Flexible Multi-Numerology Systems for 5G New Radio

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Abstract—The physical layer of 5G cellular communications systems is designed to achieve better flexibility in an effort to support diverse services and user requirements. OFDM waveform parameters are enriched with flexible multi-numerology structures. This paper describes the differences between Long Term Evolution (LTE) systems and new radio (NR) from the flexibility perspective. Research opportunities for multi-numerology systems are presented in a structured manner. Finally, inter-numerology interference (INI) results as a function of guard allocation and multi-numerology parameters are obtained through simulation.

Index Terms—3GPP, 5G, adaptive scheduling, multi-numerology, new radio, OFDM, waveform.

I. INTRODUCTION

Long Term Evolution (LTE) waveform has a fixed structure that is optimized to serve high data rate applications. There is only limited support for other applications due to the inflexibility of the waveform. An example for the limited flexibility is the extended cyclic prefix (CP) configuration utilized by macrocell base stations (BSs) at all times to keep the system operating at larger delay spreads at the cost of reduced spectral efficiency [1]. This adaptation is rather limited as the configuration is static; even when not needed by any user equipment (UE), the system is configured to operate with these parameters and does not have the flexibility to improve the efficiency by utilizing normal CP. Other than delay spread, any degradation in signal to interference plus noise ratio (SINR), regardless of the cause, is addressed solely using adaptive modulation and coding (AMC) by reducing the throughput until a fixed reliability threshold is achieved [2]. For instance, if SINR degrades due to inter-carrier interference (ICI) in high mobilities, this issue can only be addressed using AMC in LTE, reducing throughput and under-utilizing the bandwidth (BW). As can be seen from the above examples, LTE has limited flexibility and cannot support the rich application and user requirements of 5G services [3].

5G is designed to provide a wide variety of services by rendering waveform parameters flexibly [4]. The new design paradigms make an enhanced-mobile broadband (eMBB) experience possible everywhere, including highly mobile UE connected to macrocells. The flexibilities introduced to the waveform enable reduced latencies and improved reliability, empowering ultra reliable and low latency communications (uRLLC) rather than high data rate applications. In addition, massive machine type communications (mMTC) is enabled for suitable scenarios with new radio (NR).

This flexibility was provided by coexisting of numerologies, where each numerology consists of a set of parameters defining the frame and lattice structure of the waveform. In contrast to the single-numerology utilization in LTE, NR allows simultaneous multi-numerology utilization [5]. One of the first studies that incorporated multi-numerology or mixed-numerology systems and designed a framework that provides numerous services simultaneously in a unified frame was [6]. Multi-numerology structures that were included in the Third Generation Partnership Project (3GPP) NR standardization were also studied in literature [7]–[11].

In this paper, three main contributions have been made as listed below:

1) LTE and NR were compared from the flexibility perspective regard to 3GPP 38-series documents.
2) Research opportunities for multi-numerology systems are presented in a structured manner.
3) Through simulation, inter-numerology interference (INI) results as a function of guard allocation and multi-numerology parameters are obtained.

The rest of the paper is organized as follows: Section II presents the comparison between LTE and NR systems from the flexibility perspective. New concepts introduced in NR are also described in this section regarding to 3GPP 38-series documents. Research opportunities for potential improvements of multi-numerology systems are explained in Section III. Section IV shows simulation results for multi-numerology structures. Finally, the conclusion is given in Section V.

II. FLEXIBILITY OF NR COMPARED TO LTE

New concepts are introduced and building blocks are defined to provide more flexible radio access technologies (RATs) in [12] and [13]. In this section, concepts that were introduced in NR are defined and their differences with LTE are distinguished. Release 15 was taken as the reference for both NR and LTE.

In 3GPP Release 15, standalone (SA) operation according to [14], [15] and non-SA (NSA) operation coexisting with
other technologies according to [16] are defined. NSA operation was finalized in Release 15, but some issues regarding SA operation, along with details necessary to provide mMTC, was left for further study to be finalized in Release 16.

Waveform defines how the resources are placed in the time-frequency lattice and the structure (pulse shapes and filters) that maps information symbols to these resources [6]. In the downlink (DL), NR uses CP-orthogonal frequency division multiplexing (OFDM) with multi numerologies (a mother waveform plus its derivatives). The mother waveform is the same in LTE but there is only one numerology. In the uplink (UL), there is an option to use either of CP-OFDM and discrete Fourier transform (DFT)-spread-OFDM (DFT-s-OFDM) with multi numerologies for NR [17]. However, the only option in LTE is DFT-s-OFDM with a single numerology.

The time-frequency lattice is the grid of discrete resources in the continuous time-frequency plane, where each “atom” on the grid shows where the continuous plane has been sampled, thus defining where/when information can be transmitted [6]. LTE used a fixed lattice in which the frequency (and corresponding time) spacing between each point was always the same throughout the whole transmission band [4]. However, NR defines flexible time-frequency lattice enabling multi-numerology structure. For the case of OFDM, numerology set consists of number of subcarriers, subcarrier spacing ($\Delta f$), slot duration and CP duration ($T_{CP}$) [3]. The $\Delta f$, $T_{CP}$, slot duration, and maximum BW allocation options for NR numerologies according to [5] and [18] are presented in Table I. These numerologies can be used simultaneously in a cell. On the contrary, LTE is a single-numerology system thus all these parameters are fixed at all times for a BS.

A BW Part (BWP) is a new term that defines a fixed band over which the communication taking place uses the same numerology throughout the existence of the BWP [19]. It is a bridge between the numerology and scheduling mechanisms. BWPs are controlled at the BS based on UE needs and network requirements. In contrast to LTE, 5G UEs need not monitor the whole transmission BW; they only scan the BWPs assigned to themselves. BWPs allow UEs to process only part of the band that contain their symbols, reducing power consumption and enabling longer battery lives. This is very useful for the low-power communications systems, particularly mMTC services. BWPs may overlap to facilitate low latency services while providing data to noncritical services to ensure efficient utilization of resources.

BS channel BW is another new term that refers to the contiguous BW currently in use by the next generation node B (gNB) for either transmission or reception [20]. In other words, it refers to the total BW that is processed by the gNB.

Unlike LTE slots that consist of 7 OFDM symbols in case of normal CP, NR slots can consist of 14 symbols for $\Delta f$ up to 60kHz [21]. Furthermore, LTE Resource Blocks (RBs) cover 12 consecutive subcarriers over a subframe (i.e., two slots) duration, whereas NR RBs are defined only using the same BW definition; their durations are not fixed [5]. As opposed to the fixed LTE Transmission Time Interval (TTI) duration of one slot, NR TTI may be a mini-slot in the case of uRLLC or beam-sweeping operation in frequency range-2, a slot for regular operation, or multiple slots in the case of large number of eMBB packets; thus having a definition varying as a function of the service [21]. NR re-uses the LTE radio frame definition [22], however, the number of slots per sub-frame depends on the $\Delta f$ and is given by the multiplicative inverse of the slot duration seen in Table I [5].

### III. Research Opportunities for Multi-Numerology Systems

As it can be seen from the previous section, the main flexibility causative for NR is mostly focused on the new frame with multi-numerology structures. Different user and service requirements can be met using multiple numerologies. In other words, multiplexing numerologies provides the flexibility needed by NR.

This section presents exemplary multi-numerology algorithms that exploit the flexibilities in NR design pointed out in Section III. 3GPP standards give the BS and UE manufacturers the freedom to implement any additional algorithm they desire as long as it is transparent to the receiver [23]. Examples provided in this section also exploit this degree of freedom.

#### A. Non-Orthogonality of Multi Numerologies

Resource elements within the same numerology are orthogonal to each other, but resource elements of any two different numerologies are non-orthogonal to each other and interfere with one another [4]. Non-orthogonality can result either from partially or completely overlapped numerologies, or non-overlapping numerologies for synchronous communications. As it can be seen from Fig. 1 non-orthogonality is originated from overlapping subcarriers for the first case. However, the reason of non-orthogonality is out-of-band (OOB) emission in the second case. Optionally, guard bands can be employed to reduce interference for the second case. Performance analysis for the effects of guard bands between numerologies is given in Section IV. Besides these, subcarriers are non-orthogonal to each other for intra- or inter-numerology domains in asynchronous communications [24].

In [25], authors proposed a numerology-domain non-orthogonal multiple accessing (NOMA) system with overlapping multi-numerology structures. NR allows overlapping of

| Frequency Range (FR) | $\Delta f$ (kHz) | $T_{CP}$ (µs) | Slot Duration (ms) | Max. BW (MHz) |
|----------------------|-----------------|---------------|--------------------|--------------|
| FR-1                 | 15              | 4.76          | 1                  | 50           |
|                      | 30              | 2.38          | 0.5               | 100          |
|                      | 60              | 1.19 / 4.17   | 0.25              | 100          |
| FR-2                 | 60              | 1.19 / 4.17   | 0.25              | 200          |
|                      | 120             | 0.60          | 0.125             | 400          |

| TABLE I
Numerology Structures and the Corresponding Maximum BW Allocations for Data Channels in 5G

- $\Delta f$: Frequency difference
- $T_{CP}$: CP duration
- Max. BW: Maximum bandwidth

By examining the data in Table I, one can observe how different frequency ranges (FR) are allocated for various services. For instance, FR-1 is suitable for eMBB services due to its high bandwidth capacity, whereas FR-2 is more efficient for uRLLC services with its lower bandwidth allocation. This flexible allocation of bandwidths allows NR to cater to a wide range of applications, from high-speed downloads to low-latency critical communications.
Fig. 1. Orthogonality and non-orthogonality for intra-numerology and inter-numerologies cases.

BWPs using different numerologies in time-frequency grid [12]. Numerology-domain NOMA system designs can be developed to exploit this gap in 5G.

B. Numerology Selection Methodologies

BWP is a useful tool for multi-numerology systems as BWP defines a specific numerology. BS can modify UE numerologies by changing its BWPs. Parameter configuration process for the BWPs is employed by BW adaptation (BA) tool on BS [26]. There can be up to four defined BWPs for each UE but there is one active BWP for each user in Release 15. However, future NR releases are planned to allow multiple (up to four per UE in Release 16) active BWP configurations.

Active BWPs and the corresponding numerologies can be selected using different methodologies. Various trade-offs between distinct performance metrics that include spectral efficiency, INI, flexibility, and complexity can be considered while deciding on active BWPs and so numerologies.

For one active BWP at a time case, an example numerology selection methodology is proposed in [3] that uses a heuristic algorithm to configure numerologies suitable for each user. Fig. 2 illustrates this resource allocation optimization methodology. The proposed method also provides an active BWP switching mechanism.

It is possible to increase the number of numerologies in beyond 5G. Offering more numerologies simultaneously ensures that all user and service requirements are satisfied, but this requires more sophisticated numerology selection mechanisms. To reduce computational costs, BSs may use two-step numerology selection methods in the future. The first step decides on the most suitable numerology set between different sets. Then, the second step determines the best numerologies from the set that is selected in the first step. Additionally, there can be many different numerology selection methods for multiple BWPs active at a time case.

C. INI Estimation Models

INI can be simply defined as ICI between subcarriers of different numerology structures. The amount of INI can vary with $\Delta f$, BW, guards, $T_{CP}$, the number of different numerologies, alignment of different numerologies in frequency domain, filtering/windowing usage, frequency bands, user powers, and so on. All of these parameters need to be analyzed together to form estimation models for INI.

INI estimation is very important topic because it can be used as a feedback to all other adaptive systems that include adaptive guards, numerology selection, filtering/windowing decision, and optimization of the number of numerologies. Interference models can be very useful for adaptive decision on different algorithms for multi-numerology systems. For example, an INI estimation method between different transmitter and receiver windowed OFDM numerologies are provided in [27], where the exact calculation of INI using the channel impulse responses (CIRs) and data of all users, as well as estimation techniques for practical cases such as unknown data as well as unknown CIRs are provided.

D. Effects of Guard Bands Between Multi Numerologies

This subsection deals with the adjustment of frequency domain guards with respect to estimated INI after numerologies are selected. In 3GPP standards, it is revealed that there are minimum guard band requirements, a maximum or an optimum value is not enforced, making guard bands choices flexible with high granularity [20]. Adaptive guard band concept for different numerologies becomes a crucial research area at this point.

As it is well known, the OFDM signal is well localized in the time domain with a rectangular pulse shape, which corresponds to a sinc pulse in the frequency domain. Sincs cause significant OOB emission and guard bands are needed between two adjacent subbands with different numerologies to handle the interference.

The OOB emission increases as the symbol duration decreases. Therefore, more guard band is required for the numerologies with higher $\Delta f$. For the edge subcarriers of two adjacent numerologies, SINR decrease is more significant compared to the remaining subcarriers. Most of the interference comes from the edge subcarriers [28]. Grouping services in BWPs reduces the amount of necessary guards and eases scheduling when such fast numerology variations
Fig. 3. Block diagram for the simple implementation of multi numerologies. The scaling factor of $\Delta f_s$ is chosen as $2^k$, where $k$ is a positive integer.

become necessities. Moreover, passing OFDM signal through power amplifiers causes non-linear distortions. The peak-to-average power ratio (PAPR) and OOB emission increase as the number of active subcarriers increases. As a result, more guard band is needed for the transmissions with wider occupied numerology BWs.

In Section IV, the effects of guard bands between multi numerologies with the performance analysis results are shown regarding to the implementation block diagram given in Fig. 3.

E. Effects of Guard Intervals for INI Elimination

In addition to guard bands between different numerologies, the guards in time and frequency domains must be jointly optimized to boost the spectral efficiency [29]. Various slot configurations and UE scheduling guidelines reveal that few restrictions exist regarding scheduling users in time domain. This implies that the guard times can also be utilized flexibly, similar to guard bands. Combining time-frequency guard flexibility yields that empty resource elements can virtually be placed anywhere. Interpreting this at a multi-user level reveals that the UL slot of one UE and the DL slot of another UE can be scheduled to consecutive time or frequency resources with little guard time and band. This poses serious requirements in pulse shaping, making localized pulses and interference rejection techniques critical.

Also, the use case and power imbalance factors should be considered on the guard allocation. The power control mechanism mitigates the interference problem in power imbalance scenarios as well, but it prevents deployment of higher order modulation for the users that experience higher SINR. Thus, power control requires relaxation using an adaptive guard design to increase the throughput. The potential of adaptive guards can be increased further by utilizing an interference-based scheduling algorithm [29].

F. Filtering and Windowing in NR

INI cannot only be handled using guards but also with the filtering and windowing approaches that require additional guards. Applying filters and windows methods are left for the implementation in 3GPP standardization.

Allocating users optimal guards minimizes but not completely eliminates the interference on the received signal in a non-orthogonal system. The receiver may also engage in filtering and windowing to further eliminate the remaining interference, but doing so using conventional methods requires additional guards. The assigned optimum guards may not even be sufficient if extreme latencies are required. The algorithm presented in [27] deals with the minimization of aggregate inter-symbol interference (ISI), ICI and adjacent channel interference (ACI) by windowing each received subcarrier with the window function that minimizes the aggregate interference at that subcarrier. The optimal window lengths require perfect knowledge of the interfering users’ data and channels. While this can be known and applied at UL reception at the gNB in a manner similar to successive interference cancellation (SIC) or multi-user (MU) detection, this cannot be done at the UE. Therefore, the algorithm presents methods to estimate optimal subcarrier specific window durations if only the CIRs, power delay profiles (PDPs) or the power offsets of the interferers are known.

G. Optimization on the Number of Active Numerologies

Authors of [3] find the efficient number of active numerologies that should be simultaneously employed by users. The algorithm aims to minimize various overheads to provide a practical solution satisfying different service and user requirements using multi-numerology structures. All of the different numerologies that are defined in standards do not need to be used in every situation.

Basically, the amount of total guard band in the lattice increases with increasing number of numerologies. Hence,
there is a trade-off between the spectral efficiency and multi-numerology system flexibility. Although not imposed by the standard [5], they allocate BWPs configured to use the same numerologies consecutively in an effort to reduce guard bands and computational complexity.

IV. SIMULATION RESULTS ON MULTI-NUMEROLOGY

In this section, INI results as a function of guard allocation and multi-numerology parameters are provided based on the block diagram in Fig. 3. It is assumed that BWPs with different numerologies are not overlapped at a time and BWPs with the same numerologies are grouped together in the frequency domain. Also, user powers are taken as equal.

Random binary phase shift keying (BPSK) symbols are generated separately for two-numerology structure. For the first numerology, which has $\Delta f_{ref}$ kHz subcarrier spacing, $N$-point inverse fast Fourier transform (IFFT) is employed. The second numerology has $2^k \times \Delta f_{ref}$ kHz subcarrier spacing and uses $N/(2^k)$-point IFFT, where $2^k$ is the scaling factor and $k$ is a positive integer. Here, the second half of the IFFT inputs for the first numerology and the first half of the IFFT inputs for the second numerology are zero-padded to separate two numerologies in frequency domain. After each IFFT operation, CP samples are added with a ratio of $CP_R$ to every OFDM symbol. There are $2^k$ OFDM symbols with the second numerology corresponding to one OFDM symbol with the first numerology. Thus, the number of samples for each of the numerologies are the same, and they can be added to form a composite signal at the transmitter.

Wireless channel and noise are ignored to just focus on the INI in the simulation results. At the receiver side, CP samples are removed from each OFDM symbol. $N$-point fast Fourier transform (FFT) is used for the first numerology over full composite signal. However, only $N/(2^k)$ samples of the composite signal to make them input into $N/(2^k)$-point FFT for the second numerology. $2^k$ subblocks are constituted by dividing the composite signal into $2^k$ parts and these subblocks are processed one by one. The first half of the FFT output for the first numerology and the second half of the FFT output for the second numerology are taken to obtain received symbols.

Interference estimations are done for each of the used subcarriers separately. Monte Carlo method is applied to increase the statistics in simulation results. The number of tests is 500 and different set of random data is used in each of these tests. Thereafter, the average interference on the subcarriers are estimated. There are four cases in the simulation results presented in Fig. 4. Number of usable subcarriers are half of the IFFT sizes in each case.

In Fig. 4, INI results are plotted like that there is not any guard bands between the edge subcarriers of two numerologies when there are actually guard bands. The reason of this representation is to make a comparison with different amount of guard bands easily. The below basic inferences are made from the simulation results:

1) There is more INI at the edge subcarriers of different numerologies.

2) INI present at each subcarrier decreases as the guard band between different numerologies increases.

3) The effect of guard bands are more prominent for the edge subcarriers.

4) CP addition causes additional interference for the numerology with smaller $\Delta f$.

5) Subblocks of the second numerology are constituted by dividing the composite signal. Hence, the symbols of the first numerology causes an extra interference on the second numerology at the receiver side.

6) INI on every $(2^k)$th subcarrier is less than that of the other subcarriers for the numerology with smaller $\Delta f$.

Simulation results show that there are opportunities for the adaptive algorithm designs in 5G as mentioned in Section III.

V. CONCLUSION

Next generation communications systems including NR are evolving towards increased flexibility in different aspects. Enhanced flexibility is the key to address diverse requirements. Spectral guards and pulse shapes are critical part of this flexibility. These are left for the implementation as long as it is transparent to the counterpart of the communications. NR flexibility can be exploited by finding optimal and practical solutions for implementation dependent parts of the 5G standardization. The flexibility of NR brings too many open-ended research opportunities compared to the previous cellular communications generations.

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(a) Case 1: Numerology-1 has $15\,\text{kHz} \Delta f$ and Numerology-2 has $30\,\text{kHz} \Delta f$. Guard bands are 0kHz, 180kHz and 360kHz.

(b) Case 2: Numerology-1 has $15\,\text{kHz} \Delta f$ and Numerology-2 has $30\,\text{kHz} \Delta f$. Guard bands are 15kHz, 195kHz and 375kHz.

(c) Case 3: Numerology-1 has $15\,\text{kHz} \Delta f$ and Numerology-2 has $60\,\text{kHz} \Delta f$. Guard bands are 0kHz, 180kHz and 360kHz.

(d) Case 4: Numerology-1 has $15\,\text{kHz} \Delta f$ and Numerology-2 has $60\,\text{kHz} \Delta f$. Guard bands are 45kHz, 225kHz and 405kHz.

Fig. 4. Simulation results for four different cases with different guard band amounts between numerologies.