Chapter 2

Waveform Design Considerations for 5G Wireless Networks

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Additional information is available at the end of the chapter

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Abstract

In this chapter, we first introduce new requirements of 5G wireless network and its differences from past generations. The question "Why do we need new waveforms?" is answered in these respects. In the following sections, time-frequency (TF) lattice structure, pulse shaping, and multicarrier schemes are discussed in detail. TF lattice structures give information about TF localization of the pulse shape of employed filters. The structures are examined for multicarrier, single-carrier, time-division, and frequency-division multiplexing schemes, comparatively. Dispersion on time and frequency response of these filters may cause interference among symbols and carriers. Thus, effects of different pulse shapes, their corresponding transceiver structures, and trade-offs are given. Finally, performance evaluations of the selected waveform structures for 5G wireless communication systems are discussed.

Keywords: waveform design, orthogonal frequency division multiplexing (OFDM), filtered multitone (FMT), time-frequency lattice, pulse shaping, multicarrier modulation, generalized frequency division multiplexing (GFDM)

1. Introduction

In communication systems waveforms enable the allocation of data on the joint time-frequency (TF) domain by transmitting and receiving proper signals. As the waveform design deals with the methods to generate transmitted signals at the transmitter, and receive at receiver side through a channel, the design criteria depend on demands of users, channel conditions, system, and technology criteria. Therefore, the design criteria change with respect to the advancement of technologies. The waveform techniques in 2G/3G/4G mobile technologies cannot meet the demands of next-generation wireless networks. To overcome problems stemming from the new demands, either it is required to design new waveform techniques, or propose improved versions of the waveform used in 4G, i.e., the orthogonal frequency division multiplexing (OFDM) [1, 2] at least.

The answer to the question “Why do we need new waveforms?” reveals important issues. The state-of-the-art radio access technology is summarized in **Figure 1**. Accordingly, the ambitious performance goals for 5G networks are 10–100 times higher typical user data rates, 10–100 times more connected devices, 10 times lower network energy consumption, less than 1 ms end-to-end latency, and 10000 times higher mobile data traffic per geographical area [1, 3]. The 5G communication systems that are expected to have a heterogeneous network structure are planned to design in such a way that they provide service not only for people as real users but also for various kinds of equipment. While designing the system in this way, we should keep in mind that, features for each user, such as transmission packet lengths, data rates, data transmission frequencies, and capacities would be different. These various requests of users, lead to lots of issues, such as synchronization in time and frequency. To overcome these problems, it is required to design new techniques capable of utilizing the spectrum more efficiently, with higher data rates, with lower energy consumption, and latency [4, 5].

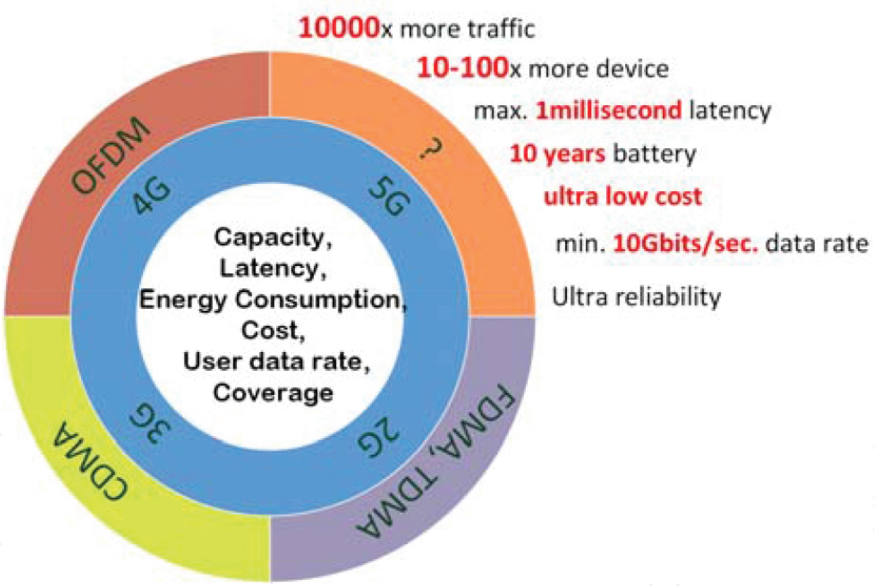

Figure 1. The state-of-the-art radio access technology: moving from voice to 5G.

An ideal waveform shall fulfill the following requirements (i) low power consumption, (ii) high data rates, (iii) spectrum efficient, (iv) low latency, (v) easy to implement, and (vi) low out-of-band emission. Additionally, a well-designed waveform must be robust to disruptive features of communication channels, and be able to easily extract these effects at the receiver side. It must be compliant with massive multiple-input multiple-output (MIMO) systems, and adaptive for users with different access requirements on heterogeneous networks. Absolutely,

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it is not possible to find a waveform that supplies to all requirements perfectly. However, the accurate waveform design procedure meets most of these features at optimum ways.

OFDM is the dominant technology for today's broadband multicarrier communications. However, it is considered as an undesirable solution for 5G wireless networks due to its shortcomings on some channel effects [6]. The other shortcomings are the out-of-band (OOB) emission [7] and peak-to-average power ratio (PAPR) problems [8]. Rectangular pulse shaping of OFDM introduces the nonnegligible out-of-band emissions, which cause interferences among adjacent bands, whereas usage of independent phases for subcarriers causes PAPR problem.

In literature, up to now several candidate waveforms are proposed to achieve 5G communication system requirements. The multicarrier waveforms based on filtering operations are good candidate waveforms to overcome OOB emission problems. Filter bank-based multicarrier (FBMC) and its varieties, generalized frequency division multiplexing (GFDM), and universal filtered multicarrier (UFMC) are among these candidate waveforms.

FBMC is one of the multicarrier waveforms using filtering operation. Filtered multitone (FMT), staggered multitone (SMT), and cosine-modulated multitone (CMT) modulations are variants of the FBMC transmission scheme [9]. The main differences of these schemes are their TF domain allocations. Contrary to FMT, the subcarriers of SMT and CMT are overlapping. So, FMT is not spectrally efficient.

GFDM can be considered as a type of filter bank-based multicarrier modulation scheme with transmission filters that are shifted in time and frequency domains. The novelty of GFDM is in its flexibility, which can address the different applications. On the other hand, most of the real-time applications (i.e., tactile Internet) need lower latency. Low latency can be obtained with small symbol durations and less complex transceiver structures. It is possible to reduce signal durations for GFDM by designing appropriate TF structures [10]. The complexity that is caused by filtering operations can be reduced by using polyphase structures of filters [11]. OOB emission can be reduced via these using filters that have low side lobe levels at their frequency responses.

UFMC is another waveform with low OOB emission [12, 13]. The distinguishing feature of UFMC is in filtering the group of subcarriers instead of filtering each subcarrier. The filters used for UFMC have large bandwidth and short impulse response. It makes short burst transmission. This scheme is not suitable for applications that need time synchronization.

The purpose of this chapter is to present the basics of waveform design for 5G networks. To achieve this, the rest of the chapter is organized as follows. In Section 2, the fundamentals of waveform design that includes TF lattice structures and pulse shaping are explained. In Section 3, the concept of multicarrier waveforms and transceiver structures such as OFDM, FBMC, and FMT with nonuniformly divided bandwidth allocations and GFDM are discussed. In Section 4, the performance comparisons of the waveforms are evaluated. Conclusion and future directions remarks are given in Section 5.

2. Fundamentals of waveform design

Forming TF lattice structures and pulse shaping are the essential steps for waveform design. Time and frequency allocation of transmitted and also received signals are performed through TF lattice structures. The pulse shaping is also an important step to avoid interferences among the symbols in both time and frequency domains.

2.1. TF lattice structures

TF lattice structures contain information about the relationship between time and frequency support information for all symbols. TF lattice structures depend on transmission schemes, i.e., single-carrier, multicarrier, time-division, and frequency-division transmission schemes.

Figure 2 shows the TF lattice structures of time and frequency division multiplexing (TDMA and FDMA, respectively). If frequency spectrum is divided into subbands, the waveform is called multicarrier waveform. Each carrier in a subband is called a subcarrier. Each grid in TF lattice structure indicates a subsymbol. The symbols are transmitted at every T seconds.

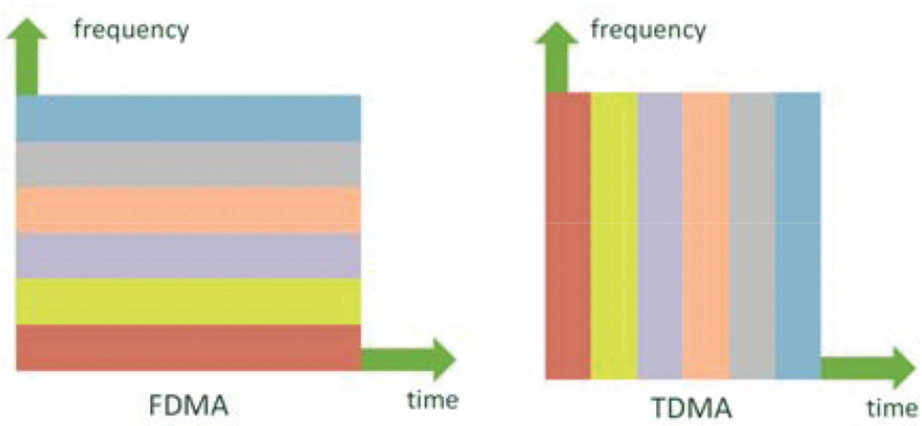

Figure 2. Frequency division and time division multiplexing as a TF lattice structure.

Data rate depends on the transmission bandwidth, channel capacity, signal-to-noise ratio (SNR), and the receiver capacity. Data rate is related to the frequency resolution that is expressed by

$$\Delta f = \frac{1}{T} = \frac{f_s}{N} \tag{1}$$

where f_S is the sampling frequency and Δf is the difference between two adjacent frequency bins. In order to resolve frequencies, it needs to make Δf sufficiently small and that is referred to as increasing the frequency resolution.

A signal $s(t)$ can be represented in the frequency domain by its Fourier transform $S(f)$ as

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$$S(f) = \mathcal{F}\{s(t)\} = \int_{-\infty}^{\infty} s(t)e^{-j2\pi ft}dt. \tag{2}$$

Time-domain signal $s(t)$ has a finite duration. Finite time duration implies infinite bandwidth. On the contrary, finite bandwidth implies infinite time duration. In practice, time duration and bandwidth are limited. A time-limited signal $s_T(t)$ can be expressed by multiplying a rectangular pulse of duration T as

$$s_T(t) = s(t)\,\mathrm{rec}(t/T). \tag{3}$$

The Fourier transform of the time-limited signal in Eq. (3) is

$$S_T(f) = S(f) * T sinc(fT) \tag{4}$$

where * is the convolution operation in the frequency domain. Because of the convolution operation, bandwidth of $S_T(f)$ becomes unlimited.The time and frequency domain representations of the rectangular pulse are given in **Figure 3**. Time domain is limited, but frequency response spreads over a large range of bandwidth.

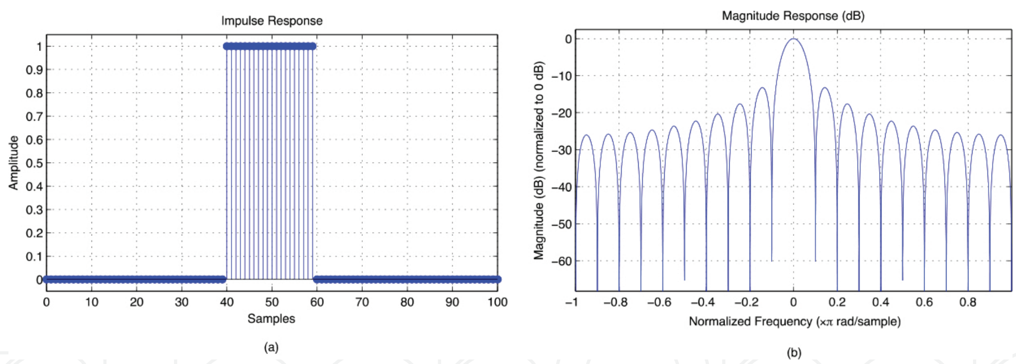

Figure 3. (a) The impulse response and (b) frequency response of a rectangular pulse: The impulse response is limited; frequency response spreads over the frequency domain and includes high-level side lobes.

Such infinite bandwidth information is not realistic. For that reason, a bandwidth that contains most of the signal energy can be used. The extreme frequencies (f_{min}, f_{max}) can be defined from the desired signal energies, and the bandwidth is $B = f_{max} - f_{min}$.

Time-bandwidth product is a design parameter of TF lattice structure. Time-bandwidth product is expressed by $B \times T$ that measures localization in time and frequency domain. The aim is to minimize the unit area of TF lattice structures. But there is a lower limit that is obtained from the uncertainty principle [14, 15]. The time domain representation of a Gaussian pulse is

$$\boldsymbol{s}(t) = e^{-\propto^2 t^2} \tag{5}$$

with time duration $T = 1/2 \propto$ and bandwidth $B = \propto /2\pi$. The time-bandwidth product of Gaussian pulse becomes

$$B \times T = \frac{1}{4\pi}. \tag{6}$$

Time-bandwidth product of Gaussian pulses in Eq. (6) is the lower limit. For all other signals, time-bandwidth product is limited below $B \times T > \frac{1}{4\pi}$ based on the celebrated uncertainty principle.

The TF lattice structures of several waveforms are shown in **Figure 4**. These structures give information about the rules of frequency division and time division of waveforms. TF lattice structure of OFDM is shown in **Figure 4(a)** for a transmission bandwidth, B. The transmission bandwidth is divided into N subbands through IFFT operations. On the other hand, according to the TF lattice structure of GFDM, the time domain is also divided into time slots.

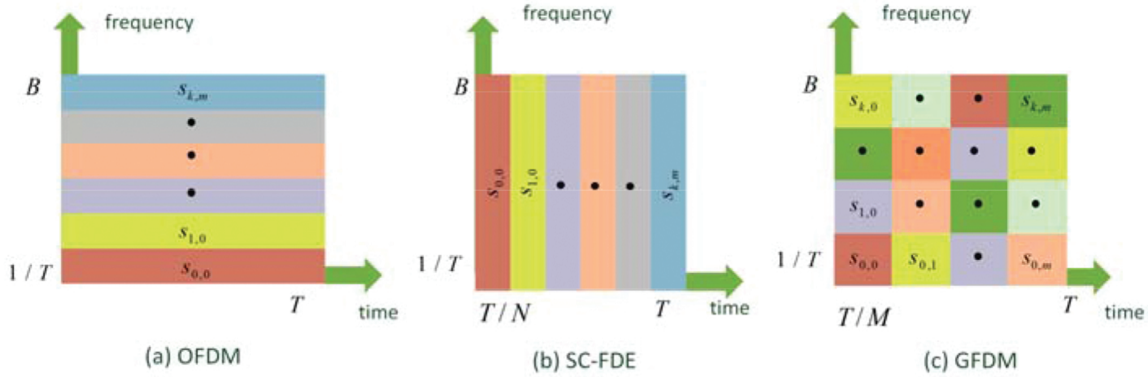

Figure 4. (a) OFDM, (b) single carrier-FDE, and (c) GFDM.

The transmitted signal with proper time and frequency shifts can be expressed as

$$\boldsymbol{x}(n) = \sum_{m=0}^{M-1} \sum_{k=0}^{K-1} s_{k,m}\, \boldsymbol{g}_m(n) e^{-j2\pi n \frac{k}{K}} \tag{7}$$

where $s_{k,m}$ is the data symbol with a subcarrier subscript k and subsymbol subscript m where $k = 0, 1, \ldots, K-1$ and $m = 0, 1, \ldots, M-1$, respectively. $g_m(n)$ is a time-shifted version of a prototype filter $g(n)$. In OFDM, prototype filter $g(n)$ is replaced with 1 and each subcarrier contains one subsymbol, which means $M = 1$. Thus, the OFDM symbol is simply

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$$x(n) = \sum_{k=0}^{K-1} s_{k,m}\, e^{-j2\pi n\frac{k}{K}}. \tag{8}$$

In the same approach, single carrier transmission is obtained by replacing $K = 1$ and $g(n)$ with Dirichlet pulse [16]. The symbols are transmitted by dividing into time slots and each sub-symbol contains all frequency components of the transmission bandwidth.

TF lattice structures of GFDM waveform are the combination of the frequency-division and time-division based waveforms that are defined in Eq. (7). The transmitted signal is obtained by convolution of data with filter $g_m(n)$ that is the time- shifted and frequency-shifted version of prototype filter $g(n)$. The projection of filters $g_m(n)$ on time-frequency domain is not rectangular as indicated in **Figure 3**.

Toroidal lattice [17] and hexagonal lattice [18] are other lattice structures proposed in the literature. Hermite-Gaussian functions are well-localized in both time and frequency domains and the time-bandwidth product of its zeroth-order function equals to the lowest time-bandwidth product, i.e., $1/4\pi$. The time- and frequency-domain representation of the third-order Hermite-Gaussian pulse and a toroidal rectangular TF lattice structure are given in **Figure 5**.

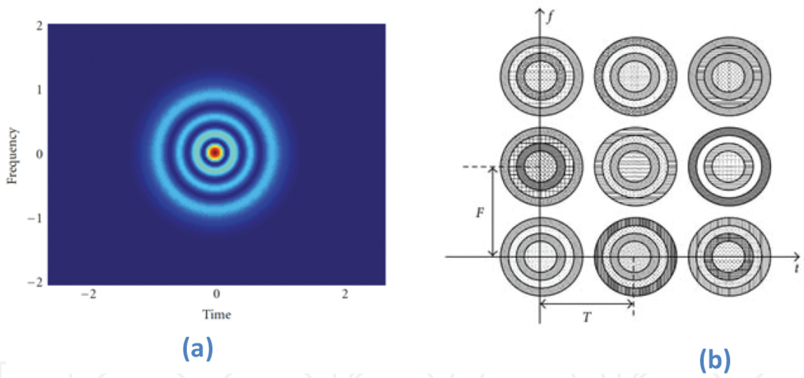

Figure 5. Toroidal lattice structure. (a) Third order of Hermite pulse and (b) rectangular lattice with Hermite pulses [17].

Toroidal rectangular lattice structure provides more data rate as indicated in [17]. On the other hand, the hexagonal lattice structure is more robust for inferences and channel effects [18, 19].

Briefly, the symbol durations and bandwidths are important parameters of TF lattice structures. These parameters are chosen according to the requirements of the users and channel conditions. The details are given in Section 4. The next step of the waveform design is pulse shaping. The pulse shaping is the determination of time and frequency limits of a pulse to fill in each grid in the TF lattice. The methods and constraints of pulse shaping are given in the following section.

2.2. Pulse shaping

In a communication system, pulse shaping is important to generate band- and time-limited transmitted signal. Limiting the signals of symbols in time and frequency domains is important to avoid interferences.

The definition of pulse shaping is the filtering process that maps modulated signals to the TF lattice to control the interferences. The main problem of pulse shaping is the reciprocal relation between time and frequency domains. It means that a narrow pulse in the time domain has wider spectrum in the frequency domain. If the width of a pulse is increased in the time domain, the width of the spectrum in the frequency domain will be decreased. Of course, the pulse cannot be widened to infinity as in the ideal case. This causes out-of-band emission in the frequency domain. Well-designed filters according to design requirements can prevent or at least decrease out-of-band emission and also interference.

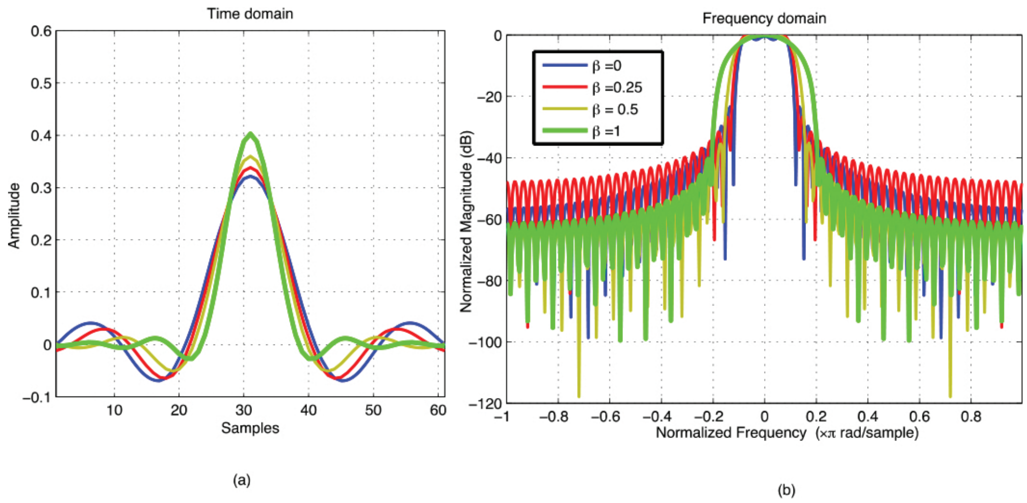

Figure 6. Raised-cosine filter: (a) time and (b) frequency responses with various roll-off factors. If roll-off factor is $\beta = 0$, the impulse response is similar to the rectangular pulse.

The Fourier transform of the rectangular pulse is a *sinc* function that has very large bandwidth because of the side lobes. The problems of reducing the level of side lobes and the signal power out of the transmitted band can be solved by windowing. The windowing operation limits the out-of-band energy by smoothing the time-domain function. So, in order to mask to spectrum, pulse shaping, i.e., time-domain windowing is used. Raised cosine filter and Gaussian filter are the famous pulse shaping filters. The impulse response of these filters are given by

$$\boldsymbol{h}_{RC}(t) = \frac{\sin(\pi t/T)}{\pi t/T} \frac{\cos(\pi \beta t/T)}{1 - 4\beta^2 t^2/T^2} \tag{9}$$

and

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$$\boldsymbol{h}_{Gaussian}(t) = \sqrt{\frac{2\pi}{In2}}\,(BT)e^{-\frac{2\pi^2}{In2}(BT)^2t^2} \tag{10}$$

respectively. Here β is called the roll-off factor that is in the range of $0 \leq \beta \leq 1$. The frequency responses are

$$\boldsymbol{H}_{RC}(f) = \begin{cases} T & 0 \leq |f| \leq \frac{1-\beta}{2T} \\ \frac{T}{2}\left\{1 + cos\left[\frac{\pi T}{\beta}\left(|f| - \frac{1-\beta}{2T}\right)\right]\right\} & \frac{1-\beta}{2T} \leq |f| \leq \frac{1+\beta}{2T} \\ 0 & |f| \geq \frac{1+\beta}{2T} \end{cases} \tag{11}$$

$$\boldsymbol{H}_{Gaussian}(f) = e^{-\frac{In2}{2}\left(\frac{f}{BT}\right)^2}. \tag{12}$$

The time and frequency responses of the raised-cosine filter for different β values are given in **Figure 6**. The roll-off factor β is the measure of the excess bandwidth of the filter. If $\beta = 0$, the impulse response approaches to *sinc(t/T)* function and the frequency response approaches to *rect(fT)* rectangular function.

The famous windowing functions and their time-domain sequences are given in **Table 1**.

	Window	**Time domain sequence** ***h(n)* for *0 ≤ n ≤ L − 1* length of filter**
1	Blackman	$0.42 - 0.5\cos\frac{2\pi n}{L-1} + 0.08\cos\frac{4\pi n}{L-1}$
2	Hamming	$0.54 - 0.46\cos\frac{2\pi n}{L-1}$
3	Hanning	$\frac{1}{2}\left(1 - \cos\frac{2\pi n}{L-1}\right)$
4	Kaiser	$\frac{I_0\left[\alpha\sqrt{\left(\frac{L-1}{2}\right)^2 - \left(n - \frac{L-1}{2}\right)^2}\right]}{I_0\left[\alpha\left(\frac{L-1}{2}\right)\right]}$ I_0: zeroth-order Bessel, α: positive real number

Table 1. Common window functions.

3. Transceiver schemes for 5G wireless networks

Multicarrier transmission is the best way to fix the problems due to frequency-selective channel conditions. Contrary to the single-carrier modulation techniques, that use only one carrier at all times, multicarrier modulation divides the band into more subcarriers. The ideal equalizer has a frequency response that is the inverse of the frequency response of the channel. So, the equalization of multicarrier transmission is easier for the frequency-selective channel. OFDM is an orthogonal multicarrier transmission scheme that has subcarriers with sin*c*-shaped spectra. The transceiver structure of the OFDM is given in **Figure 7**.

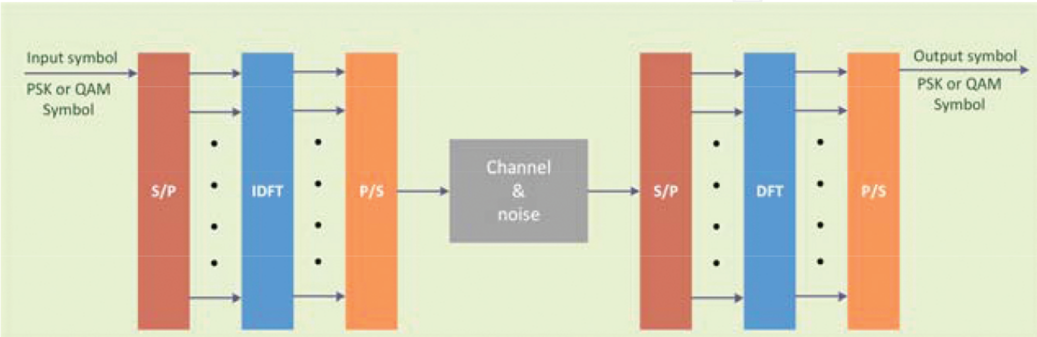

Figure 7. OFDM transmission scheme implemented using IDFT/DFT.

Accordingly, a sequence of PSK or QAM symbols is converted into N parallel streams before the N-point inverse DFT (IDFT) operation. Parallel streams are converted to a serial form after the IDFT operation. The same operations are done at the receiver sides that include DFT operations instead of the IDFT operation.

The advantages and disadvantages of OFDM are as follows:

Advantages:

- Resilience to frequency selective fading: by dividing the channel into narrow flat fading channels.
- Spectrum efficiency: by allowing overlap.
- Resilience to interference: by using acyclic prefix (CP) to avoid intersymbol and interframe interferences.
- Channel equalization: by using multiple subchannels.
- Computationally efficient: by using fast Fourier transform (FFT) and inverse FFT (IFFT) operations to implement modulation and demodulation.

Disadvantages:

- High peak-to-average power ratio (PAPR): because of using independent phases for the subcarriers.

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- Sensitive to carrier frequency offset (CFO): because of small subcarrier spacing and the necessity of good receiver synchronization.
- Out-of-band interference: because of the rectangular pulse shape.
- Loss of efficiency: because of using the cyclic prefix (CP) and guard intervals (GIs).

Therefore, OFDM is a very useful multicarrier modulation scheme because of its advantages. On the other hand, new modulation schemes are needed to overcome the drawbacks of OFDM.

3.1. Filter bank-based multicarrier

FBMC is the set of filtering operations that separate the input signal to the subbands with the frequency-shifted versions of low-pass prototype filters. The differences of FBMC from OFDM are: (i) CP extension is not required, (ii) having low side lobe and low spectral leakage depends on the filter type, (iii) more complex, and (iv) less sensitive to CFO. The benefits of FBMC are allowing to pulse shaping of filters that produce well-localized subbands in both time and frequency domain. FBMC is a candidate waveform of 5G communication networks to overcome some problems. The features such as lower side-lobes, lower sensitivity to CFO, and higher bandwidth efficiency—because of the absence of CP—makes FBMC a possible replacement of OFDM in 5G wireless communications. Furthermore, frequency allocations of subbands become more flexible with benefits of filtering operations.

FBMC modulation-based systems are more complex than OFDM due to exchange of FFT/IFFT operations by the filter banks. The CFO is caused by Doppler shift due to mobility. Orthogonality between adjacent subcarriers is destroyed by CFO and it introduces intercarrier interference (ICI) and intersymbol interference (ISI). Besides, the sin*c*-shape frequency response of each subcarrier causes large ICI in presence of CFO. Using the windows with smooth edges reduces the sensitivity of CFO, thus FBMC satisfies this condition.

In the conventional FBMC system, the frequency spectrum is divided into equal subbands and each symbol in subbands is filtered after upsampling operations. The upsampling value (K) and the number of the subbands *(M)* determine the overlapping of subbands [20] and the allocations of subbands of FBMC are given in **Figure 8**. When the K equals to the M, the filter bank is said to be critically sampled; otherwise, it is noncritically sampled.

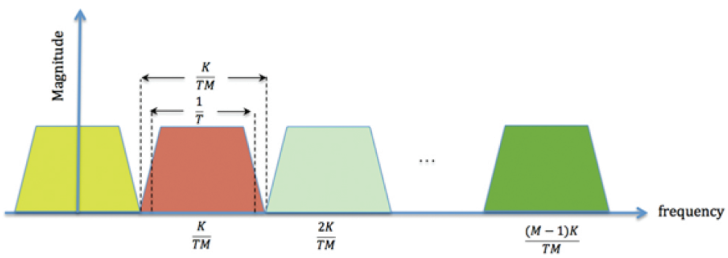

Figure 8. Frequency allocation of FBMC: the channel is uniformly divided by subbands.

According to the FMT modulation, each user symbols in subbands are filtered by the frequency-shifted versions of a low-pass prototype filter after upsampling operations. The transceiver scheme of FMT is given in **Figure 9**. Here, symbols with the same data rates share frequency spectrum equally.

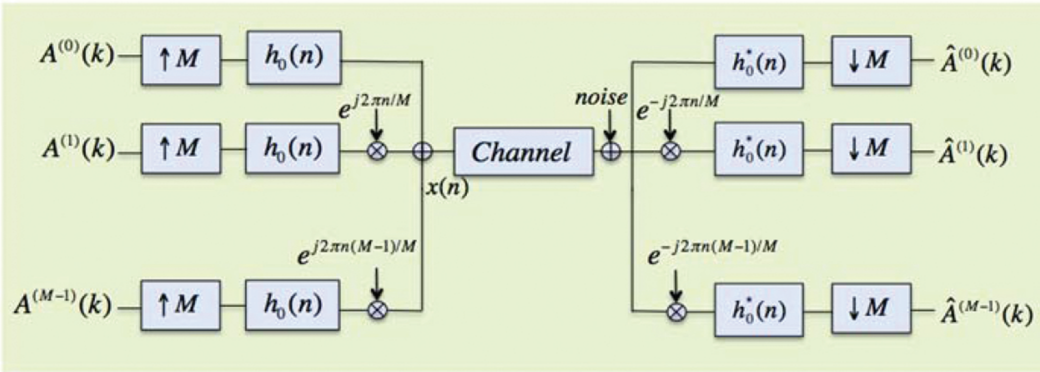

Figure 9. The transceiver structure of FMT: symbols are transmitted with multicarrier modulation by filtering. If the low-pass prototype filters $h_0(n)$ are symmetric finite impulse response (FIR) filters, then the transceiver filters are their complex conjugates.

The transmitted signal of the FMT scheme in **Figure 9** is given by

$$x(n) = \sum_{m=0}^{M-1} \sum_{k=-\infty}^{\infty} A^{(m)}(k)\, \boldsymbol{h}_0(n - kM) e^{j2\pi mn/M} \tag{13}$$

where $\boldsymbol{h}_0(n)$ is the prototype filter. The transmitted signal $x(n)$ is the sum of the convolutions of upsampled of data and the frequency-shifted versions of a low-pass prototype filter.

Generally, the bandwidth allocations of users need not be equal to each other because of different data rates. Especially, some users in 5G communication channel may upload their video streams, while some users are a part of internet-of-things/machine-type communications (IoT/MTC). The bandwidth requirements of these users are not the same and may change according to the applications of users. Hence, it is not advantageous to use traditional multi-carrier structures for the users that need different transmission bandwidths. In LTE (long-term evaluation), the frequency spectrum is shared by users with predefined bandwidths (i.e., 1.4, 3, 5, 10, 15, and 20 MHz), which is not a flexible solution for users having different data rate demands. Recent studies on FBMC modulation have not provided an effective remedy for such users. For that reason, FMT modulation can be modified for user demands on different data rates to allow nonuniformly divided bandwidth allocations as proposed by Çatak and Durak-Ata in [21]. The main contributions of [21] are as follows: (i) the classical FBMC modulation schemes are modified for user demands on data rates. (ii) The assignments of user bandwidths are done at the physical layer. (iii) The bandwidth allocations become adaptive for user requirements instead of system orders.

3.2. FMT with nonuniformly divided bandwidth allocation

The nonuniformly divided bandwidth allocation is important for users with different data rate demands. Data-rate demands of users depend on their applications. For instance, video streaming applications require higher data rates. On the other hand, machine-type communications (MTC), sensors, etc., need lower data rates. FMT with nonuniformly divided bandwidth allocation structures can serve to such heterogeneous users and applications in the same transceiver structure and assign users on bandwidth on the physical layer.

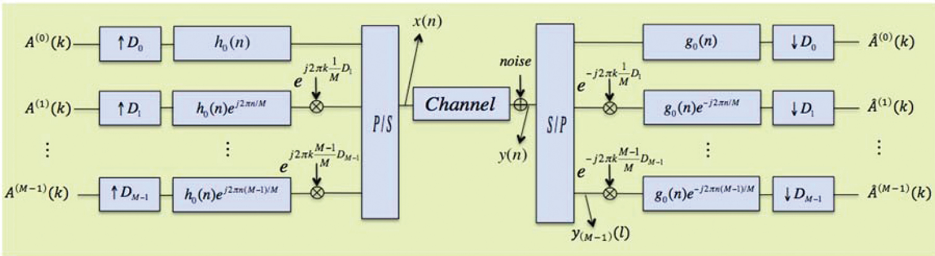

Figure 10. The block diagram of the FMT with nonuniformly divided bandwidth allocation.

The transceiver structure of the FMT multicarrier system for nonuniformly divided bandwidth allocations is given in **Figure 10**. Each user symbols ($A^{(m)}(k)$) in subbands are filtered by the frequency-shifted versions of a low-pass prototype filter after upsampling operations. The upsampling values and the filter lengths may be different for all subbands.

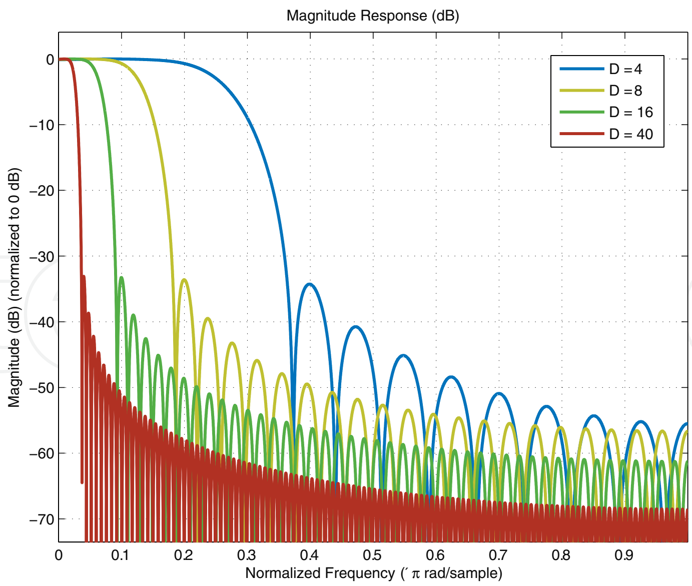

Figure 11. Frequency responses of raised cosine filters for different upsampling rates.

In **Figure 10**, the upsampling operation $\uparrow D$ is inserting $D-1$ zeros between consecutive samples. The frequency responses of the raised cosine filter for different upsampling numbers are given in **Figure 11**. Accordingly, if the sampling rate increases, the frequency resolution will be increased. Thus, the users need less bandwidth. According to the limit of time-bandwidth product, less bandwidth means longer symbol duration and also high latency.

The transmitted signal for FMT with nonuniformly divided bandwidth allocation is given by

$$\boldsymbol{x}(n) = \sum_{m=0}^{M-1} \sum_{k \epsilon T_m} \boldsymbol{A}^{(m)}(k)\, \boldsymbol{h}_0(n - kD_m) e^{j2\pi mn/M} \tag{14}$$

where D_m is the upsampling rate and T_m is the symbol length for the mth user. The prototype filter of impulse response $\boldsymbol{h}_m(n) = \boldsymbol{h}_0(n)e^{j2\pi mn/M}$ can be expressed as

$$\boldsymbol{h}_m(n - kD_m) = \boldsymbol{h}_0(n - kD_m) e^{j2\pi m(n - kD_m)/M} \tag{15}$$

And the transmitted signal in **Figure 10** becomes

$$\boldsymbol{x}(n) = \sum_{m=0}^{M-1} \sum_{k \epsilon T_m} \boldsymbol{A}^{(m)}(k)\, \boldsymbol{h}_m(n - kD_m) e^{j2\pi kmD_m/M}. \tag{16}$$

In the same way, the received signal is obtained by

$$\widehat{\boldsymbol{A}}^{(m)}(k) = \sum_{l=-\infty}^{\infty} \boldsymbol{y}_m(l) \boldsymbol{g}_m(lD_m - k) e^{-j2\pi mlD_m/M} \tag{17}$$

where $g_m(lD_m - k) = g_0(lD_m - k)e^{j2\pi m(lD_m - k)/M}$. If the transmitter filter $h_0(n)$ is assumed to be symmetric, the receiver filter $g_0(n)$ equals complex conjugate of $h_0(n)$. Finally, the received signal becomes

$$\widehat{\boldsymbol{A}}^{(m)}(k) = \sum_{l=-\infty}^{\infty} \boldsymbol{y}_m(l) \boldsymbol{h}_m^*(lD_m - k) e^{-j2\pi mlD_m/M} \tag{18}$$

3.3. Generalized frequency division multiplexing

GFDM can be considered as type of filter bank-based multicarrier modulation scheme with transmission filters that are shifted in time and frequency domains. This scheme offers more flexible pulse shaping for individual subcarriers [22]. However, GFDM has complicated receiver designs and needs high-order filtering and tail biting. To simplify transceiver structures, polyphase filters can be employed [10].

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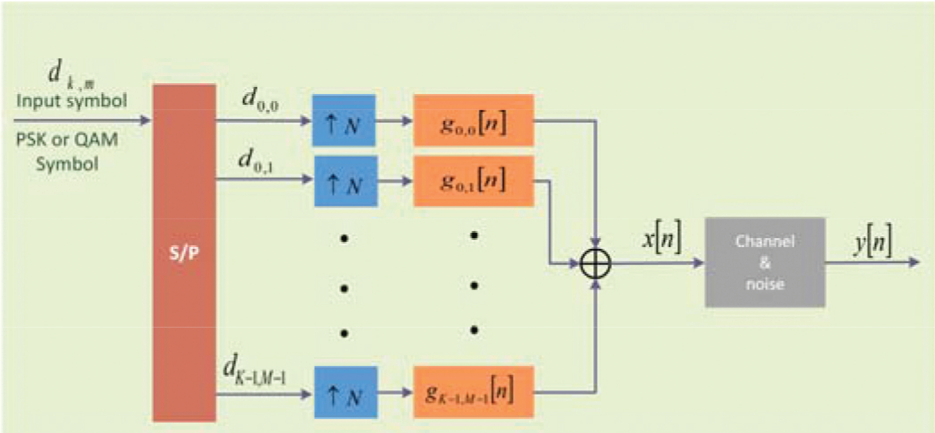

Figure 12. The transmitter structure of GFDM: the transmission filters are shifted in time and frequency domains.

The receiver structure of GFDM is given in **Figure 12**. Accordingly, the data is transmitted with K subcarriers that carry M subsymbols. Data is mapped into the complex valued QAM symbols. The mapped data are upsampled by the factor N, where $N = MK$. The transmitter filter $g_{k,\ m}[n]$ with N samples is the time- and frequency-shifted version of $\boldsymbol{g}(n)$ that is expressed by

$$\boldsymbol{g}_{k,m}[n] = \boldsymbol{g}[(n - mK)\text{mod}N]\exp(-j2\pi\frac{k}{K}n) \tag{19}$$

where k and m are the subcarrier and subsymbol indices where $k = 0, 1, \ldots, K-1$ and $m = 0, 1, \ldots, M-1$, respectively. The transmitted signal is given by

$$\boldsymbol{x}[n] = \sum_{m=0}^{M-1}\sum_{k=0}^{K-1} d_{k,m} g_{k,m}[n] \tag{20}$$

and Eq. (20) can be expressed with modulation matrix as

$$\boldsymbol{x} = \mathbf{A}\boldsymbol{d} \tag{21}$$

where x is a vector that contains transmitted samples of $x[n]$ and $\mathbf{A}$ is the $KM \times KM$ modulation matrix that contains samples of transmitter filter $g_{k,\ m}[n]$ where

$$\mathbf{A} = \begin{bmatrix} \overbrace{g_{0,0}[0] & \cdots & g_{K-1,0}[0]}^{\textit{Subsymbol } 0} & \cdots & \overbrace{g_{0,M-1}[0] & \cdots & g_{K-1,M-1}[0]}^{\textit{Subsymbol } M-1} \\ g_{0,0}[1] & \cdots & g_{K-1,0}[1] & \cdots & g_{0,M-1}[1] & \cdots & g_{K-1,M-1}[1] \\ \vdots & \ddots & \vdots & & \vdots & \ddots & \vdots \\ g_{0,0}[N-1] & \cdots & g_{K-1,0}[N-1] & \cdots & g_{0,M-1}[N-1] & & g_{K-1,M-1}[N-1] \end{bmatrix} \tag{22}$$

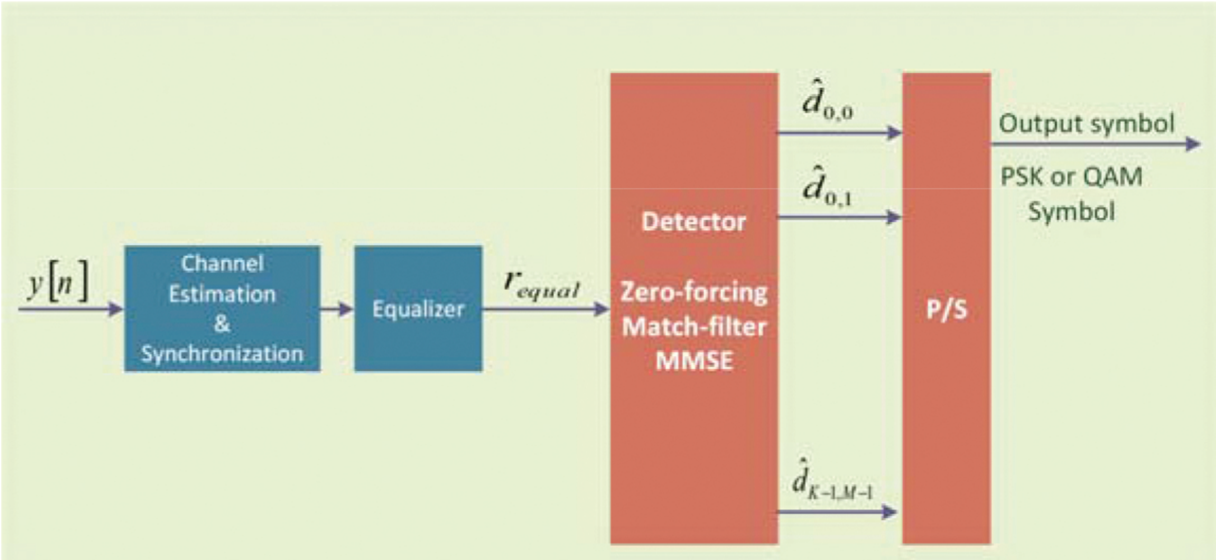

Figure 13. The receiver structure of GFDM with equalizer and detector.

The transmitter diagram of GFDM is given in **Figure 13**. The signal that passes through the channel must be equalized to clarify from the channel effects. If the number of subcarriers is high enough, the channel frequency response can be flat for each subcarrier. Thus, subcarrier bandwidths become smaller than the coherence bandwidth. In such a case, the received signal can be equalized with a zero-forcing equalizer. According to the zero-forcing equalizer, inverse of the frequency response of the channel is applied to the received signal. The implementation is simple for flat channels; otherwise, it becomes very hard due to inversing operations. The signal that passes through the channel is

$$\boldsymbol{y}[n] = \boldsymbol{h}[n] * \boldsymbol{x}[n] + \boldsymbol{w}[n] \tag{23}$$

where $w[n]$ is the additive noise and $c[n]$ is the impulse response of channel. The equalized signal with zero-forcing equalizer is given by

$$\mathbf{r}_{equal}[n] = IDFT\left\{\frac{Y(e^{j\omega})}{C(e^{j\omega})}\right\}, \tag{24}$$

where $Y\left(e^{j\omega}\right)$ and $C\left(e^{j\omega}\right)$ are the corresponding frequency responses. After equalization procees, the received signal can be estimated by a detection process. Zero-forcing receiver, matched-filter receiver, and minimum mean square error (MMSE) receiver structures are common detection methods.

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Zero-forcing receiver is based on the inverse of modulation matrix in Eq. (21). Accordingly, the detected signal is

$$\hat{\boldsymbol{d}}_{\text{zero-forcing}} = \mathbf{A}^{-1}\boldsymbol{r}_{\text{equal}} \tag{25}$$

where $\mathbf{A}^{-1}$ is the inverse matrix of the modulation matrix $\mathbf{A}$ and $\boldsymbol{r}_{\text{equal}}$ is the equalized signal. The pseudo-inverse matrix can be used for the nonsquare case of $\boldsymbol{A}$. The pseudo-inverse of $\boldsymbol{A}$ can be evaluated by

$$\mathbf{A}^{+} = \mathbf{A}^{H}\left(\mathbf{A}\mathbf{A}^{H}\right)^{-1} \tag{26}$$

where $\boldsymbol{A}^{H}$ is Hermitan matrix of $\boldsymbol{A}$. Then, the detected signal by zero-forcing receiver in Eq. (25) becomes

$$\hat{\boldsymbol{d}}_{\text{zero-forcing}} = \mathbf{A}^{H}\boldsymbol{r}_{\text{equal}}. \tag{27}$$

Matched-filter receiver maximizes the SNR per subcarrier. The detected signal by the matched-filter receiver is given by

$$\hat{\boldsymbol{d}}_{\text{match-filtering}} = \mathbf{A}^{H}\boldsymbol{r}_{\text{equal}} \tag{28}$$

According to MMSE receiver, the detected signal is given by

$$\widehat{\boldsymbol{d}}_{MMSE} = \mathbf{A}^{\dagger}\boldsymbol{r}_{equal} \text{ with } \mathbf{A}^{\dagger} = \left(\frac{\sigma^2{}_n}{\sigma^2{}_d}\boldsymbol{I} + \mathbf{A}^H\mathbf{A}\right)^{-1}\mathbf{A}^{H}. \tag{29}$$

where $\sigma^2{}_n$ and $\sigma^2{}_d$ are the variance of the noise and data symbol.

Briefly, zero-forcing receiver extracts the channel effects from the transmitted signal and removes all ISI for ideal noiseless channel condition. It amplifies the noise for noisy channels. The matched-filter receivers overperform the zero-forcing receiver in low SNR regime.

Matched-filter receiver suffers from self-interference. On the other hand, MMSE receiver is successful at high and low SNR similar to zero-forcing receiver and matched-filter receiver, respectively [23].

4. Performance evaluation

The waveform design issues depend on the requirements of users, communication types, and communication networks. These requirements are changing and evolving every year. Today, on the verge of 5G communication technology, most important requirements are data rate, latency, power, efficiency, complexity, and robustness to the channel [24]. Also, there are some design issues to execute these technology requirements. PAPR, OOB emission, interferences, and complexity issues are investigated and their importance is verified.

The PAPR is the ratio of peak power to the average power of a transmitted signal. A multicarrier signal consists of lots of modulated signals in each subcarrier, which can cause large PAPR value after addition. The comparisons of GFDM and OFDM on PAPR performances are given in **Figure 14**. Accordingly, the PAPR values of GFDM are better than OFDM. Low PAPR is important to reduce hardware cost and power consumption. One advantage of GFDM over OFDM is obviously in reducing the OOB radiation.

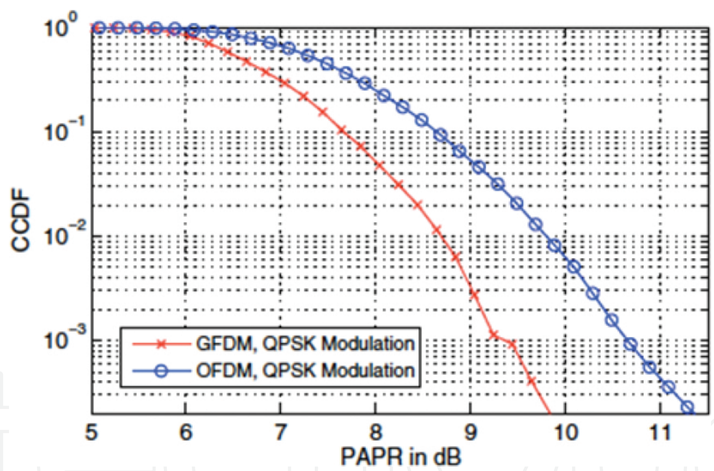

Figure 14. The comparison of PAPR of GFDM and OFDM: the PAPR of GFDM is less than OFDM. If multicarrier signals are summed up with same phases, the PAPR values increase [25].

The out-of-band (OOB) emission is the emission outside the necessary bandwidths. It causes waste of spectral resources and serious interference problems to adjacent wireless channels. These redundant emissions cause interference. Interference between carriers (ICI) and symbols (ISI) are two issues of waveform design. ICI is caused by channel frequency offsets and it is one of the major problems of OFDM. It can be avoided by frequency domain equalization, time domain windowing, and using redundant subcarrier between carriers. ISI is caused by the dispersion of the channel. It can be avoided by leaving enough space in between the transmitted symbols.

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In **Figure 15**, OOB emissions of OFDM symbol and FBMC symbol are given comparatively. Here, OFDM suffers from high-level OOB emission. Conversely, filter bank-based operations allow lower out-of-band emissions.

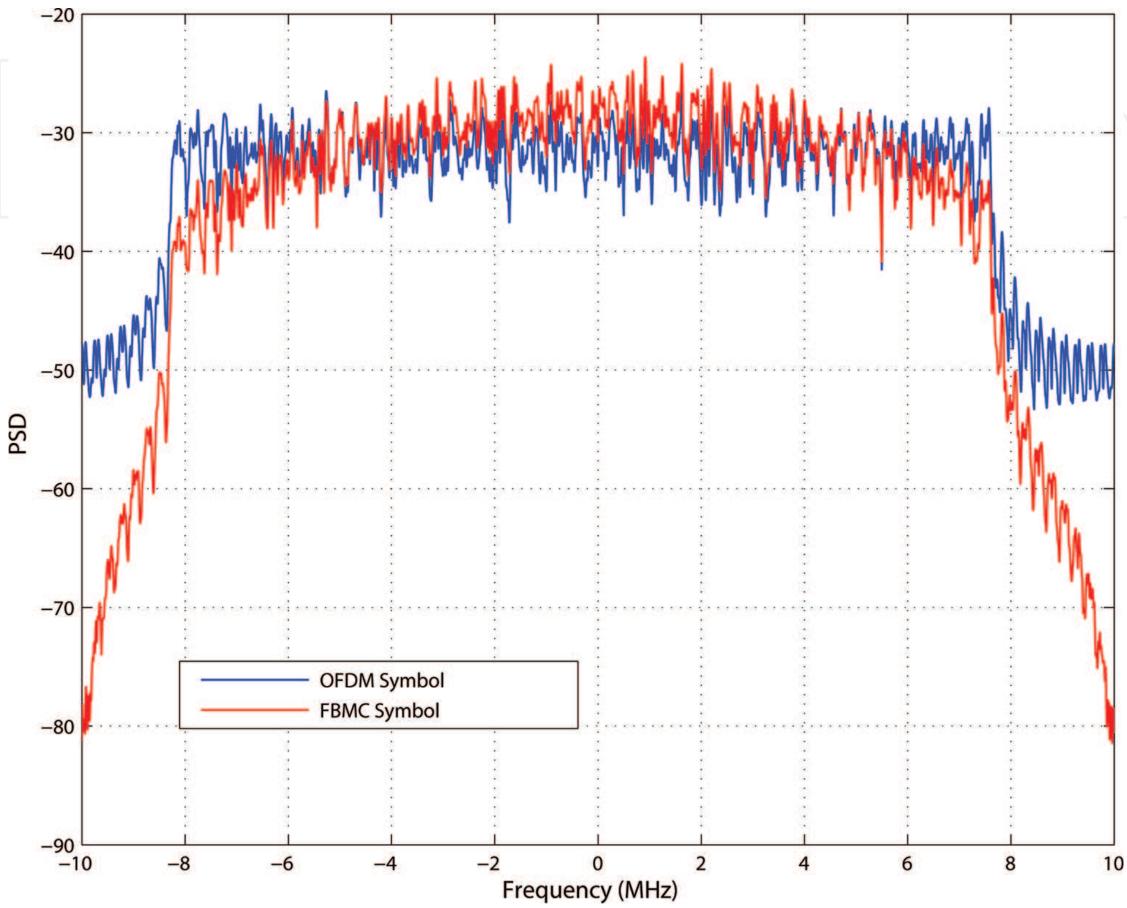

Figure 15. Power spectrum density of OFDM and FBMC symbols: FBMC scheme allows lower out-of-band emissions.

Complexity is defined by the total number of operations in the transmitters and receivers. The transmitter structures must be adapted to channel conditions and provide easy detection. Filtering operations make the systems more complex. Polyphase filter structures are used to overcome these problems. Another issue is channel equalization at the receivers while taking the inverse of a matrix. The performance evaluations are summarized in **Table 2**.

	Complexity	OOB	PAPR	Spectral efficiency
OFDM	Low	High	High	Good
FBMC [6, 9]	High	Low	Low	Bad
GFDM [6, 25]	High	Low	Low	Good
UFMC [12, 13]	High	Low	High	Good

Table 2. Pros and cons summary of waveforms.

5. Conclusion and future directions

This chapter presents the requirements of 5G communication systems and the fundamentals of waveform design to cover them for 5G wireless communication networks. According to the report of 5G PPP Architecture Working Group, the 5G network will "operate in a wide spectrum range with a diverse range of characteristics" [26]. Accordingly, the 5G communication channel will be heterogeneous and will provide users with different demands. The waveform design part of the physical layer is a critical issue in meeting the new demands and requirements, such as low latency, low power consumption, high data rates, and spectrum efficiency. TF lattice structures and pulse shaping must be determined. The transmission scheme, time and frequency allocation of symbols, resolution in time and frequency, and time-bandwidth product are the design criteria of time frequency lattice structures. Also, pulse shaping is the filtering process that maps the modulated signals to the TF lattice to control the interferences. Besides, transceiver scheme of some candidate waveforms and performance evaluations are given. Accordingly, OFDM has an easy implementation, but the high level of OOB emission and PAPR value. The waveforms that include filtering have lower OOB emission but high complexity.

In this chapter, the waveform design is assumed to be performed at baseband. On the other hand, one of the potential of 5G communication technologies under consideration is the use of millimeter wave frequencies. In this way, signals allocate more bandwidths to faster transmission, high-resolution video broadcasting, etc. Massive-MIMO and advanced beam-forming technologies will allow high data rate.

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