DOI: 10.3969/j. issn. 1673-5188. 2017. S1. 002

Enhanced OFDM for 5G RAN

Zekeriyya Esat Ankaralı[1], **Berker Peköz**[1], **and Hüseyin Arslan**[1,2]
(1. Department of Electrical Engineering, University of South Florida, FL 33620, USA;
2. College of Engineering, Istanbul Medipol University, Istanbul 34810, Turkey)

Abstract

Support of many different services, approximately 1000x increase of current data rates, ultra-low latency and energy/cost efficiency are among the expectations from the upcoming 5G standards. In order to meet these expectations, researchers investigate various potential technologies involving different network layers and discuss their tradeoffs for possible 5G scenarios. As one of the most critical components of communication systems, waveform design plays a vital role here to achieve the aforementioned goals. Basic features of the 5G waveform can be given in a nutshell as more flexibility, support of multiple access, the ability to co-exist with different waveforms, low latency and compatibility with promising future technologies such as massive MIMO and mmWave communications. Orthogonal frequency division multiplexing (OFDM) has been the dominant technology in many existing standards and is still considered as one of the favorites for broadband communications in 5G radio access network (RAN). Considering the current interest of industry and academia on enhancing OFDM, this paper drafts the merits and shortcomings of OFDM for 5G RAN scenarios and discusses the various approaches for its improvement. What is addressed in this paper includes not only enhancing the waveform characteristics, out of band leakage and peak to average power ratio in particular, but also methods to reduce the time and frequency redundancies of OFDM such as cyclic prefix and pilot signals. We present how the requirements of different 5G RAN scenarios reflect on waveform parameters, and explore the motivations behind designing frames that include multiple waveforms with different parameters, referred to as numerologies by the 3GPP community, as well as the problems that arise with such coexistence. In addition, recently proposed OFDM-based signaling schemes will also be discussed along with a brief comparison.

Keywords

5G waveform; 5G RAN; eMBB; multicarrier systems; OFDM

1 Introduction

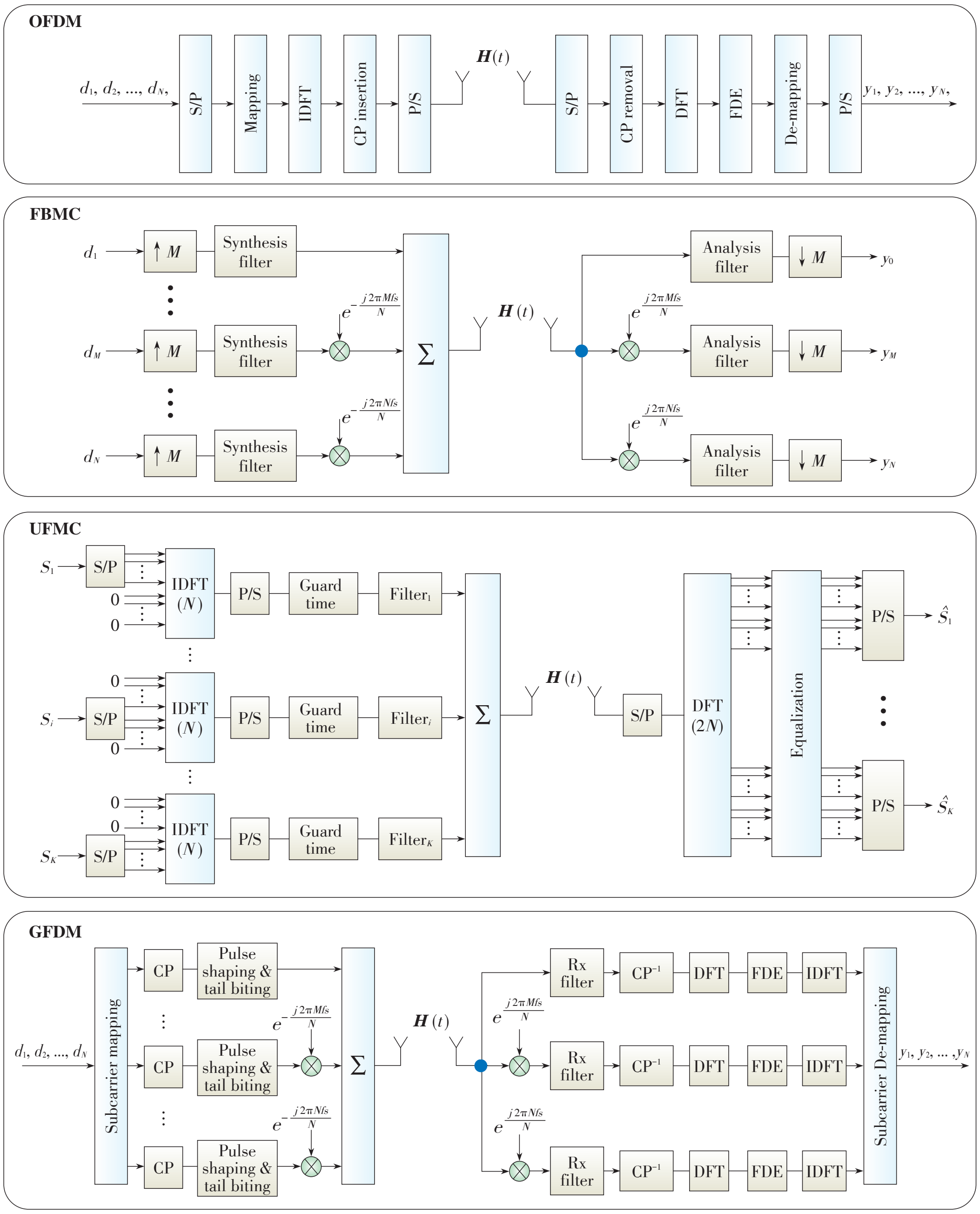
Exponential growth in the variety and the number of data-hungry applications along with mobile devices leads to an explosion in the need for higher data rates, and this is definitely the main driving factor in 5G [1]. Therefore, a wide range of data rates up to gigabits per second are targeted in 5G technologies which are expected to be deployed around 2020. In order to achieve these goals, academia has been in a great collaboration with industry as obviously seen in European Union projects as 5GNOW [2], METIS [3], MiWaveS [4] and FANTASTIC-5G [5]. Along with those, standardization has been started in 3GPP to deliver the demanded services timely.

One of the most challenging parts of achieving targeted high data rates is physical scarcity of the spectrum, and researchers have been putting an extensive effort to this challenge. One popular approach is to extend existing spectrum towards virgin higher frequencies up to 100 GHz [6]. Another approach is to increase spectral efficiency for a given spectral resource. Millimeter wave (mmWave) communications and massive multiple-input multiple-output (MIMO) are the representative concepts of these two approaches and very promising technologies for facilitating 5G goals, especially for enhanced mobile broadband (eMBB) services which constitutes one of the main service groups considered for 5G radio access network (RAN).

Even though not considered as the revolutionary part of 5G, one of the most fundamental components of any communication system is the waveform design. Therefore, intensive discussions are being conducted in academia and industry, in order to select the proper waveform meeting 5G requirements. Among all the candidates, multicarrier techniques are prominent especially for broadband wireless communications due to several advantages such as immunity against frequency selectivity, multiuser diversity support and adaptive modulation/coding techniques. Orthogonal frequency division multiplexing (OFDM) has been the dominating technology so far and successfully deployed in many of the current standards such as Long Term Evolution (LTE) and Wi-Fi. In the transition from existing technologies (4G) to the next generation, waveform selection ramifies to two paths for 5G RAN. The first one is reconsidering OFDM based methods by improving its characteristics and handling its drawbacks with proper solutions. The second one, on the other hand, is to implement alternative multicarrier technologies and redesign everything based on a different rationale. **Fig. 1** shows transceiver block diagrams for OFDM and other popular multicarrier schemes including filtered multi-tone mode of filter bank multicarrier (FBMC), universal filtered multicarrier (UFMC) and generalized frequency division multiplexing (GFDM). Let us firstly provide the merits and challenges of the multicarrier technologies considered as an alternative to OFDM in the context of 5G expectations.

1.1 FBMC

FBMC is one of the most well-known multi-carrier modulation formats in wireless communications literature which is also discussed as a 5G waveform in [7]. It offers a great advantage of shaping each subcarrier and facilitating a flexible utili-



CP: cyclic prefix
DFT: discrete Fourier transformation
FBMC: filtered multi-tone mode of filter bank multicarrier
FDE: frequency domain equalization
GFDM: generalized frequency division multiplexing
IDFT: inverse discrete Fourier transform
OFDM: orthogonal frequency division multiplexing
UFMC: universal filtered multicarrier

Figure 1.
Block diagrams of popular multicarrier schemes (OFDM, FBMC, UFMC and GFDM) considered for 5G radio access.

zation of spectral resources along with meeting various system requirements, e.g., low latency, multiple access, etc. This is also an advantage for making signal robust against channel effects, i.e., dispersion in time and frequency domains. For example, rectangular filters are preferable for time dispersive channels while raised cosine filters are more robust against frequency dispersion. Many other pulse shaping filters are also investigated to cope with various effects of the channel and provide a reliable system design based on different scenarios [8].

Despite all the advantages of FBMC, the significantly long filter lengths resulting in colossal symbol durations not only become a problem if low latency applications or short bursts of machine type communications are in focus [9], but also introduce an excessive computational complexity for MIMO detection as the channel coherence bandwidth would fall below the subcarrier bandwidth [10], which would mean problems in all main applications of 5G.

1.2 UFMC

UFMC is a generalized version of filtered multicarrier techniques where groups of subcarriers, i.e., sub-bands, are filtered rather than filtering each subcarrier individually [11]. By doing so, interference between neighboring sub-bands is decreased compared to conventional OFDM. Also, sub-band based filtering operation, when compared to the subcarrier filtering operation performed by FBMC, aims to increase the efficiency for short-burst type communications such as IoT scenarios or very low latency packets by reducing the filtered symbol duration and outperforms both cyclic prefix (CP)- OFDM and FBMC for such use cases [9]. A similar scheme is also presented as resource block (RB)-filtered OFDM in [12]. On the other hand, while UFMC aims to solve the problems of FBMC while maintaining its advantages, the increased fast Fourier transformation (FFT) length introduces complexity issues at the transmitter and receiver operations.

1.3 GFDM

GFDM is a block-based multicarrier filtered modulation scheme, designed to address the challenges in the vast usage scenarios of the fifth generation by providing a flexible waveform [9]. GFDM allows reuse of techniques that were originally developed for OFDM, as circular convolution is employed to filter the individual subcarriers, making the GFDM frame self-contained in a block structure. For tactile internet scenarios, GFDM can be distinguished from other multicarrier waveforms by how it achieves robustness over highly mobile channels. This is accomplished via taking the advantage of the transmit diversity provided by the easy generation of impulse responses simply obtained with circularly shifting the single prototype filter in time and frequency. To improve the reliability and latency characteristics even further, the GFDM waveform can be combined with the Walsh-Hadamard transform for increased performance in single-shot transmission scenarios. When combined with offset quadrature amplitude modulation mapping, GFDM avoids self-generated interference if non-orthogonal filters are employed for next generation multiple accessing.

In a different point of view, GFDM can be considered as a highly parameterizable waveform that is flexible across frames rather than a single waveform. By choosing the parameters of the GFDM waveform appropriately, one can obtain different waveforms such as OFDM, single carrier-frequency domain equalization (SC-FDE), FBMC and Faster-Than-Nyquist at the output, as demonstrated in [9]. In spite of these type of interesting flexibilities, GFDM is a computationally extensive scheme mainly because FFT/inverse FFT (IFFT) could not immediately be employed at the GFDM based transceiver [13]. Furthermore, the circular convolution used in the filtering process, referred to as tail-biting in [14], introduces non-orthogonality across subcarriers as explained in [8]. Therefore, a successive interference cancellation at the receiver side is required so as to remove inter-carrier interference (ICI) [15].

Unlike the aforementioned technologies, OFDM has been widely and successfully used in wireless digital communication systems such as LTE and Wi-Fi due to its numerous advantages such as low-complexity implementation with FFT and the robustness against multipath channels with single-tap FDE. However, plain OFDM signals suffer from the distortions due to the non-linear characteristics of power amplifier (PA). At the same time, the block nature of OFDM symbols may result in a high out-of-band (OOB) leakage and cause severe adjacent channel interference. Considering these issues, alternative schemes, GFDM, UFMC and FBMC definitely offer some advantages over OFDM. However, backward compatibility of OFDM with the existing technologies along with the other advantages makes enhancement of OFDM more appealing for the industry rather than going for a new waveform, as far as seen in the current standard discussions [16]–[18]. Therefore, in this paper, we draft various approaches addressing the shortcomings of OFDM and discuss how OFDM fits the envisioned 5G concepts and technologies.

Organized into the following five sections, this paper first presents the methods that enhance the spectral compactness, robustness against nonlinear effects of radio frequency (RF) front-end and spectral efficiency of OFDM. We provide examples of transmitter algorithms that lower peak-to-average power ratio (PAPR) and OOB leakage of OFDM without requiring major modifications at the receiver side. Secondly, considering newly introduced 5G RAN applications such as massive MIMO, we discuss the methods that address reducing the redundancies of OFDM in time (CP duration) and frequency (pilots) in order to increase spectral efficiency. Following that, we describe one of the main goals of 5G, which is to make all the diverse applications requiring different waveforms co-exist in the same frame, as addressed by 3GPP community within numerology contributions. The motivations and challenges of this concept are briefly investigated. Finally, new OFDM-derived approaches that aim to overcome the drawbacks of OFDM are provided along with the issues they encounter.

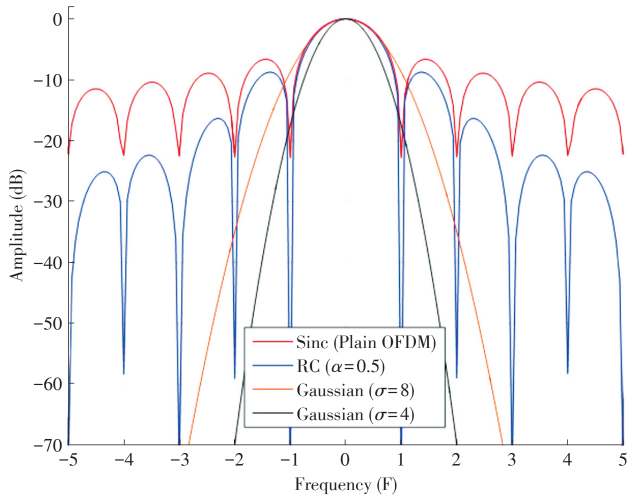
2 Improvements in Waveform Characteristics

In a general sense, the key terms characterizing a basic OFDM waveform are multicarrier modulation and rectangular pulse shape[1], and the majority of the advantages and disadvantages of OFDM are stemming from these features. In this section, we discuss how to improve characteristics of OFDM and make it a more convenient waveform for 5G RAN in terms of high PAPR, OOB leakage and redundancy introduced by CP.

2.1 OOB Leakage Suppression

High OOB leakage is a major issue in OFDM due to the inherent rectangular shape of OFDM symbols. In the frequency domain, subcarriers are shaped by sinc functions and addition of their sidelobes results in a considerable energy leakage on the neighboring channels as shown in **Fig. 2**. Although there are well-known filters emitting less energy on side bands, e.g., raised cosine and Gaussian filters, OFDM does not allow pulse shaping unlike FBMC and GFDM, and therefore, a severe interference might be inevitable for users operating on the neighboring frequencies, especially for asynchronous scenarios. Leaving sufficient guard bands between the users might be considered as a practical solution, but this would not be an efficient way of utilizing spectral resources. In 5G scenarios, as far as envisioned so far, a huge number of asynchronous and data-hungry users should co-exist within a limited spectrum. Therefore, OFDM signals should be more localized in the frequency domain by handling OOB leakage problem in a practical way to adapt OFDM to such scenarios.

For the aforementioned purpose, OOB leakage of OFDM signals has been extensively addressed with numerous techniques in the literature as reviewed and compared in [19]. For instance, a time domain windowing approach is proposed in [20], which can make the transitions between the OFDM symbols smoother and avoid signal components at higher frequencies. Hence, the OOB leakage of OFDM symbols is significantly reduced. This approach became very popular due to its simplicity, effectiveness and requirement of no modification at the receiver side. However, the introduction of an extra redundancy as much as the windowing duration remained a problem. In [21], while the total duration for CP and windowing is kept constant for all subcarriers, windowing is mostly applied to the edge subcarriers since the leakage of edge subcarriers causes more interference on the adjacent frequencies. In a practical multiuser scenario where users need different CP sizes, this approach can decrease the windowing redundancy compared to the classical approach via a convenient user scheduling. Users with low time-dispersive channels are assigned to the edge subcarriers and users having highly time-dispersive channels are assigned to the inner subcarriers. Thus, the total duration required for CP and windowing could be shorter without causing any problem. In [22]–[25], the OOB leakage is addressed from frequency domain perspective. A set of subcarriers, named as cancellation carriers, are allocated for canceling the sidelobes in [22], [23]. However, such approaches also introduce redundancy in the frequency domain and degrade spectral efficiency similar to classical windowing approach. In [24], sidelobe suppression is done by weighting subcarriers in such a way that sidelobes are combined on adjacent frequencies as destructively as possible. However, weighting leads to a pre-distortion of subcarriers and bit-error rate (BER) performance naturally reduces. In order to limit this distortion, a frequency domain precoder is proposed in [25], which only maintains the spectrum of OFDM signals under the prescribed mask rather than forcing OOB leakage to zero. By doing so, interference on the adjacent frequencies is kept on a reasonable level at the expense of a smaller degradation BER performance.



OFDM: orthogonal frequency division multiplexing RC: raised cosine

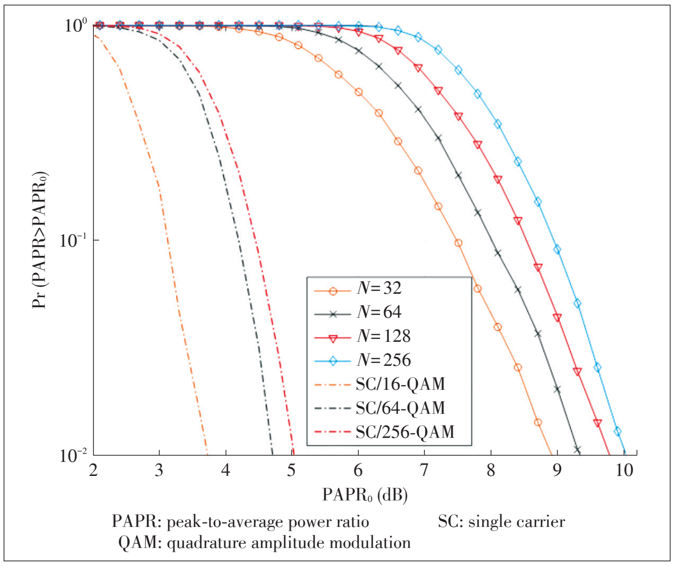
▲**Figure 2. Frequency responses of an OFDM subcarrier (sinc) and various filters.**

2.2 PAPR Mitigation

As a consequence of multicarrier transmission, i.e., transmitting multiple signals in parallel, high PAPR is inevitable for OFDM signals due to the probable constructive combination of signals in time domain. In **Fig. 3**, a comparison between SC signals having various modulation orders up to 256-QAM, and OFDM signals having a different number of subcarriers (N) is provided. Obviously, there is a huge difference in PAPR even when the number of subcarriers is as low as 32. It could be ignored for users requiring low power transmission. However, in many scenarios such as the mobile users on cell edges, a reli-

---

[1] CP deployment can also be considered among these terms, however, that will be discussed in later sections.



PAPR: peak-to-average power ratio
QAM: quadrature amplitude modulation
SC: single carrier

▲Figure 3. PAPR comparison between single carrier signals with different modulation orders and OFDM with different number of subcarriers (*N*).

able transmission requires high power and high PAPR of the signal for this scenario makes the signal vulnerable to non-linear effects of RF front-end components. These components typically have a limited linear range, and any part of the signal exceeding the linear range is non-linearly scaled. Non-linear scaling of a signal can also be referred as multiplying a part of signal components with various coefficients. This makes a time-varying channel effect on the signal, and the signal is distorted as if it is exposed to a Doppler spread effect at the transmitter. As a result, non-linearity of RF components may lead to severe interference not only in the user's band but also for the others operating on neighboring frequencies due to the spectral regrowth. At this point, one may notice that the OOB leakage is not only the function of the waveform itself but also the spectral regrowth of the ideal waveform signals due to the high PAPR in practice. Then, even if the OOB suppression performance of the related studies in the literature is quite satisfactory, a good scheme needs to address PAPR and OOB leakage jointly for fixing these two shortcomings, practically.

PAPR suppression techniques are surveyed well in [26], however, many of them tackle with PAPR individually without considering OOB. On the other hand, some existing studies use PAPR reduction concepts for suppressing OOB. This is achieved by actively selecting some predesigned sequences, i.e., selected mapping (SLM) sequences in [27]. Another well-known PAPR reduction method, partial transmit sequences are applied on OFDM signals partitioned into contiguous blocks in the frequency domain in [28]. Additionally, the optimized phase rotations are multiplied by each sub-block to provide a contiguous transition between the OFDM symbols to suppress OOB leakage along with PAPR. Another joint suppression method is presented in [29], where the constellation points are dynamically extended. For the similar purpose, a method called CP alignment is proposed in [30] similar to the interference alignment method presented in [31]. The key idea in this method is to add a perturbation signal, called alignment signal (AS), to the plain OFDM symbols in order to reduce the PAPR and OOB leakage such that the AS aligns with the CP duration of the OFDM symbols after passing through the channel. However, this method completely relies on the perfect channel estimation and any error might result in an interference on the data part. In order to fix this problem, a recent method called static CP alignment is proposed in [32] where the AS is designed according to a pre-determined filter independent of the channel. These methods also provide physical layer security to some extent by using additional signals that confuse the unauthorized users [33].

Joint PAPR and OOB leakage suppression techniques are definitely offering a comprehensive solution in enhancing characteristics of OFDM signals. However, they require symbol based active optimization, which introduces complexity issues at the transmitter side. Therefore, simpler solutions such as windowing are still needed in this field.

3 Reducing Redundancies of OFDM

Classical CP-OFDM is known as one of the most spectrally efficient transmission schemes and sufficiently satisfying the requirements of LTE-Advanced Pro and currently used IEEE 802.11 systems. However, it still suffers from redundancies, in both time and frequency domains. The redundancy in time comes from the use of CP while the redundancy in frequency domain comes from the use of pilot subcarriers and guard bands. In order to adopt OFDM for future radio access technologies and to achieve the aforementioned goals in data rate, these redundancies should be reduced, significantly.

3.1 CP Reduction

In communication channels with multipath delay spread, a guard interval (GI) is required to prevent leakage in time between the successive symbols. CP is a smart way to utilize the guard interval by copying the samples from the end of a symbol and pasting them to its beginning. Thus, the linear convolution of the channel becomes a circular convolution, which makes the channel matrix diagonalizable only by taking its Fourier transform and enables a simple equalization in the frequency domain. The length of the CP is chosen to be larger than the expected delay spread to avoid any inter-symbol interference (ISI) and ICI. Also, in order to maintain orthogonal coexistence of neighboring transmission blocks, predefined values have been used for the length of the CP and applied to all the blocks. For example, two CP rates are defined in LTE where the normal CP duration in terms of symbol duration (T_{SYM}) is given as $T_{SYM} \times 9/128$ while the extended CP duration is $T_{SYM} \times 32/128$.

Recent works have shown that extending the CP duration might not be the best approach to combat against long delay spreads [34]–[36]. The newly proposed 5G scenarios have introduced their own methods for ISI mitigation. An example is mmWave MIMO systems that employ highly directional transmission using beamforming. For such systems, beam switching reference signals are broadcasted so that the receivers can determine which predefined beam is directed to their way, resulting in higher signal to interference plus noise ratio for all receivers. Inventors have shown in [34] that such signals not only provide support for beam switching but can also be used to estimate delay spread exceeding CP duration. Then, ISI could be canceled from received symbols, which reduces the required CP. In [35], authors claim that MIMO receivers can identify the presence of any residual interference after equalization by evaluating the channel matrix. It was shown that decreasing the modulation and coding index instead of extending the CP length, would increase the throughput. In addition to these methods, advanced signal processing techniques can be employed to mitigate the interference. A good example of that is the bi-directional M-algorithm based equalizer proposed in [36]. It has shown that a system which experiences a delay spread six times longer than the CP duration exhibits the same performance of a conventional system with sufficient CP. It is achieved at only the expense of performing two iterations of the proposed algorithm referred to as trellis-based interference detection and mitigation.

In some scenarios, the maximum excess delay might be much less than the duration of normal CP which makes the minimum CP overhead of 7% a pointless guard for LTE systems. To reduce this overhead, the authors of [37] present the idea of a flexible frame design. A wider range of options in terms of subcarrier spacing and CP length are used for the OFDM symbols inside the proposed frame structure. Then, the users experiencing similar channel dispersions are grouped and the proper symbol parameters are determined for each group within the frame. Thus, overall efficiency is enhanced by avoiding inconvenient parameter selection. An extension of this approach to mmWave single user MIMO systems can also be found in [34], where the use of additional subframe configurations is presented independently for each user. Increasing the number of options for the CP duration is also recommended in the 3GPP standard contributions [38], [39].

CP overhead also constitutes a disadvantage for the low latency required applications as it introduces delays in the transmission which might cause drawbacks for 5G services such as ultra reliable low latency communications (URLLC). In the algorithm proposed in [40], the author removed the CPs entirely from all symbols except the first one for reducing total transmission delay. In the proposed method, the CP used by the first symbol is utilized to obtain a detailed estimation of the channel time and frequency characteristics. Afterwards, the subcarrier spacing is reduced to $\Delta f/(N_{SYM}-1)$, where Δf denotes the subcarrier spacing used in the first symbol and N_{SYM} denotes the total number of symbols including the first one. All symbols sent later are combined to fit in the same bandwidth used by the first symbol using an IFFT size of $(N_{SYM}-1)\times N_{OFDM}$, and sent as a single symbol without CP. Thus, the total transmission time is reduced by $(N_{SYM}-1)\times T_{CP}$, where T_{CP} is the CP duration.

3.2 Pilot Decontamination

Another redundancy that has been with OFDM since it became practical is the use of pilots within the subcarriers. In time domain duplexing (TDD) systems, inside a cell, the mobile stations transmit mutually orthogonal pilot sequences to the base station (BS) so that the BS can estimate the channel in the uplink (UL), and assuming channel reciprocity, precode accordingly for the downlink (DL). In the case of frequency domain duplexing (FDD) systems, because the channel state for the UL and DL is different, a two-stage procedure is required. The BS first transmits pilot symbols and then, the users feedback their channel state information to the BS. For the massive MIMO concept with the TDD case, many beams are established for a vast number of users compared to the past. Each beam requires a different mutually orthogonal sequence, which increases the length of the sequences immensely and decreases the resources available to transmit data symbols. For the FDD case, the same situation happens as the number of transmit antennas at the BS goes to infinity. A proposed method to reduce this overhead is reusing pilot sequences of nearby cells, which introduces inter-cell-interference and gives rise to the “pilot contamination” effect [41]. The high number of lengthy pilots also increases the latency and makes Internet of Things (IoT)-type sporadic and short messages inefficient.

Some researchers allow the use of the pilots but try to reduce the overhead, which can be referred to as soft pilot mitigation. In [42], the authors propose using only the amplitudes of the subcarriers as the pilots, and the phase of the same subcarriers can be used to transmit information in an effort to increase the data rate. In [43], the author proposes many techniques to mitigate pilot contamination for the TDD case. The terminals are suggested to match the DL reference signal powers in the UL, in order to reduce both the overall pilot interference in the neighboring cells and the pilot overhead required for closed loop power control. Another suggestion is reusing pilots softly to avoid inter-cell-interference. Some pilot sequences are proposed to be assigned for use only at the cell edge whereas the same groups of pilot sequences can be transmitted with less power near the BSs. Even further, the author suggests that the angular resolution provided by the massive number of antennas can be used to coordinate pilot allocation between cells and safely reuse the pilot sequences for spatially separated terminals. In [44], the authors have aligned the Power Delay Profiles (PDPs) of the users served by the same BS to orthogonalize the pilots sent within the common OFDM symbol. By aligning the PDPs for the same number of users that can be sounded within the same symbol, it has been shown that the average signal-to-noise ratio (SNR) can increase by half.

Another group of researchers has proposed blind channel estimation or signal detection techniques to remove pilots completely, which would be appropriately called hard pilot mitigation. In [45], the authors have shown that pilots can completely be removed as the singular value decomposition of the received signal matrix projects the received signal onto an interference-free subspace governed by an easily predictable nonlinear compound. The authors have demonstrated that the proposed subspace projection method outperforms linear channel estimation if a power margin between the users of interest and interfering users are provided, especially when the base station antennas outnumber the coherence time (in number of symbol durations). In [46], the authors have treated the detected UL data as pilot symbols to obtain the least squares estimate of the channel. Also, by estimating the channels of all users sequentially, they obtained extracting vectors that accurately extract the desired data from the mixture signal.

4 Numerology

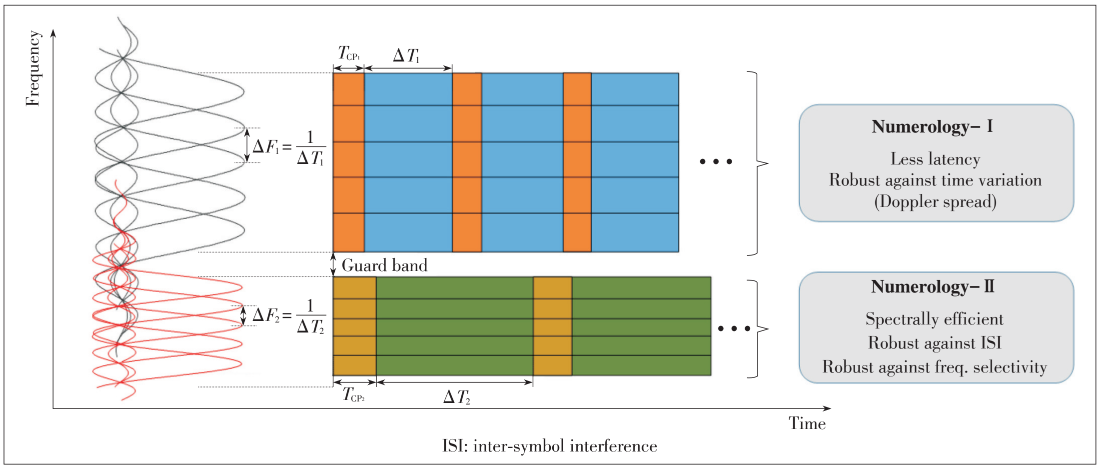
Wireless users have different requirements in waveform based on the service that they get or channel conditions that they experience. Therefore, there is not any one-size-fits-all solution for waveform design. The ongoing discussions on the usage of different numerologies also confirm this argument and consequently, one crucial expectation from future standards is the allowance to use multiple waveforms in one frame. This would definitely constitute a great relaxation in selecting the most proper waveform based on user needs. However, managing their coexistence is a critical issue. Especially, inter-user interference management for uplink/downlink, synchronous and asynchronous scenarios should be carefully investigated to utilize spectral resources efficiently.

In the context of 3GPP 5G standardization contributions, the term numerology refers to the configuration of waveform parameters, and different numerologies are considered as OFDM-based sub-frames having different parameters such as subcarrier spacing/symbol time, CP size, etc. [47]. By designing such numerologies based on user requirements, industry targets to meet the aforementioned user-specific demands to some extent. A general illustration of such numerologies is provided in **Fig. 4**. Here, numerology-I would be properly assigned to highly mobile users having more time-variant channels and the ones with low latency requirement. On the other hand, numerology-II offers more robustness against frequency selectivity and includes less redundancy due to low CP rate.

Let us give more details on the parameters and the importance of their selection for designing different numerologies:

1) CP length: The basic function of CP is to avoid inter-symbol interference and in-band interference. In order to achieve that, CP length should be specified as longer than the maximum excess delay of the channel impulse response. Therefore, users experiencing a wireless channel causing high dispersion in time (or more selectivity in frequency) should have longer CP lengths compared to the users with low dispersive channels. In addition, CP makes the signal robust against time synchronization errors. This might be very critical especially for asynchronous UL scenarios and low latency demanding services.

2) Subcarrier spacing: It can also be referred to as subcarrier bandwidth and is directly related to the duration of an OFDM symbol. When the CP size is determined on the basis of the channel conditions and application requirements, decreasing subcarrier spacing increases spectral efficiency as the CP rate decreases. However, for highly mobile users, channel responses might vary within a symbol duration which leads to ICI. Therefore, symbol time should be kept smaller by increasing subcarrier spacing in order to make the transmission robust against time-varying, i.e., frequency dispersive channels. Additionally, a proper choice of subcarrier spacing is very critical for immunity against phase noise, which is specifically important for users operating on high frequencies such as mmWave frequencies.



ISI: inter-symbol interference

Figure 4. Illustration of different numerologies.

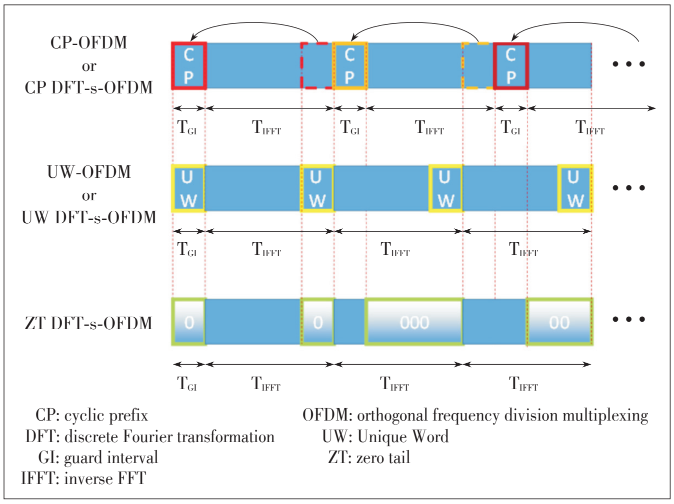
In the light of aforementioned facts, the coexistence of different numerologies offers a great advantage in serving users with different requirements. However, such a design obviously removes the orthogonality between the numerologies, i.e., sinc shaped subcarriers with different spacings as illustrated in Fig. 4, and inter-numerology interference becomes inevitable. This is a major issue in numerology design and guard band determination between numerologies. Therefore, for the sake of communication performance and spectral efficiency, minimization of OOB leakage of each numerology or keeping their orthogonality with various methods should be investigated carefully.

5 Other OFDM-Based Signaling Schemes

While many researchers take a stand on enhancing the characteristics of OFDM without changing its conventional structure, alternative OFDM based approaches, e.g., Unique Word-OFDM (UW-OFDM), discrete Fourier transformation-spread-OFDM (DFT-s-OFDM), etc., are also very popular. In this section, we will discuss the advantages and disadvantages of these technologies, illustrated in **Fig. 5**, along with a comparison with the classical CP-OFDM.

5.1 Utilizing GI with UW

In Subsection 3.1, we have denoted that CP is a smart way of utilizing the GI. There are other methods that utilize the GI as good as CP, which have recently been gaining attention. The most prominent one among these methods is UW-OFDM [48]. In UW-OFDM, the GI is filled with a deterministic sequence called the unique word. To obtain the UW, data subcarriers are multiplied by a precoding matrix, which depends on the desired UW, before the IFFT operation. This multiplication generates data dependent redundant subcarriers. Then, these redundant subcarriers are given as input to the IFFT along with the data symbols. At the output of the IFFT, UW is obtained in the time symbol, without needing any other operations such as copying and pasting as performed for CP.



▲**Figure 5. The modified structures' symbols in time below the OFDM symbol in time, to scale according to LTE extended CP specifications.**

The advantages of UW-OFDM comes from the fact that the UW is a natural part of the IFFT interval. Due to this property, symbols with different unique words can be multiplexed in time and frequency without destroying the orthogonality among various users and applications as long as the IDFT length is kept the same. Therefore, UW length can be adjusted by selecting the number of redundant subcarriers and UW-OFDM symbols can be flexibly designed based on the delay spreads experienced by different receivers [49]. Furthermore, the corresponding correlation introduced between the redundant and data subcarriers can be exploited to improve the BER performance [50]. However, due to the increased complexity stemmed from the precoding and decoding processes, UW-OFDM suffers from the complicated receiver and transmitter structures [51].

5.2 Quasi-Single Carrier Structures

DFT-s-OFDM can be obtained by adding an M-DFT block before the conventional N-IFFT operation where M < N. It is a midway between multicarrier and single carrier (SC), and is usually categorized as a quasi-single carrier structure due to this generation process. There are two main reasons this well-known modification of OFDM has been used in the UL of LTE [52]. Firstly, although higher from pure SC, it exhibits lower PAPR compared to the CP-OFDM and requires much lower power amplifier back-off resulting in a higher power efficiency. Secondly, since it is an OFDM-based structure, the scheduling flexibility provided by orthogonal frequency division multiple access (OFDMA) can still be used [53].

The circularity of DFT-s-OFDM symbols is also satisfied with the help of CP just like the conventional OFDM implemented in LTE. Recently, methods that fill the GI with different sequences have also been proposed for DFT-s-OFDM. Despite the similarity to the UW-OFDM approach discussed in the previous subsection, filling the GI with specific sequences does not require any precoding operation in DFT-s-OFDM because of its inherent structure [54]. When the sequence, desired to fill the GI, is appended to the data symbols at the input of the M-DFT, the interpolated form of this sequence is obtained at the output of the N-IFFT at no expense of complexity. Furthermore, these schemes can be used by existing DFT-s-OFDM receivers without any modifications as the guard sequences do not impact the data symbols [55]. Considering these facts, a popular alternative to the CP-based DFT-s-OFDM is zero tail (ZT)-based DFT-s-OFDM [56]. The main motivation behind using a ZT is the ability of adaptation to different channel conditions and data rates just by modifying the number of zeroes [57]. Compared to conventional CP-DFT-s-OFDM, this scheme offers a better BLER performance and reduced OOB leakage as the interference power leaking to the consecutive symbols is reduced and the zeroes are a natural part of the IFFT output [57]. Having a ZT, however, decreases the average power of the transmitted signal, resulting in a PAPR penalty [55]. This penalty recently forced this approach to evolve into what is called Generalized DFT-s-OFDM, and ZT DFT-s-OFDM remained as a special case where the head and tail are set to zeroes [58].

The UW concept can also be combined with ZT DFT-s-OFDM and gives rise to UW DFT-s-OFDM. It replaces the ZT with nonzero low energy redundant symbols that further reduce the OOB leakage, PAPR and energy in the tail compared to both UW-OFDM and ZT-DFT-s-OFDM [55]. An enhanced version of UW DFT-s-OFDM concept is given in [59], where an additional perturbation signal is introduced to suppress the ISI energy between the consecutive symbols, which remains even less than the ISI between ZT-DFT-s-OFDM symbols. However, this scheme suffers from the increased receiver complexity and transmitter complexity due to the linear precoding [55].

6 Conclusions

In this paper, we discussed various aspects of OFDM as the strongest candidate waveform technology for 5G RAN. After providing a brief discussion on other candidate waveform schemes (FBMC, UFMC and GFDM), we firstly addressed the two major shortcomings of OFDM, high PAPR and OOB leakage, and reviewed the potential solutions for handling them individually or jointly. Then, we discussed the redundancies in OFDM, e.g., CP and pilots, and provided the proposed methods in the literature for reducing them. They are specifically critical for massive-MIMO applications and majority of the proposed techniques are presented in this context. Following the redundancy reduction techniques, we discussed the concept of numerology which plays an important role for 5G technologies in terms of delivering reliable service to the users with various requirements. Since OFDM is the most prominent waveform considered in the standard contributions, we just focused on how OFDM related parameters can meet different user requirements stemming from personal and environmental conditions, and from the types of provided service. However, authors believe the concept of numerology will evolve to a more general and flexible notion that encompasses any waveform technology, not limited to OFDM. We finally went through the other OFDM-based waveforms along with their pros and cons in comparison with classical OFDM.

References

[1] J. G. Andrews, S. Buzzi, W. Choi, et al., “What will 5G be?” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014. doi: 10.1109/JSAC.2014.2328098.

[2] FP7. (2012). *European Project 318555 5G NOW (5th Generation Non-Orthogonal Waveforms for Asynchronous Signaling)* [Online]. Available: http://www.5gnow.eu

[3] FP7. (2012). *European Project 317669 METIS (Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society)* [Online]. Available: https://www.metis2020.com

[4] FP7. (2016). *European Project (FP7-ICT-619563) miWaveS (Beyond 2020 Heterogeneous Wireless Networks with Millimeter-Wave Small Cell Access and Backhauling)* [Online]. Available: http://www.miwaves.eu

[5] Fantastic 5G. (2016). *Horizon 2020 project (ICT-671660) FANTASTIC-5G (Flexible Air Interface for Scalable Service Delivery within Wireless Communication Networks of the 5th Generation)* [Online]. Available: http://fantastic5g.eu

[6] S. Methley, W. Webb, S. Walker, and J. Parker, “5G candidate band study: study on the suitability of potential candidate frequency bands above 6 GHz for future 5G mobile broadband systems,” Quotient Associates Ltd, Tech. Rep., 2015.

[7] B. Farhang Boroujeny, “Filter bank multicarrier modulation: a waveform candidate for 5G and beyond,” *Advances in Electrical Engineering*, vol. 2014, Dec. 2014. doi:10.1155/2014/482805

[8] A. Şahin, I. Güvenç, and H. Arslan, “A survey on multicarrier communications: prototype filters, lattice structures, and implementation aspects,” *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1312–1338, Aug. 2014. doi: 10.1109/SURV.2013.121213.00263.

[9] F. Hu, *Opportunities in 5G Networks: A Research and Development Perspective*. Boca Raton, USA: CRC Press, 2016.

[10] 5G Forum. (2016, Mar.). *5G white paper: 5G vision, requirements, and enabling technologies* [Online]. Available: http://kani.or.kr/5g/whitepaper/5G%20Vision,%20Requirements,%20and%20Enabling%20Technologies.pdf

[11] G. Wunder, P. Jung, M. Kasparick, et al., “5GNOW: non-orthogonal, asynchronous waveforms for future mobile applications,” *IEEE Communications Magazine*, vol. 52, no. 2, pp. 97–105, 2014. doi: 10.1109/MCOM.2014.6736749.

[12] J. Li, E. Bala, and R. Yang, “Resource block filtered-OFDM for future spectrally agile and power efficient systems,” *Physical Communication*, vol. 11, pp. 36–55, 2014. doi: 10.1016/j.phycom.2013.10.003.

[13] I. F. Akyildiz, S. Nie, S. Lin, and M. Chandrasekaran, “5G roadmap: 10 key enabling technologies,” *Computer Networks*, vol. 106, pp. 17–48, 2016. doi: 10.1016/j.comnet.2016.06.010.

[14] G. Fettweis, M. Krondorf, and S. Bittner, “GFDM—generalized frequency division multiplexing,” in *Proc. IEEE 69th Vehicular Technology Conference*, Barcelona, Spain, Apr. 2009, pp. 1–4. doi: 10.1109/VETECS.2009.5073571.

[15] R. Datta, G. Fettweis, Z. Kollár, and P. Horváth, “FBMC and GFDM interference cancellation schemes for flexible digital radio PHY design,” in *Proc. 14th Euromicro Conference on Digital System Design*, Washington DC, USA, 2011, pp. 335–339. doi:10.1109/DSD.2011.48.

[16] Qualcomm Inc., “Waveform candidates,” 3GPP Standard Contribution (R1-162199), Busan, Korea, Apr. 2016.

[17] Huawei and HiSilicon, “5G waveform: requirements and design principles,” 3GPP Standard Contribution (R1-162151), Busan, Korea, Apr. 2016.

[18] Huawei and HiSilicon, “F-OFDM scheme and filter design,” 3GPP Standard Contribution (R1-165425), Nanjing, China, May 2016..”

[19] W. Jiang and M. Schellmann, “Suppressing the out-of-band power radiation in multi-carrier systems: A comparative study,” in *Proc. IEEE Global Telecommunications Conference*, Anaheim, USA, Dec. 2012, pp. 1477–1482. doi: 10.1109/GLOCOM.2012.6503322.

[20] T. Weiss, J. Hillenbrand, A. Krohn, and F. K. Jondral, “Mutual interference in OFDM-based spectrum pooling systems,” in *Proc. 59th IEEE Vehicular Technology Conference*, Milan, Italy, May 2004, vol. 4, pp. 1873–1877. doi: 10.1109/VETECS.2004.1390598.

[21] A. Sahin and H. Arslan, “Edge windowing for OFDM based systems,” *IEEE Communications Letters*, vol. 15, no. 11, pp. 1208–1211, Nov. 2011. doi: 10.1109/LCOMM.2011.090611.111530.

[22] S. Brandes, I. Cosovic, and M. Schnell, “Reduction of out-of-band radiation in OFDM systems by insertion of cancellation carriers,” *IEEE Communications Letters*, vol. 10, no. 6, pp. 420–422, Jun. 2006. doi: 10.1109/LCOMM.2006.1638602.

[23] D. Qu, Z. Wang, and T. Jiang, “Extended active interference cancellation for sidelobe suppression in cognitive radio OFDM Systems with cyclic prefix,” *IEEE Transactions on Vehicular Technology*, vol. 59, no. 4, pp. 1689–1695, May 2010. doi: 10.1109/TVT.2010.2040848.

[24] I. Cosovic, S. Brandes, and M. Schnell, “Subcarrier weighting: a method for sidelobe suppression in OFDM systems,” *IEEE Communications Letters*, vol. 10, no. 6, pp. 444–446, Jun. 2006. doi: 10.1109/LCOMM.2006.1638610.

[25] A. Tom, A. Sahin, and H. Arslan, “Mask compliant precoder for OFDM spectrum shaping,” *IEEE Communications Letters*, vol. 17, no. 3, pp. 447–450, Mar. 2013. doi: 10.1109/LCOMM.2013.020513.122495.

[26] Y. Rahmatallah and S. Mohan, “Peak-to-average power ratio reduction in OFDM systems: a survey and taxonomy,” *IEEE Communications Surveys & Tutorials*, vol. 15, no. 4, pp. 1567–1592, Fourth Quarter 2013. doi: 10.1109/

SURV.2013.021313.00164.

[27] A. Ghassemi, L. Lampe, A. Attar, and T. A. Gulliver, "Joint sidelobe and peak power reduction in OFDM-based cognitive radio," in *Proc. IEEE 72nd Vehicular Technology Conference*, San Francisco, USA, pp. 1- 5, Sept. 2010. doi: 10.1109/VETECF.2010.5594133.

[28] E. Güvenkaya, A. Tom, and H. Arslan, "Joint sidelobe suppression and PAPR reduction in OFDM using partial transmit sequences," in *Proc. IEEE Military Communications Conference*, San Diego, USA, Nov. 2013, pp. 95- 100. doi: 10.1109/MILCOM.2013.26.

[29] C. Ni, T. Jiang, and W. Peng, "Joint PAPR reduction and sidelobe suppression using signal cancelation in NC-OFDM-based cognitive radio systems," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 3, pp. 964- 972, Mar. 2015. doi: 10.1109/TVT.2014.2327012.

[30] A. Tom, A. Sahin, and H. Arslan, "Suppressing alignment: An approach for out-of-band interference reduction in OFDM systems," in *Proc. IEEE International Conference on Communications*, London, UK, Jun. 2015, pp. 4630-4634. doi: 10.1109/ICC.2015.7249053.

[31] M. Maso, M. Debbah, and L. Vangelista, "A distributed approach to interference alignment in OFDM-based two-tiered networks," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 5, pp. 1935-1949, Jun. 2013. doi: 10.1109/TVT.2013.2245516.

[32] Z. E. Ankarali, A. Sahin, and H. Arslan, "Static cyclic prefix alignment for OFDM-based waveforms," in *Proc. IEEE Global Communications Conference and Workshops*, Washington, USA, Dec. 2016. doi: 10.1109/GLOCOMW.2016.7849051.

[33] Z. E.Ankarali, and H. Arslan. "Joint physical layer security and PAPR mitigation in OFDM systems," U.S. Patent No. 9,479,375. Oct. 2016.

[34] S.Rajagopal, S. Abu Surra, A. Gupta, et al., "Methods and apparatus for cyclic prefix reduction in mmwave mobile communication systems," U.S. Patent US20 130 315 321 A1, Nov. 2013.

[35] E. Zoechmann, S. Pratschner, S. Schwarz, and M. Rupp, "MIMO transmission over high delay spread channels with reduced cyclic prefix length," in *Proc. 19th International ITG Workshop on Smart Antennas (WSA)*, Ilmenau, Germany, Mar. 2015, pp. 1-8.

[36] T. Pham, T. Le Ngoc, G. Woodward, P. A. Martin, and K. T. Phan, "Equalization for MIMO-OFDM systems with insufficient cyclic prefix," in *Proc. IEEE 83th Vehicular Technology Conference*, Nanjing, China, May 2016, pp. 1- 5. doi: 10.1109/VTCSpring.2016.7504240.

[37] A. Sahin and H. Arslan, "Multi-user aware frame structure for OFDMA based system," in *Proc. IEEE 76th Vehicular Technology Conference*, Quebec City, Canada, Sept. 2012, pp. 1-5. doi:10.1109/VTCFall.2012.6399155.

[38] ZTE, "Consideration of cyclic prefix for NR," 3GPP Standard Contribution (R1-166406), Gothenburg, Sweden, Aug. 2016."

[39] ZTE, "Support of Multiple CP Families for NR," 3GPP Standard Contribution (R1-1608962), Lisbon, Portugal, Oct. 2016."

[40] J. Lorca, "Cyclic prefix overhead reduction for low-latency wireless communications in OFDM," in *Proc. IEEE 81st Vehicular Technology Conference*, Glasgow, UK, May 2015, pp. 1-5. doi: 10.1109/VTCSpring.2015.7145767.

[41] O. Elijah, C. Y. Leow, T. A. Rahman, S. Nunoo, and S. Z. Iliya, "A comprehensive survey of pilot contamination in massive MIMO-5G system," *IEEE Communications Surveys & Tutorials.*, vol. 18, no. 2, pp. 905- 923, 2016. doi: 10.1109/COMST.2015.2504379.

[42] P. Walk, H. Becker, and P. Jung, "OFDM channel estimation via phase retrieval," in *Proc. 49th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, USA, Nov. 2015, pp. 1161-1168. doi: 10.1109/ACSSC. 2015. 7421323.

[43] V. Saxena, "Pilot contamination and mitigation techniques in massive MIMO systems," M.S. Thesis, Lund University, Stockholm, Sweden, 2014.

[44] X. Luo, X. Zhang, H. Qian, and K. Kang, "Pilot decontamination via PDP alignment," in *Proc. IEEE Global Communications Conference*, Washington DC, USA, Dec. 2016, pp. 1-6. doi: 10.1109/GLOCOM.2016.7842147.

[45] R. R. Müller, L. Cottatellucci, and M. Vehkaperä, "Blind pilot decontamination," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 773-786, Oct. 2014. doi: 10.1109/JSTSP.2014.2310053.

[46] D. Hu, L. He, and X. Wang, "Semi-blind pilot decontamination for massive MIMO systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 1, pp. 525-536, Jan. 2016. doi: 10.1109/TWC.2015.2475745.

[47] A. A. Zaidi, R. Baldemair, H. Tullberg, et al., "Waveform and numerology to support 5G services and requirements," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 90-98, Nov. 2016. doi: 10.1109/MCOM.2016.1600336CM.

[48] C. Hofbauer, M. Huemer, and J. B. Huber, "Coded OFDM by unique word prefix," in *Proc. IEEE International Conference on Communication Systems*, Singapore, Singapore, Nov. 2010, pp. 426-430. doi: 10.1109/ICCS.2010.5686520.

[49] M. Huemer, C. Hofbauer, and J. B. Huber, "Non-systematic complex number RS coded OFDM by unique word prefix," *IEEE Transactions on Signal Processing*, vol. 60, no. 1, pp. 285-299, Jan. 2012. doi: 10.1109/TSP.2011.2168522.

[50] A. Onic and M. Huemer, "Noise interpolation for unique word OFDM," *IEEE Signal Processing Letters*, vol. 21, no. 7, pp. 814-818, Jul. 2014. doi: 10.1109/LSP.2014.2317512.

[51] M. Huemer, A. Onic, and C. Hofbauer, "Classical and Bayesian linear data estimators for unique word OFDM," *IEEE Transactions on Signal Processing*, vol. 59, no. 12, pp. 6073-6085, Dec. 2011. doi: 10.1109/TSP.2011.2164912.

[52] H. Holma and A. Toskala, Eds., *LTE for UMTS: Evolution to LTE- Advanced*, 2nd ed. Chichester, UK: Wiley, 2011.

[53] S. Sesia, I. Toufik, and M. P. J. Baker, Eds., *LTE - the UMTS Long Term Evolution: from Theory to Practice*. Chichester, UK: Wiley, 2009.

[54] C. F. Gauss, "Nachlass: Theoria interpolationis methodo nova tractata," pp. 265-303, *Carl Friedrich Gauss, Werke, Band 3*, Gottingen: Koniglichen Gesellschaft der Wissenschaften, 1866.

[55] A. Sahin, R. Yang, M. Ghosh, and R. L. Olesen, "An improved unique word DFT-spread OFDM scheme for 5G systems," in *Proc. IEEE Global Communications Conference and Workshops*, San Diego, USA, Dec. 2015, pp. 1-6. doi: 10.1109/GLOCOMW.2015.7414173.

[56] G. Berardinelli, F. M. L. Tavares, T. B. Sorensen, P. Mogensen, and Pajukoski, "Zero-tail DFT-spread-OFDM signals," in *Proc. IEEE Global Telecommunications Conference and Workshops*, Atlanta, USA, Dec. 2013, pp. 229-234. doi: 10.1109/GLOCOMW.2013.6824991.

[57] G. Berardinelli, F. Tavares, T. Sorensen, P. Mogensen, and K. Pajukoski, "On the potential of Zero-Tail DFT-spread-OFDM in 5G networks," in *Proc. IEEE 80th Vehicular Technology Conference*, Sept. 2014, pp. 1-6. doi: 10.1109/VTC-Fall.2014.6966089.

[58] G. Berardinelli, K. I. Pedersen, T. B. Sorensen, and P. Mogensen, "Generalized DFT-spread-OFDM as 5G waveform," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 99-105, Nov. 2016. doi: 10.1109/MCOM.2016.1600313CM.

[59] A. Sahin, R. Yang, E. Bala, M. C. Beluri, and R. L. Olesen, "Flexible DFT-S-OFDM: solutions and challenges," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 106-112, Nov. 2016. doi: 10.1109/MCOM.2016.1600330CM.

Manuscript received: 2016-11-30

Biographies

Zekeriyya Esat Ankaralı (zekeriyya@mail.usf.edu) received his B.Sc. degree in control engineering from Istanbul Technical University (ITU), Turkey in 2011 with honors degree and M.Sc. in electrical engineering from University of South Florida (USF), USA in December 2012. Since January 2013, he has been pursuing his Ph. D. as a member of the Wireless Communication and Signal Processing (WCSP) Group at USF. His current research interests are waveform design, multicarrier systems, physical layer security and in vivo communications.

Berker Peköz (pekoz@mail.usf.edu) received his B.Sc. degree in electrical and electronics engineering from Middle East Technical University (METU), Turkey in 2015 with high honors degree. Since August 2015, he has been pursuing his Ph.D. as a member of the Wireless Communication and Signal Processing (WCSP) Group at University of South Florida (USF), USA. His current research interests are mmWave communications, multidimensional modulations and waveform design.

Huseyin Arslan (arslan@usf.edu) received his B.S. degree from Middle East Technical University (METU), Turkey in 1992; M.S. and Ph.D. degreesfrom Southern Methodist University (SMU), USA in 1994 and 1998. From January 1998 to August 2002, he was with the research group of Ericsson Inc., USA, where he was involved with several project related to 2G and 3G wireless communication systems. Since August 2002, he has been with the Electrical Engineering Dept. of University of South Florida (USF), USA. Also, he has been the dean of the College of Engineering and Natural Sciences of Istanbul Medipol University, Turkey since 2014. In addition, he has worked as part time consultant for various companies and institutions including Anritsu Company (USA) and The Scientific and Technological Research Council of Turkey. His current research interests include physical layer security, mmWave communications, small cells, multi-carrier wireless technologies, co-existence issues on heterogeneous networks, aeronautical (high altitude platform) communications and in vivo channel modeling, and system design.