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Flexible Radio Access Beyond 5G: A Future Projection on Waveform, Numerology, and Frame Design Principles

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ABSTRACT To address the vast variety of user requirements, applications, and channel conditions, flexibility support is strongly highlighted for 5G radio access technologies (RATs). For this purpose, usage of multiple orthogonal frequency division multiplexing (OFDM) numerologies, i.e., different parameterization of OFDM-based subframes, within the same frame has been proposed in the third-generation partnership project discussions for 5G new radio. This concept will likely meet the current expectations in multiple service requirements to some extent. However, since the quantity of wireless devices, applications, and heterogeneity of user requirements will keep increasing toward the next decade, the sufficiency of the aforementioned flexibility consideration remains quite disputable for future services. Therefore, novel RATs facilitating much more flexibility are needed to address various technical challenges, e.g., power efficiency, massive connectivity, latency, spectral efficiency, robustness against channel dispersions, and so on. In this paper, we discuss the potential directions to achieve further flexibility in RATs beyond 5G, such as future releases of 5G and 6G. In this context, a framework for developing flexible waveform, numerology, and frame design strategies is proposed along with sample methods. We also discuss their potential role to handle various upper-level system issues, including the ones in orthogonal and nonorthogonal multiple accessing schemes and cellular networks. By doing so, we aim to contribute to the future vision of designing flexible RATs and to point out the possible research gaps in the related fields.

INDEX TERMS 5G, 6G, FBMC, multi-access communications, numerology, OFDM, radio access networks, waveform, wireless communications.

I. INTRODUCTION

Exponential growth in variety and quantity of mobile devices along with the mobile applications lead to an explosion in the need for higher data rates, reliability, power efficiency, low latency and vast number of diverse connectivity [1], [2]. Such needs are the main driving factors in 5G and many projects have been launched to deliver them on time, as done in European Union projects e.g., 5GNOW [3], METIS [4], MiWaveS [5] and FANTASTIC-5G [6]. Mainly, three services in 5G agenda can be given as; enhanced-mobile broadband (eMBB), ultra reliable and low latency communications (URLLC) and massive machine type communications (mMTC). The standardization has already started by Third Generation Partnership Project (3GPP) and the first products are expected to be available by 2020.

Although there is not an expectation of a major shift in base waveform selection for 5G new radio (NR),[1] the need for flexibility is strongly highlighted for embracing diverse applications, channel conditions and system scenarios [7]. For example, large subcarrier spacing is preferable for URLLC applications due to the smaller symbol time. It is also better for highly mobile users because of the robustness against Doppler spread. On the other hand, small subcarrier spacing is more convenient for supporting massive connectivity which is required for mMTC scenarios and for reducing the effect of delay spread. Considering numerous cases as these examples, academia and industry agreed on the need

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[1] Orthogonal frequency division multiplexing (OFDM) will most likely remain as the base technology for 5G.

of more flexible radio access technologies (RATs). Thus, usage of resource blocks with different parameters can be enabled and various user requirements can be met properly. For that purpose, co-existence of different numerologies, i.e., different parameterization of different subframes, have been intensively discussed in ongoing 5G standardization activities [8].

As a matter of fact, the number of users and the diversity in user requirements, e.g., demanded services, channel conditions, used applications, types of mobile devices etc., are going to keep increasing with the lapse of time. For example, in a forecast provided by [9], the number of smartphone users will be 264.3 million in the United States by 2021, while it was 189 million in 2015. As a result of a global projection of that increase, monthly mobile data traffic will reach up to 30.6 exabytes which is eightfold of the one in 2015 [10]. Such a growth in traffic will likely lead to some enhancements on current concepts such as operation in much higher frequencies beyond the currently discussed millimeter wave (mmWave) bands (<100 GHz), deployment of more antennas than the presented massive-MIMO systems. In this case, current problems faced in these concepts will definitely be more severe. On the other hand, researchers should get ready for brand new problems as well, with the development of the novel future concepts which are hard to predict for the time being. Considering these facts, potential future scenarios will lead to an increase in aforementioned radio access flexibility requirement for the standards beyond 5G. However, the majority of the current discussions on flexibility for the RATs in NR design are conducted in a limited range by only focusing on adopting OFDM-based waveform parameters. Reviewing the user requirements along with the trend from 2G to potential 5G technologies, we believe that the definition of radio access flexibility should gain a much broader meaning for meeting the future service needs optimally. Therefore, in this paper, we discussed some potential directions and provide our proposals on RATs that enable much more flexibility for standards beyond 5G. In order to avoid any confusion in terminology, let us define the fundamental terms of RATs in the context of our discussions and wireless communications literature.

> ***Waveform:*** Signal shape in the physical medium formed by a specific method. We consider waveform as the most basic component of RATs.
>
> ***Numerology:*** Waveform parameterization to form resource blocks based on user requirements and channel conditions. It could be applied to all the users uniformly, or specifically to user subgroups having similar requirements.
>
> ***Frame:*** The data unit encapsulating the resource blocks generated for the users in the system. It can be formed using single or multiple numerologies.

The core discussions of this paper are conducted on the flexibilization of these three elements representing the RATs. These elements and the challenges to be addressed in order to achieve the future expectations beyond 5G are visualized in Fig. 1. Our contributions in this direction can be given herein as follows:

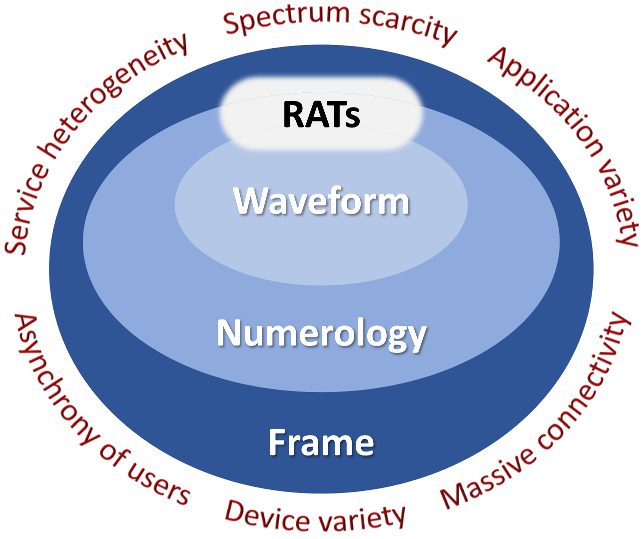

FIGURE 1. Future wireless challenges aimed to be addressed by flexible RATs components.

- Selected waveform technologies and their flexibility aspects considering the basic waveform expectations are analyzed.
- Promising concepts are proposed for more advanced parameterization schemes in numerology design.
- Novel frame design principles are proposed and a framework is provided for developing more flexible radio accessing schemes.
- Potential solutions for the issues of future heterogeneous cellular systems are discussed utilizing flexible RATs.
- Future research directions to develop more efficient multiple accessing schemes using flexible RATs are provided.

In the rest of the paper, we provide a historical overview on flexible signaling and radio accessing schemes from 2G to 5G in Section II. Then, discussions evaluating the selected waveform technologies are provided in Section III. In Section IV, potential improvements upon the numerology design principles are proposed in order to serve various users more properly with the existing waveform technologies. In Section V, we introduce new frame design concepts based on the proposed numerology principles and two different numerology containment strategies. The first strategy is based on forming the frame with numerologies set by *one-waveform and multiple-parameter*, while the second strategy expands that to a hybrid frame consisting of *multiple-waveform and multiple-parameter* numerologies. Then, the role that will potentially be played by the flexible RATs for handling the problems of future cellular systems is discussed in Section VI. Finally, how different multiple accessing schemes can be enhanced using flexible RATs is discussed in Section VII, and Section VIII concludes the paper.

II. A HISTORICAL OVERVIEW ON FLEXIBLE SIGNALING AND RADIO ACCESS SCHEMES

Flexible signaling was introduced to cellular communications as early as 2G standardization via link adaptation techniques, e.g., power control, adaptive modulation and coding (AMC) [11]–[14]. Such methods improved the user experience by satisfying user needs in various ways [15]. For example, with AMC, users with low signal-to-noise ratio (SNR) could still receive the data by maintaining the error performance with lower coding rates or low order (less sensitive) modulations, while users with higher SNR are able to experience higher data rates [16]. Also, via power control techniques, SNR of a user can be controlled and a balance between the error performance and power efficiency is provided.

Link adaptation techniques operate based on the observed SNR without considering the elements forming the noise[2] effect on the signal. If the increase in the error rate occurs due to the insufficient received power compared to the thermal noise floor, aforementioned link adaptation techniques are quite useful for sustaining the communication quality. However, degradation in SNR might also be caused by interference effects (self-interference, other user interference) and hardware impairments, and link adaptation techniques are usually ineffective in such cases [17]. At this point, waveform design emerges as another degree-of-freedom to cope against various signal distortions and interference types. By adapting the waveform parameters properly, wireless signals can easily gain more robustness against interference [18] and maintain the communication performance [19]. For example, if the time dispersiveness of the medium increases for any reason, extending the cyclic prefix (CP) rate as much as the increase in time dispersion avoids inter-symbol interference (ISI) for OFDM-based signals at the expense of some degradation in spectral efficiency. In addition, different waveform technologies exhibit different inherent advantages under specific scenarios and circumstances [20]. Therefore, flexibility in waveform selection and parameter adaptation based on varying medium and user conditions are very critical to optimize the communication performance for all the users.

The early indications of the paradigm shift from the constant waveform design is seen in 4G standardization for all the links. In Evolved Universal Mobile Telecommunications Service (UMTS) Terrestrial Radio Access (E-UTRA), usage of different waveforms was proposed for the first time to address the different requirements in the uplink (UL) and downlink (DL) [21]. As a matter of fact, DL prioritizes spectral efficiency to satisfy the data hungry users whereas power efficiency is more critical in the UL to minimize the power consumption of the size limited and battery operated mobile terminals. Therefore, OFDM is used for the DL while the single carrier-frequency division multiple accessing (SC-FDMA) is deployed for the UL [22]. Also, in Long Term Evolution (LTE)-Advanced (LTE-A), the first flexible parameter utilization is offered for OFDM based waveforms. Depending on the cell size, OFDM symbols are designed with either normal CP or extended CP at the base station in order to maintain interference-free communications [23]. These steps could be considered as the initial phase of the transition from the fixed waveform to the flexible waveform paradigm. However, provided flexibility still remains very limited since all the users in a cell are still forced to operate with a predefined waveform even if they have different requirements.

In order to address the diversified user requirements more conveniently, the trend in 5G standardization is to extend waveform flexibility to additional parameters such as subcarrier spacing [24]. For carrying that out, the concept of multiple numerology usage, i.e., assigning specific numerologies to the subgroups formed by users with similar requirements/channel conditions, is proposed and mostly accepted in 3GPP discussions [25], [26]. This concept constitutes a critical milestone in the development of flexible RATs, however, peaceful coexistence of different numerologies should be investigated carefully.

III. FLEXIBILITY IN WAVEFORM DESIGN

Many waveform schemes addressing various issues have been proposed in the literature so far and each of them provides different advantages on different use cases and medium conditions. In 3GPP standardization discussions, OFDM-based technologies have become prominent especially for broadband systems because of their tempting advantages experienced in the previous generation and backward compatibility with the existing technologies [27]. However, OFDM is not the optimum waveform for meeting all the user requirements and has serious shortcomings in some specific scenarios. Based on the applications, channel conditions and user requirements, alternative waveforms have obvious advantages and flexibilities not present in OFDM. For example, inherent rectangular pulse shaping of OFDM symbols forms the OFDM subcarriers with a sinc function. Therefore, a significant interference on the neighboring frequencies occurs due to the combination of many subcarrier sidelobes. Also, sinc shaped OFDM subcarriers are very sensitive to channel frequency dispersions and not preferable for highly mobile scenarios. On the other hand, filter bank multicarrier (FBMC) allows subcarrier based filtering with various pulse shaping functions, and forms the time-frequency characteristics of the signal flexibly. Therefore, aforementioned OFDM problems can easily be solved by FBMC with a frequency localized pulse shaping function such as root-raised cosine (RRC).

As a matter of fact, each waveform technology is formed by their own specific parameters. Since these parameters constitute the flexibility aspect of waveform design, their investigation is critically important for future RATs. However, our goal is to introduce a framework for designing flexible RATs beyond 5G, rather than a detailed investigation of existing technologies. Therefore, our arguments and concept

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[2] Noise represents all the distortion sources in the given SNR expression, here.

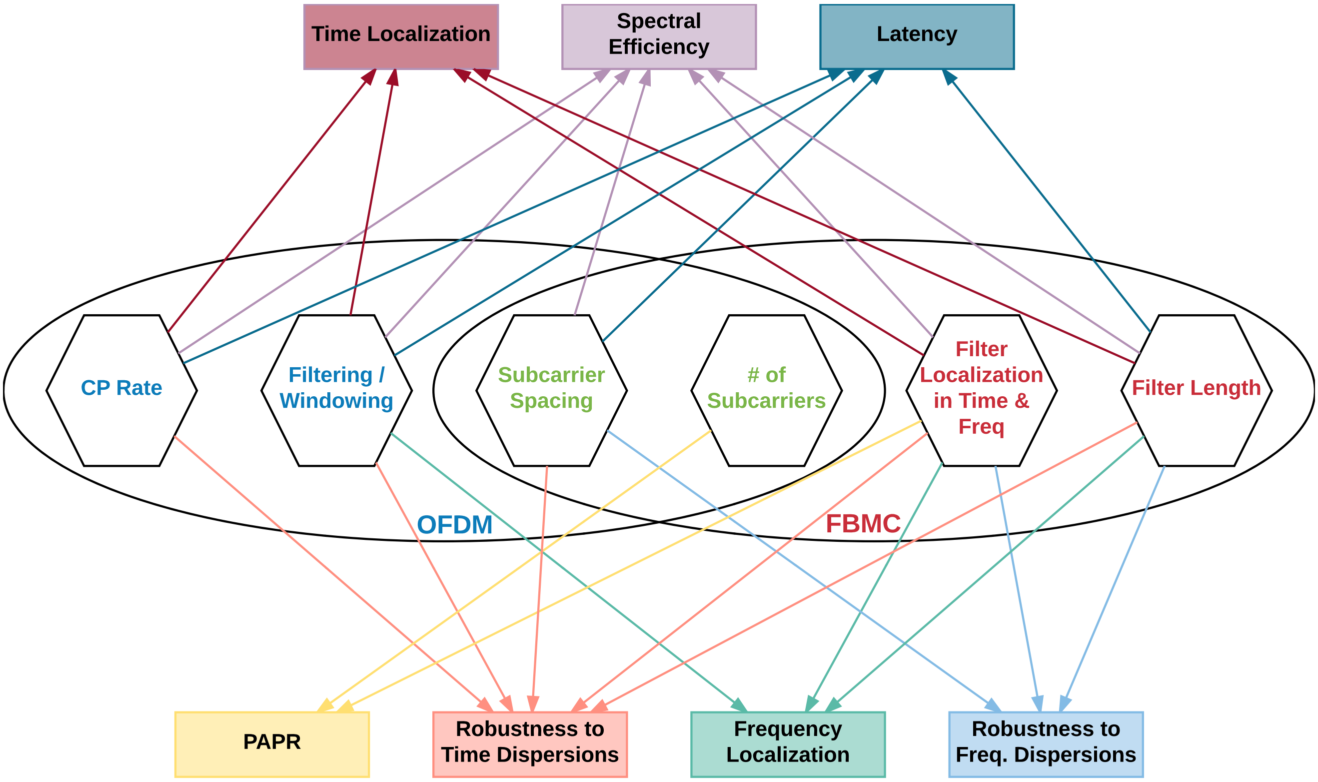

FIGURE 2. The various parameters of OFDM and FBMC waveforms and the physical metrics they primarily affect. Further indirect relations could be considered, however, only the primary relations are embodied for the sake of clarity.

proposals will be provided for two fundamental waveforms, OFDM and FBMC, for the sake of a clear presentation. However, proposed concepts can be generalized over other popular waveforms such as universal filtered multicarrier (UFMC) and generalized frequency division multiplexing (GFDM) as well.

Various waveform parameters representing the flexibility aspects of OFDM and FBMC are summarized and matched with the main waveform requirements in Fig. 2. Note, more parameters and further relations between these parameters and metrics could be established. However, our goal is to draft the general picture containing various metrics that could be primarily controlled by widely known given parameters. These parameters will also be re-visited for the later sections in which we discuss the potential concepts for developing a fully flexible radio accessing scheme including the proposals on numerology and frame design principles.

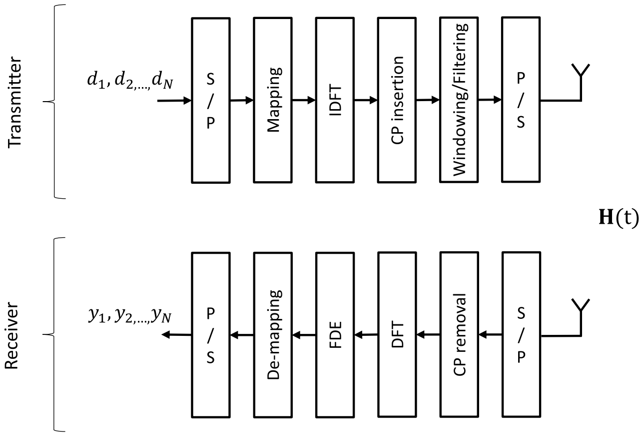

FIGURE 3. OFDM transceiver block diagram including windowing and filtering.

A. OFDM

OFDM is firstly proposed in the 1960s by Chang [28] and Saltzberg [29], and became very popular following the development of fast Fourier transformation (FFT) algorithm. A basic block diagram of its transceiver is given in Fig. 3. It has already been widely deployed in previous wireless digital communication standards such as LTE and Wi-Fi because of its tempting advantages, e.g., low-complexity implementation and the robustness against multipath channels with single-tap frequency domain equalization (FDE) [30]. However, plain OFDM signals have high peak-to-average power ratio (PAPR) as a result of parallel signal transmission, and therefore, suffer from the distortions due to the non-linear characteristics of the power amplifiers (PAs) [31]. In addition, sinc shaped subcarriers make OFDM vulnerable against Doppler spread and result in a high out-of-band (OOB) radiation which degrades the efficiency of overall spectrum utilization. Considering these advantages and shortcomings, the main parameters representing the flexibility aspect of OFDM can be given as follows.

- ***CP Rate***: One of the most critical and characteristic parameters of OFDM is CP which enables converting the linear convolution of the wireless channel and signal to a circular convolution, and facilitates the single-tap FDE. When CP length is determined as large as the delay spread, an ISI-free transmission is guaranteed. Therefore, CP rate directly provides robustness against the time dispersion effect of the wireless medium. Also, CP enables compensation of timing errors unless the error is smaller than the CP duration [32]. In addition to these advantages, CP could be exploited for many useful receiver operations such as signal parameter estimation [33], synchronization [34] and channel estimation [35] without pilot signals, i.e., blindly. However, increasing CP rate results in a degradation in spectral efficiency along with more latency and the introduced cyclic features might degrade the signal security [36].
- ***Windowing/Filtering***[3]: In order to suppress OOB leakage, transmitter windowing and filtering operations are well-accepted methods in the literature because of their low complex implementation and compatibility with the conventional receivers. Also, windowing at the receiver reduces the interference received from adjacent channels [37]. However, they require an extension in CP size for maintaining ISI-free transmission which decreases the spectral efficiency and increases the latency.
- ***Subcarrier Spacing***: Multicarrier systems inherently provide robustness to time dispersions by dividing the wide transmission band into smaller subcarriers whose bandwidth is less than the coherence bandwidth. However, that cause a serious extension in symbol time and in highly mobile/time-varying medium, OFDM signals may seriously suffer from Doppler spread if the channel response significantly changes within a symbol duration. Therefore, subcarrier spacing should also be large enough to keep the symbol time shorter than the effective channel coherence time [38]. This is also critical for users demanding low latency requiring services [39] and mmWave systems that experience high phase noise with increasing carrier frequency. Yet, reducing symbol time corresponds to a proportional increase in CP rate for a given CP length and therefore, degrades the spectral efficiency.
- ***Num. of Subcarriers***: Data transmission speed is directly related to the bandwidth and the only way of increasing it for a given subcarrier spacing is to increase the number of subcarriers. However, this corresponds to parallel transmission of more signals which leads to a proportional growth in PAPR problem [40].

Backward compatibility with the existing technologies along with the aforementioned advantages makes OFDM an appealing technology. Therefore, the primary waveform preference will be in favor of OFDM rather than going for a new waveform, as can be seen in the current standard discussions [41]–[43] conducted for 5G. However, alternative schemes, e.g., GFDM, UFMC and FBMC, offer critical advantages over OFDM in various scenarios and should still be considered for future standards.

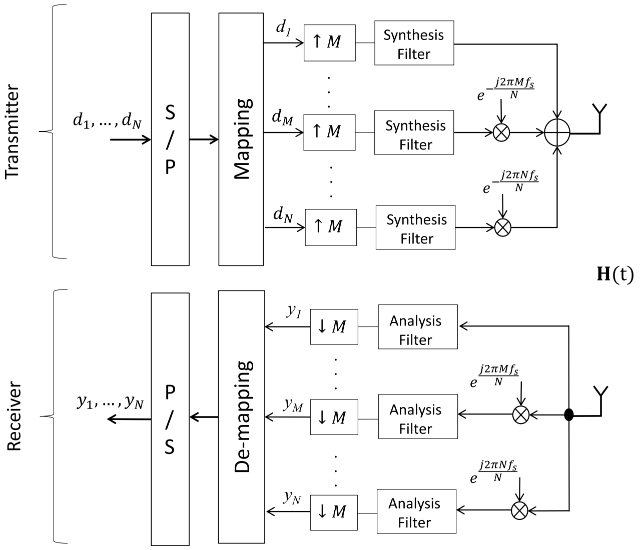

FIGURE 4. **FBMC transceiver block diagram.**

B. FBMC

FBMC is one of the most well known multicarrier modulation methods in wireless communications literature whose basic transceiver block diagram is given in Fig. 4. It is also discussed as a waveform candidate for 5G and beyond in [44]. Its main advantages stem from the shaping ability of each subcarrier individually and the availability of many pulse shaping filters in the literature as drafted in [31]. There are filters fully orthogonal in both domains while being very sensitive against impairments in one domain, e.g., rectangular, raised cosine, Mirabbasi-Martin etc. On the other hand, non-orthogonal pulse shaping functions such as Gaussian and Prolate introduce some interference between neighboring symbols but confines the pulse energy well in both domains. Freedom in selecting any of these filters facilitate a great flexibility in the utilization of spectral resources along with meeting various user requirements such as robustness against channel dispersions. For example, a rectangular filter is preferable for time dispersive channels while raised cosine filter is more robust against frequency dispersion. Many other pulse shaping filters are investigated in the literature to cope against channel dispersions and to provide a reliable system design based on different scenarios [31].

Besides the filter selection flexibility of FBMC, filter specific parameters could be used to enable more sensitive adjustments in filter characteristics and enhance the flexibility further. Additionally, unlike OFDM, there is no CP or guard time requirement in FBMC. Therefore, spectral

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[3] Windowing and filtering based OFDM signals are also considered as different waveforms in the literature, i.e., filtered-OFDM and WOLA-OFDM. However, we prefer to include them in OFDM parameters for providing a better understanding of OFDM flexibility.

efficiency is not degraded by such redundancies. Some of the important parameters providing flexibility in FBMC waveforms can be given as follows.

- ***Filter Length***: Especially for ideally infinite filters, this is an important parameter. Keeping the filter length shorter reduces the effect of one symbol on other successive symbols. Also, latency could be decreased by truncating filter tails for small size frames. However, truncation corrupts the ideal structure of these filters and cause orthogonality loss in the time domain and spectral growth in the frequency domain.
- ***Filter Localization in Time/Frequency***: For a given filter length, time and frequency domain localization of various filters could be adjusted in a trade off fashion by filter specific parameters, e.g., the roll-off factor (α) of RRC and standard deviation (σ) for Gaussian filters. This is a significant advantage for adapting the signal against varying channel effects, i.e., dispersion in time and frequency domains. For example, making filters more frequency localized increases the robustness of signal against Doppler spread. On the other hand, time localized filters are better for time dispersive channels and also prevent the filter tails from being added on top of consecutive symbols which lowers the PAPR.

"Subcarrier spacing" and *"number of subcarriers"* have similar effects as explained for OFDM. Therefore, they are not given for FBMC, separately.

Despite all the advantages offered by FBMC, implementation and equalization are not as simple as OFDM for many scenarios and this constitutes its primary drawback [45]. Also, usage of long filters introduces an excessive computational complexity for MIMO detection as the channel coherence bandwidth would fall below the subcarrier bandwidth [46], which would cause a problem in one of the most popular services in 5G. However, aforementioned advantages still keep its potential for many of the future applications and scenarios.

IV. FLEXIBILITY IN NUMEROLOGY DESIGN

Providing the aforementioned flexibility requirements by utilizing the parameters of a single waveform is not possible as each technology has its own advantages and drawbacks. If a novel waveform technology addressing all the user requirements and channel conditions could be developed and widely accepted by the academia and industry, a system design with a single waveform would be possible. However, the existing technologies can only provide a different trade-off for a given set of parameters. Therefore, the only option for a sufficiently flexible radio access is to enable the coexistence of multiple numerologies as proposed in the 5G standardization. However, currently proposed numerologies provide a limited flexibility due to the fix parameterization strategy. In this section, we discuss how to apply more advanced waveform parameterization methods to achieve further flexibility in numerology design.

Since OFDM is the dominant candidate as the base waveform of 5G technologies, current numerology discussions are mostly done on OFDM parameters, e.g., CP rate, subcarrier spacing etc. To the best of our knowledge, one of the first schemes proposing the usage of multiple numerologies is presented in [47] for OFDM blocks divided in the time domain. Based on the user needs, these blocks are generated with different CP sizes and subcarrier spacings, and successively aligned (i.e., consecutively transmitted) in the time domain. Since OFDM is a well-localized waveform in time domain, orthogonality between the consecutive blocks (subframes) is perfectly maintained as well. However, limiting the placement of numerologies only to time domain prevents a fully flexible utilization of time/frequency plane especially for the users requiring different numerologies at the same time. Therefore, aligning different numerologies in the frequency domain is also included in 3GPP discussions even though there will be a non-orthogonality issue between the subframes.

A similar numerology design can also be considered for FBMC schemes in terms of FBMC parameters. Prototype filters, filter specific parameters and subcarrier spacing values could be selected based on the user groups to provide a proper service. In order to show how such a parameterization affects the time-frequency characteristics of FBMC numerologies, an illustration of RRC filters with different roll-off factors (αs) and filter lengths (Ks) is provided in Fig. 5 via ambiguity functions (AFs). which is a two-dimensional correlation function in the time-frequency plane, whose analytical expression is given as

$$\Im(\tau, \nu) = \int_{-\infty}^{\infty} p_{tx}(t + \frac{\tau}{2}) p_{rx}^{*}(t - \frac{\tau}{2}) e^{-j2\pi\nu t} dt, \qquad (1)$$

where $p_{tx}(t)$ represents the transmitter filter and $p_{rx}^{*}(t)$ is the complex conjugate of receiver filter. By taking the projection of the receiver filter on the transmitter filter, AFs not only show the distribution of pulse energy in time and frequency domains but also visualize the required time/frequency offset values for keeping the filters orthogonal. In another aspect, AFs illustrates the filter robustness against inter-carrier interference (ICI)/ISI due to different effects, such as the dispersion of the wireless channel.

As seen in Fig. 5, α and K are very critical parameters for RRC shaped signals and should be selected carefully considering the user requirements and channel conditions. Although the examples are given over RRC pulses, aforementioned statements are also valid for different pulse shaping functions. Considering their inherent advantages, alternative filters along with their design parameters should also be considered in FBMC numerology design for meeting the user requirements more properly [48].

FBMC numerologies would be very convenient for different users sharing the frequency resources at the same time. Since FBMC blocks can be designed as well localized in frequency domain, orthogonality between the different numerologies will not be lost when they align in frequency

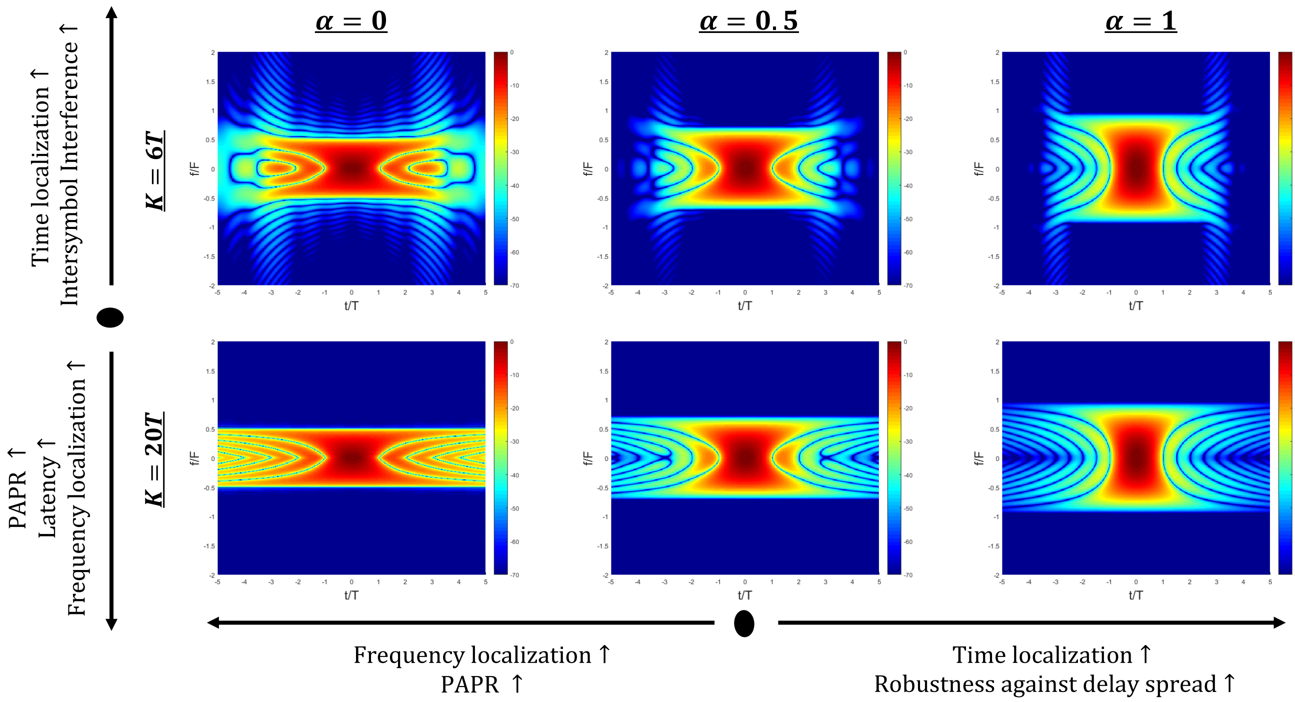


FIGURE 5. Ambiguity functions ($10log_{10}(|\Im(\tau, \nu)|^2)$) generic root-raised cosine filters generated with various design parameters, used for adapting signal characteristics in time and frequency domains.

domain unlike the case with OFDM numerologies. From that perspective, OFDM and FBMC numerologies are perfectly complementing each other.

Aforementioned numerology design, based on user specific determination of the parameters such as CP and subcarrier spacing in OFDM and prototype filters in FBMC, definitely provides important flexibility features for an efficient sharing of the spectral resources. However, in order to enable further flexibility and increase the overall efficiency, different parameters and more advanced parameterization methods should be jointly considered. For example, in OFDM signals, there are other critically important parameters such as windowing which can be utilized to develop much-advanced OFDM numerologies. A good example of this claim is presented in [49] where the size of windowing functions are gradually applied within a subframe. By keeping the total guard interval the same, edge subcarriers are designed with more windowing while the inner subcarriers have lower windowing. Since the OOB leakage mostly occurs due to the edge carriers, interference emission of the OFDM block is well suppressed while the inner subcarriers conserve their robustness against larger delay spreads. By performing an OFDM numerology design with this concept along with a proper scheduling, a subgroup of the users could be served in the same numerology much more properly. The users experiencing higher delay spreads could be assigned to the inner subcarriers while the ones with low delay spread can utilize the edge subcarriers [50]. By doing so, no need remains for a separate numerology design for the users with different CP requirements, which is a great advantage compared to the classical numerology design strategies. An illustration of this advanced parameterization is exampled in Fig. 6 which is referred to as edge-windowed OFDM numerology. As seen in this example, usage of such parameters and parameterization methods can enable much flexible numerology designs. Also, there is an obvious research gap in this direction considering other various windowing and filtering techniques as presented in [51].

A similar parameterization strategy is proposed in [52] for filtered multitone (FMT) mode of FBMC schemes. Rather than using a prototype filter for all the users, user-specific filters are dynamically utilized to control the effect of time and frequency dispersions, i.e., ISI and ICI. RRC filters are deployed for this study and filter adaptation is done with α. This strategy is presented for a specific scenario, however, it could be generalized for forming more flexible numerologies. For example, if the interference between successive blocks in time is the main issue, edge symbols in time can be shaped with sharper filters in time domain (designed with larger αs) as illustrated in Fig. 6 which is referred to as edge-filtered FBMC numerology. For the same purpose, shorter filter lengths can also be applied to the edges. One may note that such methods might introduce some ICI for the edge symbols due to the expansion in frequency caused by either filter truncation or larger α usage. However, by assigning those symbols to the users that are more computationally capable and be able to perform interference cancellation, error performance can be maintained and energy leakage from the FBMC block can easily be controlled in time domain.

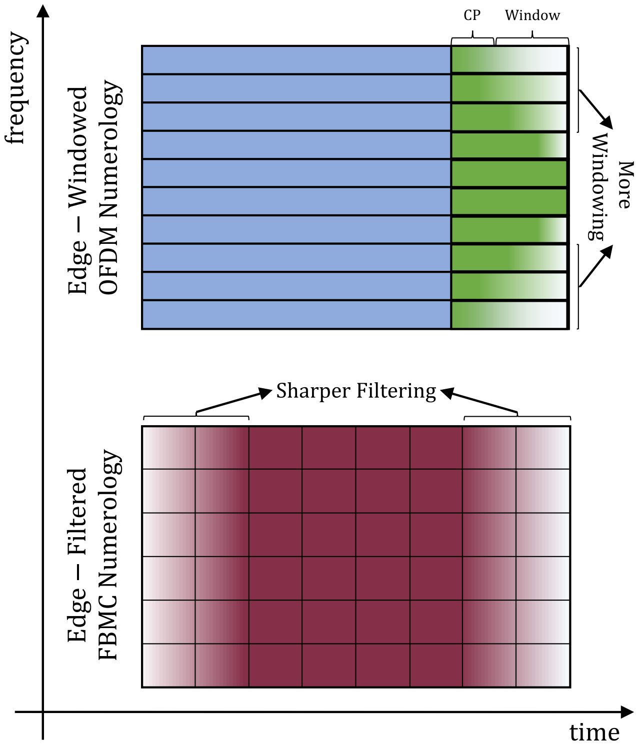
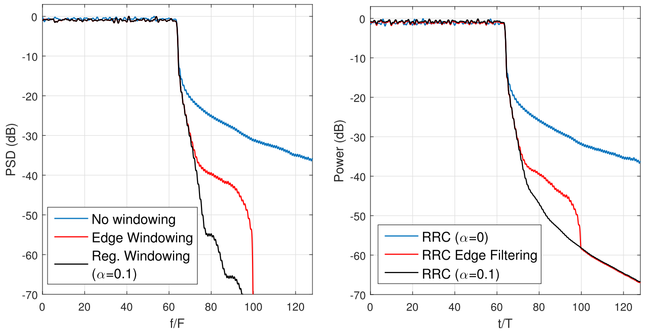


FIGURE 6. Two samples of flexible numerology design: Edge-windowed OFDM and edge-filtered FBMC numerologies.



(a) (b)

FIGURE 7. Power leakage of OFDM subcarriers (sidelobes) and FBMC filters (tails) for edge filtering/windowing techniques and conventional approaches. (a) OFDM. (b) FBMC.

In order to understand the effect of such techniques and compare with the classical approaches, power emission of OFDM subcarriers in frequency domain and FBMC filter tails in time domain are given in Fig. 7. For OFDM, 64 edge subcarriers on the right side are windowed with a raised cosine function where $\alpha = 0.1$ and no windowing is applied for the 64 subcarriers on the left side (having negative indices). Then it is compared with no windowing and regular windowing approaches. Similarly, 64 FBMC symbols on the right edge are shaped with an RRC filter whose α is 0.1 while the symbols on the left side are shaped with an RRC having $\alpha = 0$. Then it is compared with regular prototype filtering for $\alpha = 0$ and $\alpha = 0.1$. As obviously seen, edge operations are significantly suppressing the sidelobe/tail energies on a target region while providing more flexible numerology structures.

It should be noted that these examples are only given to express how such concepts can enable a flexible numerology design for a given waveform and to fix specific problems such as the interference emitted by numerologies. Considering different problems, user needs, system requirements and waveform parameters many research opportunities can be created in flexible numerology design context.

V. FLEXIBILITY IN FRAME DESIGN

In order to provide a complete picture of our future vision, in this section, we raise the question of how to form flexible frames in the light of our earlier discussions and proposals. We firstly discuss how to improve the existing frame design paradigm where multiple numerologies based on a single waveform coexist in one frame. Secondly, in order to provide further flexibility and spectral efficiency for future radio access schemes, we propose and investigate the concept of hybrid frames including multiple numerologies based on multiple waveform technologies.

A. SINGLE WAVEFORM NUMEROLOGY BASED FRAME DESIGN

In single waveform numerology based frame design procedure, frames are formed with multiple numerologies which differ in parameterization while the base waveform technology is the same. The 5G frame design discussions can be considered in this category since the numerology discussions are mostly conducted on the OFDM waveforms and parameters.

The main issue discussed for multiple numerology based frame design is inter-numerology interference (INI). OFDM based numerologies are fully orthogonal in time domain, however, mismatch in some parameters such as different subcarrier spacings leads to INI in frequency domain. Therefore, coexistence of OFDM numerologies is addressed via OOB leakage suppression of each numerology which is mostly done by applying classical windowing and filtering techniques. Thus, the required guard bands between numerologies could be significantly reduced. However, classical windowing and filtering techniques either require an extension in CP size or introduce ISI as mentioned earlier. Therefore, spectral degradation or signal distortion still remains as an issue to solve. In order to overcome this problem, we propose to deploy aforementioned flexible numerology designs such as the ones generated with edge-windowing. In Fig. 8, such a frame structure is exemplified in Frame-1 and an edge-windowed numerology is illustrated (O_{14}). When this structure is combined with the proper user scheduling, spectral efficiency and the flexibility can jointly be provided for satisfying a wide variety of user requirements [50]. Note that, edge windowing represents a concept here and can be generalized to different techniques with different parameters

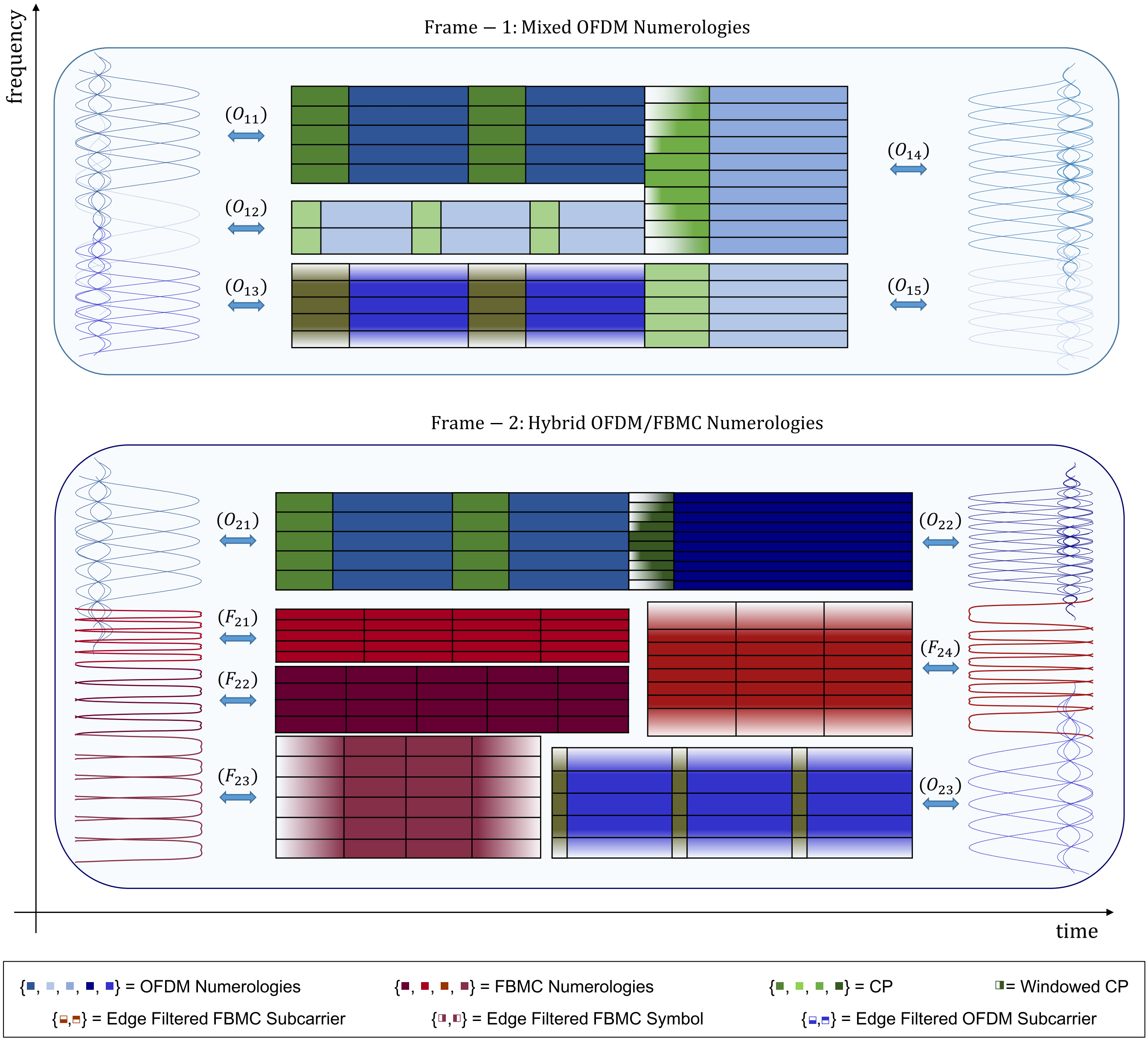


FIGURE 8. Examples of proposed single waveform numerology based frame design (Frame-1) and multiple waveform numerology based frame design (Frame-2) consisting of mixed OFDM and FBMC numerologies. Frame-1 can be considered as an improvement over currently discussed frame designs for achieving more flexibility. On the other hand, Frame-2 extends that flexibility to the usage of multiple waveforms based on the user needs, enabling the system to select the best waveform for each user.

such as sharper filtering (in frequency domain) of edge carriers as shown in Fig. 8 (O_{13}).

FBMC numerology based frames should also be evaluated in this context for future standards. Due to the good frequency localization and subcarrier based filtering ability of FBMC numerologies, inherent and complementary advantages can be provided for many scenarios over OFDM based frames. For example, multiplexing different numerologies in frequency domain might be highly preferred for designing a frame with the purpose of serving the users who need multiple services simultaneously. Furthermore, FBMC can easily handle the high mobility scenarios that are problematic for OFDM. All in all, FBMC based frames could close the gaps of OFDM-only based frame deployments. In case of a time domain multiplexing scenario, which is the dual problem of FBMC analogous to the frequency domain multiplexing issue of OFDM numerologies, edge filtering type of concepts can lower the required guard times and facilitate a spectrally efficient frame design.

B. HYBRID WAVEFORM NUMEROLOGY BASED FRAME DESIGN

The agreement on usage of multiple numerologies in the same frame represents a critical milestone and we provided our proposals to enhance this structure via using more advanced numerologies. However, defining multiple numerologies in terms of the same base waveform technology is still a limitation for the flexibility. Therefore, we propose a novel concept of hybrid frame design via the inclusion of multiple waveform based numerologies as illustrated in Fig. 8 (Frame-2).

As mentioned in the previous subsection, the main concern in coexistence of multiple numerologies is the INI, which might occur even if they are generated with the same waveform technology. For example, in Fig. 9a, AF of two OFDM subcarriers with different bandwidths (subcarrier spacing) is given where $\Delta F_1 = F/2$, $\Delta F_2 = F$. As obviously seen, they are only orthogonal when the narrower subcarrier is aligned with the null of broader subcarrier. That means, half of the subcarriers are interfered for the numerology with smaller subcarrier spacing while all the subcarriers are interfered on the side of numerology with larger spacing. At this point, we raise our question: *Does this issue get worse when different waveforms are used in a hybrid fashion?*

Let us consider two user groups where the group-1 suffers from high delay spread while the group-2 is highly mobile. In the context of 5G discussions, both numerologies would be OFDM based and subcarrier spacing for the group-2 would be determined as larger to increase robustness against Doppler spread. On the other side, smaller subcarrier spacing is more preferable for the group-1 in order to keep CP redundancy lower and to make subcarriers more robust against frequency selectivity. At this point, let us extend this structure to a hybrid frame and allow the group-2 to use an FBMC based numerology whose subcarriers are shaped with RRC filters. From the group specific perspective, FBMC numerology is definitely a better option for the group-2's scenario as the subcarriers could be well-localized and robust against Doppler spread. The critical question here is how an OFDM numerology and FBMC numerology can coexist. Intuitively, an FBMC numerology causes lower interference to an OFDM based numerology on a neighboring frequency compared to another OFDM based numerology with different subcarrier spacing. In Fig. 9b, this is illustrated via the AF of one OFDM ($\Delta F = F/2$) and one RRC shaped FBMC subcarriers ($\Delta F = F/2, \alpha = 0$). Obviously, periodic nulls exist on time and frequency axes for this example which means coexistence of OFDM and FBMC pulses does not create more severe problems compared to the coexistence of two differently parameterized OFDM subframes. One may point out the interference pattern in time axis of Fig. 9b, however, proper adjustments on filter parameters would provide a solution as shown in Fig. 9c where the RRC filter is generated for $\alpha = 1$. For instance, in Fig. 8, the guard time requirement between (F_{23}) and (O_{23}) can be decreased via using sharp filters (in time domain) for edge symbols of (F_{23}). Additionally, adjusting OFDM and FBMC numerologies jointly with aforementioned windowing/filtering methods could also enable a more peaceful coexistence. For example, required guard band between the OFDM numerology, (O_{22}), and FBMC numerology, (F_{24}), can be reduced via jointly applying edge windowing and edge filtering techniques.

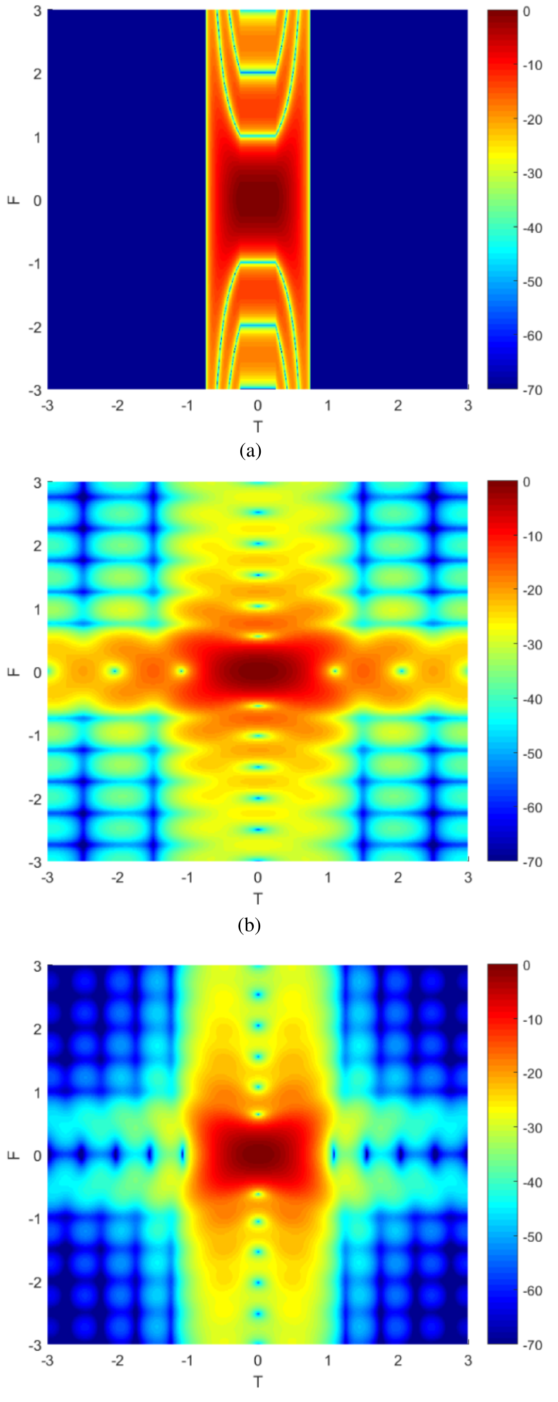


FIGURE 9. **AF illustrations of various waveform subcarriers. (a) AF of two OFDM subcarriers ($\Delta F_1 = F/2$, $\Delta F_2 = F$). (b) AF of an OFDM subcarrier ($\Delta F = F/2$) and an FBMC subcarrier (RRC, $\alpha = 0$). (c) AF of an OFDM subcarrier ($\Delta F = F/2$) and an FBMC subcarrier (RRC, $\alpha = 1$).**

Considering such examples from a wider perspective including alternative waveform and numerology design strategies, we strongly believe that extending the flexibility in frame design with hybrid waveform numerologies would not only provide a more satisfactory experience to the users with a wide variety of requirements, but also can lead to a more efficient usage of spectral resources.

VI. ENHANCING CELLULAR SYSTEMS WITH RAT FLEXIBILITY

The aim of the methods discussed in the previous sections was to address the increasing variety of user requirements by utilizing the flexible aspects of the RAT. However, RAT is not the only flexible component of the communication systems. For instance, deploying cells with several sizes by using base stations (BSs) with different transmit powers could be considered as a flexibility at the system level. Heterogeneous networks (HetNets) utilize this flexibility and aim to increase the system capacity along with addressing various mobile station (MS) densities and regions with higher data demands [53]. In this section, we question whether the aspects we have previously discussed are relevant to the different challenges experienced in HetNets and how these problems can be handled by utilizing different aspects of RAT flexibility.

In HetNets, there are several advantages and challenges of associating with smaller and larger cells. The mobile network operators (MNOs) desire to offload users to smaller cells for reducing the traffic congestion at the macro BS and increase overall system capacity [54]. Most users desire to connect to smaller cells as well since there are less number of users sharing the resources. Also, smaller link distances decrease the power consumption drastically [55]. However, users connected to smaller cells experience elevated inter-cell interference due to increasing frequency reuse and decreasing re-use distances [56].

Since local small cell networks are not available everywhere, users may have to associate with larger cells regardless of their applications. Furthermore, there are exceptional user groups that require association with larger cells, such as high mobility users. As associating with smaller cells would cause an infeasible rate of hand-offs, high mobility users prefer association with larger cells [57]. Nevertheless, the variation of the delay spread experienced by a cell increases proportionally to cell size [58]. Combining this variation with the coexistence of low and high mobility users, it can be seen that the variation in the Doppler spread is also proportional to the cell size [59].

Based on the given observations, we conclude that MSs associated with larger cells experience a wider variety of channel conditions and require support of a comprehensive range of applications. The methods described in the previous sections effectively address these problems and lay guidelines to support such challenging medley of requirements.

Quite the reverse, coexistence issues become irrelevant for MSs associated with smaller cells as they experience similar channels and request support for less variety of applications. The inter-cell interference problem, on the other hand, gains importance as cell sizes get smaller. Until now, most researchers who attempted to reduce the interference on small cells either from larger cells [60] or from other small cells [61] have based their work on coordination in the network layer. On this basis, one may erroneously conclude that the flexibility aspects of the RAT components can only increase the performance within larger cells and remain useless for this problem. However, the flexibility aspects of RATs are not limited to the examples discussed above.

Flexible RATs can be developed to address this problem, such as the concept of partially overlapping tones (POT) in [62]. It is a flexible waveform design framework that allows networks to interchange between other user interference and self-interference flexibly by creating an intentional frequency offset and adjusting the pulse shaping filter accordingly. Let us clarify the process with a brief example by considering small cells that use FBMC waveform and utilize Gaussian filters in their numerologies. In any case, BSs first determine unique frequency offset values using the sensed spectrum with the intention to align the center of their pulses to the nulls of other BSs' pulses. In case of low inter-cell interference power, BSs utilize wideband pulse shapes so that the desired high power signals overlap little and the interfering signals are allowed to overlap more with the desired signals as they have low power, as demonstrated in Fig. 10 (a). However, as inter-cell interference power increases, because self-interference is easier to mitigate than other-user-interference using equalizers, the desired signals are allowed to overlap in time by utilizing narrow band pulse shapes as doing so decreases the interference power received from other users, as demonstrated in Fig. 10 (b). In addition to provide such a smooth solution to inter-cell interference, this concept is more practical than the network layer solutions, as it can be used even in uncoordinated networks frequently encountered in dense and unplanned deployments.

In conclusion, we have demonstrated that the inter-cell interference can be overcome using the flexibility of the RATs. This proves that challenges faced in other domains can also be dealt with adaptations in the RAT. Furthermore, the solutions presented in this paper provide an overview of the literature; however, flexibility aspect of the RAT is open to further investigation.

VII. ENHANCING MULTIPLE ACCESSING SCHEMES WITH RAT FLEXIBILITY

In Section V, we have shown that several numerologies using different signaling schemes can be freely utilized in the same frame as long as the guard time and band requirements are met. In this section, we investigate how to use this flexibility in order to improve current multiple accessing (MA) schemes and address the different user requirements conveniently. We first briefly go over the advantages and disadvantages of various MA schemes for the future radio access and show how they affect the system performance under different cellular scenarios and user requirements. It will be clear that none of the available MA candidates can meet all the expectations for the use cases pointed out, therefore, similar to proposed

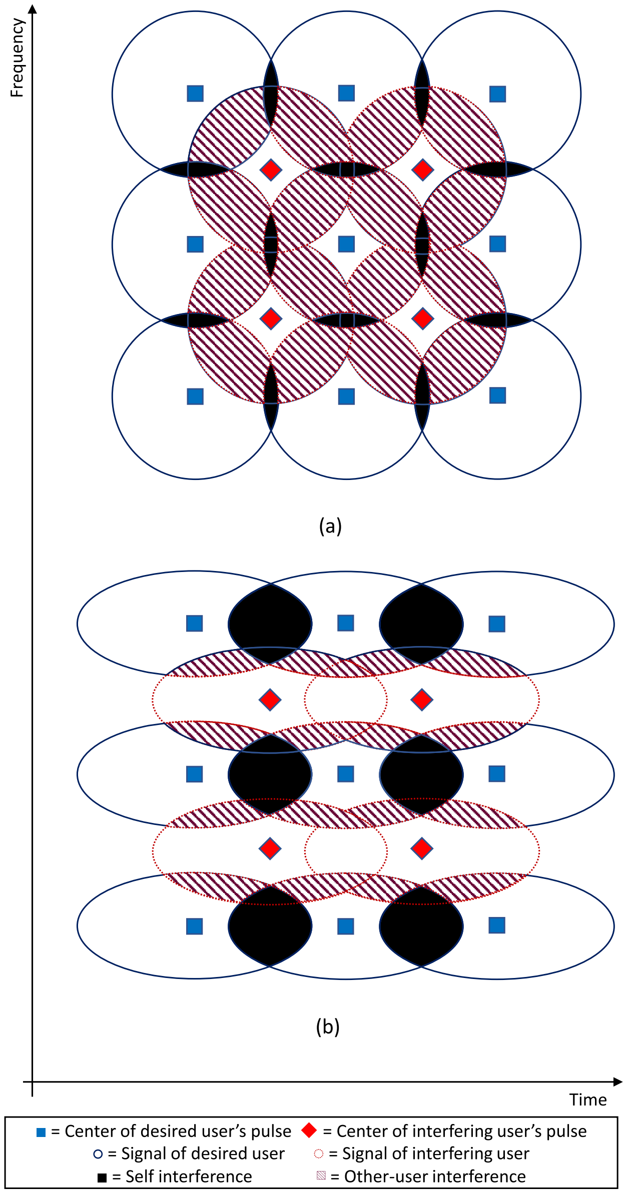


FIGURE 10. Figure showing how self-interference and other-user-interference from adjacent cells can be interchanged using POT. (a) More other user interference. (b) More self interference.

numerologies and waveforms, several MA schemes should coexist in the future radio-access network (RAN) to achieve further efficiency and reliability. We aim to show how these schemes can be further improved by extending the flexibility aspects of the RATs as explained in the rest of this study.

A. Orthogonal MA (OMA)

In OMA schemes, each user receives their own symbols in a resource block orthogonal to the other users', in either time, frequency or code domains [63]. OMA schemes must always be part of the RAN as they;

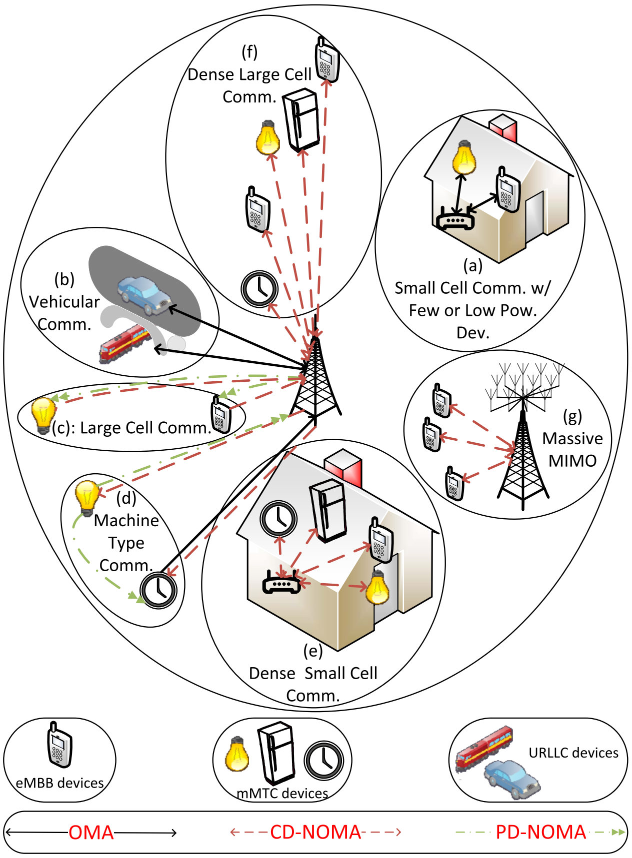


FIGURE 11. Comprehensive visualization of several MA and cellular scenarios.

- work best to provide high data rates to a relatively low number of users when overloading is not necessary, as can be exampled in a scenario where few eMBB MSs connected to smaller cells [54] (Fig. 11 (a)),
- are required by very low power mMTC devices due to their low computational complexity (Fig. 11 (a)),
- are required by applications that rely on time critical information such as URLLC services due to their low computational delay [64] (Fig. 11 (b)).

However, for massive number of mMTC devices that sporadically access the network for small packets, OMA schemes;

- limit the maximum number of connections [65],
- cannot achieve the sum rate capacity in the downlink if knowledge of the channel is unavailable at the BS [66],
- require dynamic scheduling (request and grant) especially in the UL which increases the latency and overhead significantly for small packets [67].

Non-OMA (NOMA) schemes outperform OMA schemes for the aforementioned use cases by assigning multiple users on the same resource element. If compressive (sensing) random access is used, grant-free UL is possible which significantly decreases the scheduling overhead for massive number of connections [68].

The techniques aforementioned in this study are already addressing how OMA schemes can be flexibly utilized. Let us review the strengths and weaknesses of major NOMA schemes and explore how they can be improved using RAT flexibilities.

B. Power domain NOMA (PD-NOMA)

Introduction of multiuser superposition transmission (MUST) to improve the system capacity [69] in LTE-A Pro was a milestone since commercial cellular systems implemented a NOMA scheme for the first time. PD-NOMA schemes exploit the power variation between cell center and cell edge users, and consist of superposed signals of these users inversely proportional to their received powers. The receiver at the cell center, referred to as near receiver in this context, experiences a high SNR. Therefore, it can extract their own low power signal by detecting the far users high power signal first and subtracting it from the received signal. When the signals reach the cell edge user, referred to as the far receiver, the low power signal of the near receiver fades heavily, therefore the far receiver proceeds detection of their signal without further processing [70]. Two main reasons got PD-NOMA adoption ahead of Code domain NOMA (CD-NOMA). Firstly, the successive interference cancellation (SIC) detector is only required at the near receiver, reducing the computational complexity. Secondly, because the far receiver is able to use classical receiver algorithms, the scheme is backward compatible to some extent as the process itself is almost invisible to the far user.

Unfortunately, because this scheme exploits solely the variation of channel conditions of different users, it is considered to be useful only for the DL of larger cells [71], as shown in Fig. 11 (c).

A future direction of research for PD-NOMA would be an attempt to couple UL transmissions with sidelink (SL)[4] transmissions to close proximity fellow receivers, as demonstrated in Fig. 11 (d). An example to how such a scheme would be useful is the combination of vehicle-to-vehicle (V2V) signaling with the vehicle-to-infrastructure (V2X) signaling.

Furthermore, the current schemes use the same numerology for both the near and the far receivers. Forcing the same numerology to be used by receivers experiencing different delay spreads reduces the efficiency as we have concluded in Section III and Section VI. The theoretical proof in [72] suggests that PD-NOMA concept could be made flexible in terms of waveform and numerology with different numerologies used for the near and far receiver. The solutions presented in [72] can be generalized to partial overlapping of different waveforms. Further theoretical investigation of this approach along with case studies for different waveforms is needed.

C. CD-NOMA

CD-NOMA schemes achieve high overloading in any link type regardless of the cell size as shown in Fig. 11 (e) and user density as demonstrated in Fig. 11 (f) by using codebooks with different overloading factors [73]. The cost of using CD-NOMA schemes is the advanced transmitter design, but more importantly, the complexity of the message passing algorithm (MPA) decoder at the receiver [74]. However, receiver complexity is not an issue in the UL, making this scheme attractive for UL connections, as shown in Fig. 11 (c) [75]. If the channel state information (CSI) is unavailable at the transmitter, CD-NOMA schemes benefit from spreading gain which increases the reliability under bad channel conditions, providing a viable solution to the pilot contamination problem experienced by massive multiple-input-multiple-output (MIMO) networks, as shown in Fig. 11 (g). Also they can further benefit from shaping gain if bandwidth can be sacrificed [76]. Well studied CD-NOMA schemes are thoroughly worked;

- for code division MA (CDMA) ([77] and references therein),
- by replacing the chips with subcarriers, using orthogonal frequency division MA (FDMA) (OFDMA) [78],
- by utilizing the sparse CDMA codes at the mapping and spreading to combine these codebooks with OFDMA, [79].

It is easy to predict that the same concept can be applied to the many flexibility aspects of mmWave frequencies, such as beam switching and polarization, which can be utilized in the implementation of the same concepts. Numerous other future research directions may be proposed for CD-NOMA, however to make this concept feasible for use in real life implementations, the decoding complexity under doubly dispersive channels need to be reduced for various channel conditions, which can be made possible through careful real-time adaptation of the more flexible RATs. For the development of this direction, one can observe that the further degrees of freedom could be obtained for other, more parameterized waveforms. For example, the filter type and parameter selection flexibility of the FBMC numerologies can be utilized to shape the future of CD-NOMA [80], and can be used as a distinguishing feature reducing the interference between users in the physical layer under doubly dispersive channels.

VIII. CONCLUSION

In this paper, considering the future growth in the quantity of wireless devices, applications and heterogeneity of user requirements, we presented a framework for developing flexible RATs aimed at standards beyond 5G. This framework is supported via proposing novel concepts for forming advanced and flexible RAT elements. Pointing out the inefficiency of the fixed waveform parameterization of 5G numerologies, advanced numerology design principles are explained over flexible parameterization methods for a more efficient exploitation of existing waveform technologies. Then, in order to achieve further flexibility, we proposed novel frame design strategies based on the advanced numerologies. Thus, a comprehensive picture of our vision on future flexible RATs is provided to facilitate supporting a wide variety of services and meeting highly diversified user requirements. In addition, we show the benefits of flexible RATs for handling the chal-

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[4] SL refers to device-to-device (D2D) links in the 3GPP terminology.

lenges in HetNets and various multiple accessing schemes via selected case studies. By doing so, we exemplify how flexible RATs can be used to address system level challenges. Then, to complete the picture of flexible radio access, we briefly summarized why several MA schemes are required to address the user and system level requirements in future communication systems using generic scenarios. We finally laid down concise directions of future research demonstrating how flexible RATs can be utilized in increasing the efficiency of NOMA schemes.

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