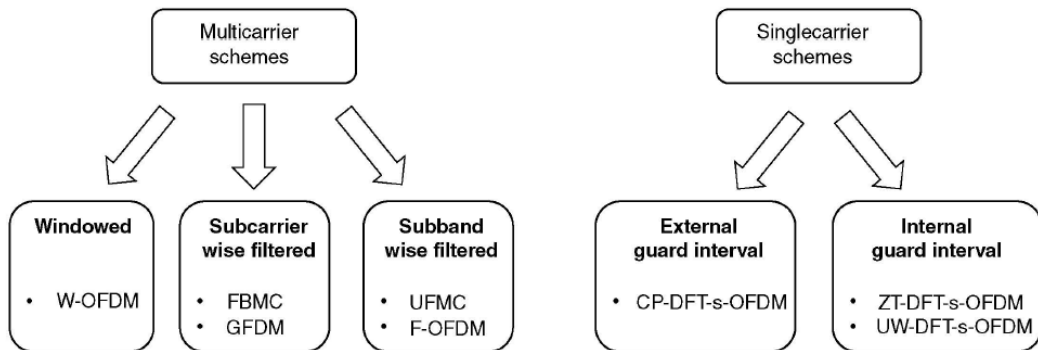


Fig.6. Main Waveform Candidates for 5G and Beyond [6]

The fundamental question arises: why do we need to design new waveforms? Approximately every ten years, a new mobile wireless communication system is introduced, which, thanks to new technological features, also expands to meet the growing market demand. For 5G, the expectations set by the European Union's METIS project for the

2020 horizon include a 1000-fold increase in mobile data volume per coverage area, a 10 to 100-fold increase in the number of connected devices, a 10 to 100-fold increase in user data rates, a 10-fold increase in battery life for massive low-power machine communications, and a 5-fold reduction in overall latency [23]. In reality, these extensive quantitative increases in the mentioned parameters will only be possible by combining several complementary factors: better utilization of the available spectrum, licensing new frequency spectrum above 6 GHz, generalizing small cells, and introducing massive MIMO systems [24]. Researchers also believe that the 4G LTE modulation scheme is not well-suited to meet some of the fundamental requirements of 5G, and therefore, a new air interface must be defined. LTE and LTE-Advanced are designed for mobile broadband (MBB) applications and are based on CP-OFDM modulation. In this context, multi-carrier modulation alternatives to CP-OFDM can only bring improvements by eliminating the cyclic prefix interval in the time domain and reducing guard bands in the frequency domain, which may be considered marginal and unhelpful given the stated expectations for 5G. However, beyond MBB applications, two main drawbacks of CP-OFDM—its inappropriate spectral limitations and inflexible waveform structure might be serious and concerning for telecommunications systems with diverse 5G services.

Firstly, to achieve optimal use of the available sub-6 GHz frequency bands, dynamic spectrum aggregation (DSA) will be a key challenge. The main idea of spectrum aggregation technology is to obtain a wider spectrum by combining several continuous or discrete spectra. This technology can not only meet the requirements of LTE-Advanced but also improve the utilization rate of spectrum segmentation. In this regard, an LTE-OFDM-based approach suffers from high out-of-band emissions (OOB) and its resource block granularity, which, for instance, prevents assigning a single subcarrier to low-data-rate machine-type communication (MTC) services. Moreover, the proliferation of the Internet of Things (IoT) shows a higher frequency of unsynchronized machine-to-machine (M2M) communications, which can disrupt orthogonality. Out-of-band emissions (OOBE) severely contaminate services and users operating in adjacent frequencies if the spectrum is not properly utilized, as in the case of OFDM. Similar problems may arise with frequency shifting and/or spreading due to Doppler effects that describe high-mobility 5G applications. Additionally, as another challenge noted by Wunder et al., the use of CP-OFDM can be problematic for significantly reducing latency. In fact, when reducing the CP-OFDM duration, to avoid interference issues, the length of the CP must be maintained, which naturally leads to a severe decrease in spectral efficiency. Furthermore, to simultaneously support mobile broadband (MBB) and low-latency critical communications (MCC) with different transmission time intervals, severe inter-service interference would occur if CP-OFDM is used. For these reasons, finding a system based on a flexible waveform that can address the various challenges posed by 5G at the physical layer is essential [24].

#### **4. COMPARATIVE ANALYSIS OF PROPOSED 5G WAVEFORMS**

Based on recent research [6], all proposed waveforms for 5G exhibit lower out-of-band emissions (OOBE) compared to CP-OFDM and its single-carrier equivalent, CP-DFT-s-OFDM. Subcarrier-wise filtering operations in FBMC result in the best frequency localization among the proposed waveforms due to the use of longer filters. GFDM, another subcarrier-wise filtered waveform, suffers from sudden transitions and increased OOBE due to its rectangular window shape in the time domain; however, applying windowing to the GFDM waveform, resulting in W-GFDM, also offers good spectral containment. Additionally, shorter filter lengths in subband-wise filtered waveforms lead to better time localization but increased OOBE compared to subcarrier-wise filtered waveforms. Most multi-carrier schemes are affected by high PAPR and are not suitable when high energy efficiency is required. Nevertheless, GFDM offers reduced PAPR characteristics due to its equivalence with DFT-spread waveforms. Single-carrier schemes are preferable in energy-limited use cases as they offer better spectral containment and improved PAPR through flexible guard intervals.

Spectral efficiency (SE) is another critical design metric heavily influenced by the window/filter duration, filter shape, and additional overheads. Well-frequency-localized waveforms reduce the need for guard bands, leading to better frequency domain efficiency. Conversely, waveforms without guard intervals, such as FBMC, are expected to have higher time domain efficiency. However, the lack of guard intervals significantly degrades BER/BLER performance in multipath fading channels, necessitating complex receivers as frequency-domain equalization (FDE) is not feasible. Compatibility with MIMO is also essential for achieving high throughput. Schemes that permit interference, such as FBMC and GFDM, cannot easily deploy and develop MIMO algorithms. Moreover, the guard

interval in the time domain makes the waveform more resistant to ISI and time offsets. Additionally, guard bands or well-localized waveforms in the frequency domain create a waveform resilient to carrier frequency offset (CFO) and Doppler effects, reducing inter-carrier interference (ICI) and adjacent channel interference (ACI) in a multiple access environment. Consequently, FBMC has the best immunity to ICI but is most vulnerable to ISI. Based on conducted studies, a summary of the main advantages and disadvantages of the key proposed 5G multi-carrier and single-carrier waveforms is provided in Table 2:

**Table 2.** Advantages and Disadvantages of Proposed 5G Waveforms [6]

Multi-carrier Schemes		
Waveform	Benefits	Disadvantages
CP-OFDM	<ul style="list-style-type: none"> <li>• Easy Frequency Domain Equalization (FDE)</li> <li>• Easy aggregation with MIMO</li> <li>• Flexible frequency allocation</li> <li>• Low implementation complexity</li> </ul>	<ul style="list-style-type: none"> <li>• Lots of OOB and PAPR</li> <li>• Need for precise synchronization</li> <li>• Poor performance in high mobility applications</li> <li>• Hard-coded CP</li> </ul>
W-OFDM	<ul style="list-style-type: none"> <li>• Easy Frequency Domain Equalization (FDE)</li> <li>• Easy aggregation with MIMO</li> <li>• Flexible frequency allocation</li> <li>• Low implementation complexity</li> <li>• Less OOB than CP-OFDM</li> </ul>	<ul style="list-style-type: none"> <li>• Poor spectral efficiency or poor BER performance (depending on windowing type)</li> </ul>
OQAM-FBMC	<ul style="list-style-type: none"> <li>• Best frequency localization (lowest OOB)</li> <li>• Appropriate spectral efficiency (no guard band or CP)</li> <li>• Suitable for applications with high mobility</li> <li>• Suitable for asynchronous transmission</li> </ul>	<ul style="list-style-type: none"> <li>• Aggregation challenge with MIMO and pilot design</li> <li>• Vulnerability to ISI due to lack of CP</li> <li>• High implementation complexity</li> <li>• Increased power consumption due to OQAM signaling</li> </ul>
GFDM	<ul style="list-style-type: none"> <li>• Flexible design</li> <li>• Appropriate frequency localization</li> <li>• Reduced PAPR</li> </ul>	<ul style="list-style-type: none"> <li>• High latency due to block processing</li> <li>• Aggregation challenge with MIMO and pilot design</li> <li>• High implementation complexity</li> </ul>
UFMC	<ul style="list-style-type: none"> <li>• Appropriate frequency localization</li> <li>• Shorter filter length compared to subcarrier-wise operations including GFDM and OQAM-FBMC</li> <li>• Compatible with MIMO</li> </ul>	<ul style="list-style-type: none"> <li>• Vulnerability to ISI due to lack of CP</li> <li>• The high complexity of the receiver caused by the increase in FFT size</li> </ul>
F-OFDM	<ul style="list-style-type: none"> <li>• Better frequency localization</li> <li>• Flexible filtering (differential)</li> <li>• Shorter filter length compared to subcarrier-wise operations including GFDM and OQAM-FBMC</li> <li>• Compatible with MIMO</li> </ul>	<ul style="list-style-type: none"> <li>• Very high implementation complexity</li> </ul>
Single-carrier Schemes		
Waveform	Benefits	Disadvantages
CP-DFT-s-OFDM	<ul style="list-style-type: none"> <li>• All the mentioned advantages of CP-OFDM</li> <li>• Low PAPR</li> </ul>	<ul style="list-style-type: none"> <li>• A lot of OOB</li> <li>• Need for precise synchronization</li> <li>• Hard-coded CP</li> </ul>
ZT-DFT-s-OFDM	<ul style="list-style-type: none"> <li>• Flexible protective span</li> <li>• Better spectral efficiency</li> <li>• Less OOB compared to CP-DFT-s-OFDM</li> </ul>	<ul style="list-style-type: none"> <li>• Need for precise synchronization</li> <li>• Additional signaling control</li> <li>• Limited link performance for higher order modulation</li> </ul>
UW-DFT-s-OFDM	<ul style="list-style-type: none"> <li>• Flexible protective span</li> <li>• Best spectral efficiency</li> <li>• Lowest OOB and PAPR</li> </ul>	<ul style="list-style-type: none"> <li>• Need for precise synchronization</li> <li>• Additional signaling control</li> <li>• Limited link performance for higher order modulation</li> <li>• High implementation complexity</li> </ul>

Based on the research conducted by Y. Qi and M. Al-Imari [20], the newly proposed waveform for 5G, QAM-FBMC, has been evaluated. This waveform enables QAM modulation using prototype filters for various subcarriers. The analysis and evaluation of this waveform have been conducted from different perspectives, including equalization methods, channel estimation error, phase noise effects, out-of-band emissions (OOBE), and complexity. Simulation results indicate that QAM-FBMC can offer performance similar to CP-OFDM without compromising spectral efficiency (SE). The impact of channel equalizer and channel estimation error has also been examined. The results show that QAM-FBMC is resistant to phase noise. The authors suggested that future research could focus on investigating the 'reference signaling overhead' for the QAM-FBMC waveform and the impact of other RF impairments, such as power amplifier non-linearity.

Furthermore, a comprehensive review and comparison of proposed waveforms for the 5G air interface have been presented in a study by Eeckhaute et al. [21]. This review includes comparing waveforms such as FBMC, UFMC, GFDM, and RB-F-OFDM against OFDM (used in 4G) regarding spectral efficiency (SE), computational complexity, resilience to multi-user interference (MUI), and flexibility concerning power amplifier non-linearity. According to the results, FBMC offers the best spectral management (mitigating spectral challenges) and is almost insensitive to multi-user interference. However, FBMC suffers from poor spectral efficiency for short bursts and weak compatibility with MIMO. GFDM is one of the most promising proposed waveforms, as it provides the best spectral efficiency and the lowest complexity overhead compared to OFDM. Additionally, GFDM, after FBMC, is the most resistant to multi-user interference and is compatible with MIMO under interference management conditions. UFMC and RB-F-OFDM are very close to OFDM; thus, they benefit from better compatibility with existing systems (especially with MIMO techniques), although their performance is generally lower than FBMC and GFDM. As concluded in this study [21], GFDM, offering the best energy efficiency after OFDM and the best time-frequency containment among all proposed waveforms, appears to be the most suitable waveform for 5G applications, followed by FBMC as a viable choice [25-26].

Based on the conducted studies, it can be concluded that there is no single waveform that meets all requirements, and the 5G physical layer must be designed considering specific use cases and existing requirements.

## **5. CONCLUSION**

In this paper, an overview of the recent discussions on 5G NR was presented, and the main waveform candidates for 5G and beyond were briefly outlined. The main 5G use cases and the essential design requirements and needs of the associated waveforms, along with a brief description of CP-OFDM as the baseline for 5G waveform discussions, were provided. The proposed waveforms are classified based on spectrum utilization (single-carrier and multi-carrier), another classification where different signal processing methods are employed (windowing, subcarrier-wise filtering), and based on the type of guard interval implemented (internal and external). Based on the conducted studies, a summary of the main advantages and disadvantages of the key proposed 5G multi-carrier and single-carrier waveforms was provided. It can be concluded that no single waveform meets all the requirements, and the 5G physical layer must be designed considering specific use cases and existing requirements.

### **Transparency Statement**

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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### **Declaration of Interest**

The authors declare that they have no competing interests.

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