# Post-OFDM modulations for 5G and beyond

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**Abstract** In this chapter, we present a quick overview of the most popular multicarrier modulation techniques that could potentially be adopted in future wireless and cellular networks. Starting from the widely adopted OFDM, we present strong and weak aspect of each strategy, describing how it is possible to model all considered formats by means of a unified signal processing framework. We then propose an information-theoretical framework for performance evaluation, followed by a few numerical examples in wireless scenarios. Our analysis shows that the best format should be selected depending on the channel model and transceiver constraints.

## 1 Introduction

One of the key technologies that allowed the impressive data rate increase from tens of kbits/s in 2G systems to the current state of the art of tens of Mbits/s in long term evolution (LTE) systems has been the evolution from single-carrier modulation schemes with binary constellations to multicarrier modulations with multilevel constellations [1]. 5G mobile communications aim at delivering gigabit transmission to mobile users [2]. To achieve such an ambitious goal, new techniques and strategies must be applied to different network layers and aspects. At the physical layer, an intense research activity has been dedicated to the study of different modulation formats (see [3] and references therein). Orthogonal frequency division multiplexing (OFDM) and its natural extension OFDMA are the modulation and multiple access format adopted by the current LTE standard; OFDM offers a series of attractive properties and features, that made it widely popular, but it is not exempt of defects and drawbacks.

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Hence, the aim of this chapter is twofold. First, we will provide a short overview of the most credible competitors of OFDM, detailing for each of them the strong and weak aspects. Then, we will offer an information-theoretical framework that allows us to compare the different formats using a common tool, based on a unified signal processing description. At the end of the chapter we will show some examples of performance comparison of the proposed waveform techniques using standard wireless channel models.

## 2 Modulation Formats

In this section, we briefly introduce OFDM [4, 5] and three alternative schemes, namely filterbank multicarrier (FBMC) [6, 7], generalized frequency-division multiplexing (GFDM) [8], and universal filtered multicarrier (UFMC) [9, 10]. For each scheme, we provide a general description and we underline the strong and weak points. We refer the reader to [11] for a complete mathematical formulation of the different modulation formats. Moreover, as demonstrated in [11], all these modulation schemes can be represented by means of a unique discrete-time model, which allows to easily compare them and to define a common framework for their performance evaluation (see [11] for the details).

### 2.1 OFDM

OFDM is a popular multicarrier technique widely employed for wireless communications and specifically for 4G cellular systems [4, 5]. A key feature of OFDM is the simple generation of the transmitted signal by means of inverse fast Fourier transform (IFFT) processing and the simple recovery of the received data by means of fast Fourier transform (FFT) processing. For each OFDM block, a cyclic prefix (CP) is inserted at the transmitter and removed at the receiver. Therefore, if the duration of the multipath channel does not exceed the duration of the cyclic prefix, consecutive OFDM data blocks do not overlap in the time domain: hence, the OFDM transmission and reception can be performed independently on each block. In addition, OFDM with CP tranforms a frequency-selective multipath channel into a parallel set of frequency-flat single-path channels, thereby enabling a simple equalization that uses only a scalar gain compensation for each subcarrier. The reduced-complexity equalization of OFDM is one of the main factors of the popularity of OFDM for multipath channels. Besides, OFDM is suitable to multiple-input multiple-output (MIMO) systems based on multiple antennas, leading to a separate MIMO channel for each subcarrier. A variant of OFDM consists in replacing the CP with zeros, and it is denoted as zero-padding (ZP) OFDM [12].

One of the drawbacks of OFDM is the loss of spectral efficiency and capacity caused by the CP or the ZP. Furthermore, the spectral sidelobes of the signal transmitted in each subcarrier are non-negligible: therefore OFDM is sensitive to frequency offsets and Doppler effects, which destroy the frequency orthogonality, leading to intercarrier interference (ICI). Another weakness of OFDM (and of multicarrier techniques) is the relevant nonlinear distortion caused by high-power amplification at the transmitter side: the signal to be transmitted is the IFFT combination of the signals of many subcarriers, and hence the transmitting amplifier has to deal with a signal with large peak-to-average power ratio.

## 2.2 FBMC

FBMC [6, 7] is a multicarrier scheme with some key differences with respect to OFDM. A specific feature of FBMC is that consecutive data blocks overlap in time: with respect to OFDM, the duration of the prototype filter applied to each FBMC data block is increased. A longer prototype filter yields a signal with larger duration and allows for reduced frequency-domain sidelobes. As a consequence of the low sidelobes, when frequency offsets or time synchronization errors are present, FBMC collects a reduced ICI with respect to OFDM. For the same reason, FBMC generates less adjacent channel interference (ACI) than OFDM: this simplifies the coexistence with other signals allocated in nearby bands. Hence, FBMC is suitable for multiple-access and cognitive radio applications.

On the other hand, FBMC requires more advanced data detection techniques, with respect to OFDM, because of the time-domain overlap of consecutive data blocks: FBMC intentionally introduces intersymbol interference (ISI) between consecutive data blocks and ICI, also in the absence of frequency offsets. In other words, the non-orthogonality of FBMC produces ISI and ICI. By comparison, OFDM uses a prototype filter with duration equal to the duration of a data block, thereby avoiding the ISI between consecutive data blocks by separating the waveforms of different data blocks in the time domain; in addition, OFDM avoids the ICI in the absence of frequency offsets, because of its carriers orthogonality. The advanced detection techniques required by FBMC can be interpreted as ISI mitigation/cancellation techniques, with additional complexity with respect to OFDM, whose detection is independently performed on each single block.

## 2.3 GFDM

GFDM [8] is a multicarrier method that combines the advantages of both OFDM and FBMC techniques. Indeed, like in FBMC, GFDM uses prototype filters with duration larger than the duration of a data block: this reduces the spectral sidelobes with respect to OFDM. However, differently from FBMC, multiple data blocks of GFDM constitute a single superblock that does not interfere with the adjacent ones because the prototype filters of GFDM are chosen to avoid the time-domain overlap among consecutive superblocks. Besides, similarly to OFDM, GFDM adopts a CP to separate the consecutive superblocks and to reduce the equalization complexity in multipath channels: the CP of GFDM is inserted on a superblock basis, that is, the same CP is shared by multiple data blocks. This way, compared to OFDM, GFDM reduces the spectral efficiency loss caused by the CP insertion. In summary, GFDM is a non-orthogonal data-block technique that aims at reduced sidelobes (like FBMC schemes) and keeps time-domain orthogonality and per-subcarrier equalization on a data-superblock basis (like CP-based schemes).

The main drawback of GFDM is its increased complexity with respect to OFDM, since the signal processing has to be performed on a data superblock basis, rather than on a data block basis like in OFDM. With respect to FBMC, if we assume the same duration of the prototype filters, the complexity of GFDM has the same order of magnitude (approximately).

### 2.4 UFMC

UFMC [9, 10] is a multiuser multicarrier technique where each user employs a subband with consecutive subcarriers. The main goal of UFMC is to reduce the ICI with respect to OFDM and its multiple access counterpart OFDMA, which simply distributes carriers among users. The key idea of UFMC is to adopt prototype filters that reduce the sidelobes on a subband basis: differently, FBMC aims at the same purpose on a subcarrier basis. This choice in UFMC produce prototype filters whose duration is significantly reduced with respect to that of FBMC. Typically, the UFMC filter duration is similar to the CP duration of OFDM, that is, by far lower than the data block duration; instead, the FBMC filter duration is an integer multiple of the data block duration.

Like in OFDM, the UFMC data blocks do not overlap in time at the transmitter: however, in multipath channels, since UFMC does not employ a CP, a limited amount of ISI between consecutive data blocks is present. With respect to OFDM, another weakness of UFMC is the increased equalization complexity. Anyway, since the UFMC signal detection is performed on a data block basis, the UFMC equalization complexity is generally lower than for FBMC. Note that the UFMC subbands have adjacent subcarriers: on the other hand, in frequency-selective channels, frequency diversity considerations would suggest a frequency interleaved allocation where each user exploits maximally separated subcarriers.

## 3 Equalization and Detection Strategies

In this section, we discuss some equalization and detection strategies that are common to all the previously described modulation techniques. Based on the unified discrete-time model [11], we can express the received samples in a compact vector form, as a function of a system matrix, which takes into account a possible transmitter processing and the propagation channel, the transmitted data on all subcarriers, and the thermal noise (refer to [11] for the details). We remark again that, depending on the modulation format, different kinds of interference can arise, and these can all be modeled by properly designing the system matrix in the unified model.

Different equalization options can be envisaged to cope with the arising interference. We briefly present some of them in the list below.

- Least square (LS) linear equalizers can be designed to remove only the ICI, or both ICI and ISI. In the former case, ISI is treated as additional noise, and the ISI-plus-noise term is often amplified. The latter equalizer design tries to jointly remove both ICI and ISI, resulting in better performance at the cost of an increased complexity.
- Alternative to LS, linear minimum mean-square error (MMSE) equalizers are less sensitive to the noise enhancement phenomenon, and, like LS equalizers, can be designed to remove ICI only, or ICI and ISI jointly.
- Many other linear equalization techniques can be designed, which often involve variants or modifications of the previous approaches [13].
- Popular nonlinear equalization approaches involve the use of interference cancellation techniques [14, 15, 16, 17], usually performing the following four steps: a) preliminary estimation of the data by a linear equalizer; b) reconstruction of the interference based on the preliminary estimates; c) hard (or soft) cancellation of the interference, performed by subtracting the reconstructed interference from the received signal; d) final equalization by a second linear equalizer. Interference cancellation can be done either serially, or in parallel, or in groups. In serial cancellation, a single interference subcarrier is estimated and subtracted, and then the same process is repeated for the other data subcarriers, in a decision-feedback way. In parallel cancellation, all interference subcarriers are preliminarly estimated and subtracted jointly, and then all the data subcarriers are detected using a second equalizer. In group cancellation, subcarriers are divided in groups: the interference among different subcarriers of the same group is cancelled in a parallel way, while the interference among different groups of subcarriers is cancelled in a serial way. In all cases, turbo approaches are also possible, to iteratively refine the equalization of the data already equalized [18, 19].
- An alternative nonlinear equalization method is based on maximum likelihood (ML) techniques [20, 13]. The key idea of ML equalization is to exploit the finite alphabet of the data symbols. From a performance viewpoint, ML equalization is a promising approach: for equiprobable data symbols, the ML detector minimizes the probability of error detection and hence yields the best performance. However, the main weakness of this approach is its computational complexity, which depends on the chosen transmission scheme and on several system parameters, like the number of subcarriers, the number of interfering symbols, and the size of the adopted constellations. The complexity of the ML detector can be reduced by exploiting the special structure of the transmitted signal (which might be designed to avoid the presence of ISI and/or ICI, depending on the adopted transmission scheme), or by reducing the search space by excluding impossible or

unlikely combinations of symbols [21]. However, the complexity of ML equalization often makes this approach unfeasible in multicarrier wireless communication systems.

## 4 Channel Capacity and Spectral Efficiency

Rather than focusing on complexity issues, we are more interested in comparing the different transceiver architectures from a performance viewpoint. Several alternative figures of merit can be used to evaluate and compare different modulation formats. Among these, we can think of computing the bit error rate (BER) performance in different scenarios or channel conditions. The downside of this perspective resides in being dependent on the specific adopted code, which might be unsuitable for all application scenarios, or might require a particular design or optimization. To avoid this problem, and to offer a wider perspective on the different modulation formats, we intend to provide the reader with the instruments to compare different transceiver architectures from an information-theoretic point of view. Our aim is to take into account that different non-orthogonal waveforms may use the time-frequency resource in different ways, may introduce (and may be able to tolerate) a different amount of interference, and may (or may not) enable suboptimal low-complexity receivers. As a figure of merit we will use the achievable spectral efficiency (ASE), with the constraint of arbitrarily small BER. The ASE is computed by dividing the channel capacity, or an achievable lower bound of it, by the employed symbol time and frequency spacing, which are the time-frequency resource of every waveform.

As far as the computation of the channel capacity is concerned, we are mainly interested in the achievable performance when using suboptimal low-complexity detectors. Therefore, we consider simple receivers based on linear processing followed by symbol-by-symbol detection, using the framework described in [22, 23]. This framework allows to compute a lower bound on the channel capacity (and thus on the ASE) by substituting the actual channel with an arbitrary auxiliary channel that has the same input and output alphabets of the original channel. This approach is called mismatched detection theory [22, 23]. An auxiliary channel that approximates the true channel with increased accuracy (with respect to another auxiliary channel) produces a lower bound that is closer (with respect to another auxiliary channel) to the true capacity. If the considered suboptimal receiver is optimal for the adopted auxiliary channel, the obtained lower bound is *achievable* by that detector, according to the mismatched detection theory [23]. Therefore, when that auxiliary-channel-optimal receiver is employed, we say that the computed lower bound is the ASE of the considered channel with the considered waveforms and receivers. When Gaussian inputs are considered, closed-form achievable lower bounds of the ASE can be provided. The same mismatched detection framework can also be used when finite constellations are employed, but in this case no closed-form expressions for the lower bounds exist: these lower bound expressions have to be computed numerically, by feeding the auxiliary-channel-optimal detector with the output of the true channel [23].

Depending on different receiver architectures and different assumptions on the channel model, we can resort to different auxiliary channels. Each auxiliary channel will result in a different lower bound on the channel capacity. Herein we neglect interference-cancellation-based receivers, because it is not possible to find an auxiliary channel for which these receivers are optimal: for these receivers the principle of mismatched detection cannot be adopted [22]. We focus on the following auxiliary channel models.

- *Vector input, vector output, before equalization.* The use of multicarrier modulation formats allows us to exploit channel capacity results related to multiantenna systems. We can model the received samples as a classical MIMO channel, characterized by a channel matrix which multiplies the transmitted data, followed by the addition of the noise. In the absence of an equalizer, ISI cannot be removed, so it must be taken into account by properly modifying the covariance matrix of the noise term. Assuming Gaussian input symbols, the mutual information for this auxiliary channel can be computed in closed form [11].
- *Vector input, vector output, after equalization.* The use of a linear equalizer is expected to enhance the contribution of the useful signal component and, possibly, to reduce the contribution of the interference, at the expense of some noise amplification. Basically, a linear equalizer (LS or MMSE, for example) consists in multiplying the observed vector by a properly designed matrix. Also in this case, the use of Gaussian symbols allows to compute in closed form the mutual information for this auxiliary channel model [11].
- *Scalar input, scalar output, after equalization.* If, instead of considering all subcarriers at the same time, we focus on the data symbol transmitted on a single subcarrier, we can obtain a scalar auxiliary channel model. In this case, all symbols transmitted on the other subcarriers are regarded as interference, and considered as additional noise. Also in this case, the use of a linear equalizer can help to cope with the interference, but the fact that the receiver operates on a symbol-by-symbol basis, neglecting the possible correlations among the various elements, tells us that, with this scheme, we should expect worse performance compared to the equalized vector model. Assuming Gaussian distributed symbols, a closed form for the mutual information is available also for this case [11]. On the other hand, when input symbols belong to a finite constellation, as is the case with practical transmission schemes, no closed form exists, but we can compute the mutual information by numerical simulations [24].

The expressions for the mutual information that we can compute through the previously described techniques are based on a single channel realization. To take into account the effects of a block fading channel model (as usual in wireless communications scenarios), we can define the ergodic mutual information by computing the statistical average with respect to the channel realization of the mutual information expression. This problem can be solved in a semi-analytical way by performing a numerical average of the mutual information over many channel values.

We can define the ASE as the ratio between the obtained ergodic mutual information (which, we recall, is an achievable lower bound to the channel capacity) and the product between the frequency spacing between subcarriers and the symbol interval of each subcarrier. Using the ASE as a performance measure allows a fair comparison between orthogonal and non-orthogonal waveforms, since it represents exactly the amount of information that can be transmitted in the units of time and frequency. Typically, non-orthogonal formats will reduce the achievable mutual information, due to the increased interference. However, they also reduce the time and/or frequency occupation, so their overall ASE can be higher than that achievable with orthogonal formats. In general, it is necessary to optimize the values of the time and frequency spacings to obtain the best performance [25]. When the channel is slowly varying or constant over a block, it is likely that there will be blocks for which it is impossible to achieve an arbitrarily low error probability. In these circumstances, the channel is defined to be in outage, and a more significant measure is the outage capacity [26]. Due to the space limitations, we will not consider this aspect further.

## 5 Numerical Results

In this section, we compare the different signal waveforms in terms of ASE. The results reported in this chapter are far from being exhaustive of all the possible use cases and scenarios that can arise in 5G systems. We refer the reader to [11] for a more comprehensive set of results. Here, we limit our analysis to two cases representative of a single-antenna downlink system, which are sufficient to give meaningful insights on the potential of each signal waveform. Regarding the channel models, we adopt the classical and general multipath fading models, like those with sparse power-delay profiles, selected according to LTE channel models [27], and those with exponentially decaying profiles, widely used for WLAN applications [28]. The ASE of the different waveform schemes massively depends on a large set of parameters, such as the possible CP length and the number of subcarriers, as well as the parameters characterizing the adopted shaping pulses, which change depending on the selected scheme. A full parameters optimization is outside the scope of this chapter; the interested reader can find in [11] the details on the selected parameters and the rationale of these choices. For the results in this section, we just select the best parameters configurations among those considered in [11].

We will compare the ASE of the different signal waveforms by semianalytically computing the lower bounds derived in the previous section. We will consider only the vector and scalar bounds computed after MMSE equalization, since we have verified that the absence of the equalizer does not change the performance significantly [11]. For a fair comparison, the scalar bound is summed over all the symbols constituting the vector used for the vector model.

Figs. 1 and 2 compare the ASE of the considered techniques on the sparse Extended Pedestrian A (EPA) channel [27], and on the WLAN A exponential model [28], as a function of the signal-to-noise ratio (SNR). Even from this limited set of results, we can clearly evince that the best technique depends on the channel model. On the EPA channel, ZP-OFDM achieves the best performance, followed by OFDM and UFMC. The loss of OFDM (with respect to ZP-OFDM) is due to the additional energy spent for transmitting the CP: this loss is reduced, since the EPA channel has a small delay spread, hence a short CP is sufficient. Also GFDM and UFMC give good ASE results: in case of UFMC, the ASE is quite large also for the scalar bound. On the other hand, FBMC and the scalar bound of GFDM give inferior ASE results, due to the presence of interference. Therefore, for the EPA channel, orthogonal and non-overlapping multicarrier techniques like OFDM and UFMC are preferable with respect to overlapping methods like GFDM and FBMC. Fig. 2 exhibits the ASE comparison in the WLAN channel A. In this scenario, the best ASE performance is achieved by UFMC. However, the ASE performance of the orthogonal techniques (OFDM and ZP-OFDM) is still acceptable. On the other hand, the ASE performance of the overlapping techniques (FBMC and GFDM) is quite good at low SNR: at high SNR, the FBMC or GFDM receiver should target the vector bound.

In conclusion, there is no single winner in all the cases, at least from the ASE viewpoint. The choice among different techniques can be driven by the specific channel scenario. In addition, the complexity of the receiver should be taken into account, to grant such a capacity promise. Orthogonal methods (OFDM and ZP-OFDM) produce good results in all scenarios, except when the length of the CP or ZP is excessive. Overlapping techniques (FBMC and GFDM) promise larger ASE if the receiver can achieve the vector bound: however, in many scenarios, the scalar bound for overlapping techniques is reduced with respect to OFDM. UFMC is able to outperform OFDM in some scenarios. Summarizing, no specific technique is able to largely outperform the competitors in all scenarios.

## 6 Concluding Remarks

In this chapter, we have provided a brief overview of the most popular multicarrier waveforms proposed for 5G cellular systems and beyond. Basing our analyses on a unified signal processing framework, able to encompass all modulation formats, we proposed to compare and evaluate the performance of the different techniques from an information-theoretical point of view, based on the computation of the ASE, which allows to obtain a fair comparison of the alternative formats without being constrained to adopt a fixed coding scheme. Our results show, unsurprisingly, that the final choice of a specific signal waveform should depend on the channel conditions, as well as on the system requirements and available computational complexity.

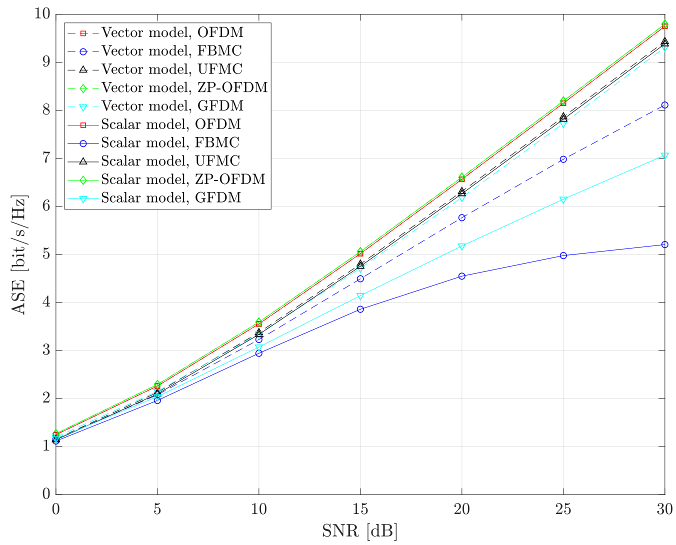


**Fig. 1** ASE versus SNR on the EPA channel.

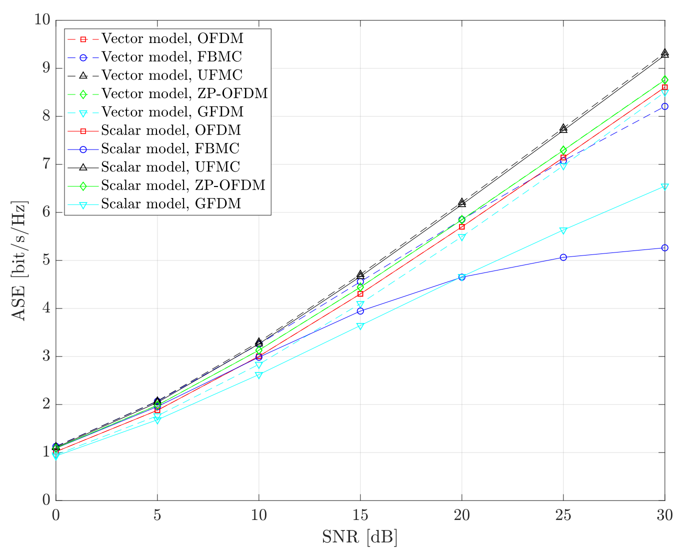


**Fig. 2** ASE versus SNR on the WLAN A channel.

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