Waveform and Numerology to Support 5G Services and Requirements

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***Abstract*—The standardization of the next generation 5G radio access technology has just started in 3GPP with the ambition of making it commercially available by 2020. There are a number of features that are unique for 5G radio access compared to the previous generations such as a wide range of carrier frequencies and deployment options, diverse use cases with very different user requirements, small sized base stations, self-backhaul, massive MIMO, and large channel bandwidths. In this paper, we propose a flexible physical layer for the New Radio access technology (NR) to meet the 5G requirements. A symmetric physical layer design with OFDM is proposed for all link types including uplink, downlink, device-to-device, and backhaul. A scalable OFDM waveform is proposed to handle the wide range of carrier frequencies and deployments.**

I. Introduction

The standardization of the next generation radio technology has started in 3GPP (3rd Generation Partnership Project) this year (2016) with the ambition of making 5G wireless systems commercially available around 2020. There are three main challenges that need to be addressed by 5G Radio Access Technology to enable a truly networked society: i) a massive growth in the number of connected devices, ii) a massive growth in traffic volume, and iii) an increasingly wide range of applications with varying requirements and characteristics. Broadly, we can classify 5G use cases (or services) in the following groups:

- Enhanced Mobile Broadband (eMBB), requiring very high data rates and large bandwidths;
- Ultra Reliable Low Latency Communications (URLLC) requiring very low latency, very high reliability and availability;
- Massive Machine Type Communications (mMTC), requiring low bandwidth, high connection density, enhanced coverage, and low energy consumption at the user end.

The requirements for the above mentioned 5G services are diverse and have implications for new spectrum and deployments. New spectrum for 5G is expected to be available by 2020. The actual frequency bands and the amount of spectrum, have not been identified yet. All bands, from below 1 GHz up to 100 GHz are potential candidates for 5G [1]. 5G services will require a range of different bandwidths. At the low end of the scale, support for massive machine connectivity with relatively low bandwidths is envisioned. In contrast, very wide bandwidths may be needed for high capacity scenarios, e.g., 4K video and future media. Millimeter wave spectrum bands (i.e., near and above 30 GHz) will play a role in some deployments to reach the envisioned capacity [2].

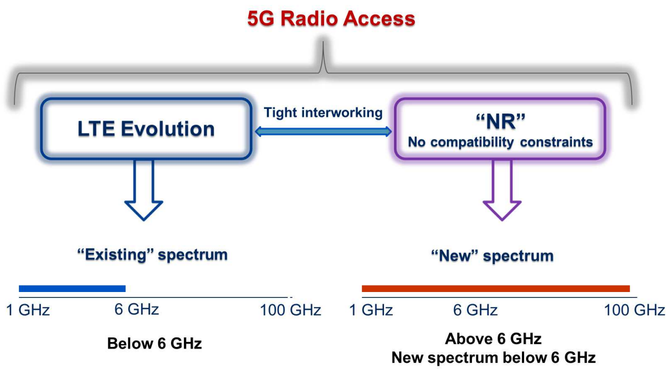


Figure 1: Radio Access Vision for 2020 and beyond: 5G Radio Access comprises of LTE Evolution and a New Radio Access Technology (NR) that is not backwards compatible with LTE and is operable from sub-1 GHz to 100 GHz.

3GPP aims to develop and standardize components for a new Radio Access Technology (RAT) which is envisioned to operate in frequencies up to 100 GHz to serve the diverse use cases. The new radio access technology is referred to as NR throughout this paper, which is currently the accepted acronym in 3GPP [3]. NR is intended to be optimized for performance without considering backward compatibility in the sense that legacy LTE UEs do not need to be able to camp on an NR carrier. LTE is also expected to evolve to capture a part of the 5G requirements. The vision of 5G wireless access is shown in Fig. 1, where NR and LTE Evolution are integral parts of 5G. LTE evolution is expected to operate below 6 GHz frequencies and NR is envisioned to operate from sub-1 GHz up to 100 GHz. A tight integration of NR and LTE is envisioned, in order to efficiently aggregate NR and LTE traffic.

Designing physical layer of NR will be the first step towards its development. This paper provides principles for the design of waveform and numerology[1]. The paper is organized as follows. In Section II, we highlight key design requirements for NR. Based on the design requirements, we propose waveform and numerology in Sections III–V. Finally, Section VI

[1]Numerology refers to waveform parametrization, e.g., cyclic prefix, subcarrier spacing in OFDM.

concludes the paper.

II. PHY Design Requirements for NR

In the following, we list important features of NR that have implications on new waveform and numerology.

- NR has to support a wide range of frequencies, bandwidths, and deployment options. NR should support diverse use cases such as eMBB, URLLC, and mMTC. These requirements asks for a flexible waveform, numerology and frame structure.
- NR has to support applications with very low latency, which requires very short subframes.
- NR should support both access and backhaul links by dynamically sharing the spectrum. NR should also support Device-to-Device (D2D) communication, including Vehicle-to-Anything (V2X) communication. This implies that NR waveform and numerology should be designed keeping in view various link types including uplink (UL), downlink (DL), sidelink[2], and backhaul.
- NR has to enable full potential of Multi-antenna technology. The number of antenna elements may vary, from a relatively small number of antenna elements in LTE-like deployments to many hundreds, where a large number of active or individually steerable antenna elements are used for beamforming, single-user MIMO (SU-MIMO) and multi-user MIMO (MU-MIMO). NR waveform and numerology must unleash the full potential of massive MIMO.
- NR is envisioned to be based on mainly TDD at high frequencies (above 3 GHz) and mainly FDD in lower frequencies. The waveform, numerology, and frame structure should be chosen to enable efficient time/frequency utilization for the respective FDD and TDD deployments.
- At very high frequencies, base stations can be small sized (low cost) access nodes, putting similar requirements in downlink as are in uplink (e.g., transmit power, hardware impairments etc). This suggests a physical layer design that is symmetric in uplink and downlink.

The key features of NR that have implications on the design of waveform and numerology are also summarized in Fig. 2.

III. NR Waveform

OFDM is currently used in LTE for downlink transmission. In March 2016, 3GPP has agreed to study various features of NR assuming OFDM, unless significant gains can be demonstrated by any other waveform [3]. This section assesses OFDM for a number of key performance indicators for different link types (uplink, downlink, sidelink, backhaul) and concludes that OFDM is indeed an excellent choice for NR. A few other relevant multi-carrier and single carrier waveforms are also discussed briefly.

[2]D2D link is referred to as sidelink in 3GPP.

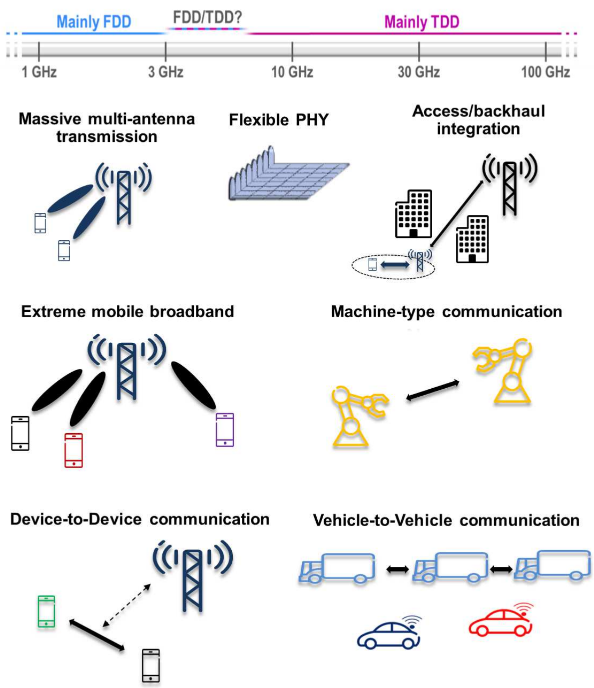


Figure 2: Massive MIMO, flexible physical layer, (mobile) self-backhaul, operation in sub-1 GHz to 100 GHz with mainly TDD above 6 GHz to support diverse uses cases are the key features of the 5G radio access.

A. Assessment of OFDM

OFDM has been widely studied in the literature [4]. In the following, we assess the performance of OFDM for a number of key performance indicators. Different link types impose different level of requirements on the waveform performance indicators at different frequencies. An assessment of OFDM is therefore made for all link types. The key performance indicators for NR waveform are:

- ***Spectral efficiency***: OFDM is well-known to be highly spectral efficient. Spectral efficiency is vital to meet extreme data rate requirements. In general, spectral efficiency is more crucial at lower carrier frequencies than at higher frequencies, since the spectrum is not as precious at higher frequencies due to the availability of potentially much larger channel bandwidths. Spectral efficiency is very important for UL and DL, however, the requirements are even more stringent for backhaul (due to large amount of data). Vehicular communication also requires very high spectral efficiency in dense urban scenarios when the system is capacity limited and the large number of vehicles are periodically broadcasting signals in an asynchronous fashion;
- ***MIMO compatibility***: OFDM enables a straightforward use of MIMO technology. With the increase in carrier frequency, the number of antenna elements will increase in the access nodes (base stations) as well as in the devices. The use of various MIMO schemes will be essential in providing high spectral efficiency (by enabling SU-MIMO/MU-MIMO) and greater coverage (via beamform-

ing). Beamforming will be instrumental in overcoming high propagation losses at very high frequencies (coverage limited scenarios);

- ***Peak-to-Average-Power-Ratio (PAPR)***: OFDM has high PAPR (like other multi-carrier waveforms). A low PAPR is essential for power efficient transmissions from the devices (e.g., UL, sidelink). Low PAPR becomes even more important at very high frequencies. It is noteworthy that small sized low cost base stations are envisioned at high frequencies, therefore, low PAPR is also important for DL. High PAPR in OFDM can also be substantially reduced via various well-known PAPR reduction techniques with only minor compromise in performance [5]. For NR, OFDM with PAPR reduction (without DFT precoding[3]) is an attractive option for uplink and sidelink. The use of one waveform for all link types will also make transceiver designs and implementations symmetric for all transmissions. Moreover, it is important to note that the requirements on PAPR for uplink and downlink will become more similar in the future due to low cost small sized base stations.;
- ***Robustness to channel time-selectivity***: is vital in high speed scenarios. High speed scenarios are relevant in large cell deployments. The large cell deployments are not expected at very high frequencies due to harsh propagation conditions (coverage limitation). At very high frequencies, the deployments are expected in the form of small cells where mobility is not a major concern. However, V2X services may be enabled at very high frequencies, making robustness to channel time selectivity very important performance indicator at very high frequencies. Traditionally backhaul link is fixed and mobility is not a concern, however for the envisioned mobile backhaul (e.g., access nodes on vehicles), robustness to channel time selectivity will become relevant. OFDM can be made robust to channel time-selectivity by a proper choice of sub-carrier spacing;
- ***Robustness to channel frequency-selectivity***: Channel frequency-selectivity is always relevant to the transmission of large bandwidth signals over wireless channels. Channel frequency selectivity depends on various factors such as type of deployment, beamforming technique, and signal bandwidth. OFDM is robust to frequency selective channels;
- ***Robustness against phase noise***: An OFDM system can be made robust to phase noise by a proper choice of sub-carrier spacing. Phase noise robustness is crucial for all link types where a device (transmitter/receiver) is involved. In particular, low-phase noise oscillators may too expensive and power consuming for devices. Phase noise robustness is also important for future low cost base stations. Basically, any link that involves a device and/or low cost base station puts a high requirement on phase noise robustness of waveform, especially if the communication takes place at high frequencies since phase noise increases with carrier frequency;
- ***Transceiver baseband complexity***: The baseband complexity of an OFDM receiver is lowest among all candidate waveforms that have been studied in the past for 5G RAT [7]. Baseband complexity is always very important for the devices, especially from the receiver perspective. For NR, complexity is even a major consideration for base stations, since a base station can be small sized access node (especially at high frequencies) with limited processing capability. At very high frequencies and large bandwidths, the receiver may also have to cope with severe RF impairments;
- ***Time localization***: OFDM is very well-localized in time domain, which is important to efficiently enable (dynamic) TDD and support latency critical applications such as URLLC. Dynamic TDD is envisioned at high frequencies and provision of low latency is essential for all link types, especially backhaul and V2X links may impose very high requirement;
- ***Frequency localization***: OFDM is less localized in frequency domain. Frequency localization can be relevant to support co-existence of different services potentially enabled by mixing different waveform numerologies in frequency domain on the same carrier. Frequency localization is also relevant if asynchronous access is allowed in UL and sidelink. In general, frequency localization of a waveform may not be important at high frequencies where large amount of channel bandwidth is available;
- ***Robustness to synchronization errors***: The provision of cyclic-prefix in OFDM makes it robust to timing synchronization errors. Robustness to synchronization errors is relevant when synchronization is hard to achieve such as sidelink. It can also be relevant if asynchronous transmissions are allowed in the uplink[4];
- ***Flexibility and scalability***: OFDM is a flexible waveform, that can support diverse services in wide range of frequencies by proper choice of subcarrier spacing and cyclic prefix. Further discussion on OFDM numerology design that fulfills a wide range of requirements is given in Sec. IV.

In Table I, we provide a summary of OFDM assessment. An OFDM assessment "High" in second column means that OFDM has good performance in general for the given KPI, whereas a link requirement "High" for a KPI tells that the given waveform KPI is important for the given link type in general. We assess D2D and V2X cases separately due to different levels of requirements. For example, V2X communication has higher requirements on mobility, system capacity, whereas lower requirements on power efficiency when compared with UE-to-UE communication. Based on the assessment in Table I, we conclude that OFDM is an excellent choice for NR air interface.

[3]LTE uses DFT-Spread OFDM (DFTS-OFDM) for both UL and sidelink link due to its lower PAPR than OFDM. However, DFTS-OFDM has certain drawbacks compared to OFDM such as lesser flexibility for scheduling (in case of SC-FDMA) and more complex MIMO receiver with degraded link level and system level performance [6]. Since MIMO will also be a key component for UL and sidelink in NR, DFTS-OFDM is not a preferred option.

[4]We note that LTE only supports synchronous uplink transmission (except for PRACH), which is realized via timing advance at the UEs.

Table I: Assessment of OFDM

Performance Indicators	OFDM Assessment	DL Req.	UL Req.	Sidelink Req.	V2X Req.	Backahul Req.
Spectral efficiency	High	Very High	Very High	High	Very High	Very High
MIMO compatibility	High	Very High	Very High	High	Very High	Very High
Time localization	High	High	High	High	Very High	Very High
Transceiver baseband complexity	Low	Very High	High	Very High	High	High
Flexibility/Scalibility	High	High	High	High	High	High
Robust. to freq. selective chan.	High	High	High	High	High	High
Robust. to time selective chan.	Medium	High	High	High	Very High	Low
Robust. to phase noise	Medium	High	High	High	High	High
Robust. to synch. errors	High	Medium	Medium	High	High	Medium
PAPR	High (can be reduced)	Low	High	High	Medium	Low
Frequency Localization	Low (can be improved)	Medium	Medium	Medium	Medium	Low

B. Other Multi-carrier Waveforms

In recent years, a number of multi-carrier and single-carrier waveforms have been investigated and proposed for 5G radio access technologies. An assessment of these multi-carrier and single-carrier waveforms can be found in [7], for all KPIs given in Sec. III-A. Besides OFDM, the other major multi-carrier waveforms (FBMC-OQAM and FBMC-QAM) are based on filter bank implementations where each sub-carrier is filtered. OFDM is well-localized in time and less localized in frequency, whereas FBMC is less localized in time but well-localized in frequency. The good time localization of OFDM along with its lower implementation complexity than FBMC, makes OFDM the preferred choice for NR that has to support TDD, delay critical use cases, and efficient processing of large bandwidth signals. If necessary, the frequency localization of OFDM can be improved via low complex windowing [8], [9] or subband filtering. The windowing or filtering can be employed either at the transmitter or at the receiver or at both transmitter and receiver. An example of transmitter and receiving windowing in OFDM is provided in Sec. V.

C. Single Carrier Waveforms

Single carrier waveforms can be useful at very high frequencies, where power efficient transmission is desired. Among single-carrier waveforms, there are two main categories: i) DFTS-OFDM, ii) Pure single carrier. Pure single carrier waveforms can have very low PAPR and are inherently robust to phase noise and Doppler. However, they do not allow efficient and flexible spectrum resource utilization; they require more complex receiver design due to lack of frequency domain equalization (if CP is not enabled); have lower compatibility with MIMO and are less spectrally efficient in general. On the other hand, DFTS-OFDM offers better scheduling flexibility, allows low complex frequency domain equalization, has higher compatibility to MIMO than pure single carrier waveforms. DFTS-OFDM has lower PAPR than OFDM [10], however, not as low as pure single carrier waveforms. These properties make DFTS-OFDM an attractive option for uplink and downlink at very high frequencies, where low PAPR is desired.

IV. OFDM Numerologies for NR

NR is envisioned to operate from sub-1 GHz to 100 GHz for a wide range of deployment options and to support variety of services. It is not possible for a single waveform numerology to fulfill all these requirements. Therefore, we propose to adopt a family of OFDM numerologies for NR air interface.

A. Numerology Design Principles

For a given carrier frequency, phase noise and Doppler set requirement on the minimum subcarrier spacing. Use of smaller subcarrier spacings would either result in high Error Vector Magnitude (EVM) due to phase noise or in undesirable high requirements on the local oscillator. Too narrow subcarrier spacings also lead to performance degradations in high Doppler scenarios. Required cyclic prefix overhead (and thus anticipated delay spread) sets an upper limit for the subcarrier spacing; selecting too large subcarriers would result in undesirable high CP overhead. The maximum FFT size of the OFDM modulator together with subcarrier spacing determines the channel bandwidth. Based on these relations the subcarrier spacing should be as small as possible while still being robust against phase noise and Doppler and providing the desired channel bandwidth. In Sec. IV-B, we provide further discussion on the choice of sub-carrier spacing and cyclic-prefix taking into account phase noise effect and realistic delay spread at different carrier frequencies.

As discussed earlier, a set of OFDM numerologies has to be defined for NR to handle wide range of frequencies and deployment options. These OFDM numerologies could either be unrelated to each other, i.e. OFDM numerology for a given frequency and deployment is only based on this frequency and deployment, not considering numerologies for other frequencies and deployments at all. Another possibility is to define a family of OFDM numerologies which are related to each other via scaling, i.e.,

$$\Delta f_i = n_i \Delta f_{i-1}, \quad T_{cp,(i)} = \frac{T_{cp,(i-1)}}{n_i}, \tag{1}$$

where Δf_i and $T_{cp,(i)}$ denote subcarrier spacing and cyclic-prefix duration of the i-th numerology and $n_i \in \mathbb{N}$ is a scaling factor. The duration of OFDM symbol is inverse of subcarrier spacing. With this scaling approach, sampling clock rates of different OFDM numerologies relate to each other via the scaling factors $\{n_i\}$, which simplifies the implementation. We therefore propose to adopt this scaling approach, i.e., OFDM numerologies are derived from a base OFDM numerology via the scaling. In principle, the scaling factors $\{n_i\}$ can be selected independently of each other, however, it is desirable that the scaling factors follow certain relationship (given in (2)) which will be discussed in the following.

We propose that the number of OFDM symbols per sub-frame should be equal for all numerologies, meaning that the subframe duration would shrink with the increase in sub-carrier spacing. Maintaining equal number of OFDM symbols per subframe for all numerologies simplifies scheduling and reference signal design. Furthermore, this would enable shorter latencies for wider subcarrier numerologies (to be used in high frequency small cell deployments where some of the URLLC applications are envisioned). If equal number of OFDM symbols are assumed for all numerologies, then the following relationship holds for subframe durations between different numerologies:

$$T_{sf,(i)} = \frac{T_{sf,(i-1)}}{n_i} = \frac{T_{sf,(i-2)}}{n_i n_{i-1}} = \cdots = \frac{T_{sf,(1)}}{\prod_{k=1}^{i} n_k}.$$

For adjacent TDD networks that are using different OFDM numerologies, it is desirable that an integer number of sub-frames from one OFDM numerology fits into one subframe of the other OFDM numerology to enable time aligned downlink and uplink periods. If the sub-frame durations of different numerologies do not fulfill the above condition, then two neighbouring TDD networks would require guard time in the frame structure to enable synchronous operation, which will not be an efficient resource utilization. Therefore, we propose that the scaling factors are chosen such that a subcarrier spacing is integer divisible by all smaller subcarrier spacing, i.e.,

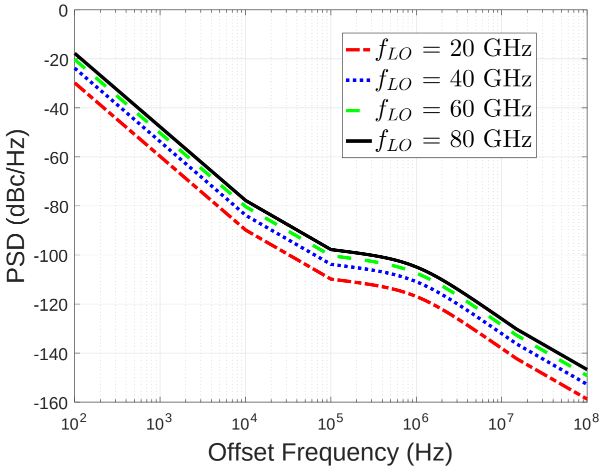
$$\Delta f_i = 2^{L_{(i)}} \Delta f_1, \qquad \forall i \in \{1, 2, ..., M\}, \tag{2}$$

where $L_{(i)} \in \mathbb{Z}$, M is the number of OFDM numerologies, and Δf_1 is sub-carrier spacing of the base numerology. This implies that the scaling factor in (1) should be chosen as $n_i = 2^L$, where L is an integer.

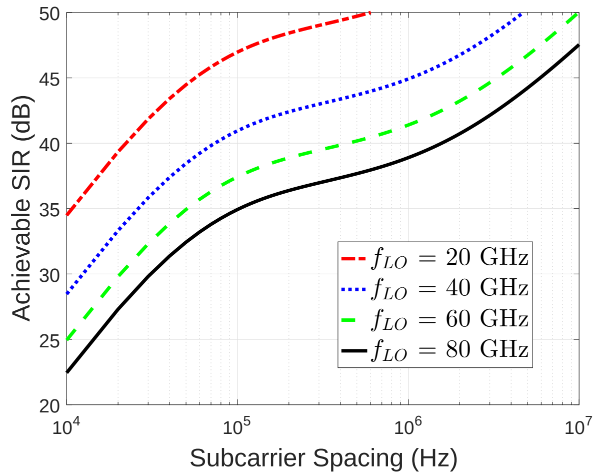
B. Impact of Phase Noise and Channel Delay Spread

Phase noise in an OFDM system causes two main effects: i) Common Phase Error (CPE), ii) Inter Carrier Interference (ICI) [11]. CPE refers to phase rotation of all sub-carriers by an equal amount and can be corrected easily with the use of pilot subcarriers. ICI is an additive noise (not always Gaussian) and usually hard to compensate for depending on how fast the phase variations are. In the following, we evaluate the effect of ICI in OFDM as a function of sub-carrier spacing at different oscillator frequencies. First, we will briefly describe the phase noise model used in the evaluations and then present the evaluation results.

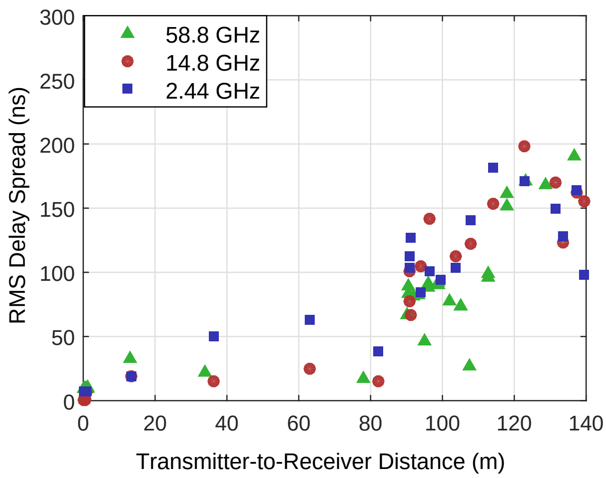
The local oscillator (LO) consists of a crystal oscillator (XO) and a voltage-controlled oscillator (VCO) connected in



(a) Phase noise power spectral densities at different oscillator frequencies.



(b) Achievable SIR subject to phase noise (due to inter-carrier-interference) at different oscillator frequencies.



(c) Channel delay spread has a weak dependency on carrier frequency.

Figure 3: Phase noise impact and channel delay spread at different frequencies.

Table II: Proposed OFDM Numerologies

OFDM paramteres	Up to 6 GHz	Up to 20 GHz	Up to 40 GHz	Above 40 GHz
Subcarrier spacing	15 kHz	30 kHz	60 kHz	$2^L\times$ 60 kHz
Clock frequency	61.44 MHz	122.88 MHz	245.76 MHz	$2^L\times$ 245.76 MHz
Samples per OFDM symbol	4096	4096	4096	4096
OFDM symbol duration	66.77 μs	33.33 μs	16.67 μs	$16.67/2^L$ μs
CP samples	288	288	288	288
CP duration	4.69 μs	2.35 μs	1.17 μs	$1.17/2^L$ μs

a Phase-Locked Loop (PLL). At low offset frequencies, the LO phase noise is dominated by the XO phase noise, shifted up by $20\log(f_{LO}/f_{XO})$. At high offset frequencies, the LO phase noise is dominated by the -20 dB/dec of the VCO. In the following evaluations, the considered LO design is based on XO running at 490 MHz and VCO with Figure-of-Mertit[5] (FOM) = -190 dB and a power consumption of 30 mW. With this design, the Power Spectral Density (PSD) of the phase noise is given in Fig. 3a. The Signal-to-Interference Ratio (SIR) due to ICI for a subcarrier can be computed according to the expression in Sec. 5.2 in [11]. In Fig. 3b, we have evaluated SIR of the middle subcarrier (suffering from highest ICI) as a function of subcarrier spacing for four different oscillator frequencies. According to Fig. 3b, 40 dB SNR can be achieved with Δf = 30 kHz at 20 GHz oscillator frequency, Δf = 60 kHz at 40 GHz oscillator frequency, Δf = 500 kHz at 60 GHz oscillator frequency.

For a fixed CP overhead in an OFDM symbol, larger subcarrier spacing implies smaller CP. Cyclic-prefix has to be greater than the delay spread of the channel. Therefore, channel delay spread sets an upper limit on the subcarrier spacing. Some recent channel measurements at different carrier frequencies (2.44 GHz, 14.8 GHz, and 58.8 GHz) in a street micro cell scenario have shown that delay spread is similar at different frequencies assuming omni-directional antennas, see Fig. 3c [13]. Similar conclusions are made in a recent white paper [14], which shows that delay spread has a weak dependency on frequency. Furthermore, it has been observed that delay spread is much lower in LOS conditions compared to the NLOS conditions. According to Fig. 3c, the max. value of RMS delay spread is 0.2 μs, which is important to keep in mind while setting the upper limit on subcarrier spacing. It is also important to note that the observed delay spread of the channel depends on few other factors such as deployment scenario and beam forming. Delay spread is usually smaller in indoor environments and use of narrow beams may reduce delay spread as well.

C. Proposed Numerologies

We now propose a set of OFDM numerologies following the design principles discussed in Sec. IV-A and the important observations made in Sec. IV-B related to impact of phase noise and channel delay spread at different carrier frequencies. We choose LTE numerology as the base numerology, i.e., Δf_1 = 15 kHz, $T_{ofdm,(1)}$ = 66.67 μs, and $T_{cp,(1)}$ = 4.69 μs. The other numerologies are derived from the base numerology according to (2) and (1). The derived numerologies are given in Table II. We note that in LTE, CP duration of the first OFDM symbol in a slot is 5.2 μs. We propose the same for NR base numerology (which is LTE numerology), although not explicitly mentioned in Table II. Moreover, LTE provides an option for extended CP which should also exist in NR. As proposed in Table II, different numerologies are suitable for different frequency ranges considering the achievable SNR subject to phase noise and channel delay spread discussed in Sec. IV-B. According to Fig. 3c, CP duration must be greater than 0.2 μs which implies $L = 3$ in the last column of Table II, meaning that the largest subcarrier spacing should be 480 kHz if the numerologies are derived according to (2) [6]. We recall that in presence of ICI (due to phase noise), 480 kHz subcarrier spacing can achieve approx. 40 dB SNR at 60 GHz oscillator frequency and approx. 35 dB SNR at 80 GHz oscillator frequency (cf. Fig. 3b).

There are a few important reasons for proposing LTE numerology as the base numerology, that are listed below:

- 3GPP has specified LTE numerology for Narrow-Band Internet-of-Things (NB-IOT). NB-IOT devices are designed to operate for 10 years and more on a single battery charge. Once such an NB-IOT device is deployed it is likely that within the device life time the embedding carrier gets reframed to NR.
- NR deployments can happen in the same band as LTE. With adjacent carrier LTE TDD, NR must adopt the same UL/DL switching pattern as LTE TDD does. Every numerology where (an integer multiple of) a subframe is 1 ms can be aligned with regular subframes in LTE. In LTE, duplex switching happens in special subframe. To match the transmission direction in special subframes, the same numerology as in LTE is needed.
- LTE Release-8 was standardized after a thorough numerology study, therefore, it is reasonable to aim for similar numerology at LTE-like frequencies and deployments.

D. Frame Structure

In LTE, one radio frame comprises of 10 subframes and each sub-frame consists of two slots with seven OFDM symbols per slot. The notions of slot may not be necessary,

[5]FOM has been defined according to (1) in [12].

[6]In practice, maximum delay spread is typically four to five times greater than RMS delay spread and CP should be chosen accordingly.

therefore, we only define subframe for NR. The proposed subframe consists of N_{symb} OFDM symbols, but not all symbols in a subframe are always used for active transmission. We define two basic subframe types, one for UL and one for DL. Transmission in a DL subframe always starts at the beginning of the subframe and can extend from 0 up to at most N_{max} OFDM symbols. Transmission in an UL subframe always stops at the end of the subframe and can extend from 0 up to at most N_{max} OFDM symbols. The gaps between DL and UL transmission, if present, are used as guard in TDD for transmission in the reverse direction within a subframe.

The duration of a single subframe has to be very short. Depending on the numerology, a sub-frame duration can be tens of micro seconds to a few hundred micro seconds. For the OFDM numerologies given in Table II, we propose seven OFDM symbols per subframe, i.e., $N_{max} = 7$. This implies sub-frame duration of 500 μs for 15 kHz numerology, 250 μs for 30 kHz numerology, 125 μs for 60 kHz numerology, and reaching down to 15.62 μs for 480 kHz subcarrier spacing. Very short subframes are important for URLLC applications requiring low latency and such devices will typically check for control signaling transmitted at the beginning of every DL subframe. Given the latency critical nature, the transmission itself can also be very short, e.g., a single subframe. For eMBB devices, extremely short subframes are typically not needed. Therefore, one can aggregate multiple subframes and schedule the subframe aggregate using a single control channel.

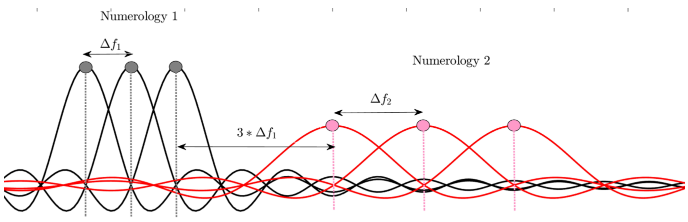
V. Mixing Numerologies

For some use-cases, mixing of different numerologies on the same carrier frequency may be beneficial, e.g., to support different services with very different latency requirements. In an OFDM system with different numerologies (subcarrier bandwidth and/or cyclic prefix length) multiplexed in frequency-domain, only subcarriers within a numerology are orthogonal to each other. Subcarriers of one numerology interfere with subcarriers of another numerology, since energy leaks outside the subcarrier bandwidth and is picked up by subcarriers of the other numerology. The inter-numerology interference is illustrated in Fig. 4a, where a numerology based on subcarrier spacing Δf_1 interferes with another numerology based on subcarrier spacing Δf_2, even though there is a small guard band between the two transmissions.

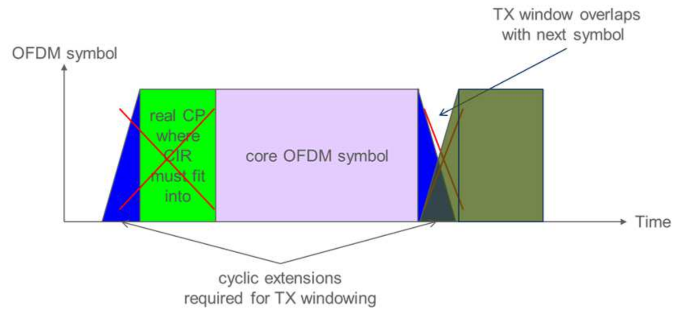
The inter-numerology interference can be reduced by either applying time-domain filtering per numerology (sub-band) or time-domain windowing. In the following, we consider windowing approach due to its low complex implementation and superior performance [9].

A. Transmitter Windowing

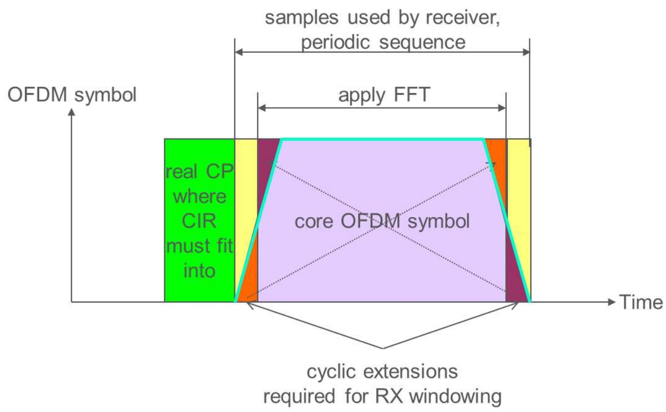
The main reason for the slow decay of OFDM spectrum is signal discontinuities at OFDM symbol boundaries. With transmitter windowing, the boundaries of each OFDM symbol are multiplied with a smooth slope in time-domain, increasing smoothly from 0 to 1 (increasing slope) or 1 to 0 (decreasing slope), see Fig. 4b. The increasing slope is applied at the beginning of the cyclic prefix while the decreasing slope is applied after the end of the core OFDM symbol within an extra added cyclic suffix. Fig. 4b also shows that the increasing slope of the next OFDM symbol overlaps with the decreasing slope of the previous OFDM symbol. Since the receiver keeps only the samples of the core OFDM symbol, transmitter windowing is transparent to the receiver.



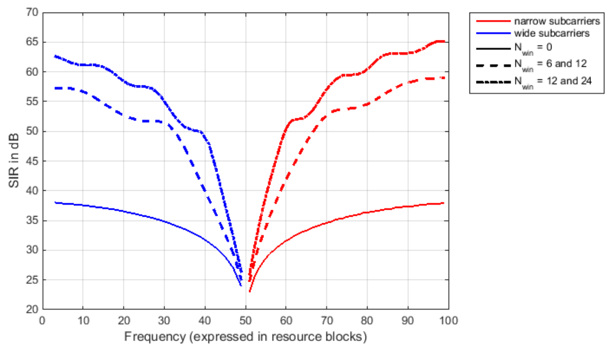
(a) Inter-numerology interference.



(b) An illustration of transmitter windowing.



(c) An illustration of receiver windowing.



(d) Windowing reduces inter-numerology interference.

Figure 4: Transmitter and/or receiver windowing is an attractive option if different OFDM numerologies are mixed on the same carrier.

B. Receiver Windowing

A standard OFDM receiver cuts out the desired OFDM symbol period by applying a rectangular window in time-domain to the received signal and subsequently applies an FFT. Application of a rectangular window in time-domain corresponds to convolution in frequency-domain with a sinc-like function. The sinc-like function leads to high interference pick-up from adjacent non-orthogonal signals such as OFDM signals with other numerologies. To reduce interference pick-up, the rectangular window must be replaced by a smooth window function. To this end, a smooth increasing window slope is applied at the boundary between cyclic prefix and core OFDM symbol (half within cyclic prefix and half within core OFDM symbol); a decreasing smooth window slope is applied at the boundary between core OFDM symbol and added cyclic suffix, see Fig. 4c. If the applied window slopes fulfil the Nyquist criteria (i.e. they are centre asymmetric) the signal part cut away by the decreasing windowing slope (indicated by the upper-right orange triangle in Fig. 4c) is the same as the remaining signal part after application of the increasing window slope within the cyclic prefix (indicated by the lower-left orange triangle in Fig. 4c since the cyclic prefix is a copy of the last part of OFDM symbol. If the windowed cyclic prefix part (lower-left orange triangular in Fig. 4c) is added to the last part of the core OFDM symbol the core OFDM symbol is restored at its second boundary. The core OFDM symbol can also be restored at the first symbol boundary by applying the same trick. Now the complete OFDM is restored and subcarriers are orthogonal again. The FFT is applied to the restored core OFDM symbol as indicated in Fig. 4c. Interference pick-up remains reduced as long as the interference does not have a periodicity equal to the OFDM symbol duration.

In Fig. 4d, we show the effect of transmitter and receiver windowing on inter-numerology interference assuming 15 kHz and 30 kHz numerologies (cf. Table II) multiplexed in frequency domain. It can be observed that windowing substantially increases the achievable Signal-to-Interference Ratio (SIR). (SIR is averaged across subcarriers within one resource block which is assumed 12 subcarriers.) Windowing has extremely low complexity. Only the windowed samples are scaled and overlap-and-add over the windowed periods is performed.

VI. Conclusions

We proposed a symmetric physical layer for all link types (e.g., UL, DL, sidelink, backhaul link) based on OFDM with scalable numerology. OFDM was assessed for a number of performance indicators, link types, and frequency ranges. We observed that OFDM is an excellent choice for all link types in NR, due to its high time localization, low complex transceiver design, high spectral efficiency and easy integration with MIMO technologies. The main drawback of OFDM (like all multi-carrier waveforms) is its high PAPR, which can be a limitation at very high frequencies. There exist well-known methods to reduce PAPR of OFDM with minor degradation in performance. OFDM with PAPR reduction can be particulary useful for UL and sidelink. For very high frequencies, DFTS-OFDM may also be an interesting waveform due to its low PAPR and frequency domain equalization. However further investigations are necessary to conclude if DFT precoding is necessary at very high frequencies.

We proposed a family of OFDM numerologies considering implementation complexity, phase noise robustness and realistic channel delay spreads at different carrier frequencies. The proposed family of numerologies consists of a base numerology and the remaining numerologies in the family are derived by scaling up the subcarrier spacing and scaling down the cyclic-prefix of the base numerology by the same factor. The scaling approach is simple implementation wise. Enabling different numerologies merely requires scaling of the sampling clock frequency without changing any other waveform (OFDM) parameter. Furthermore, the preferred option for the numerology scaling factor is 2^L times the base numerology, where L is an integer. Such scaling is important to allow two neighbouring TDD networks to enable two different numerologies without any resource waste (i.e., without using guard time). The preferred choice for the base numerology is LTE numerology due to various reasons. The most important reason is co-existence with NB-IOT, for which 3GPP has already specified LTE numerology. Finally, we showed that if different numerologies are multiplexed on the same carrier, then the low complex (transmitter/receiver) windowing of OFDM can be useful to significantly suppress inter-numerology interference.

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