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A Comprehensive Survey of Candidate Waveforms for 5G, beyond 5G and 6G Wireless Communication Systems

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Abstract

The evolution of global mobile data over the past decades in broadcasting, Internet of Things (IoT), education, healthcare, commerce, and energy has put strong pressure on 3G/4G mobile networks to improve their service offerings. These generations of mobile networks were initially invented to meet the requirements of the above-mentioned applications. However, as the requirements in these applications continue to increase, new mobile technologies such as 5G (fifth generation), 5G and beyond (B5G, beyond fifth generation), and 6G (sixth generation) are still progressing and being experimented. These networks are very heterogeneous generations of mobile networks that will have to offer very high throughput per user, good energy efficiency, better traffic capacity per area, improved spectral efficiency, very low latency, and high mobility. To meet these requirements, the radio interface of future mobile networks will have to be flexible and rationalized the available frequency resources. Therefore, new modulation methods, access techniques and waveforms capable of supporting these technological changes are proposed. This review presents brief descriptions of the types of 5G, B5G, and 6G waveforms. The 5G consists of OFDM including its transmission techniques: generalized frequency division multiplexing (GFDM), filter bank based multi-carrier (FBMC), universal filtered multi-carrier (UFMC), and index modulation (IM). Meanwhile, the 6G covers orthogonal time frequency space (OTFS), orthogonal chirp division multiplexing (OCDM) and orthogonal time sequence multiplexing (OTSM). The networks' potentialities, advantages, disadvantages, and future directions are outlined.

Keywords

Modulation, 5G, B5G, 6G, Waveforms

1. Introduction

The growing demand for large data transmissions in recent decades has led to the remarkable evolution of telecommunication systems. The IoT for the streaming of videos requires large data. Several generations of communication networks have been developed to satisfy the different demands on speeds, and mobility. In recent years, mobile technologies have evolved considerably to respond to the rapid growth of smart objects.

The Mobile communication begins with the appearance in 1980 of the first generation of analog telecommunication standards called 1G. This technology only offered voice service at a rate of 2.4 kbps. The quality of this one service was poor and the phone was bulky. In view of these limits, a new telecommunications standard called 2G was invented around 1990 to solve the problem [1]. The new standard known generally by the acronym GSM, is a digital technique and offers two services namely voice and low data with a speed of 64 kbps. Both technologies were developed based on the public switched telephone network (PSTN) [1] [2]. In 2000, a total break with the past was made with the invention of a third-generation network based on In the year 2000, the transmission techniques in the third generation (3G) network were invented such as time division multiplexing (TDD), WCDMA, WiMax, code division multiplexing access (CDMA), and time division-synchronous code division multiple access (TD-SCDMA) [3]. 3G used a HSPA technology and is capable of transmitting multimedia data at a rate of up to 2 Mbps. Despite this technological advance, 3G could no longer meet user demands, leading to the invention of 4G LTE mobile network in 2010. The 4G offered a large secure connection capacity and access to streaming multimedia data with a speed of 150 Mbps (LTE) and 1 Gbps (LTE-advanced) because it employs the combination of techniques such as coordinated-multiple transmit/receive (CoMP), OFDM, and multiple-input multiple-output (MIMO) [4].

However, these first four generations could not always meet the challenge in terms of spectrum crisis, high energy consumption, poor interconnectivity, poor quality of service and flexibility, although they had changed lifestyles.

To meet the needs that have remained unsatisfied by 4G, 5G is deployed to promote the IoT progress and accentuate the change in lifestyle.

In addition to the role, it should play in the IoT, three categories of use are assigned to 5G technology, namely [5] [6]:

- Enhanced mobile-broadband (eMBB): it improves broadband services in 5G providing a good user experience, large capacity and very high throughput.
- Massive-machine-type connectivity (mMTC): dedicated to the IoT and spe-

cific communications intended to control autonomous cars, the monitoring of health systems and virtual realities. The numbers of mMTC application is large due to low power consumption.

- Ultra-reliable and low-latency connectivity: The system requires a latency time of less than milliseconds with a very low error rate, packet loss out of 105 packets [6].

5G technology should therefore use the combination of several key technologies such as MIMO, Massive MIMO, beamforming, millimeter waves, Small Cell, D2D) [7] on the one hand and advanced multiple access techniques called multiple access by beam splitting (BDMA) on the other hand in order to meet the challenges [8].

Due to asynchronous and heterogeneous scenarios of 5G technology, several modulation techniques are proposed [9]. To implement these different techniques, performance indices are established by the International Telecommunications Union (ITU) to identify the best modulation techniques explored for 5G technology and beyond, namely OFDM and its variants, UFMC, FMBC, GFDM and IM. The explosion of smart devices and applications has resulted in the large-scale use of the IOT requiring huge data rates, latency, frequent sensing, and computation that can exceed the capabilities of 5G networks. These latest concerns have motivated research to evolve mobile technologies towards 6G. This future technology should meet the IoT requirement in order to increase the coverage of network. For this purpose, 6G should rely on network slicing, applies the artificial intelligence (AI), and THz frequencies [10]. The advancement of mobile communication technologies throughout the years is shown in **Table 1**.

the main objectives of this paper is to analyze the waveforms of 5G networks and beyond, namely OFDM and its variants, FBMC and its variants, GFDM, UFMC, IM…looking at the pros and cons of each wave form. We also analyze some waveforms explored for 6G such as OTFS, Optical Code Division Multiplexing (OCDM), OFDM and Orthogonal Time Sequency Multiplexing Modulation (OTSM), highlighting their potential. Future research direction are also presented in this article.

2. OFDM and Its Variants

Used since the 1950s in the field of wireless communications [11] [12] [13] [14], orthogonal frequency-division multiplexing is a commonly used multi-carrier modulation technique in the industry [15] [16]. The principle of OFDM consists in subdividing the available frequency band into several sub-bands called sub-carriers on which the data is transmitted in parallel. **Figure 1** below functionally depicts the baseband OFDM modulation and demodulation [17].

However, despite the interest that researchers attach to this technique, it suffers from some drawbacks such as interference between symbols and lower throughput. To overcome these drawbacks, several variants of OFDM modulation have appeared over these past years. The major categories most used in the new

Table 1. The advancement of mobile communication technologies throughout the years.

Generation	1G	2G	3G	4G	5G	6G
Technologies	Analog	GSM	CDMA 2020, W-CDMA	LTE, LTE-A, WiMAX	5G, NR, IPv6, LAN, WAN, PAN	SD WAN, Cloud Edge computing, MPLS network, Optical network
Modulation Technique	FDMA	TDMA	TDMA, CDMA	OFDMA	OFDMA, BDMA	CP-OFDM, OTFS, Smart OFDMA plus IM
rate	2.4 to 14.4 kb/s	14.4 to 64 kb/s	3.1 to 14.7 Mb/s	100 Mb/s to 1 Gb/s	1 Gb/s et plus	1 Tbps
Types of Antenna	SISO	SISO	SISO	MIMO	Massive MIMO	Massive and ultra-massive MIMO, Intelligent surface
Core Network	RTPC	RTPC	Packet	Internet	IoT	IoT
Service	Voice	Voice and SMS	Data and voice	Video	VoIP/Ultra HD	Tactile/IA/ML
Band	Narrow	Narrow	Large	Ultra-large	Ultra-large	Ultra-large
Commutation	Circuit	Packet/Circuit	Packet	All-packet	All-packet	All-packet

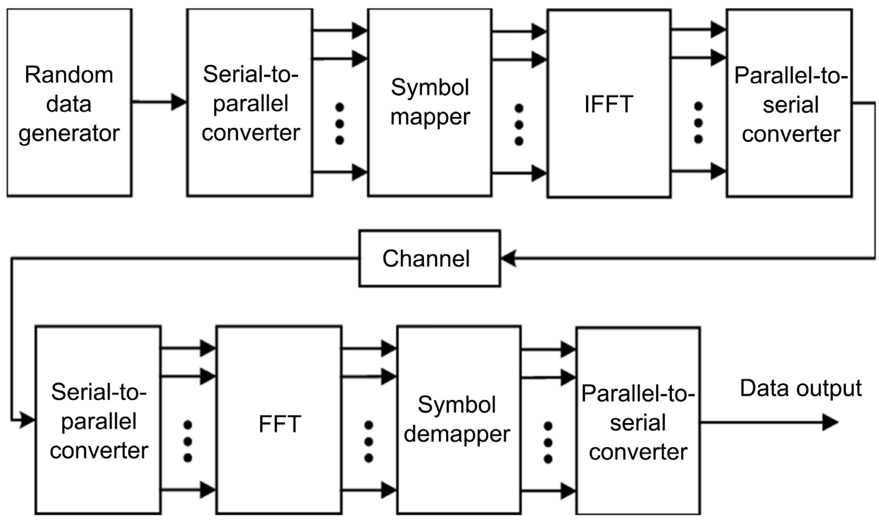

Figure 1. Block diagram of OFDM modulation and demodulation [17].

generations of wireless communications are zero-padding-OFDM (ZP-OFDM), CP-OFDM, CO-FDM, vector OFDM (V-OFDM), flash OFDM (F-OFDM), and WOFDM [18] [19].

In general, OFDM modulation and its variants have enormous advantages and some points of weakness. These advantages have made it widely used for 5G and more [20] [21]. Thus, researchers have proposed solutions to minimize the latency time in 5G under the Rayleigh fading channel based on system performance comparison analysis using BPSK modulation techniques [21]. The analysis of BER, power spectral density and SNR showed that, F-OFDM has best performance of bandwidth for wireless communication system. In the same vein, S. Venkatesan *et al.* [22] presented a unified signal model for OFDM by proceeding with a comparative study between the cyclic prefix (CP) and null postfix (ZP) of one hand, windowing, and filtering on the other hand. The study shows that CP-OFDM throughput is improved by up to 20% at 12 dB SNR when using both modulation and demodulation filtering. The use of such filtering will therefore allow the 5G network to operate with much more flexible timing requirements and respond more effectively to the needs of various types of traffic. In [23] an extensive study of waveforms proposed for 5G communication, was made. First, the authors evaluated the performances according to the spreading time and the multipath effect. It results that UF-OFDM is very sensitive to delay spread, while WOLA-COQAM, and FFT-FBMC are much more robust. BF-OFDM has greater capacity upon delay spread exceeding the predefined guard interval. Then the authors made the study according to mobility. It appears when the mobility is less than 5 km, all waveforms have the same performance.

For distances greater than or equal to 150 km, WOLA-COQAM, FFT-FBMC, and BF-OFDM present a rate of bit errors ten times greater than that obtained with the other waveforms.

In [24] the PAPR performance of F-OFDM for 5G communications using protected tactical service (PTS) was investigated. The technique has a positive impact on the PAPR value of an F-OFDM system and removes OBB and BER. T. Khaled and al [25] also investigated on the performance of signal processing based PAPR reduction methods to increase the efficiency of power amplifiers for 5G and B-5G with multi-carrier modulations (**Figure 2**) [24].

More recently, Figuerie Felipe A. P and al [26] assessed the influence of interference between adjacent signals using BER in a MIMO (modulation type: OFDM and f-OFDM, detection method: MRC, ZF, MMSE, SD and SD). The study concludes that systems with f-OFDM perform well in terms of spectral efficiency showing F-OFDM as better option for future generation wireless networks. Peng

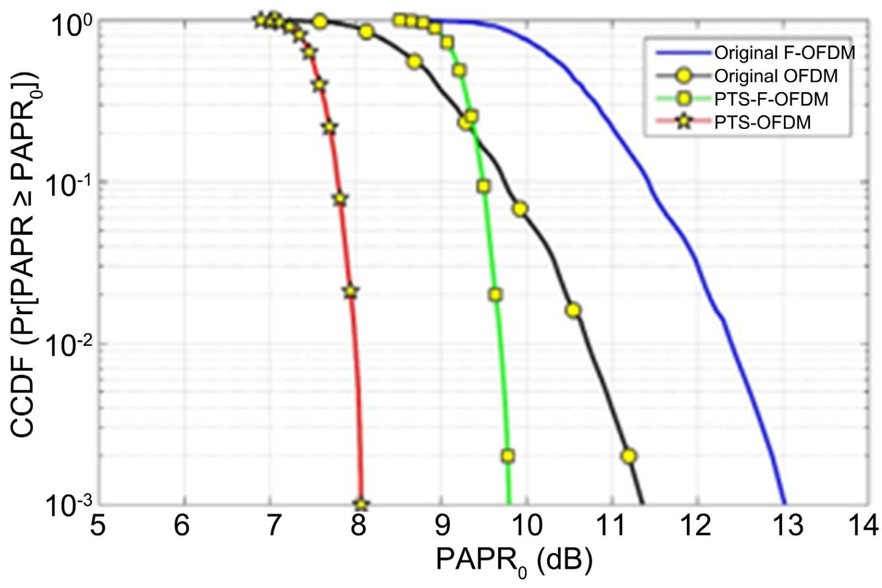

Figure 2. Comparison of PAPRs of OFDM and F-OFDM [24].

Guen and al [27] did a study on the different OFDM waveforms proposed for 5G. In comparison with the CP-OFDM and W-OFDM, results showed that F-OFDM has the best spectral efficiency and robustness in high SNR regime. These factors increase with higher inter-numerology out-of-band interference. Thus, the ideal spectrum utilization can be achieved by F-OFDM (guard band completely removed). Jamal Mes oui *et al.* [28] presented an effective CE-OFDM-CDMA type modulation scheme for 5G communication since it has good spectral efficiency and good energy efficiency depending on the modulation index.

From this analysis, we find that the ODFM modulation system and its variants respond with great satisfaction to certain 5G mobile network scenarios [29] [30] and that the best waveforms are those using the filters. Weaknesses such as losses in spectral efficiency and the introduction of strong side lobes have prompted researchers to implement FBMC type modulation [31].

3. FBMC and Its Variants

The inter-symbol interference problem of OFDM prompted researchers to introduce Filter Bank based Multi-carrier (FBMC) as a solution. This solution is a combination of multiplexing and modulation in order to section the wideband channel into small narrowband channels, called sub-channels. Specific filters as shown in **Figure 3** are then used to filter each carrier [32]. These filters have the role of reducing the significant side lobes observed in OFDM modulation, which makes FBMC offer a very high transmission rate and good spectral efficiency [33].

This technique has some very important strengths, which is why it is proposed as a potential modulation technique for fifth-generation mobile communication [34] [35]. The limitations observed on this technique have prompted scientists to design new, more efficient variants of FBMC. FBMC-OQAM (offset QAM) is the first variant that has been implemented. It solved the problems of out-of-band loss, orthogonality and time-frequency location [36]. The limits of FBMC

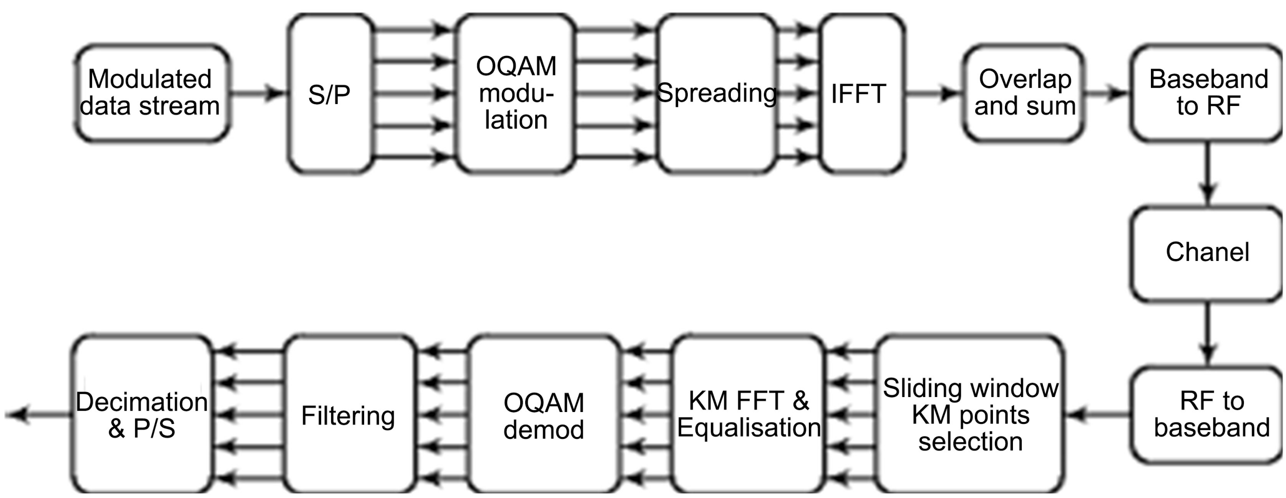

Figure 3. The FBMC chain of transmission [34].

have been taken into account by FBMC QAM [37] since it always presents the non-orthogonality in time and frequency.

New studies have proposed the use of matched filters as a reception filter taking into account the MMSE criterion [38].

In the literature, several works are presented with a view to adopting FBMC as a 5G waveform. We can cite as an example the work of Adnan Mohammed Osman *et al.* [39] on the modified filtering method for 5G communications based on FBMC to minimize doppler shift.

The performance of FBMC for 5G communication has been studied in [40] and the result shows that BER is reduced in FBMC.

Authors Ronald Nissel *et al.* [41] proposed a FBMC scheme for future wireless communications. They demonstrate that the FBMC-based scheme is effective for multi-antenna solutions and for channel estimation. In [42] a low-power FBMC transceiver architecture for different number of multi-users or subscribers using a feedback loop with an FFT core is designed. The proposed method presents a 15% reduction in resources compared to the conventional implementation.

Authors such as Jae Hoon Park *et al.* [43] have proposed solutions based on the use of the OQAM-FBMC variant to present an effective WOLA structured transceiver for communication. The designed transceiver has better performance in terms of BER.

Another study presents a modulation recognition method for FBMC-OQAM signals in 5G mobile communication system. The simulation results demonstrate that the method can identify the FBMC-OQAM signal when the SNR is low [44]. In [45], the performance of an FBMC-OQAM system with nonlinear amplifiers for 5G wireless networks are analyzed. Z. He *et al.* showed in [46] that an improved filter significantly reduces out-of-band emission and secondary lobe for the FBMC-OQAM system in 5G. Other authors have instead presented work on the FBMC-QAM variant. We can enumerate the low complexity recoding scheme to maximize the signal-to-leakage-to-noise (SLNR) power ratio presented in [47] and the new QAM-FBMC waveform which provides a high spectrum confinement and spectral efficiency higher for the proposed 5G communication [48]. In [49], the transceiver architecture, QAM-FBMC signal model, channel estimation error, RF degradation and phase noise are modeled.

4. Ufmc and Its Variants

Universal Filtered Multi-Carrier, known by the acronym UFMC, is an advanced version of OFDM modulation using filtering by group of sub-carriers (**Figure 4**).

The use of filters makes it possible to reduce out-of-band leakage, the main drawback of conventional OFDM [50].

Considered as the promising waveform for 5G networks, UFMC is nowadays highly sought after in research [51]. Thus in [52], a technique for shaping pulses in UFMC based on the Bohman filter was proposed. The presented technique offers better SIR and robust against carrier frequency offset (CFO) in a weakly

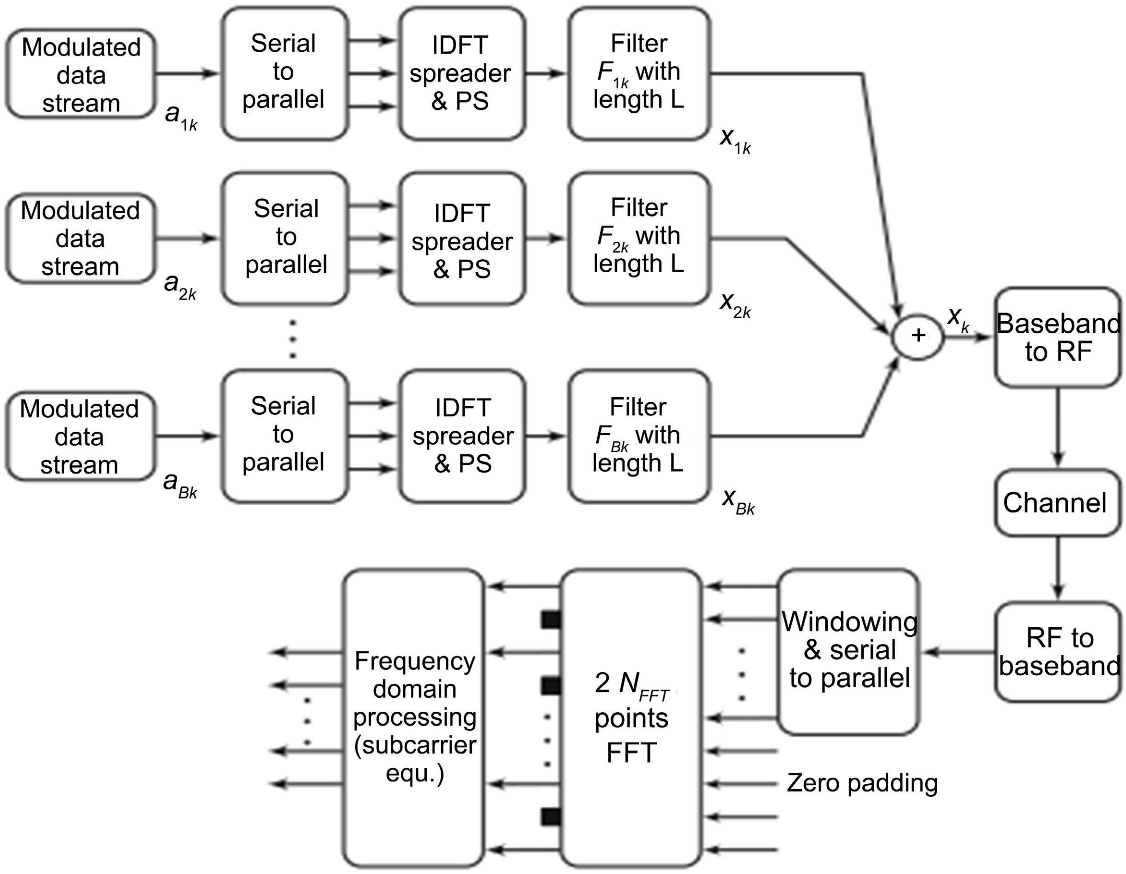

Figure 4. The chain of transmission for the UFMC form [33].

synchronized scenario. Yunhua Li and al [53], proposed a new CFO estimation scheme on a multipath Rayleigh fading channel for UFMC-based systems, descrited by **Figure 5**. The method provides good estimation accuracy, a wide estimation range and its feasibility is confirmed by simulations.

In [54], several clipping techniques to reduce the Peak-to-Average Power Ratio of the universal filtered multicarrier signal an Additive white Gaussian noise channel were evaluated. The results presented show in that deep clipping is the technique that reduces PAPR the most, but has the worst performance in terms of BER. In the same vein, a Discrete-Hartley Transform (DHT)-P-UFMC scheme with low PAPR has been proposed by Imran Baig *et al.* in [55]. The evaluation of the PAPR and SER performance by rigorous Monte-Carlo simulations, allows to conclude that the proposed universal filtered multicarrier system, based on low PAPR DHT pre-coding, outperforms the UFMC system based on Selected-Mapping on SLM and the conventional UFMC system available in the literature. Another scheme of UFMC based on SLM and GCL pre-coding has been proposed in [56] to reduce PAPR and SER. The results concluded that the proposed pre-coded UFMC scheme based on SLM is better than the GCL pre-coded UFMC scheme. A PAPR reduction solution based on the partial transmission sequence technique in the UFMC waveform has been analyzed in [57]. The proposed technique effectively minimizes the PAPR.

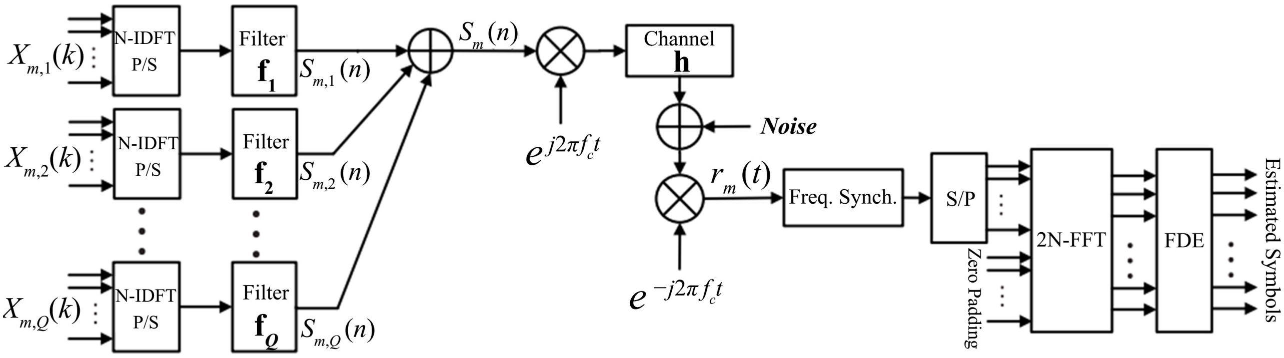

Figure 5. Block diagram of a universal filtered multicarrier system [53].

In [58], an effective solution to the high Peak-to-average power ratio problem of UFMC signals using the MBO-SLM technique has been proposed. The simulation results clearly prove that the migrating birds optimization based SLM scheme has great potential to be among the most preferred Peak-to-average power ratio reduction techniques due to its superior performance on Peak-to-average power ratio reduction of universal filtered multicarrier signals. Extensive studies on PAPR reduction techniques in universal filtered multicarrier systems in 5G proposed in [59] [60].

5. GFDM and Its Variants

GFDM modulation is a technique similar to traditional OFDM where its block structured symbols. The blocks are time and frequency filtered to make the system more flexible [61]. To transmit data consisting of K sub-carriers and separated by M time intervals, the GDFM transmitter illustrated in the **Figure 6** below will transmit modulate N = KM modulated symbols [62].

Characterized by high flexibility, high energy efficiency and high throughput, GFDM is considered as a key promising technology for 5G [63] [64]. It has been proposed in [65] for cognitive radio and 5G type wireless communication. The authors first investigated the possibility of compensating for nonlinear noise effects in GFDM by proposing a new scheme that improves system error rates for two or four iterations. GFDM systems based on Local Discrete Gabor Transform (LGDT) with good performance in terms of BER have also been proposed for 5G communication in [66]. As a result, Meryem Maraş *et al.* [67] proposed the LWT-GFDM method responding to the scenarios of 5G systems such as low latency, low Peak-to-average power ratio and low emission off bandaged. Alexander Hilario-Tacuri and al presented closed-form analytic expressions that improve the spectral efficiency of GFDM systems in nonlinear channels with memory [68]. An interference cancellation method based on OMP for GFDM system is introduced by Mohanraj S *et al.* [69]. The use of the extended Kalman filter (EKF) to decrease the CFO, improve the performance of 5G GDFM is studied in [70]. The DFT-DSSS GFDM technique is used by Huanyu Liu [71] to design a transceiver capable of effectively suppressing PAPR performance, while

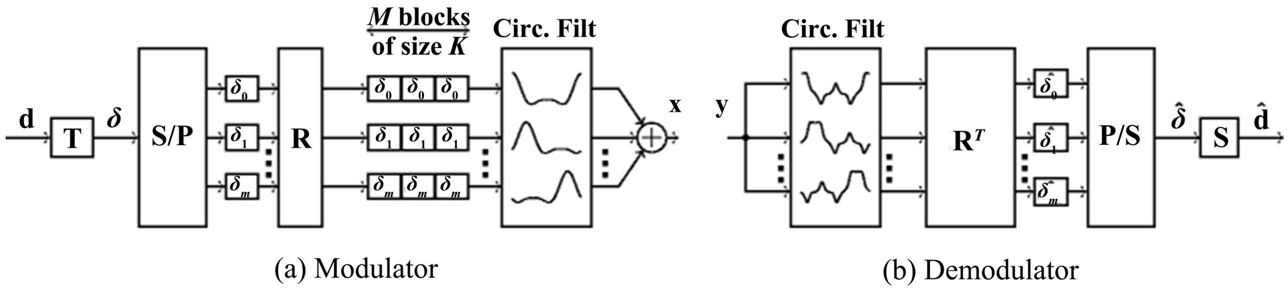

Figure 6. Block diagram of a low complexity modulator and demodulator with precoding [61].

maintaining satisfactory BER performance on AWGN and satellite channels of the radio. Meyer RRC filter, zero forcing filter (ZF), matched filter (MF) and minimum mean square error (MMSE) filter are used in [72] to design and compare GFDM receivers for communication systems 5G in terms of computational complexity.

In [73], the performance of GFDM waveforms in a Long Term Evolution-Advanced type system has been evaluated and compared using the 3D channel model 3GPP-ITU. The study shows that out-of-band emission is reduced, so GFDM is a good waveform to enable a smooth transition between 4G and 5G. Ghaith Al-Juboori and al [74] came to the same conclusion when they resumed the study at the MIMO-GDFM system level.

The technique of regularized channel inversion (RCI) is integrated in the multi-user MIMO-GFDM system to maintain the performance of the system against interference between users caused by the multi-user environment [75].

More recently, the cyclo-stationary detection of the GFDM signal for 5G has been the subject of several works. In literature, temporal smoothing algorithm in cognitive radio transmission is used in [76] for GFDM signal detection, two-color VCSEL is used for power envelope detection provide by wired GFDM 64-QAM at 40 Gbit/s in the 5G network [77].

Borges Ramon Maia and al [78] have proposed the integration of a 5G transceiver based on GFDM in a GPON using radio over fiber technology. The simulation of this method gives interesting results when implemented in a 5G multi-band wireless network based on GPON, GFDM and MIMO.

6. Index Modulation (IM)

The Multi-carrier modulation techniques currently proposed do not effectively meet the objectives of the new generations of mobile networks. These techniques exhibit high PAPRs and high inter-carrier interference. It is therefore imperative to overcome these limitations by using techniques that meet the objectives of 5G, 5GB and 6G.

Over these past years in order to meet the needs new techniques such as index modulation have emerged [79]. Index modulation is a modulation technique that relies on the states of communication equipment, such as antenna, subcarrier, and time slot, for information integration [80]. Generally speaking, the index modulation divides information into bits depending on the active antennas and the constellation symbols capable of being carried by the active resources. It emerges under two designs: spatial modulation (SM-MIMO) for MIMO-type transmit antennas and orthogonal frequency division multiplexing with IM (OFDM-IM), subcarriers.

Spatial modulation (SM-MIMO) describes the way information is transmitted by the indices of the transmitting antennas and the constellation symbols of the signals. In the transmission structure of the SM-MIMO system is given by **Figure 7**, the transmission and reception antennas are represented respectively by n_T and n_R and M the constellation size [81].

OFDM-IM is a new multi-carrier transmission scheme which additionally transmits the data symbols as in conventional OFDM, the indices of the active subcarriers which are used for the transmission of the corresponding data symbols for the scheme OFDM-IM. In sum, index modulation is a new technique that is very simple to implement, flexible in MIMO systems and offers potential advantages in terms of SE/BER compared to conventional OFDM [82]. It is the object of several research works to situate its use in the new generation of wireless communication [83] [84].

Offering a new way of transmitting data bits, the framework for efficient use of IM and the relationship between instant messaging and 5G services was developed by Seda Dogan Tusha and al [84]. A multidimensional generalized quadrature index modulation scheme robust to channel estimation errors (CEE) is also proposed by Taissir Y and al [85]. Energy efficiency is a very important parameter in 5G systems, Piya Patcharamaneepakorn and al [86] proposed the use of quadratic space-frequency index modulation (QSF-IM) after a performance

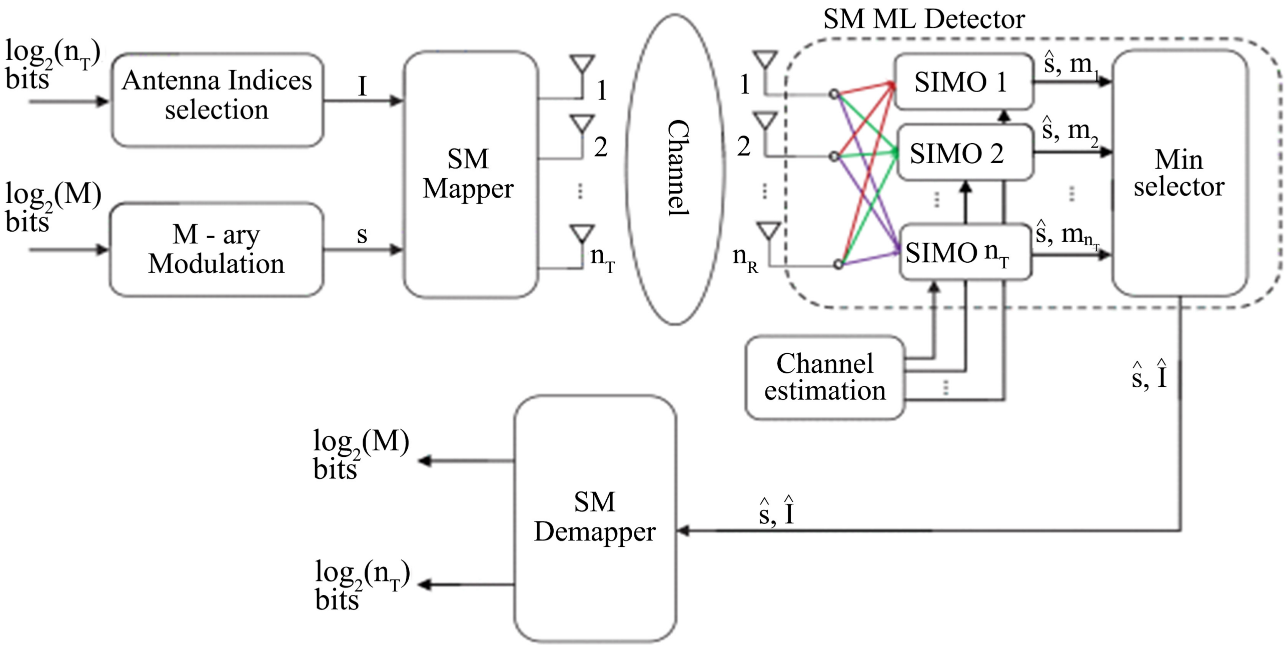

Figure 7. SM system model with n_T transmit and n_R receive antennas [81].

study carried out in the channels Rician and Rayleigh fading. It has also been demonstrated in [87] that the indexed modulation (IM) applied in OFDM systems provides an improvement in energy efficiency and spectral efficiency depending on the number of active subcarriers, but this performance in terms of of BER is degraded that it is important to use OFDM-IM-SM in 5G systems. The authors Jovana Mrkic and Enis Kocan have proposed a hybrid system consisting of OFDM-IM at high SNR values and conventional OFDM at low SNR values [88]. It is shown in [89] that the use of DM-OFDM-IM gives a reduced bit error rate (BER) compared to the conventional DMOFDM-IM system. In the same vein, it is proposed a FG (Fixed-Gain) relay assisted OFDM-IM scheme providing good power efficiency [90], Beamforming for 5G MIMO-OFDM with index modulation to reduce the rate error rate (BER), mean square error (MSE) and PAPR [91].

In [92] a state of the art on the use of SM-MIMO in future 5G wireless communications is made. The study by Seyfettin Uluocak and al highlighted the interest of using massive multi-user (MU) MIMO-SM systems in the 5G network [93].

7. 6G Waveforms

5G technology has been deployed since 2020 and research to make it more latency-efficient and ultra-reliable is being carried out. However, this technology will not be able to meet the demand for high-speed data transmission in a high-mobility scenario, with the large-scale use of artificial intelligence, in the decades to come [94] [95]. Research is launched for the development of the sixth generation of mobile communications system capable of meeting the challenges. To do this, this future generation of mobile networks will rely on different techniques to provide high energy efficiency, permanent global coverage, data rates of up to 1 Tbps and highly ecological [96] [97].

Waveforms that can satisfy the above requirements and be very flexible, robust therefore need to be invented or adapted from the old ones. To this end, OFDM is proposed as the waveforms respectively usable in the RAN of 6G networks to support machine learning, deep learning [98] [99]. The OFDM Hybrid Number and Index Modulation (OFDM-HNIM) is suggested. This hybrid modulation technique modifies index and numbers of active subcarriers in each OFDM sub-block. It gains spectral improvement, power efficiency, high reliability, and low complexity [100]. The new OTFS is characterized by high mobility at very high frequencies [101]. OTFS operating principle is shown in **Figure 8** [102]. OTFS transforms the time-varying multipath channel into a two-dimensional time-independent channel in the Delay-Doppler domain whilst solving the tracking time-varying fading that occurs in high-speed communications of vehicles.

OTFS able to extract full channel diversity over time and frequency. It has linear throughput scaling with antenna count in moving vehicle.

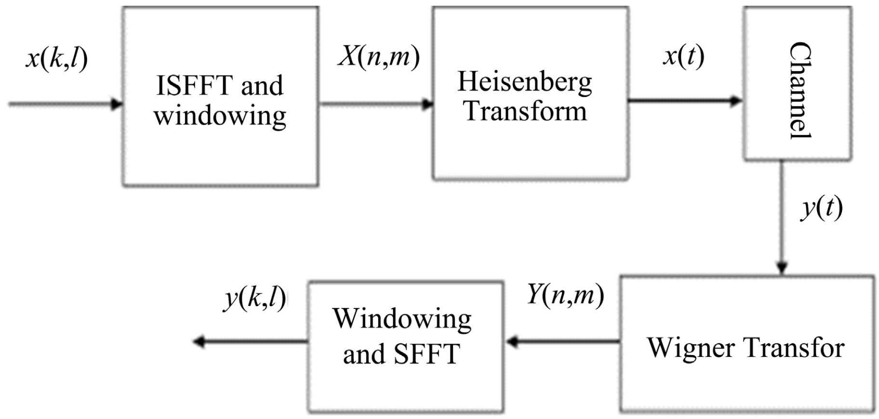

Figure 8. OTFS modulation scheme [102].

Additionally, the delay-Doppler channel representation is compacted. The OTFS allows dense and flexible stacking of reference signals. The signals are key requirement for supporting large antenna arrays used in massive MIMO. Arguably the biggest advantage of OFTS is its ability to transform a channel that randomly fades in the time-frequency frame into a stationary, deterministic, non-fading channel between transmitter and receiver.

In this modulation technique, a 2D Inverse Fourier transform is applied to the signals in the delay-Doppler to move to the frequency domain and then a Heisenberg transform applied to obtain a transmit signal in the time domain. In reception, the Wigner transform and the Fourier transform are applied.

It has many advantages, the management of high Doppler effects [103] [104], the support of massive MIMO [102] [105]. That is why enormous research is being conducted to design less complex detection schemes [106] [107].

Variations of OFTS, circular pulse shaped OTFS (CPS-OTFS) and Circular dirchilet pulse shaped OTFS (CDPS-OTFS), are beginning to emerge in future mobile communications research [108].

In the same order of research on the waveform on 6G orthogonal modulation by time-frequency multiplexing (OTSM) has also been proposed.

OTSM is a single-carrier modulation technique using both Walsh-Hadamard transform (WHT) and zero-fill (ZP) row-column interleaving between blocks in the time domain [109]. OTSM has better characteristics compared to OFDM, widely used in high mobility channels, gains close to OTFS and its modulation/demodulation is less complex [110].

Other research focuses on the use of multi-carrier waveforms based on the use of Discrete Fresnel Transform (DFnT) and Discrete Fourier Transform (DFT), called Orthogonal Chirp Division Multiplexing (OCDM).

This modulation has better performance for mobile communication in a time-selective channel (TSC) and/or a frequency-selective channel (FSC) [111].

It can be easily exploited on radar communication (RadCom) MIMO systems [112], autonomously process very small sub-blocks to provide multiple access and low complexity equalization [113], and exhibits an error rate on the weaker bits [114].

More recently, a modulation almost identical to OCDM modulation called AFDM is proposed. This modulation technique uses the generalized discrete Fresnel transform to match the chirp slope to the channel profile [115]. This operation of adaptation of the chips to the channels makes it possible to obtain all the temporal diversities of the latter.

The advantages of AFDM make it an efficient waveform for next generation high mobility communications, unlike OFDM and other multi-carrier techniques based on Discrete Affine Fourier Transform (DAFT) [115].

In [116], the authors proposed a new non-orthogonal waveform of the Non-Orthogonal Waveform (NOW) type associated with DFT-s-OFDM for 6G communication.

The proposed technique presents better performance in terms of spectral efficiency and PAPR compared to conventional DFT-s-OFDM and CP-OFDM orthogonal waveforms. Researchers Affan Affan and collaborators have proposed a new spatial multiplexing technique for 6G communication named Orbital Angular Momentum (OAM) with index modulation applied to MIMO. In their studies, they analyzed bit error rates (BER) over different distances mainly for single user cases [117].

8. Comparative Study of Candidate Waveforms for Future Mobile Communications Networks

In order to comprehensively compare the waveforms for 5G, B5G and 6G wireless communication systems (**Table 2**). Compiles the wireless communication waveforms and their main advantages and disadvantages.

9. Research Directions

In this section we propose some research direction in the context of 5G, B5G and 6G. Future mobile networks should be very demanding since heterogeneous scenarios and broadband demand will increase significantly [118]. To this end, future work on waveforms should focus on spectral adequacy, localization and robustness of time/frequency dispersions, and latency between PAPR. 6G system is a unified network of mass applications with various modulation techniques of low power consumption. The system is expected to be better than 5G. Therefore, massive connectivity (remote nodes from renewable energy source) via IoT is vital [119]. Data retrieval by receiver and transmitter via channel state information (CSI) is challenging. In 5G system, initial signals will be transmitted to the receiver for channel estimation. CSI retrieval at the transmitter depends either on receiver's interchange or response [120]. Application of many antennas (transmit/receive signals) can prevent initial signal overhead. Therefore, channel state information retrieval is needed in 6G system. Adjustment on the distance of initial signal (time and frequencies), application on limited circular spread of the channel [121], and advanced signal processing methods are highly recommended to reduce the noise at the initial signal [122].

Table 2. Candidate waveforms for future mobile communications networks.

Modulation type	advantages	Inconvenience
OFDM and its variants	sélective fading immunity; Resilience to interferences; Spectrum Efficiency; Resilient to ISI; Resilient to narrow band effects; Simpler channel equalization;	High peak-to-average power ratio; Sensitive to offset and drift of the Unsuitable for communication with high mobility;
CP-OFDM	Easier frequency domain equalization Flexible frequency assignment Low implementation complexity Easier MIMO integration	PAPR and high out-of-band emissions (OOBE) Cyclic Prefix Encoding Time Poor performance in case of high mobility Tighter sync limits
W-OFDM	Lower OOBE Lower implementation complexity	Low spectral efficiency Low BER.
F-OFDM	Flexible filter granularity Better frequency localization Shorter filter length MIMO-compatible	Great complexity of implementation
CP-DFT-s-OFDM	Lower PAPR	High OOBE Strict timing requirements
ZT-DFT-s-OFDM	Flexible guard interval Superior spectral efficiency Lower OOBE than CP-DFT-s-OFDM	Additional control signaling Limited link performance (for higher order modulation)
UW-DFT-s-OFDM	Optimal spectral efficiency Lowest OOBE and PAPR	All inconvenients of ZT-DFT-s-OFDM High implementation complexity
FBMC	High Spectral Efficiency and Selectivity; Strength of bands; Removal of side lobes	Overlapping symbols; Difficulty of use in MIMO systems; Requires very long filter usage; Difficult to be used in IOT and M2M communication.
OQAM-FBMC	Optimal frequency localization High spectral efficiency - No resistance to intersymbol interference (ISI) (due to no guard band or CP) Suitable for asynchronous transmission Suitable for high mobility use cases	Hard driver design No resistance to inter-symbol interference (ISI) High implementation complexity High energy consumption
UFMC	Significant reduction of out-of-band waves; Well localized filtering Shorter length compared to subcarrier size MIMO compatibility	High PAPR Difficulty designing the receiver due to OQAM No immunity to ISI High receptor complexity
GFDM	effective suppression of out-of-band emissions. Reduced PAPR on average Superior frequency localization Flexible design	Management of ISI/ICI very difficult; Modulation complexity due to prototype filter; discontinuities between blocks Higher latency due to block processing Intégration MIMO difficile High implementation complexity

Continued

IM	Provide high throughput Simple to implement	Lack of model to be used in all waveforms
OTFS	Ability to handle strong Doppler channels Exploiting frequency dispersion for diversity Efficient UE multiplexing	Higher implementation complexity Suboptimal equalization architectures

Table 3. List of abbreviations.

Abbreviations	Description
AF	Amplify-and-forward
AFDM	Affine Frequency Division Multiplexing
AWGN	Additive White Gaussian Noise
BER	bit error rate
BPSK	Binary phase-shift keying
CP-OFDM	Cyclic Prefix, Orthogonal Frequency Division Multiplexing
DFT-S-OFDM	discrete Fourier transform spread orthogonal frequency division multiplexing
DFT-DSSS	discrete Fourier transform-direct sequence spread spectrum
ML	Machine learning
CE-OFDM-CDMA	onstant Envelope OFDM--CDMA
M2M	Machine to machine
CFO	carrier frequency offset
GFDM	generalized frequency division multiplexing
IOT	Internet of things
W-OFDM	Wide-Band Orthogonal Frequency Multiplexing (W-OFDM)
IM	index modulation
mMTC	Massive-machine-type connectivity
UFMC	universal filtered multi-carrier
OFDM	Zero-forcing
OTFS	orthogonal time frequency space

Machine learning application can be taken into full consideration [123].

Orthogonal Time Frequency Space also has many unresolved issues. Channel estimation and driver design are more difficult than OFDM [124], and equalization becomes more complex than traditional OFDM [125]. The combination of Orthogonal Time Frequency Space with high-order Multiple-Input Multiple-Output should also be investigated.

For future 6G communication systems and beyond, integrating ML into OFDM communications will improve performance and efficiency. ML has been used to solve some problems in OFDM-based communication systems, including frequency offset estimation, PAPR reduction, and channel estimation.

However, implementing ML in communication systems poses challenges such as computational complexity and cost, distribution, security, privacy, and hardware cost;

The extensive studies on the perforating of CE-OFDM-CDMA and OTFS on a multipath Rayleigh fading channel with the CFO estimator can be done.

Table 3 reflects the abbreviations and acronyms we have used throughout this paper.

10. Conclusions

In this article, an exhaustive study of waveforms for 5G, B5G and 6G wireless communication systems has been presented.

OFDM has two drawbacks: Low frequency localization and high power to peak ratio (PAPR) like all multi-carrier waveforms. However, there are simple, well-established techniques to improve frequency localization and reduce PAPR. These techniques can be applied to CP-OFDM at the transmitter level. DFT-S-OFDM signals have the best characteristics from the energy point of view, compared to OFDM signals.

This is the main reason for choosing DFT-S-OFDM for uplink transmissions. The major difference between DFT-S-OFDM and OFDMA is that OFDMA is a multi-carrier transmission technique while DFT-S-OFDM is a single-carrier technique.

FBMC has good spectral efficiencies for 5G telecommunications but cannot be used in 5G applications such as M2M, IOT since it does not use the cyclic prefix. The GFDM offers a good spectral efficiency on the bandwidth considered thanks to the use of cyclic prefix per packet compared to the UFMC whose transmitter structure is complex. UFMC has good spectral efficiencies close to that of OFDM but GFDM is one of the best candidates for 5G thanks to its better spectral efficiency, and be compatible with the MIMO channel and the suppression of inter-band interference. The other waveforms such as IM and OTFS have very good performance compared to existing modulation schemes, which can meet the scenarios of 5G, B5G, 6G but in-depth studies must be made in this direction.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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