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Review paper

Overview of 5G modulation and waveforms candidates

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Abstract: The 5G (fifth generation) mobile communications aim to support a large versatile type of services with different and often diverging requirements, which has posed significant challenges on the design of 5G systems. Modulation and waveforms are one of the key physical layer componentsthat determine the system throughput, reliability, and complexity, therefore their design is critical in meeting the variety requirements of 5G services. A comprehensive overview was presented on the modulation and waveforms that have been considered for their potential application to 5G in the literature, identifying their design requirements, and discussing their advantages to meet such requirements. Additional considerations that extend our view to higher layer aspects and air interface harmonization are provided as the final remarks. As a result of this article, it is hopeful to draw greater attentions from the readers on this important topic, and trigger further studies on the promising modulation and waveform candidates.

Key words: 5G, modulation, waveforms, FQAM, APSK, USTM, OFDM, FBMC

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1 Introduction

One of the primary contributors to global mobile traffic growth is the increasing number of wireless devices that are accessing mobile networks. Each year, several million new devices with different form factors and increased capacities are being introduced. Over half a billion (526 million) mobile devices and connections were added in 2013 and the overall mobile data traffic is expected to grow to 15.9 exabytes per month by 2018, nearly an 11-fold increase over 2013[1]. Such unprecedented growth in the number of connected devices and mobile data places new requirements for the 5G wireless access systems that are set to be commercially available around 2020[2].

Driven by the growing mobile access, 5G is also aiming at providing a large versatile type of mobile services, from xMBB (Extreme Mobile BroadBand) service which will require very high (up to 20 Gbit/s) data rates[3,4], to mMTC (Massive Machine Type Communications) where low complexity and low power consumption is highly desired[3,4]. In addition, stringent reliability and latency constraints are imposed for uMTC (Ultra-reliable Machine Type Communication)[3,4]. An overview of the disruptive 5G capabilities and their requirements is given in Fig.1[5], where significant enhancement in different KPI (Key Performance Indicators) from 4G

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to 5G is envisaged.

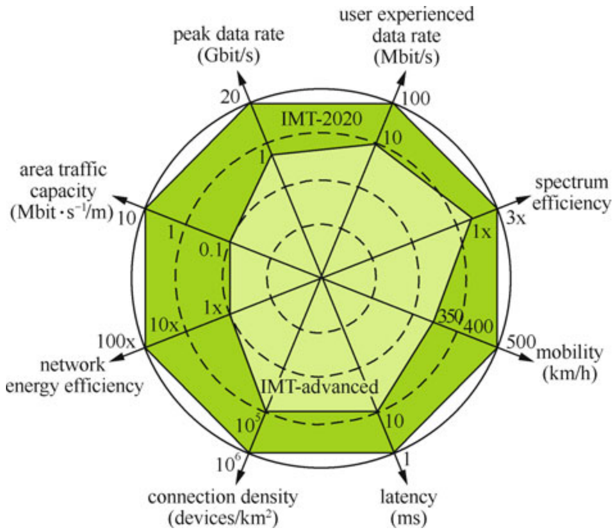

Figure 1 5G capabilities and requirements

Key technology enablers from different perspectives of the 5G technologies are proposed to meet the significant enhancement in KPIs. Those that have been widely discussed to date, include new modulation and waveforms[3,4], milli-meter (mm-wave) system[2,3,6], massive MIMO (Multi-Input Multi-Output)[3,7], Multi-RAT (Multi-Radio Access Technology) and small cells[8], and SDN (Software Defined Network) and NFV (Network Function Virtualization)[9].

From the physical layer perspective, modulation and waveform design is one of the most critical aspects that plays a major role in determining the system throughput, complexity, and reliability, and therefore it has received significant interest among industry and the research community. To date, tremendous efforts have been made in identifying the key challenges and requirements, as well as in analysing the suitable candidates for the evolving 5G technologies.

In Europe, highly targeted research collaborations among industry, research institutions and universities have been enabled through the EU's Horizon 2020 5G-PPP (5G Public Private Partnership) initiative. The first phase of this ambitious program started in July 2015 and comprised a portfolio of 19 collaborative projects, covering wireless access, network and management aspects of 5G systems. The investigation on modulation and waveforms techniques in 5G-PPP includes research on 5G air interface for access, backhaul and fronthaul, which is being carried out in the mmMAGIC (mmWave based Mobile Radio Access Network for 5G Integrated Communications) project[10], led and coordinated by Samsung, research on 5G air interface below 6 GHz, which is being carried out in the FANTASTIC-5G (Flexible Air Interface for Scalable Service Delivery within Wireless Communication Networks of the 5th Generation) project, and the harmonization activities of the air interface variants with the goal to provide a highly flexible 5G air interface design to support multi-service, multi-connectivity, carried out in the METIS-II (Mobile and Wireless Communications Enablers for Twenty-twenty (2020) Information Society-II) project[4].

Recently, a review of modulation formats and waveforms was provided in Ref.[11], where different candidate waveforms, such as OFDM (Orthogonal Frequency Division Multiplexing), FBMC (Filter Bank Multi-Carrier), TFS (Time-Frequency Packed Signalling), and SCM (Single Carrier Modulations), were analysed and compared, mainly from the spectral efficiency and performance perspective.

Although the potential modulation schemes and waveforms in 5G have been overviewed in the literature to some extent, they either focused only on waveforms and largely neglected new modulation schemes[7], or considered limited KPI aspects orapplication scenarios in 5G[10,11]. To date, there is a lack in the literature that provides a comprehensive overview on the modulation and waveform candidates in 5G, and analyses their advantages and disadvantages to meet the variety of requirements in 5G services. In this paper, we aim to fill such a gap. We identify design requirements for new modulation and waveforms in 5G, provide overviews and report recent findings on a state-of-art list of potential modulation and waveforms, analyse their suitability for the identified requirements, and finally extend our views to higher layer aspects and air interface harmonization as concluding remarks. As a result of this paper, we hope to help the 5G research community in industry and academia develop overall know how in this important area in 5G technologies, as well as to trigger greater interest among the readers to study the promising modulation and waveform candidates.

2 Requirements for new modulation and waveforms

While the air interface design in LTE and its evolution are expected to meet many of the requirements of xMBB, they are limited in their support of uMTC and mMTC. In this section, which draws inspiration from Refs.[4,12], we identify major requirements for new modulation and waveform designs in 5G, based on joint considerations of xMBB, uMTC, and mMTC with more challenging KPIs than 4G is able to meet today. With ambitious goals set for 5G of supporting services with different (and often diverging) requirements, a highly flexible 5G air interface design will be needed to meet this challenge[4].

2.1 Throughput requirement

3GPP has achieved remarkable data rates through the LTE and beyond set of standards. LTE-A can in theory deliver a peak rate of 3 Gbit/s on the downlink[13]. This however is the best-case scenario and does not answer the 5G challenge of 100 Mbit/s[14] (or according to some projections, 1 Gbit/s everywhere [3]), with peak data rates of 10~50 Gbit/s required [3,8]. LTE-A will of course be improved upon through forthcoming releases-improvements such as massive MIMO and enhanced carrier aggregation will contribute to around five times increase in peak performance[14]. However this will not necessarily help with cell-edge rates, or get anywhere near the projected 5 000-fold increase in system capacity required by the year 2030[14] arising from the anticipated data traffic explosion mentioned above. The comprehensive answer is suggested in greater network densification and new spectrum, both of which impose specific requirements for waveform and modulation design. It is no longer simply the matter of increasing the MCS (Modulation and Coding Scheme) order-with the increased densification we need to take into account the impact on inter-cell and cross-tier interference. Additionally, in the era of massive MIMO, suitability for MIMO of a waveform and modulation choice becomes an important differentiating factor. These and other aspects are covered in sections that follow.

2.2 Coverage requirement

One of the key KPIs for 5G is the ubiquitous service availability, which is strongly correlated with the satisfaction of the end user as well as system reliability. Therefore, and in addition to conventional techniques for coverage extension, modulation techniques and time-frequency resource mapping schemes which by design have an impact on the statistical distribution of inter-cell interference are of great interest for further study.This is especially important given the fact that cell edge users in particular suffer most from the inter-cell interference.

2.3 Latency and reliability requirement

5G aims to provide ultra-reliable communications, especially when service types such as control and safety is considered. As a result, improving current modulation and waveform designs to achieve high reliability and short latency is critical to meet the service requirements of uMTC. Achieving the joint requirements of sub-1 ms latency and over 1 Gbit/s downlink speed have been identified as a true generational shift from 4G to 5G, and a hugely exciting challenge that will define 5G[15]. Modulation and waveforms, as the key enabler to meet this challenge, need to be carefully designed, jointly taking into account the complexity increase that the new technique may cause.

2.4 Minimizing signalling overhead and supporting energy efficiency

Minimizing signalling overheadis important for xMBB in order to squeeze out the maximum amount of goodput, but also for services such as mMTC with their short, bursty transmissions. LTE is not well suited for MTC (Machine Type Communication) traffic comprising short data packets and transmitted in quick bursts. It should be noted that 3GPP has initiated activities, namely LTE-M, to improve 4G with respect to the support of MTC. However, the support of MTC is expected to be done intrinsically for 5G. This could be done by using a waveform that, e.g., reduces PAPR (Peak to Average Power Ratio), making it well suited for energy constrained services. Additionally, for MTC applications, energy efficiency based on LTE is comparatively poor, and efficiency of active mode in 5G should be flexible so as to also support sensors or other low cost devices.

2.5 Multi-service support

LTE evolution, with its well-established resource grid and frame structure suited for a limited set of frequency bands and geared mainly towards xMBB support, may not meet all the 5G requirements. In addition to meeting more ambitious KPIs than 4G is able to meet today, 5G will need to natively offer multi-connectivity, support for a wide range of frequencies, and multi-service support. Different services such as mMTC, uMTC and xMBB have different (and often diverging) requirements. Evolutions of 4G modulation and waveforms may meet some of the KPIs of these individual 5G services, but not the key 5G requirement to natively integrate multi-service support. 5G additionally needs to facilitate the use of alternative connection types such as D2D (Device to Device) communication.

2.6 Support for a wide range of frequencies

In all likelihood, 5G systems will operate across a wide range of mm-wave and cm-wave frequencies. This may mean that traditional modulation and waveforms (or waveform families), so far used for a limited number of bands and services, will need to be redesigned to support flexible parameterisation, such as adaptable HARQ (Hybrid Automatic Repeat Request) settings, or TTI length, or sub-carrier spacing, to ensure suitability for a wide range of frequencies.

3 Candidate modulation schemes

A number of candidate modulation schemes have been reported for consideration as potential modulation schemes for 5G. In this section we select three representative modulation schemes that have raised great interest in 5G, due to their significant respective advantages.

3.1 FQAM

In order to provide ubiquitous and high data rate connectivity, the emerging 5G wireless access network is envisaged to deploy large number of base stations with higher density and smaller sizes, where ICI (Inter-Cell Interference) becomes a critical problem. Recently, a new type of modulation, namely FQAM (Frequency Quadrature Amplitude Modulation), has been shown to be able to significantly improve the transmission rates for cell-edge users[16] and therefore raised great interest in its application in 5G[3,17,18]. Variants of FQAM such as the generalized OFDM

(Orthogonal Frequency Division Multiplexing) IM (Index Modulation)[19], which activates multiple subcarriers in each transmission period, and the generalized space and frequency IM, which combines FQAM and SM (Spatial Modulation)[20], have been reported in the literature.

The signal constellation of FQAM can be considered as a combination of QAM and FSK (Frequency Shift Keying), where the constellation of a (M_F, Q)-FQAM symbol is formed by M_F-ary FSK modulation and Q-ary QAM modulation. It is known from Ref.[16] that a total of lb$Q$ + lbM_F bits are mapped to one FQAM symbol, with the first lbM_F bits indicating the frequency index and the last lb$Q$ bits indicating the QAM index using Grey mapping. Fig.2 gives an example of the signal constellation of a 16-ary FQAM[3].

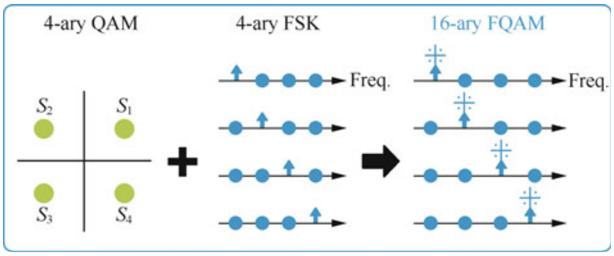

Figure 2 Example of 16-ary FQAM

FQAM, when used with OFDM, has a same transceiver structure as that of a QAM-OFDM. A block diagram of the FQAM-OFDM transceiver with turbo code is shown in Fig.3, where the two functional blocks that are different from a QAM-OFDM transceiver, namely the FQAM modulation at the transmitter, and the log-likelihood (LLR) computation at the receiver,are highlighted in blue.

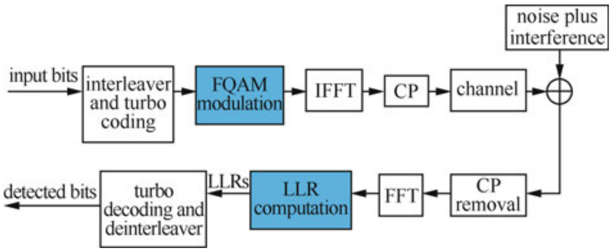

Figure 3 An FQAM-OFDM transceiver structure

It is seen from the figure that a FQAM-OFDM transmitter is similar to QAM, where a sequence of transmission bits, modulated as FQAM symbols, are processed with an IFFT (Inverse Fast Fourier Transform), then a CP (Cyclic Prefix) is added at the beginning of the IFFT output, yielding one OFDM symbol for transmission. These OFDM symbols then go through respective fading channels between each base station and the UE. When downlink transmission is considered, interference from the base stations other than the intended transmitter is aggregated. At the receiver, the CP is removed, and a FFT (Fast Fourier Transform) is performed, after which a soft-decoding metric in the form of log-likelihood (LLR) is computed as inputs to thesubsequent turbo decoder, where the transmit bits are detected following a deinterleaver.

The difference in LLR computation for a FQAM detector is caused by the fact that the distribution of aggregated ICI, created by transmitting FQAM symbols at the interfering BSs, is shown to have a CGG (Complex Generalized Gaussian) distribution[16], especially at the cell edge, whereas the ICI has the normal Gaussian distribution in a QAM detector. Such a distribution of aggregated ICI in FQAM is simulated and shown in Fig.4. It can be observed that there is a big gap between the real part of ICI plus noise and the Gaussian distribution. The probability density of ICI plus noise is more concentrated while the Gaussian distribution has larger spreads.

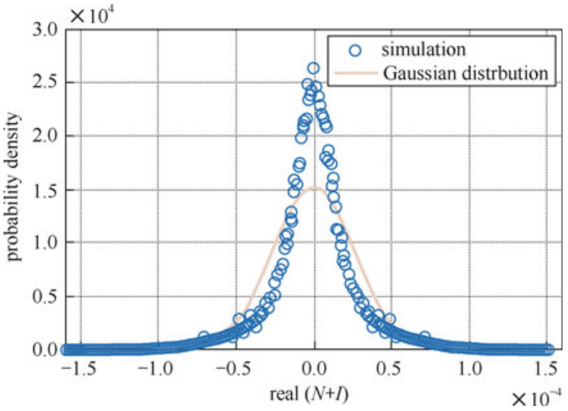

Figure 4 Distribution of the real part of noise plus ICI in a 19-site (4, 4) FQAM network

Because a Gaussian distributed ICI generated by QAM symbols is known to be the worst-case additive interference in wireless networks with respect to channel capacity [21], having non-Gaussian distributed ICI in FQAM, especially at the cell edge, significantly increased the transmission rate at the cell edge. As an example, such a performance advantage in terms of FER (Frame Error Rate) of FQAM over QAM is depicted in Fig.5[15], where a multi-cell OFDM network and zero mean unit variance i.i.d. complex Gaussian channel was assumed, and rate 1/3 rate Turbo code was used[17]. Worst case scenario of ICI was considered where users are located at the edge of the cells[17]. As is observed from the figure, when the number of interfering base station is two, as in the usual macro cell deployment, FER of FQAM for the cell edge users significantly outperforms these of QAM. Similar performance advantages of FQAM at the cell edges have also been shown in the literature, e.g., Refs.[3,16]. The use of FQAM in 5G is therefore beneficial to services where coverage and reliability are the major KPIs to achieve.

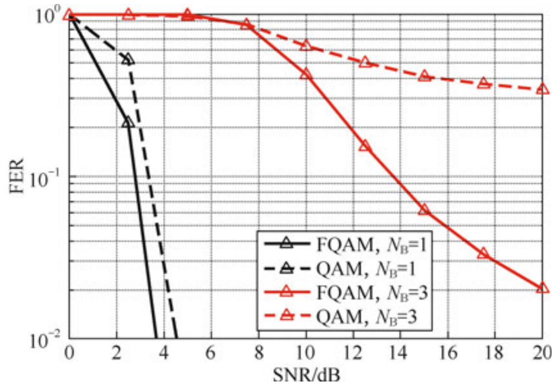

Figure 5 FER of FQAM and QAM with different numbers of BSs.

Despite the advantage of having a non-Gaussian distributed ICI in FQAM, when it comes to LLR computation, it actually requires a more complex detector than QAM which has the Gaussian distributed ICI[18]. Such a complexity issue at the detector was studied in Ref.[18], where a low complexity detector was proposed and was shown to yield the same performance than the conventional FQAM detector, while at the same time reducing the computational complexity by a factor of Q for each FQAM symbol. The proposed low complexity algorithm is therefore especially beneficial to FQAM with higher order of QAM. For example, for 256 QAM that has recently being considered in 3GPP Release-12 and beyond, the computational complexity indicates a reduction of factor of 64 for each FQAM symbol, accumulatively a factor of 2^{16} complexity reduction if 1 024 FQAM symbols are transmitted in one frame. The low complexity receiver[18] allows FQAM to achieve considerably increased coverage and reliability at no cost of significant complexity increase compared to QAM, therefore greatly facilitates its potential application to 5G.

3.2 APSK

Another modulation scheme that has recently drawn increasing attention in 5G, in particular in the IMT-2020 (5G) Promotion Group[22], is APSK (Amplitude and Phase Shift Keying)[23]. Similar to FQAM, APSK can be considered as the combination of ASK (Amplitude Shift Keying) and PSK (Phase Shift Keying). An example, 16 APSK constellation diagram is illustrated in Fig.6. The co-centric ring like constellation results in the amplitude distribution being very close to Gaussian compared to QAM[22].

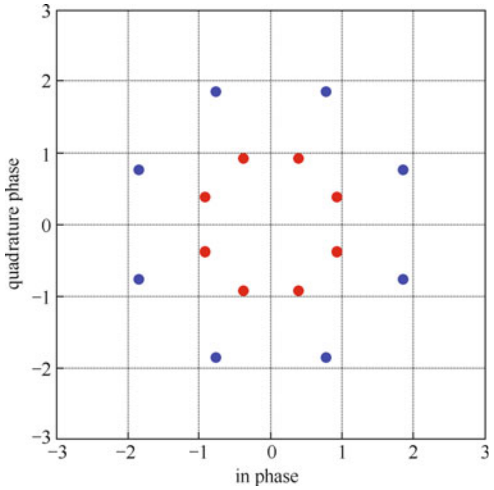

Figure 6 Constellation of a 16 APSK

This new constellation, together with channel coding and advanced demodulation algorithms, can be designed to achieve channel capacity that is very close to Shannon's capacity[22]. In particular, it has been shown in Ref.[23] that APSK is able to achieve Gaussian capacity when the constellation size grows to infinity[23], whereas a gap of 1.56 dB to the Gaussian capacity exists when conventional QAM constellation is used.

The capacity achievable APSK constellation needs to be carefully designed. In Ref.[23], a Gaussian shaped constellationwas proposed for Gaussian channel by applying a Box-Muller transform to pairs of uniformly distributed random variables to generate a set of two-dimensional pointswith a Gaussian shape. There are other APSK constellation designs for different types of channels. For example, the optimal APSK modulation for nonlinear channel with phase and amplitude distortions to the transmitted signal due to high-power amplifier is given in Ref.[24]. In addition to the advantage of approaching channel capacity, simulations have also shown that APSK has a lower PAPR compared to conventional QAM[25], due to the smaller number of amplitude levels. In addition, an APSK signal can be optimized by adjusting the constellation diagram, particularly in terms of reducing its PAPR.

Performance between APSK and QAM was compared in Ref.[22], where it has been shown that in an AWGN (Additive White Gaussian Noise) channel, the performance improvement by using APSK is about 0.5~0.9 dB at 0.01% BER (Bit Error Rate), and the gain becomes more pronounced when the modulation order gets higher[22]. It is noted however, such performance gain in APSK relies on advanced channel coding and demodulation algorithms, therefore renders more complexity at the transmitter and receiver.

3.3 USTM

USTM (Unitary Space-time Modulation)[26,27] is a modulation scheme that allows high throughput MIMO communication without the need of CSI (Channel State Information) at either the transmitter or the receiver, therefore is especially beneficial in scenarios where channel coefficients become extremely difficult to track due to high mobility, or the number of antennas grows significantly in a massive MIMO system.

USTM is applicable to systems where the channel coherence time T (in multiples of the symbol duration)is larger than the number of transmit antennas M. In particular, it has been proven in Refs.[26,27] that the high throughput transmission with non-coherent reception relies on the design of a capacity achieving transmit signal, $\boldsymbol{S}$, which is constructed by the product of a non-negative, real, diagonal matrix $\boldsymbol{V}$, and an isotropically distributed unitary matrix $\boldsymbol{\Phi}$, given by

$$\boldsymbol{S}=\boldsymbol{\Phi}\boldsymbol{V},$$

where $\boldsymbol{\Phi}$ and $\boldsymbol{V}$ are of dimension $T\times M$, and $M\times M$, respectively.

The method of identifying $\boldsymbol{\Phi}$ and $\boldsymbol{V}$ such that the designed signal can achieve channel capacity has been studied in the literature. In particular, it has been proved in Refs.[26,27] that as the channel coherent time T tends to infinity, capacity can be achieved when the diagonal elements in $\boldsymbol{V}$ are identical.

Further studies in Ref.[28] proposed a systematic method for creating constellations of USTM for multiple-antenna communication links, wherea Fourier-based construction of $\boldsymbol{\Phi}$ were proposed. It has been demonstrated in Ref.[27] that when the coherence interval of the channel is sufficiently large, using USTM and non-coherent detection can approach the channel capacity as if the receiver knew the propagation coefficients.

Based on USTM, the DUSTM (Differential Unitary Space-Time Modulation) generalizes the DPSK (Differential Phase Shift Keying) to multiple transmit antennas[29]. The design of DUSTM relies on the fact that the fading channel needs to be approximately a constant during two consecutive symbol durations. Transmit data is then encoded by matrices in the Stiefel manifold whose dimensionsare related to the coherence time and the number of receive antennas[29].

In DUSTM, the currently transmitted matrix is constructed by the product of a unitary matrix $\boldsymbol{V}_t$, and the previously transmitted matrix $\boldsymbol{S}_{t-1}$, given by

$$\boldsymbol{S}_t = \boldsymbol{V}_t \boldsymbol{S}_{t-1}$$

which is seen as extension of standard DPSK to more than one antenna[29].

Simulations in Ref.[30] demonstrated that when the coherence time of the channel is proportional to the number of antennas, DUSTM can achieve a BER of less than 0.001 at moderate SNR. The capacities of DUSTM and USTM were investigated in Ref.[28], showing that in the low SNR regime (SNR << 0 dB), USTM outperforms DUSTM. However, at high enough SNRs (SNR >> 0 dB), DUSTM outperforms USTM.

USTM and its extensions represent a non-coherent modulation family that is considered to be extremely beneficial to certain 5G services, for example,when high mobility makes it extremely difficult to track the channel coefficients, or when the exchange of short packets, especially under stringent latency and reliability constraints, is required[31].

3.4 Other modulation schemes

In addition to the modulation schemes we discussed earlier, there are also other modulation schemes that have been considered under the context of 5G due to their respective advantages. For example, when MIMO transmission is considered, SM[20] where only one antenna is active at each transmission instant and antenna indices are utilized to convey information, has been shown to be able to mitigate ICI, as well as simplifies inter-antenna synchronization and radio chain design, therefore has been discussed as potential technologies in 5G systems[32,33].

Other modulation schemes, such as WAM (Wave Modulation) and OTFS (Orthogonal Time Frequency and Space), are also reported with significant advantages of its application to 5G in terms of increasing the throughput. These modulation schemes are however proprietary therefore are unavailable to be further analyzed or compared with other modulation schemes.

4 Candidate waveforms

Waveform design plays an important role in addressing the challenges imposed by extremely diverse use cases, deployment scenarios and service requirements in 5G systems. Many challenges specifically to waveform design need to be taken into consideration. Based on the requirements presented in Section 2, here we highlight these challenges for waveforms:

High spectral efficiency: The currently adopted multicarrier technique, i.e., OFDM, uses CP (Cyclic Prefix) to eliminate inter-carrier interference and has strong OOB (Out-Of-Band) emission.As a result, guard bands are required to mitigate interference. To satisfy the throughput requirement in 5G, waveforms are expected to have high spectral efficiency by avoiding the use of CP, and to have low out-of-band emission therefore eliminate the need for using guard bands.

Efficient use of non-contiguous spectrum: considering the fact that having large amount of contiguous spectrum is getting very hard, especially for these that are below 6 GHz, the aggregation of non-contiguous frequency bands is considered for 5G systems to make the best use of the scarce spectrum. The need for efficient utilization of the non-contiguous spectrum has motivated the search for multicarrier waveforms that provide lower out-of-band emission without sacrificing spectral efficiency.

Support for sporadic access: In order to reduce the power consumption, especially for mMTC, low-power devices need to transmit their data immediately after waking up with very low overhead, and to enter a dormant state directly after data transmission. As devices cannot be fully synchronized in this scenario, 5G waveforms need to be robust against timing and frequency offset to limit the amount of required signalling.

Compatibility with MIMO technologies: 5G systems are expected to deliver an efficient use of the spectrum by using MIMO technologies, such as massive MIMO. As a result, waveforms that can efficiently support MIMO are very desirable. For above 6 GHz bands, due to the hostile propagation condition in mm-wave radio channels, e.g., severe path loss, vulnerability to blockage, large antenna gains at both transmitter and receiver sides are required to overcome propagation losses. As per the Friis Law the single antenna aperture size reduces with the square of the carrier frequency and negatively impacts the amount of radio energy captured at the receiver. In this regard, very large scale antenna arrays are needed that enable highly directive transmit and receive beamforming, and corresponding waveform designs need to follow.

Robustness against RF impairments: Waveforms should in general address challenges caused by RF impairments, e.g., phase noise, I/Q-imbalance, sampling jitter, sampling frequency offset, carrier frequency offset, PA (Power Amplifier) nonlinearity. In particular, when it comes to higher frequency bands such as mm-wave bands, RF impairments become more severe because the phase-noise variance grows with the square of carrier frequency. As a result, robustness against RF impairments in waveform designs needs to be enhanced in such frequency bands.

In addition to main challenges listed above, there are many other issues that need to be taken into consideration when designing 5G waveforms.In the sections that follow, taking into the challenges specified above, we provide overviews onwaveforms that are being considered as potential candidates for 5G systems that aim to tackle these challenges.

4.1 OFDM based waveforms

OFDM has been widely accepted in many wireless standards such as WiFi, WiMAX and LTE/LTE-A[30,34,35]. It is well-known to provide a simple transceiver design and easy integration with advanced multiple antenna technologies such as higher order MIMO and massive MIMO for beamforming. With the use of CP, multipath fading can be effectively tackled with a one tap frequency domain equalizer, as long as the duration of CP is longer than the time domain span of the channel impulse response. A typical OFDM transceiver architecture is illustrated in Fig.7.

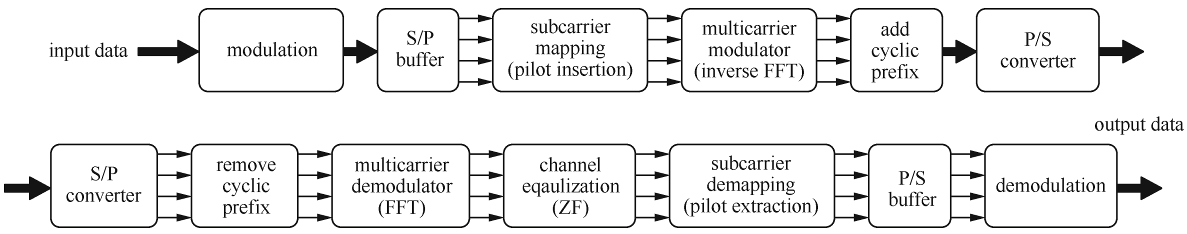

Figure 7 OFDM transceiver architecture

The drawbacks of CP-OFDM include comparatively high OOB leakage, posing the need of using large guard bands, and degraded overall spectral efficiency due to the added CP overhead. An OFDM system is known to have $TF<1$, with F is the subcarrier spacing and T is the symbols spacing in time domain. The large side-lobe of CP-OFDM also results in ICI when synchronization cannot be achieved or when affected by Doppler spread in the cases of high mobility users, degrading the overall system performance. As a result, currently, enhanced OFDM based waveforms are being investigated to address the requirements for 5G wireless systems and to enable a more flexible adaptation to the needs of providing diverse services.

4.1.1 F-OFDM (Filtered OFDM)

The unfavorable spectrum confinement property of OFDM is due to the usage of rectangular pulses whose PSD (Power Spectrum Density) in the frequency domain is a sinc function. F-OFDM filters the subcarriers to achieve much smaller OOB leakage while at the same time maintaining strict separation of the signals in the time domainand the complex field orthogonality[36]. The major advantage of F-OFDM, in addition to full compatibility with OFDM, is its capability to be adapted to address various 5G requirements with flexible choices of filter design, e.g., fast roll-off rate when good frequency localization is needed.

The transceiver architecture of an F-OFDM is shown in Fig.8. The only difference with the traditional OFDM is the addition of subcarrier filter block which shapes the PSD of each subcarrier in the frequency domain to reduce OOB leakage.

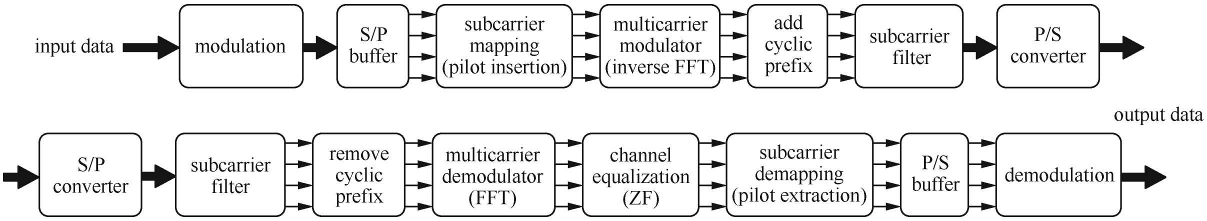

Figure 8 F-OFDM transceiver architecture

4.1.2 W-OFDM (Windowed OFDM)

Instead of frequency domain filtering, time domain non-rectangular windows/pulses can also be applied in the time domain to smoothen the transition at the symbol edges, therefore reducing the OOB leakage. The time domain windows, or prototype filters, can be flexible designed to improve spectrum confinement[37]. Some common designs of the windowing functions are available, such as Hamming, Hanning and Blackman windows. The reduced side-lobe also facilitates asynchronous transmission, due to the reduced interference power caused by frequency or time errors.

The architecture of W-OFDM is the same as F-OFDM except that the subcarrier filter block is to be replaced by time domain windowing therefore a figure is not presented here.

4.1.3 UF-OFDM (Universal Filtered OFDM)

While F-OFDM filters all subcarriers, UF-OFDM, i.e., UFMC, filters a block of subcarriers[38], i.e., a subband to keep OOB emission as shown in Fig.9.

In addition, it is possible for UF-OFDM to employ different frame structure and numerology at each operating sub-band, which could be of variable bandwidth, thereby enabling adaptive deployment and link types[38]. It is also possible to apply zero-tail DFT (Discrete Fourier Transform)spreading to particular sub-bands when additional delay spread protection is needed.

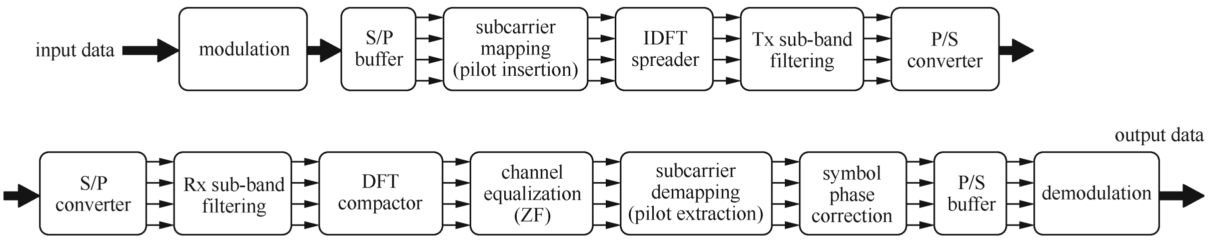

Figure 9 UF-OFDM transceiver architecture

4.1.4 UW-OFDM (Unique Word OFDM)

UW-OFDM employs a similar structure as CP-OFDM with CP replaced by a UW (Unique Word) known to the receiver[39]. The unique word provides extra training signals to improve synchronization and channel estimation accuracy.

However, as a result, the orthogonality among subcarriers maintained by CP-OFDM will be lost,and more complicated receiver needs to be designed.

Despite the efforts of enhancing the spectral efficiency of OFDM based waveforms from different aspects, none of the OFDM based waveforms can achieve the maximum spectral efficiency, i.e., one cannot reach TF=1 with any OFDM based waveforms.

4.2 FBMC based waveforms

FBMC, as an enabling technology for enhancing the fundamental spectral efficiency because of the well-localized time and frequency traits adopted from a pulse shaping filter per subcarrier, can reduce the overhead of guard band required to fit in the given spectrum bandwidth, while meeting the spectrum mask requirement[40]. The advantages of FBMC are achieved by expanding the prototype filter pulse and symbol duration over K symbol intervals in the time domain, resulting in overlapping pulses with duration KT, where T specifies the symbol intervals.

In FBMC, the effectively increased symbol duration is suitable for handling the multi-path fading channels even without CP overhead. Consequently, FBMC reduces the inherent overheads such as CP in CP-OFDM. Since it is well localized in frequency domain,FBMC is also attractive in specific asynchronous scenarios, for example, in coordinated multi-point transmission and reception (CoMP) when signals arrive BSs at different time, and in dynamic spectrum access (DSA) where a fragmented spectrum are employed to support the much higher traffic demand in 5G.

In order achieve the maximum spectral efficiency, OQAM (Offset QAM) for OFDM has been proposed in the literature[40,41]. However, the orthogonality in OQAM is in the real part of the signal only. To maintain the transmission symbol rate, the conventional FBMC system generally doubles the lattice density either in time or in frequency compared with OFDM while adopting OQAM, where in-phase and quadrature-phase modulation symbols are mapped separately with half symbol duration offset. Since complex domain orthogonality cannot be achieved in an OQAM-FBMC system, intrinsic interference will occur in OQAM-FBMC, which makes it challenging toapply the conventional CP-OFDM pilot design and corresponding channel estimation algorithms, as well as the MIMO techniques. In this regard, QAM-FBMC system which can transmit the QAM symbols is proposed to enable fundamental spectral efficiency enhancement whilst keeping the signal processing complexity low and facilitating the compatibility with CP-OFDM[42].

With a base-filter that takes into consideration the spectrum confinement and the orthogonality among adjacent subcarriers, QAM-FBMC performs comparable to CP-OFDM even without the CP overhead, while the guard-band overhead reduction is also available from the well-confined spectrum, as shown in Fig.10[3]. Improved receiver algorithms including channel estimation and equalization can further mitigate the multi-path fading channel impact without the CP.

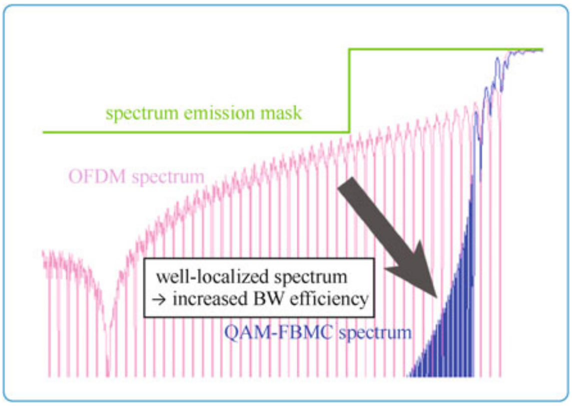

Figure 10 One QAM-FBMC symbol generation

The QAM-FBMC system separates adjacent subcarriers with B filter-banks keeping near orthogonality in complex domain. The transmitted signal of QAM-FBMC can be expressed as

$$x(n)=\sum_{k=-\infty}^{+\infty}\sum_{b=0}^{B-1}p_b[n-kM]\left(\sum_{s=0}^{\frac{M}{B}-1}D_{b,s}[k]\mathrm{e}^{\mathrm{j}\frac{2\pi n}{M/B}s}\right),$$

where $D_{b,s}[k]$ is the complex data symbol on the $(SB+b)$-th subcarrier in the k-th symbol, M is the total number of subcarriers and $p_b[n]$ is the b-th prototype filter.

As an example, an QAM-FBMC system with two different prototype filters for the even and odd subcarriers is illustrated in Fig.11[42]. On the left is the transmitter structure. The information symbols are divided into the even-numbered sub-carrier symbols and the odd-numbered sub-carrier symbols. Then the symbols are oversampled, IFFT transformed and repeated. Finally pulse shaping transmitting filtering with two prototype filters are performed to the symbols by means of windowing (element-wise multiplication) and added. The symbol transmission rate achieves the maximum spectral efficiency of TF=1.

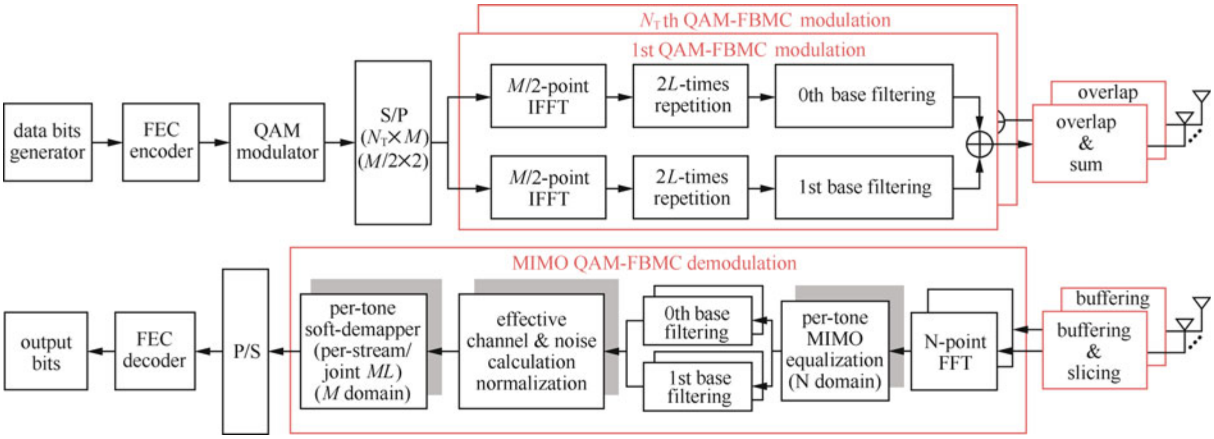

Figure 11 Transmitter and receiver of a QAM-FBMC system

On the right is the block diagram at the receiver. The received symbols are FFT transformed and equalized in frequency domain. Then received symbols are filtered by the receiver filter for even-numbered sub-carrier symbols and due to certain orthogonality conditions identified in Ref.[42], the odd-numbered sub-carrier symbols are filtered out. The same procedure is applied in the receive filter for odd-numbered sub-carrier symbols. By doing this, the received symbols are divided into the even-numbered symbols and the odd-numbered symbols. Each symbol is filtered by the prototype filter and then FFT transformation is performed. The output symbols of FFT can then be demodulated. It has been shown that such a QAM-FBMC system can achieve comparable the same performance as to OQAM-FBMC and CP-OFDM in multipath fading channels[43].

Note a QAM-FBMC can be efficiently implemented using M/B-point IFFT (Inverse Fast Fourier Transform), BL-times repetition, and time domain filtering. Compared with OFDM, the complexity of IFFT is reduced from $O(M\,\mathrm{lb}M)$ to $O\left(M\,\mathrm{lb}\frac{M}{2}\right)$, due to the reduced IFFT length. The repetition will only add negligible complexity. The time domain filtering is implemented by element-wise multiplication. At the receiver side, PPN-FFT scheme can be used with minor complexity addition. Overall, however, a QAM-FBMC has a higher transceiver complexity than that of a QAM-OFDM.

4.3 Single carrier waveforms

In addition to the aforementioned multi-carrier waveforms, a few single carrier waveforms are proposed due to their advantages of achieving low PAPR, thus low implementation complexity and low powerconsumption. SC-FDMA is the underlying waveform for uplink transmission in LTE. However, compared with OFDM, SC-FDMAsuffers from performance degradation in frequency selective channels and poor frequency localization.

Advanced SC-FDMA waveform, e.g.,zero-tail DFT-s-OFDM, is proposed with zero-head and zero-tail samples inserted before DFT to improve the frequency localization[44]. Another generalized version of SC-FDMA is the so-called CPM-SC-FDMA, where samples of a CPM (Continuous Phase Modulation) signal are used as generalized coded modulation input symbols[45]. Extremely low PAPR can be achieved by CPM-SC-FDMA. With low PAPR, hardware complexity and energy consumption can be reduced for the mobile terminals with stringent requirement on cost and energy, e.g., the mMTC devices.

5 Considerations beyond PHY

A number of modulation and waveform candidates have been considered for their potential use of 5G in the literature. This paper provides an overview of some potential modulation and waveforms, in particular selecting a few representative designs that have raised great interest in 5G, due to their respective advantages. The major advantages of each modulation and waveform have been discussed and highlighted in the paper, according to the design requirements we identified.

Up to now, the paper heavily focused on the PHY (Physical Layer) aspects of the 5G system.In addition to the physical layer aspects, air interface that comprises the entire protocol stack that is common in the communicating nodes is also considered critical in terms of achieving the 5G requirements.In particular, generating a reliable signal for transmission over a mobile air interface is a very intricate task, and the steps can differ for DL and UL.

Under such context, specific design of the 5G physical layer, requirements of which we have elaborated on in the paper, additionally need to take into account the various functions that PHY needs to offer to upper layers. This is in turn informed by the various system requirements including QoS support, need for multicast support, and so on, and may differ for UL and DL. As an example, typical functions that the LTE PHY layer needs to offer are:

- Transport of system information

- User data transport

- Transport of control messages
- Paging information transport
- Support for multicast
- Support for random access(through different time/frequency allocations, timings of events, and so on)

Support for these functions is enabled through the design of specific physical channels-in LTE these include data channel, broadcast/multicast channel, and control channels-which are in practice “virtual” or “logical” channels, accessing the same medium (although possibly in different parts of the resource grid) using identical or almost identical technology components.

Specifically for 5G, we need to understand how any air interface design can accommodate network slicing. In other words, what sort of APIs (Application Program Interfaces) need to be offered to higher layers.

Additionally, implementation of RRM (Radio Resource Management) schemes will very likely be a super-set of algorithms required for individual air interface variants, and will be an aggregated set of L2/L3 functionalities.

On the other hand, it is possible to try and design a common protocol stack, doing away with intra-RAT handover delay and increasing implementation and standardization efficiency. In such context, harmonizing the air interface variants (from same or different waveform families) with the aim of finding an optimal compromise between potentially highly specialized solutions for specific services and/or frequency bands, and the broader goal to only have one air interface supporting multiple services, according to Ref.[12], results in following benefits.

- Better utilization of available resources due to the flexibility even in short time scales, e.g., multiple services being provided using the same frequency, and potential of utilizing multiple bands for the same service in a very flexible manner.
- Reduced complexity in the access nodes and the end devices, as less functionalities may need to be implemented.
- Lower delay in case of switching between air interface variants, as this can happen on a rather low protocol layer.
- Less standardization and implementation effort, as less functionalities have to be specified and tested.
- Simpler upgrading of an existing system by implementing additional air interface variants.

6 Conclusion

Modulation and waveforms designs, and when extending to air interface designs, are important yet open problems in archieving the large variety of requirements in 5G. This paper presents our views on the design requirements of modulation and waveforms, the major advantages of the potential candidates, as well as additional considerations when extending to higher layers. With these background presented, we hope that this paper can provide to the readers inspirations on the challenges that need to be tackled in 5G modulation and waveform design, and can trigger further studies on this important area in 5G.

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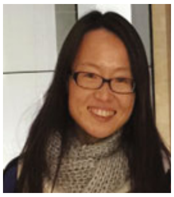

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