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Original Article

Evaluation of PAPR, PSD, Spectral Efficiency, BER and SNR Performance of Multi-Carrier Modulation Schemes for 5G and Beyond

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Abstract - *Next-generation wireless communication systems (5G/6G) are intended to offer extensive features and capabilities. Higher data rates, more mobility, reduced latency, and improved service quality are the primary criteria for 5G/6G. The various services and applications expected for 5G/6G will have different expectations for the network's design. The 5G network is necessary to support massive data traffic and an enormous variety of remote connections. Orthogonal Frequency Division Multiplexing (OFDM) was the most effective choice for 4G networks. However, OFDM has a high Peak to Average Power Ratio (PAPR) and Out of Band (OoB) leakage. More improved Multi-Carrier Modulation (MCM) methods are necessary to meet the expected needs of 5G/6G. So, other MCM approaches are offered to overcome the drawbacks of OFDM. Filtered MCM techniques give feasible solutions for future mobile networks. Multiple access techniques, such as Filter-Bank Multi-Carrier (FBMC), Universal-Filtered Multi-Carrier (UFMC), and Generalized Frequency-Division Multiplexing (GFDM), can be used to analyze the enormous data offered by 5G/6G systems. This paper examines the performance of 5G/6G MCM methods such as FBMC, UFMC and GFDM. After that, we evaluate the results in terms of PAPR, Power Spectral Density (PSD), Computational Complexity (CC), Bit Error Rate (BER) and Spectral Efficiency (SE).*

Keywords - *5G, 6G, Bit Error Rate, Computational Complexity, FBMC, GFDM , Multi-Carrier Modulation, OFDM, Power Spectral Density, Spectral Efficiency, UFMC.*

1. Introduction

Wireless communications systems have existed for over a decade, beginning with the 1G communication technologies. Over time, new advancements towards 2G, 3G, and 4G wireless communication technologies have occurred. All of these offered digital modulation methods [1]. All of these factors have considerably increased the progress of utilizing smart devices daily. Data rates, bandwidth allocation, and other parameters have been enhanced from 1G to 4G. A typical client is expected to download 1TB of data every year.

Long-Term Evolution (LTE) systems are being investigated for new research using Multiple Input Multiple Outputs (MIMO), Hetnets, small cells, and multiple antennas to improve capacity and data rates. This traffic growth is unlikely to be supported by 4G LTE. As data traffic grows, so does the demand for the 5G/6G system. LTE technologies are utilized in 4G networks. However, developing newer apps in 4G is not the most possible [2-3]. Global 5G network deployment was projected to be finished by 2025, with extra high capacity connections, excellent reliability, and extremely low latency.

Nevertheless, the capabilities of 5G are expected to face challenges in fulfilling the diverse range of anticipated uses beyond the year 2030. Moreover, the 6G network is expected to offer an expanded spectrum, improved cost-efficiency, and enhanced security measures to optimize coverage and reduce energy usage. Many technological advancements are utilised to address these requirements within the context of a 6G network, such as waveform design, multiple access approaches, channel coding techniques, novel antenna technologies, network slicing, and cloud edge computing. Four crucial future development keys are impacted by 6G: global coverage, diverse spectra, innovative applications and services, and excellent security. Figure 1 represents the development of cellular mobile communications.

OFDM is flexible to multipath fading and easy to implement because it utilizes FFT/IFFT frameworks, reduces multi-carrier interference, and is simple to combine with adaptive modulation and multiple antenna systems. So, OFDM is extensively used in various wireless systems, including LTE and IEEE 802.11 families [5, 6]. Because OFDM is the most widely used modulation technology in today's wireless networks, it has several inherent limitations.

High Out-of-Band (OoB) emission, low Spectral Efficiency (SE) caused by adding a Cyclic Prefix (CP) and high PAPR affect system efficiency [7]. To address these drawbacks, several new MCM techniques, including FBMC, UFMC, filtered OFDM and GFDM, have recently been proposed [8].

Much research has been conducted to assess the performance of various prospective MCM approaches. [9] provides a complete review of modulation and different access techniques for 5G networks. The authors present an overview of Orthogonal and Non-Orthogonal Multiple Access (OMA and NOMA) systems. The performance is compared in terms of OoB emission and BER. They demonstrate that NOMA improves throughput and extensive connectivity while improving SE. A comparison of study provides the study of OFDM and FBMC. BER, SE, PSD, and Computational Complexity (CC) of OFDM and FBMC are investigated.

The article discusses the disadvantages of OFDM and suggests that FBMC could serve as an alternate option. The authors of [10] compare UFMC and OFDM. They prove that UFMC outperformed OFDM. [11] compares the performance of UFMC with CP-OFDM based on PSD and PAPR. They demonstrate that UFMC has higher PSD than OFDM and almost equal PAPR. [12] compares the performance of FBMC, GFDM and UFMC in terms of PSD, SE, Computational Complexity and PAPR. According to the authors, UFMC has equivalent spectral efficiency to OFDM. Only the AWGN channel is used for SE comparison. [13] investigated the operation of Full Duplex-FBMC. The OFDM system's effectiveness regarding spectral leakage has been described.

5G waveform possibilities were studied in [14]. PAPR, SE, computat ional complexity and latency were used to measure performance. According to the results, FBMC and UFMC offered more potential cohabitation than other techniques. The authors of [15] analyzed MIMO systems based on OFDM, UFMC, and FBMC. Their effectiveness was evaluated using BER, PSD, data rate, and SE. According to outcomes, UFMC provided the most significant data rate, while FBMC provided the lowest PSD. This paper examines the modulation schemes OFDM, FBMC, GFDM, and UFMC. We begin by reviewing the fundamental concepts and properties of each waveform. The various waveforms' PSD, CC, BER, PAPR, and SE are then compared.

The remaining part of the article is structured as follows. In section 2, we explained about 5G and 6G. Section 3 covers the fundamentals of multi-carrier modulation methods. Section 4 contains performance analysis parameters. Section 5 describes the simulation results, and conclusions are provided in section 6.

2. 5G/6G Communication System

This section discusses 5G and 6G basics such as evolution, applications, development, capabilities, and features. The mobile communication system has experienced significant change since the first wireless network was built over 40 years ago.

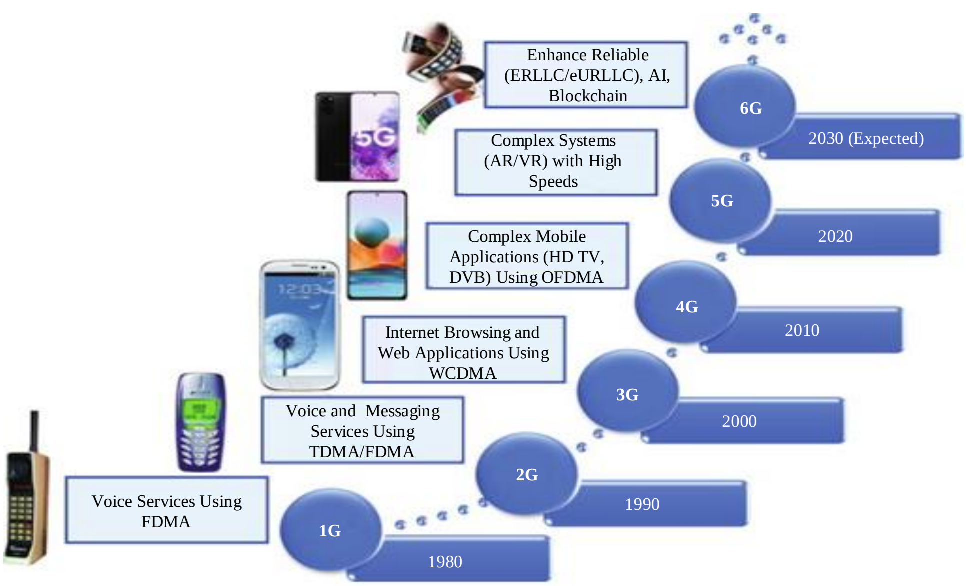

Fig. 1 The evolution from 1G to 6G [5]

2.1. 5G

Compared to earlier wireless systems, 5G is an important advancement and a framework for digital transformation. Users will benefit from three new services as a result of 5G: extreme Mobile Broadband (MBB), extreme Machine Type Communication (MTC), and Ultra-Reliable Low Latency Communication (URLLC). eMBB offers consumers fast internet, higher bandwidth, reduced latency, and UltraHD streaming movies [16].

The eMTC provides high-speed, high-bandwidth MTC across extensive distances while consuming little power. The URLLC is the developed 5G for minimal latency and extremely reliable connectivity. 5G technology offers consumers infinite internet access while enhancing reliability, flexibility, and energy efficiency. 5G employs two primary frequency ranges: sub-6 GHz and millimeter (mm) wave [17].

All wireless networks employ a spectrum ranging from 300 MHz to 3GHz. However, the current scope has become overloaded with traffic, making it difficult to overcome. The issue of high-frequency bandwidth has emerged as a crucial element in developing 5G wireless networks.

These networks explore using an underutilized spectrum inside the mmWave (mmW) band, spanning frequencies from 3GHz to 300GHz. Figure 2 illustrates the accessibility of the mmW range. The 5G general physical architecture is shown in Figure 3. The key features of 5G are illustrated in Figure 4. The various applications of 5G are represented in Figure 5. The security issues with 5G are shown in Figure 7.

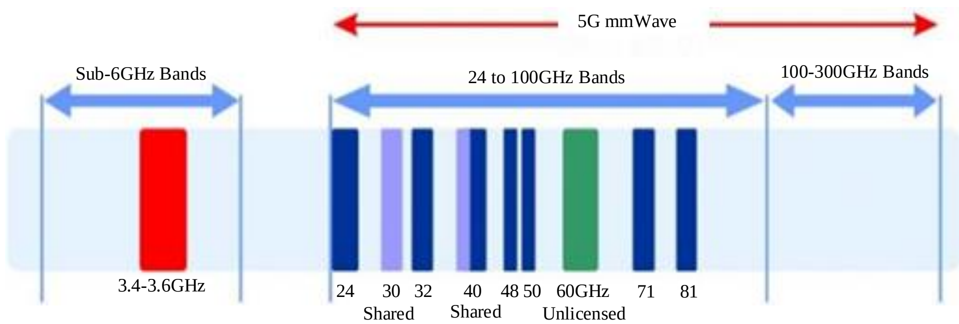

Fig. 2 mm spectrum: 3GHz to 300GHz

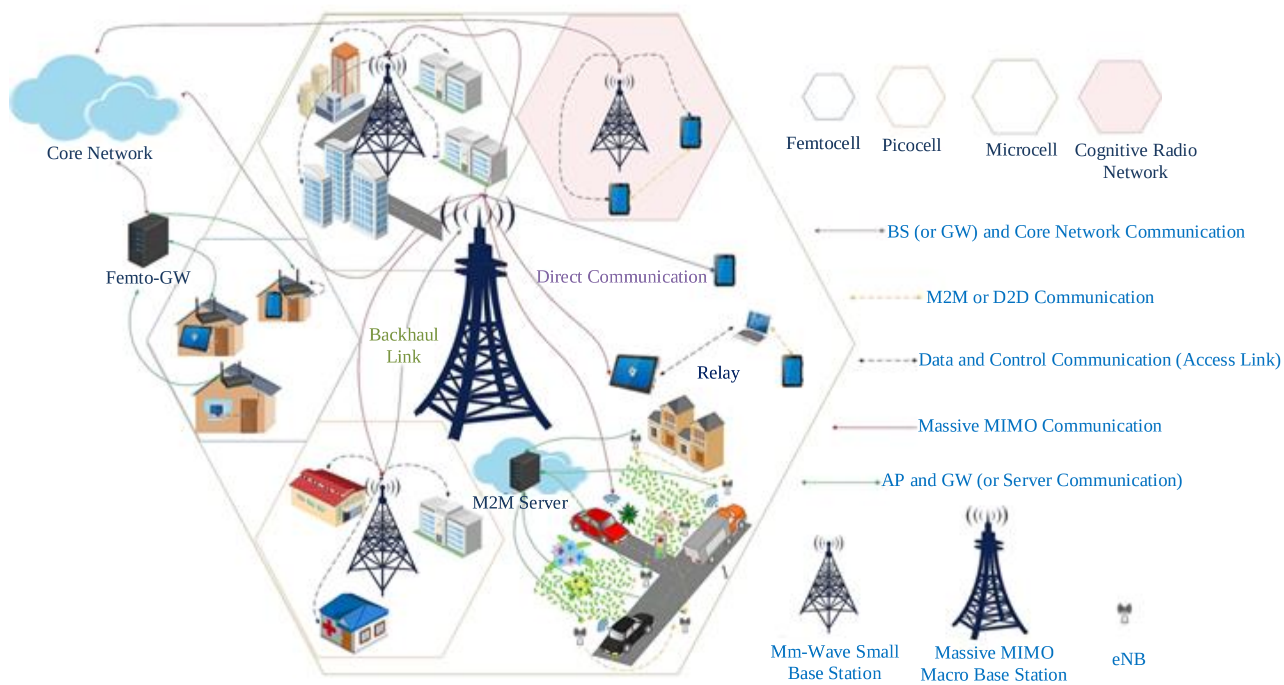

Fig. 3 General 5G physical architecture [18-23]

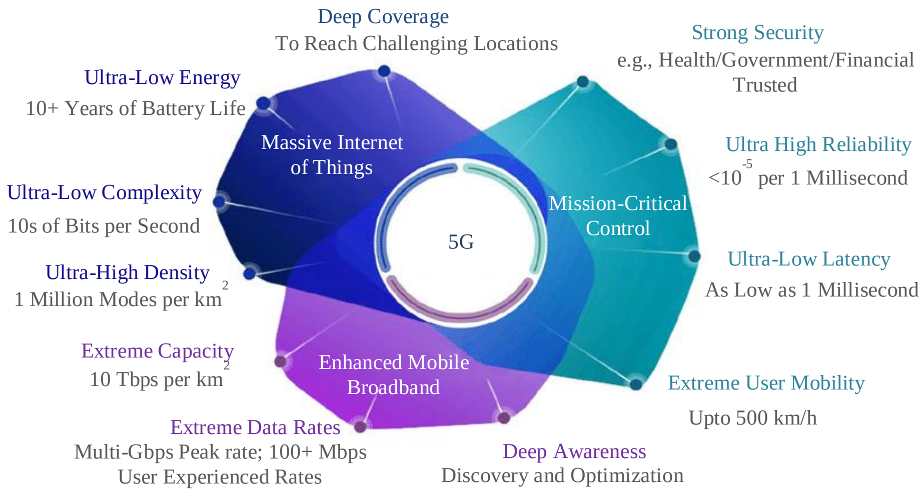

Fig. 4 Key features of 5G [24]

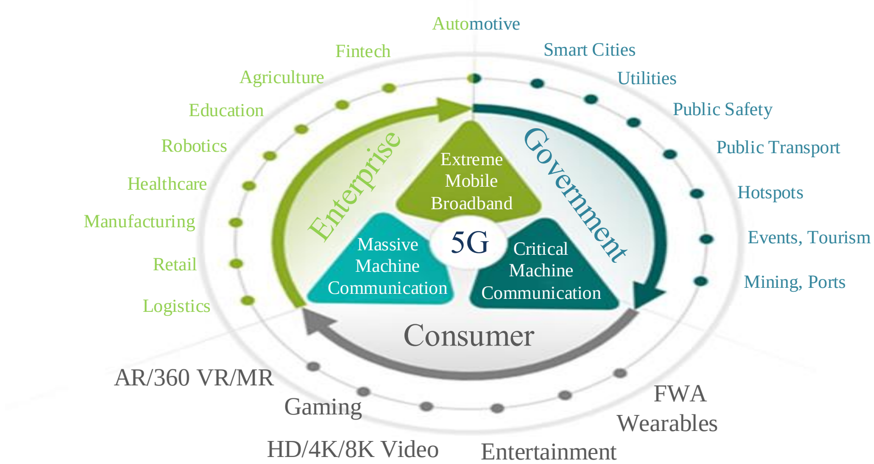

Fig. 5 Applications of 5G technology

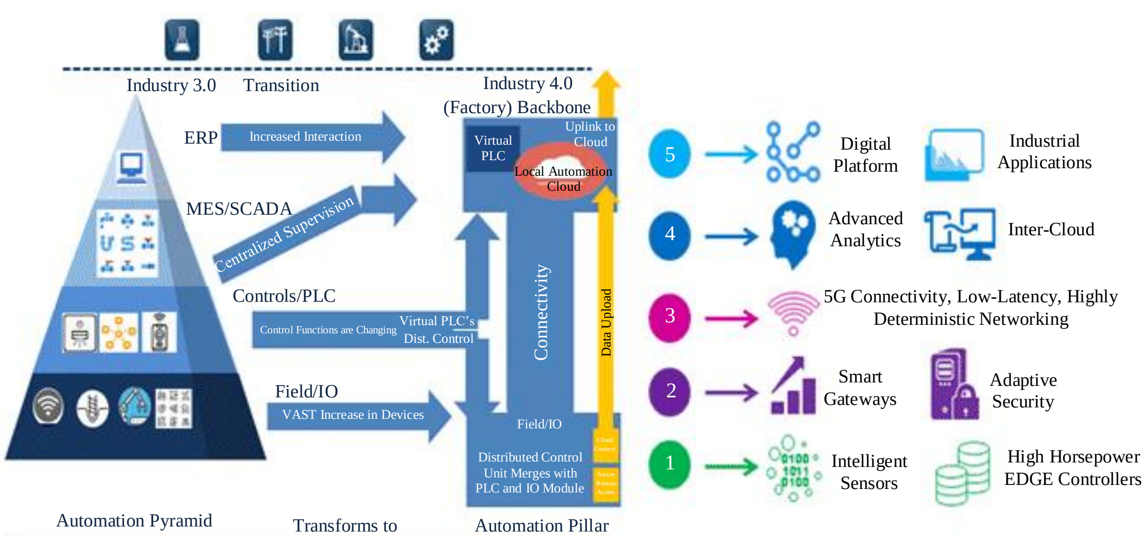

Fig. 6 5G as a key enabler for oil and gas digitalization [25]

Fig. 7 Security issues with 5G [26]

2.2. 6G

For new 6G services, there will be an increased demand and require higher network capacity than present 5G. Therefore, future 6G services will require higher network capacity than 5G. Future wireless networks will play an essential role in our lifestyles, businesses, and society. Wireless networks will connect people and intelligent machines. So, researchers and industry should work together to develop these networks further to achieve a common objective [27].

Wireless communication will have significantly advanced by 2030. The current era is anticipated to see a substantial transformation towards automation, wherein the emergence of 6G technology is expected to assume a pivotal position as a fundamental infrastructure for information and communication. The potential of achieving ubiquitous and uninterrupted communication across all locations and timeframes is anticipated by implementing 6G technology. Due to increasing application needs, the future development of wireless systems should achieve numerous aspects to match these services' QoS.

Moreover, we may expect the following development to continue with increased demands that wireless technologies should serve on the way to 2030. To handle highly demanding applications such as virtual, enhanced, mixed reality and remote management of critical activities, future generations should enable high data rates, extremely low end-to-end latency, increased reliability, large cell capacity, and expanded coverage area [28]. The features of 6G are shown in Figure 8. Figure 9 depicts the new situations that are emerging in 6G networks. Figure 10 represents the applications, trends, and enabling technologies of 6G.

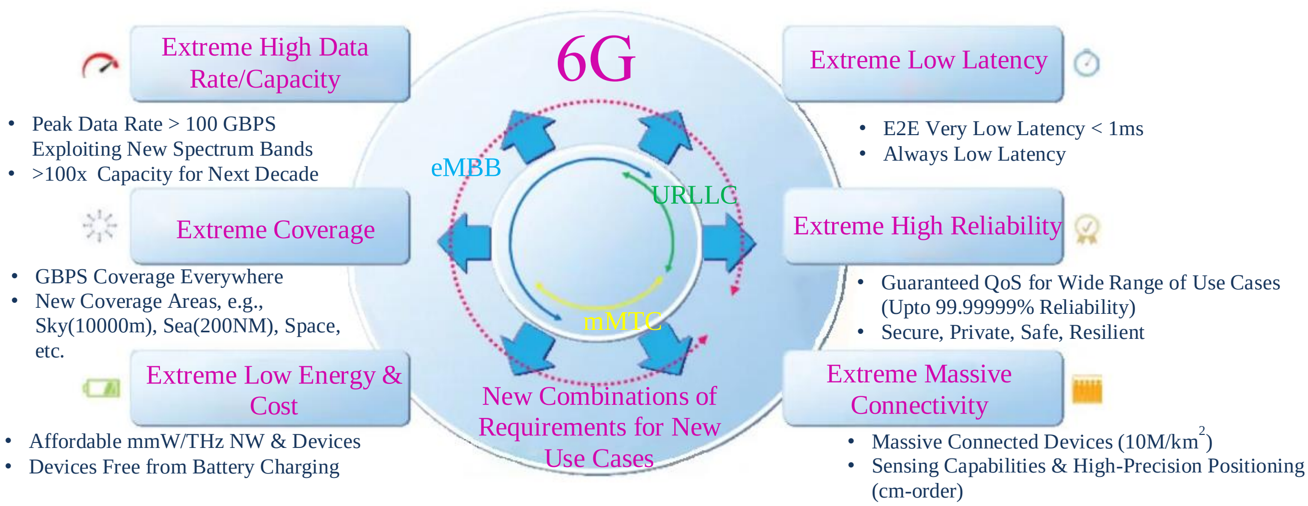

Fig. 8 Requirements of 6G

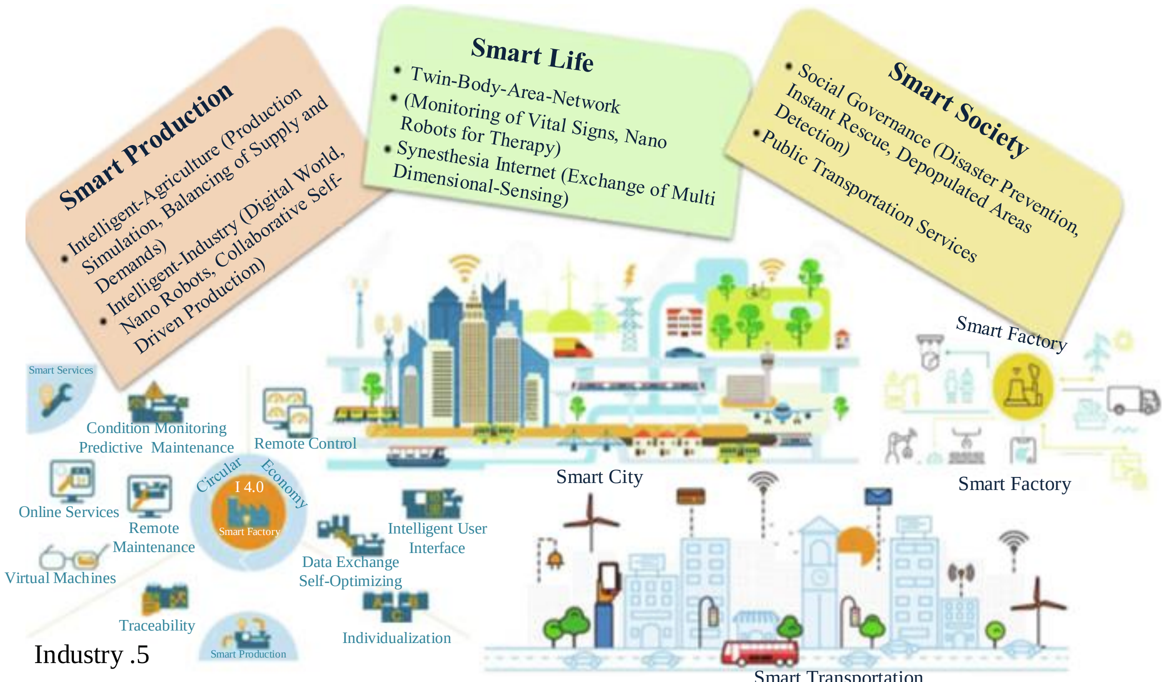

Fig. 9 Scenarios of 6G beyond 2030 [4]

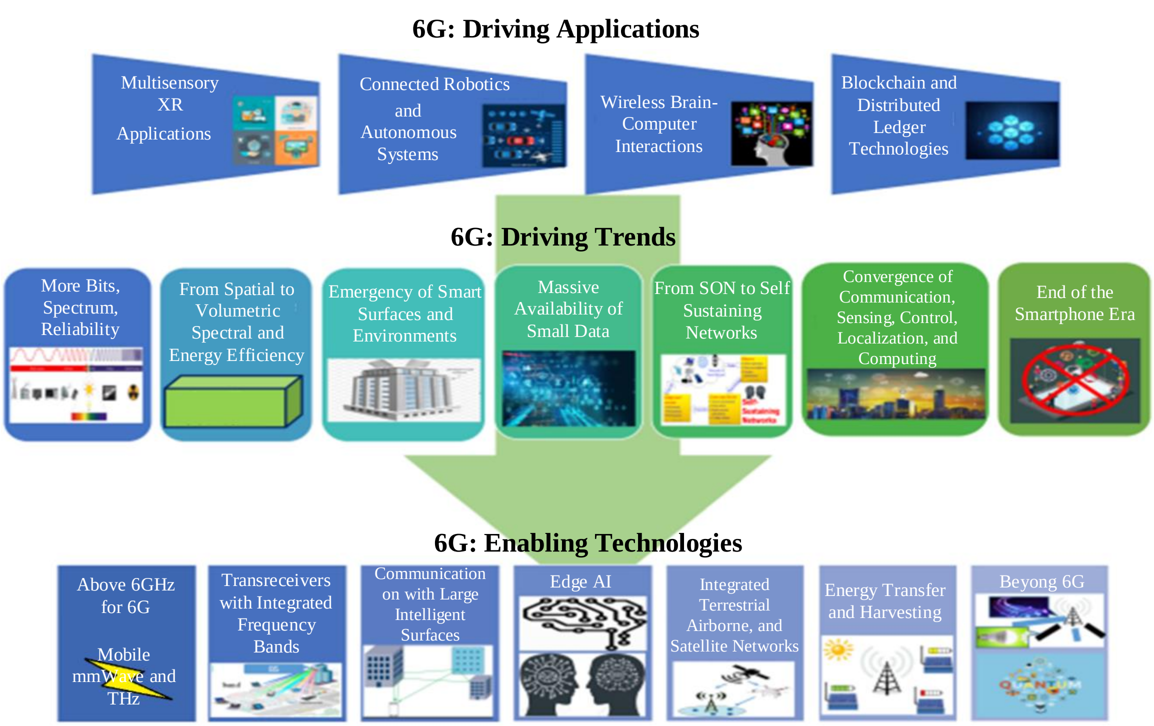

Fig. 10 6G: applications, trends, and technologies [29]

3. Multi-Carrier Modulation (MCM) schemes

MCM is a new developing technique in 5G for changing the physical-layer technique. The MCM is being deployed to operate mMIMO base stations. Candidate waveforms are used to use the restricted frequency range best. The accessibility of the frequency spectrum creates a tremendous demand in WCS. Because of the rapid expansion of WCS, the frequency spectrum is becoming an essential resource. So, MCM methods are employed in the 5G system. The existing issues of MCM include difficulty in design, reliability, flexibility, OoB emission and PAPR. Therefore, new MCM methods are being developed to defeat these issues. The principle of MCM is to divide significant signals with high symbol rates into smaller signals with lower rates.

Orthogonal narrow-band subcarriers are currently being utilised to modify lower-rate transmissions. This supports simultaneous data transfer via the channel. Dividing wide-band signals into small-band orthogonal signals provides excellent SE. The more potential MCM approaches for the next generation of networks include OFDM, GFDM, FBMC, and UFMC. The key differences among these modulation schemes are the MCM block, CP insertion, and filtering process.

3.1. CP-OFDM

OFDM is a modulation and multiplexing technique. It is frequently utilized in LTE and LTE-A networks. The method mentioned above pertains to encoding digital information among multiple carrier systems. A significant quantity of closely spaced orthogonal subcarrier signals are utilised to facilitate data transmission across several concurrent data streams over various channels.

Each subcarrier is modulated using a typical modulation method such as QAM or PSK. As a result, the symbol rate will be low. These digital modulation methods are used to map the digital input. These modulation methods are used to generate complex symbols. The orthogonal sub-carriers are utilized for mapping utilizing IFFT.

The IFFT converts a signal from the Frequency Domain (FD) to the Time Domain (TD). CP is used to prevent transmitted symbols from overlapping. The CP is introduced to offer greater resilience to signal propagation. Instinct CP is used to solve the ISI and ICI issues.

The end of transmitted symbols attached to its beginning is essentially a duplicate of additional CP. The key criterion of the CP-OFDM system is channel estimation. The increased CP causes poor SE. Another con of CP-OFDM is the loss of bandwidth caused by the insertion of CP. Figure 11 depicts the CP-OFDM block diagram.

The signal representation of the OFDM system is

$$x(t) = \sum_{n=-\infty}^{\infty} x_n\left(t - n\tau\right)$$

$$x_n(t) = \sum_{m=0}^{K-1} S_{n,m}\delta(t) \otimes f(t)e^{j2m\pi t\partial f}$$

$$x_n(t) = \sum_{m=0}^{K-1} S_{n,m} f(t)e^{j2m\pi t\partial f}$$

So,

$$x(t) = \sum_{n=-\infty}^{\infty}\sum_{m=0}^{K-1} S_{n,m} f(t-n\tau)e^{j2m\pi(t-n\tau)\partial f}$$

Where, convolution operation is $\otimes$, symbol duration is τ, impulse function is $\delta(t)$, prototype filter f(t), subcarrier index is m, subcarriers are K, $S_{n,m}$ is complex data symbol of m^{th} subcarrier and n^{th} OFDM symbol, subcarrier spacing is ∂f.

3.2. FBMC

A set of filters in FBMC performs standard input to produce an expected output. SFB is constructed using an IFFT followed by a Poly-Phase Network (PPN) structure, whereas AFB uses a PPN followed by an FFT. The filter bank allows the response to the frequency of the transmitted signal to be controlled. As a result, many filter design approaches have been developed, including FMT, CMT, and SMT [30].

The primary distinction between OFDM and FBMC is the kind of filter employed. In the context of OFDM, a rectangular filter is applied to facilitate the transmission of each subcarrier. However, in FBMC, a pulse-shaping filter is utilized to enhance the spectral features by reducing the occurrence of OoB radiation. Following the OQAM pre-processing stage, data symbols are transmitted across the SFB set. Using the prototype filter facilitates the effective management of nearby spectral leakage and frequency localization.

The transmitted signals are routed through a series of AFB at the receiver to achieve optimal signal reconstruction, followed by OQAM post-processing. Because of self-interferences, FBMC compatibility with MIMO is relatively complicated. When the interference becomes controlled, this will be compatible with MIMO. In OFDM systems, it is imperative to retain orthogonality across all subcarriers. The orthogonality criteria are observed between the neighbouring subcarriers in FBMC, as stated in [31]. In OQAM, the complex signal is decomposed into its constituent real and imaginary components. The signs are partitioned in the temporal dimension by 50% of the symbol duration, enhancing frequency spectrum utilisation. The FBMC system is shown in Figure 12.

The FBMC-QAM signal is

$$x(t) = \sum_{n=-\infty}^{\infty}\sum_{m=0}^{K-1} S_{n,m}\delta(t-n\tau) \otimes f(t)e^{j2m\pi(t-n\tau)\partial f}$$

$$x(t) = \sum_{n=-\infty}^{\infty}\sum_{m=0}^{K-1} S_{n,m} f(t-n\tau)e^{j2m\pi(t-n\tau)\partial f}$$

3.3. UFMC

To achieve asynchronous reception and transmission, a novel waveform is needed for future wireless communication networks, utilizing non-orthogonal waveforms to enhance SE and reduce latency. UFMC has been proposed as a novel waveform design that represents a generalization of this approach to collect the benefits while avoiding the drawbacks of previous modulation schemes.

UFMC is a technique that combines the benefits of orthogonality in OFDM along with the filter bank idea in FBMC. However, sub-bands of carriers are filtered rather than filtering every carrier like in FBMC. Every sub-band comprises many carriers, and the length of the filter is determined by the sub-band width [32]. The entire band of the OFDM is divided into N sub-carriers. The N subcarriers are separated into subbands and then filtered.

FD signals are converted into TD by employing N-point IFFT conversion. A bandpass filter filters the transmitted symbols, which are summed; subsequently, the signal is propagated over a multipath fading channel. The serial data/signal is converted into parallel data at the receiver side using the serial-to-parallel converter [33]. These signals are filtered and converted from TD to FD using an FFT block. The demodulated signal is sent to the demapper block, a demodulator responsible for extracting the data bits from the received symbols. Figure 13 shows the block diagram of UFMC.

3.4. GFDM

GDFM is a powerful multi-carrier system that may be used for various 5G applications. The fundamental limitation of the GFDM system is high PAPR. Linear power amplifiers are used at the transmitter section of the system. High Power Amplifiers (HPA) are placed on the transmitter side to improve communication. Because HPA must be functioning saturation region, the operating point will be in the nonlinear region. Switching the operating point into the nonlinear region causes non-linearities in the output signal.

To address this, we must raise the dynamic range of the HPA to keep the operating point in the linear region, which affects efficiency and raises the power amplifier price [34]. As a result, there is a trade-off between efficiency and nonlinearity. Transferring a powerful PAPR signal through the HPA saturates the device, producing OoB radiation; the BER increases. To improve the efficiency of the HPA, we should reduce the PAPR value.

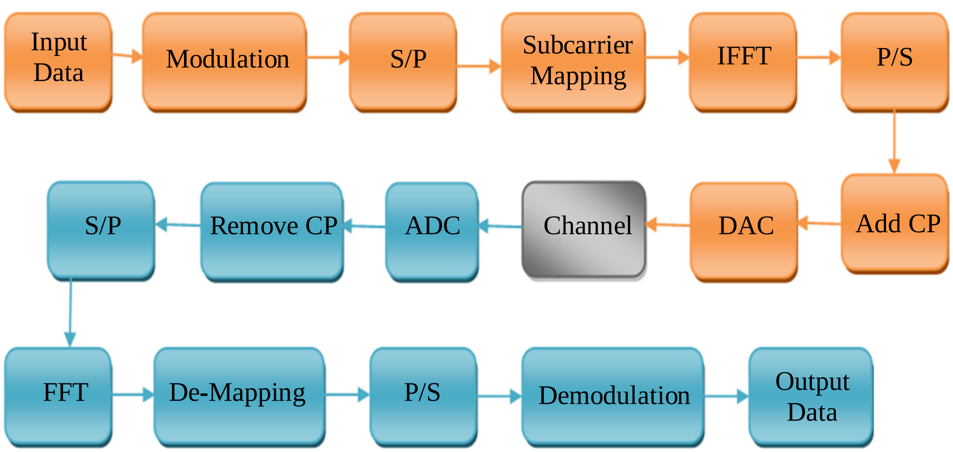

Fig. 11 CP-OFDM

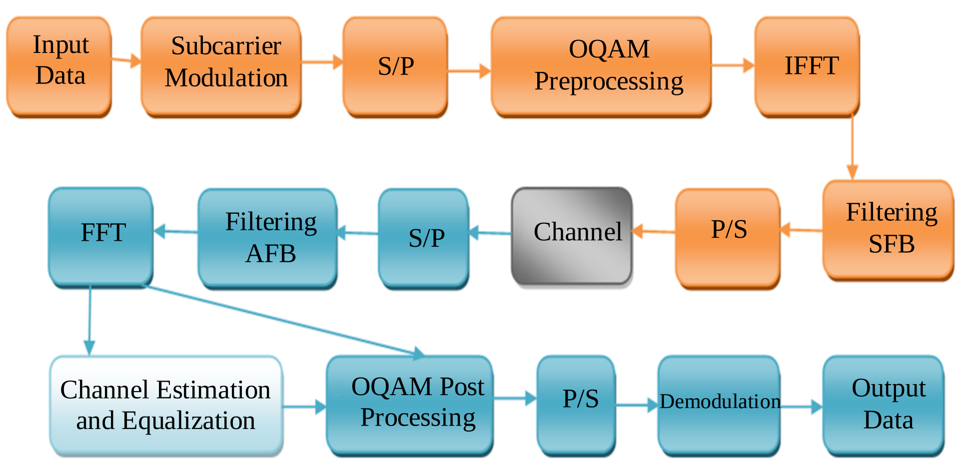

Fig. 12 FBMC system

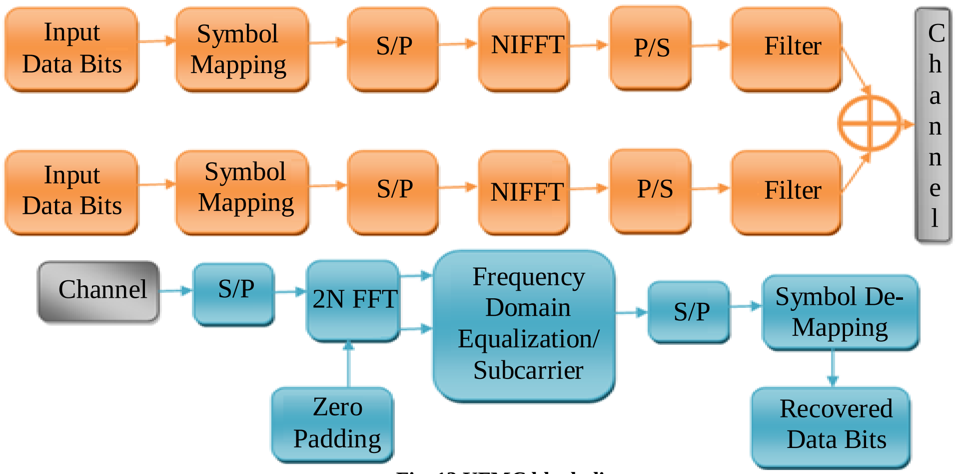

Fig. 13 UFMC block diagram

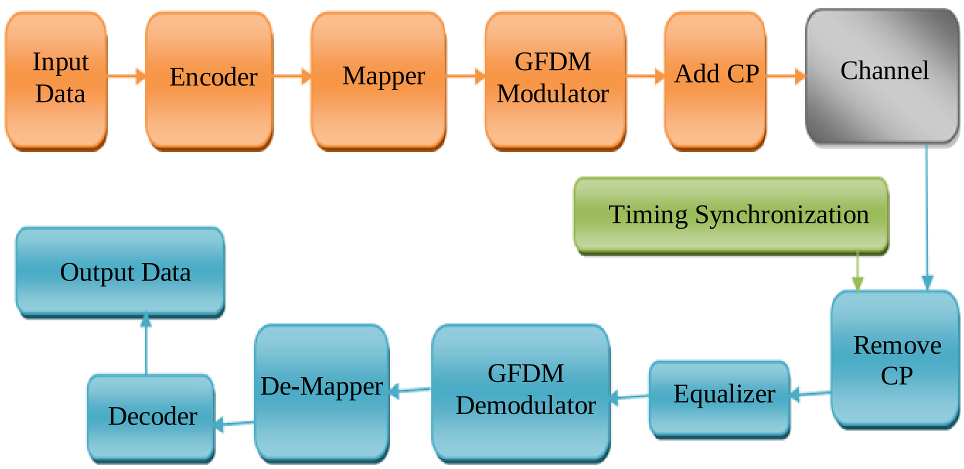

Fig. 14 GFDM block diagram

The input binary data is changed into complex data symbols in the transmitter section using a mapper block with QAM/PSK modulation. Now, these serial complex data symbols are applied to the GFDM modulator. This decomposes the data symbol into sub-carriers and sub-symbols simultaneously.

The main benefit of the GFDM system is selecting the filter type to be utilized for pulse shaping [35]. Then, a CP is added, and the corresponding signal is transmitted through a multipath fading channel. At the receiver section, the CP of the movement, which is received from the multipath fading channel, is removed. The GFDM demodulator demodulates the corresponding signal. The complex data symbols are converted to binary data by using a demapper. This approach will decrease the impacts of OoB emissions. Figure 14 describes the GFDM block diagram.

4. Performance Analysis Parameters

The performance of MCM schemes is evaluated using several parameters, like PSD, SE, BER, Computational Complexity (CC) and PAPR. PSD and SE are considered on the transmitter side; BER and CC are used to measure performance at the receiver section.

4.1. PSD

The PSD is the frequency domain distribution of the average power of a signal. The PSD demonstrates the magnitude of energy changes with frequency. It proves which frequencies have high energy variations and which have small energy variations. Adding the PSD of each subcarrier provides the PSD of MCM schemes. Furthermore, the PSD can also be used to measure the sidelobe radiation.

The PSD of OFDM and FBMC signals may be calculated as follows:

$$PSD_{OFDM}(f) = \sigma_S^2 \tau \sum_{m=0}^{K-1} \left| \operatorname{sinc}\left(\tau(f - m\partial f)\right) \right|^2$$

$$PSD_{FBMC}(f) = \frac{\sigma_S^2}{\tau} \sum_{m=0}^{K-1} \left| \sum_{a=-l+1}^{l-1} F_c \frac{\sin\left\{lK\pi\left(f - \frac{a}{lK} - \frac{m}{K}\right)\right\}}{lK \sin\left\{\pi\left(f - \frac{a}{lK} - \frac{m}{K}\right)\right\}} \right|^2$$

Where, overlapping factor *l*= 4, the coefficient of PHYDYAS filter is F_c, and the standard deviation of $S_{n,m}$ is σ_s.

4.2. BER

BER is an essential aspect in determining the performance of data channels. The BER is a metric that quantifies the ratio of bit errors to the total amount of bits transferred during a particular period. Noise and multipath propagation are the primary causes of transmission degradation in quality and BER. To analyze the BER characteristics of the MCM schemes, we assume that the noise has a Gaussian distribution and that the propagation model has a Rayleigh distribution.

4.3. Spectral Efficiency-SE (Bandwidth Efficiency)

The most significant amount of data that may be transferred to a certain number of users/second is SE. SE generally determines the effectiveness of the digital modulation technique. The combination of time efficiency and modulation efficiency gives SE.

$$SE = \lambda_t \lambda_m$$

$$\lambda_t = \frac{S_t}{S_t + S_{oh}}$$

$$S_t = \mu N$$

$$S_{oh} = \begin{cases} \mu L_{cp};\ for\ OFDM \\ N\left(K - 0.5\right);\ for\ FBMC \\ \mu\left(L_{zp} + L_f - 1\right);\ for\ UFMC \end{cases}$$

$$\lambda_t = \begin{cases} \dfrac{N}{L_{cp} + N};\ for\ OFDM \\ \dfrac{\mu}{\mu - 0.5 + K};\ for\ FBMC \\ \dfrac{N}{N - 1 + L_f + L_{zp}};\ for\ UFMC \end{cases}$$

$$SE = \begin{cases} \dfrac{mN}{L_{cp} + N};\ for\ OFDM \\ \dfrac{m\mu}{\mu - 0.5 + K};\ for\ FBMC \\ \dfrac{mN}{N - 1 + L_f + L_{zp}};\ for\ UFMC \end{cases}$$

Where, λ_t is the time efficiency λ_m modulation efficiency of MCM schemes, S_t indicates the samples on the transmitted signal, S_{oh} is the overhead sample due to CP, μ is transmitted symbols in a burst, FFT size is N, and the number of loaded bits in each subcarrier is m, overlapping factor is K, length of CP is L_{cp}, length of filter L_f and length of ZP is L_{zp}.

4.4. Computational Complexity (CC)

The quantity of real-valued multiplications and additions is used to determine computational complexity. The overall CC of any MCM approach is computed by summing the number of additions and multiplications on both the transmitter and receiver sides. Table 1 indicates the required reserves and multiplications of various MCM schemes. OFDM has a relatively low complexity. FBMC is around six times higher in complexity than OFDM. GFDM is roughly 12 times greater in complexity than OFDM. UFMC has the highest level of complexity.

Table 1. Comparison of CC for various MCM schemes

Parameter	No. of Additions	No. of Multiplications
FFT	$FFT^{+} = 3N\log_2 N - 3N + 4$	$FFT^{*} = N\log_2 N - 3N + 4$
OFDM Tx Side	$3N\log_2 N + 2L_{cp} - N + 4$	$N\log_2 N + 4L_{cp} + N + 4$
OFDM Rx Side	$3N\log_2 N + 2L_{cp} + 2N_0 - N + 4$	$N\log_2 N + 4N_0 - 3N + 4$
FBMC Tx Side	$6N\log_2 N - 10N + 4NK + 2N_0 + 8$	$2N\log_2 N - 6N + 8 + 4N_0 + 4NK$
FBMC Rx Side	$6N\log_2 N - 10N + 8 + 4N_0 L_{eq} - 2N_0 + 4NK$	$2N\log_2 N - 6N + 8 + 4N_0 L_{eq} + 4NK$
UFMC Tx Side	$4N_{sb}(D-1) + 3DN_{sb}(FFT^{+}) + 2N(FFT^{+})$	$3D(FFT^{*}) + 8DN_{sb} + 2N(FFT^{*})$
UFMC Rx Side	$2N(FFT^{+}) + 2N_0$	$2N(FFT^{*}) + 4N_0$

Where N is subcarriers (N-point FFT), N_0 is symbols, poly-phase filters length of Lp = KN, data blocks are D, and IFFT size on each sub-band is N_{SB}.

5. Results

This section analyses a comparison of the following performance parameters: PAPR, BER, CC, and SE. The MATLAB tool was used to evaluate the performance of MCM with variations in design parameters. Table 2 shows the simulation parameters used in this research. The simulation parameters may be different depending on the comparison measures.

Figure 15 illustrates the PSDs of MCM schemes. A compromise exists between Leakage Suppression (LS), and spectral resolution. The CP-OFDM roll-off rate is lower than the others, indicating poor spectrum LS. Furthermore, the sidelobe level is not much reduced. As a result, a significant quantity of power is transferred in the not-utilised spectrum. W-OFDM has a lower sidelobe level than CP-OFDM. As a result, W-OFDM provides superior LS. Furthermore, the roll-off rate is visibly larger, indicating a quick reduction in PSD in the sidelobes. CP-OFDM has the lowest overall roll-off rate, while FBMC has the most significant rate after F-OFDM, UFMC, and W-OFDM. As a result, FBMC has a substantial depth at the sidelobe level. So, it provides better leakage suppression compared to other schemes. At a normalized frequency of 0.5, the PSD amplitude values are 33.12 81.64. 136.02, 72.43, and 160.13dBW/Hz for CP-OFDM, W-OFDM, F-OFDM, UFMC and FBMC, respectively.

Table 2. Simulation parameters

MCM	Parameter	Value
FFT	Subcarriers with Spacing	15 kHz
	FFT Size	1024 / 64
	Modulation	QAM
	Noise	Gaussian Distribution
	Propagation Model	Rayleigh Distribution
UFMC Parameters	Filter Length	73
	Subband Size/Block Size	12
	Guard Interval	72
	Filter	Dolph-Chebyshev Filter
	Stop-Band Attenuation	40dB
	length of padding	72
	Size of FFT	64
FBMC Parameters	Prototype Filter	PHYDYAS filter
	Filter with Length	N.K
	Overlapping Factor	4
OFDM	Length of CP	72

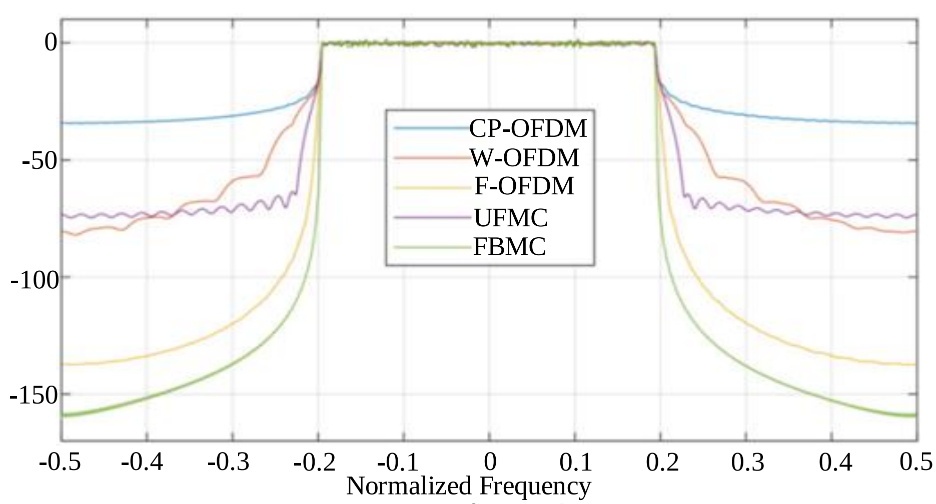

Fig. 15 PSD of MCM schemes

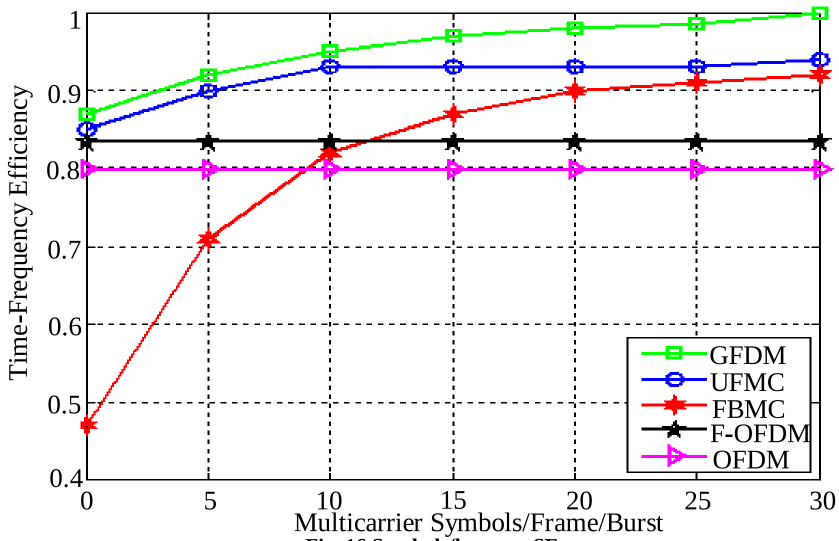

Fig. 16 Symbols/burst vs SE

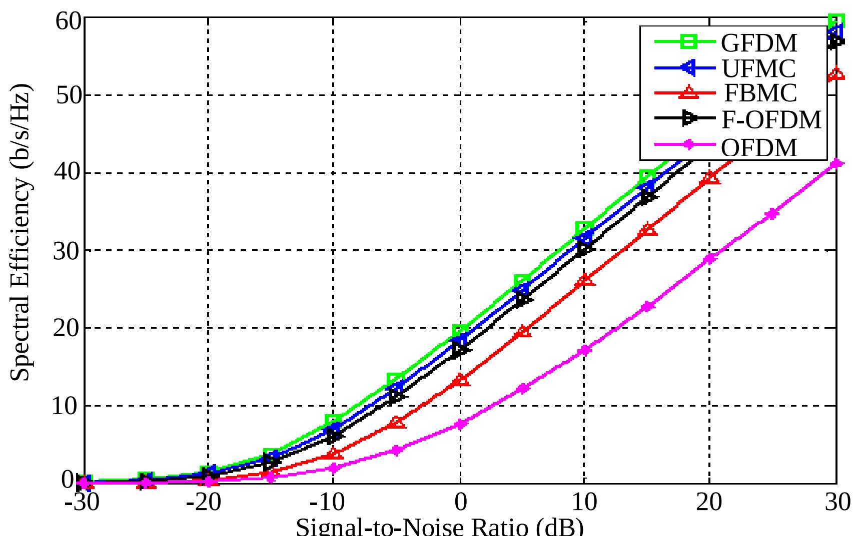

Fig. 17 SNR vs SE

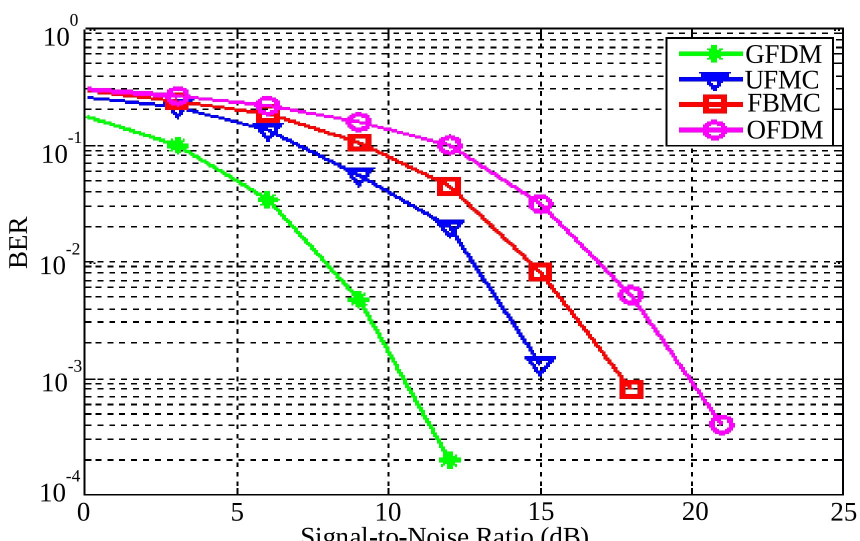

Fig. 18 SNR vs BER

Figure 16 compares the spectral efficiency of several MCM approaches to the number of multi-carrier symbols in each burst. The overall SE of OFDM and FOFDM decreases by 10%. It can also be shown that as the burst size approaches 5, the overall SE of FBMC comes from that of OFDM, and it demonstrates superior efficiency when the burst size exceeds five multi-carrier symbols. Based on the analysis, it can be concluded that UFMC and GFDM exhibit more excellent suitability for short-burst transmissions than other MCM systems. FBMC is more suitable for transmitting long bursts than short burst communication when its efficiency is limited. Unlike UFMC or OFDM, FBMC does not use additional guard interval insertion to address the frequency selectivity of the channel. Consequently, FBMC exhibits channel-type independence. Figure 17 compares our proposed MCM technique to SNR and SE. Figure 18 represents the BER analysis of various MCM schemes. The GFDM scheme improves BER performance more than OFDM, UFMC, and FBMC. At a BER of 0.001, the SNR of OFDM is 19.1dB, FBMC is 17.2dB, UFMC is 15dB, and GFDM is 11.5 dB. Therefore, it is identified that GFDM reduces BER more effectively than other MCM approaches.

The GFDM scheme provides better BER performance. Figure 19 shows the PAPR analysis of various MCM schemes. The PAPR of the OFDM method is very high. The explained MCM methods can address the problem of PAPR and generate results that outperform OFDM. The PAPR of OFDM is 11.7dB at a CCDF of 0.001. When CCDF=0.001, the PAPR values are 11.2dB, 9.8dB, 8.7dB, and 8.3dB for F-OFDM, FBMC, UFMC and GFDM, respectively. Compared to OFDM, the PAPR reduction is 0.5dB, 1.9dB, 3dB, and 3.4dB for F-OFDM, FBMC, UFMC and GFDM, respectively.

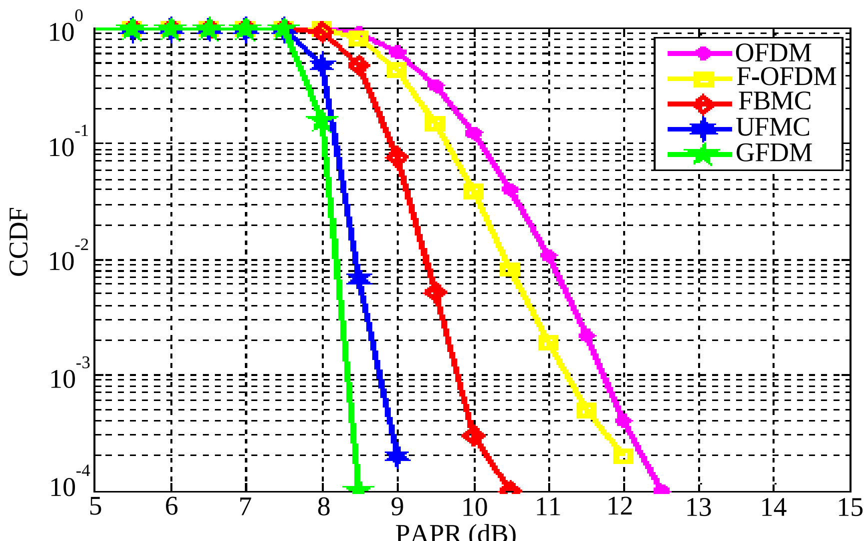

Fig. 19 PAPR analysis

Table 3. MCM schemes comparison

Parameter	**OFDM**	**FBMC**	**UFMC**	**GFDM**
PAPR	H	H	H	M
OBE	H	L	L	L
SE	L	H	H	H
CC	L	H	H	H
CP	Y	N	N	N
Short-burst traffic	N	N	Y	Y
Fragmented spectrum	N	Y	Y	Y
TO resiliency	P	G	G	G
CFO resiliency	P	G	G	G
Reliability	M	H	H	L
Orthogonality	Y	Y	Y	N
Synchronization requirement	H	L	L	M
Time-frequency efficiency	L	H	H	H
H-High, L-Low, M-Moderate, N-NO, Y-Yes, P-Poor, G-Good				

6. Conclusion

This article investigates all potential candidate waveforms for 5G wireless communication systems and analyses the performance of FBMC, OFDM, GFDM, and UFMC concerning PSD, CC, BER, and SE. Among these, GFDM provides better performance. The results indicate that FBMC exhibits less OOB by using pulse-shaping filters.

FBMC is remarkably unaffected by multiuser interference. The complexity of UFMC and FBMC is more than that of OFDM. UFMC provides lower OOB leakage than OFDM due to block filtering. Simulation results show that the GFDM system is the most suitable for 5G. The GFDM approach reduces PAPR effectively, improves BER performance and has an excellent spectral efficiency.

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