OFDM Numerology Design for 5G NR

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***Abstract*—The 5th Generation New Radio (5G NR) mobile network, is a new Radio Access Technology (RAT) developed by the 3rd Generation Partnership Program, which is envisioned to work with various frequency bands, namely FR1 and FR2 Frequency bands. [3] The use cases designed have a greater vision than just eMBB (Enhanced Mobile Broadband) but also include URLLC (Ultra Reliable Low Latency Communications), mMTC (Massive Machine Type Communications), and MBSFN (MultiMedia Broadcast Single Frequency Network). To support all these use cases, which have different design aspects and implementations including the likes of required Cyclic Prefix Length and sub-carrier spacing, 5G NR makes use of the numerology parameter. In this paper we are going to take a deep dive into the intricacies of design implementations of different numerologies and the constraints (like symbol alignment in slots, phase noise, delay, doppler spread, multiplexing numerologies in TDD and FDD, etc.) we have to keep in mind to implement the same. [1]**

***Index Terms*—3GPP, 5G NR, LTE, numerology, sub-carrier spacing, CP length, OFDM**

I. Introduction

ONE may also ask what are the main differences between 4G LTE and 5G NR? There are many starting from the core network implementation, as LTE uses Evolved Packet Core (EPC) while 5G NR uses 5GC. 5G has the capability of providing a latency of 1 ms, while 4G has a latency of 30-50 ms, which opens up the window of applications for real-time applications like autonomous vehicles and remote surgeries. 5G can provide up to 20 Gbps while 4G can provide up to 1 Gbps. 5G supports network slicing, which provides virtual connections, and in the following section, we will see its use cases. 5G also supports higher connection density, 1 million devices per square kilometer vs 100,000 for 4G. In the Discontinuous reception cycle, 5G introduces a new state INACTIVE_MODE for the UE, which is a tradeoff between power efficiency and latency. Also, there are differences in the frame structure of 5G NR which shall be elaborated on later, but owing to its big size, there was a need to support a smaller scale scheduling known as mini-slot scheduling, in which we are able to schedule for symbols within a slot, which is a new concept in 5G NR. [7] Mini slots enable 5G NR to support time-sensitive applications, such as URLLC applications like industrial automation, vehicle-to-everything (V2X) communication [6], and remote control of critical infrastructure. By using mini slots, 5G NR can dynamically allocate resources to meet the diverse requirements of different use cases and applications. There are many more differences but hopefully, it is clear that 5G NR is the future and it is important to study it.

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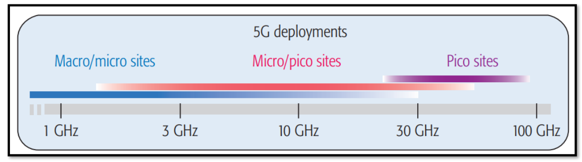

Fig. 1: Cell Size vs Carrier Frequency

Another important aspect of 5G includes its frequency bands for transmission (Figure 1) which include a. Frequency Range 1 (FR1): Sub-6 GHz bands, which include both low-band frequencies (below 1 GHz) and mid-band frequencies (1-6 GHz). These bands provide a good balance between coverage and capacity and b. Frequency Range 2 (FR2): Millimeter-wave (mmWave) bands, which include frequencies above 24 GHz. These bands offer very high data rates and capacity but have limited coverage due to higher propagation losses and susceptibility to obstacles. [3]

Before we talk about the various use cases and numerology design constraints, it is imperative we first understand the basics of 5G NR which are important for understanding all the topics related to numerology design.

II. Frame Structure

The 5G NR frame structure [1](Figures 2 and 3) consists of the following components:

1) **Frame:** A frame is the basic unit of the 5G NR time-domain structure. It has a duration of 10 ms and is divided into ten equally sized subframes.
2) **Subframe:** A subframe is a smaller unit within a frame, with a duration of 1 ms. Each subframe consists of 14 OFDM (Orthogonal Frequency Division Multiplexing) symbols in the time domain and is further divided into slots.
3) **Slot:** A slot is the smallest unit of the 5G NR time domain structure, containing 14 OFDM symbols, and the details of the OFDM symbol will be spoken about immediately afterwards. The number of slots in a subframe depends on the subcarrier spacing, which can vary from 15 kHz to 480 kHz. The higher the subcarrier spacing, the shorter the slot duration, and the more slots in a subframe. Given a numerology n, the number of slots within a subframe is equal to 2^n.
4) **Resource Block:** A resource block (RB) is a group of contiguous subcarriers in the frequency domain. In 5G NR, a resource block consists of 12 subcarriers. The total number of resource blocks in a channel depends on the channel bandwidth.
5) **Resource Grid:** A resource grid is a two-dimensional matrix representing the time-frequency structure of a

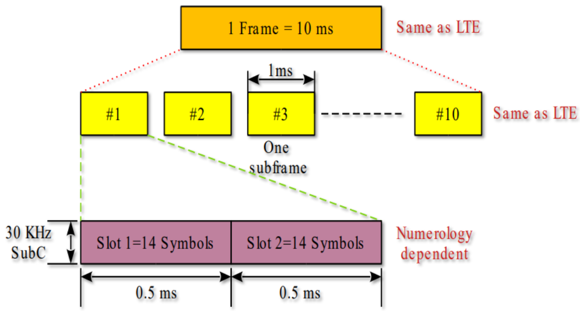

Fig. 2: Frame structure

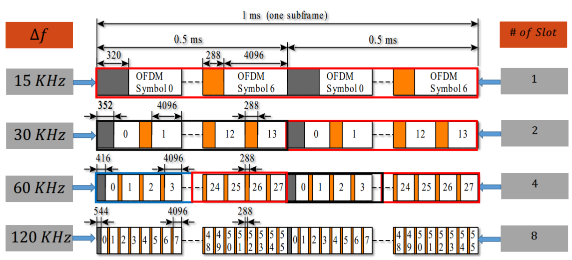

Fig. 3: Varying slot divisions with numerology

slot. It consists of multiple resource blocks in the frequency domain and multiple OFDM symbols in the time domain. Each cell in the resource grid is called a resource element.

6) **Resource Element:** A resource element (RE) is the smallest unit in the 5G NR resource grid, representing one subcarrier in the frequency domain and one OFDM symbol in the time domain. Data and control information is transmitted over the air interface using resource elements.

III. OFDM Symbol

OFDM (Orthogonal Frequency Division Multiplexing) is a key technology used in 5G NR to transmit data over the air interface. It isn't a new concept, it was used in LTE for downlink transmission, while for 5G, this is available for both downlink and uplink. It is a multi-carrier modulation scheme that divides the available bandwidth into multiple, closely spaced subcarriers. Each subcarrier carries a modulated data symbol, and these symbols are transmitted simultaneously. The OFDM symbol is an essential component of the 5G NR frame structure. Their properties are: -

1) **Orthogonality:** The term "orthogonal" in OFDM refers to the mathematical property of the subcarriers, which ensures that they do not interfere with each other. The subcarriers are designed with a specific spacing so that their peaks align with the nulls of the adjacent subcarriers. This orthogonality allows efficient utilization of the available spectrum and minimizes inter-carrier interference (ICI). [5] We can see this is Figure 4a.
2) **Cyclic Prefix (CP):** The cyclic prefix is a technique used in OFDM to combat the effects of multipath propagation, which can cause inter-symbol interference (ISI). It involves copying a portion of the end of an OFDM symbol and appending it to the beginning of the same symbol. This creates a guard interval between consecutive OFDM symbols, allowing the receiver to distinguish between them even in the presence of multipath reflections. The cyclic prefix also maintains the orthogonality of the subcarriers, as it preserves their relative phase relationships. The various configurastions for different numerologies is defined in the table, figure 5.
3) **Subcarrier Spacing:** In 5G NR, the subcarrier spacing is a critical parameter that determines the duration of an OFDM symbol and the number of slots in a subframe. It can vary from 15 kHz to 480 kHz, depending on the use case and deployment scenario. Higher subcarrier spacing results in shorter OFDM symbol durations and more slots per subframe, which can be beneficial for low-latency applications. However, it also increases the sensitivity to frequency offsets and Doppler shifts, making it more challenging to maintain orthogonality.
4) The **Subcarrier Spacing** and **Cyclic Prefix** as mentioned above are subjected to scaling. The scaling parameter is the numerology and for a corresponding numerology, we have specific Cyclic Prefix and Sub Carrier Spacing as set by the 3GPP norms.
5) **Modulation Schemes:** The data symbols transmitted on the OFDM subcarriers can be modulated using various modulation schemes, such as QPSK (Quadrature Phase Shift Keying), 16-QAM (Quadrature Amplitude Modulation), 64-QAM, or 256-QAM. The choice of modulation scheme depends on the channel conditions and the desired trade-off between data rate and robustness.

IV. Use Cases

A. *eMBB - Enhanced Mobile Broad Band*

eMBB is designed to provide an enhanced mobile broadband experience to users, delivering faster data rates, lower latency, higher capacity, and improved network performance compared to previous generations of wireless networks. In 5G NR, eMBB is achieved through the use of new radio technologies, including higher frequency bands, wider channel bandwidths, and advanced modulation and coding schemes. These technologies enable the 5G network to deliver data rates up to several gigabits per second. One of the key features of 5G NR that enables eMBB is the use of mmWave frequency bands, which operate in the range of 24 GHz to 100 GHz. These high-frequency bands provide a significantly wider bandwidth than lower-frequency bands. However, mmWave signals have a shorter range and are more prone to attenuation, which requires the use of new antenna technologies and beamforming techniques to overcome these challenges. [9] Another feature of 5G NR that enables eMBB is the use of wider channel bandwidths, which can be up to 400 MHz. In addition to these features, 5G NR also uses advanced modulation and coding schemes, such as 256-QAM and LDPC coding, to further improve spectral efficiency and enable higher data rates. Overall, eMBB is expected to enable new applications

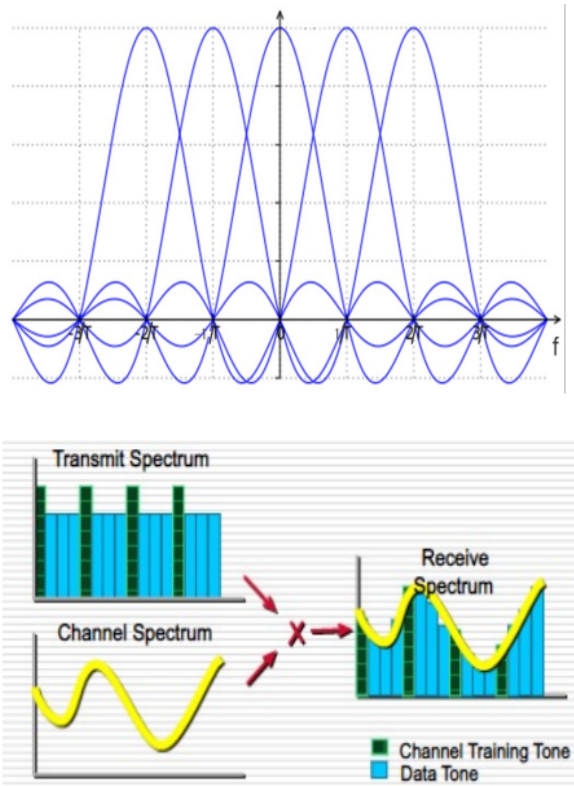

Fig. 4: OFDM symbol structure. a.) shows the orthogonality in frequency domain b.) shows that due to sub-carriers a frequency selective channel appears flat fading at sub-carrier level

μ	$\Delta f = 2^{\mu}.15$ KHz	Useful Symbol Duration $T_u = 1/\Delta f$	Cyclic Prefix (CP) Duration T_{cp}	FR1	FR2	Number of slots per frame N_{slot}^{frame}	Slot Duration T_{slot} (Min scheduling Interval)
0	15 KHz	66.67 μs	4.69 μs	√	×	10	1 ms
1	30 KHz	33.33 μs	2.34 μs	√	×	20	0.5 ms
2	60 KHz	16.67 μs	1.17 μs	√	√	40	0.25 ms
3	120 KHz	8.33 μs	0.57 μs	×	√	80	0.125 ms
4	240 KHz	4.17 μs	0.29 μs	×	√	140	0.0625 ms

Fig. 5: Frame configurations for numerologies

that require high data rates and low latency, such as virtual and augmented reality, high-quality video streaming, and cloud gaming. It is also expected to provide a better user experience for existing applications, such as web browsing and social media, by delivering faster data rates and lower latency. [4]

B. URLLC - Ultra-Reliable Low-Latency Communication

URLLC or Ultra-Reliable Low-Latency Communication [10] is a key feature of the 5G New Radio (NR) technology, designed to support mission-critical applications that demand high reliability and low latency. URLLC is essential for enabling various use cases, such as industrial automation, autonomous vehicles, remote surgery, and smart grid management. URLLC aims to provide a high level of reliability, typically up to 99.999% (also known as ”five nines” reliability). This means that the probability of a packet being successfully transmitted within a specified latency budget is extremely high, ensuring that critical data is delivered with minimal risk of failure. URLLC targets end-to-end latency as low as 1 millisecond, which is significantly lower than the latency offered by previous generations of mobile networks. This low latency is crucial for applications that require real-time communication and rapid response times, such as remote control of machinery or vehicle-to-vehicle communication. Also, To achieve the desired reliability and latency, 5G NR employs advanced scheduling and resource allocation techniques. These include flexible numerology, mini-slot-based scheduling, and pre-emption of lower-priority traffic. These techniques allow the network to dynamically allocate resources to URLLC traffic, ensuring that it meets the stringent requirements. URLLC can benefit from multi-connectivity, which involves simultaneous connections to multiple base stations or network nodes. This redundancy helps to improve reliability by providing alternative paths for data transmission in case of a failure in one of the connections. Also, 5G NR supports network slicing, which allows operators to create virtual networks tailored to specific use cases. A dedicated network slice can be created for URLLC applications, ensuring that they receive the necessary resources and priority over other types of traffic.

C. mMTC - Massive Machine-Type Communication

mMTC or Massive Machine-Type Communication is another key feature of the 5G NR, designed to support a large number of connected devices and enable the Internet of Things (IoT) applications. [9] Some use cases include smart cities, agriculture, logistics, and environmental monitoring. mMTC aims to support a high device density, with the capability to connect up to 1 million devices per square kilometer. This scalability is essential for accommodating the growing number of IoT devices and sensors in various industries. Also, Devices connected via mMTC are often battery-powered and expected to have long lifetimes, sometimes up to 10 years. To achieve this, 5G NR incorporates power-saving features such as extended Discontinuous Reception (eDRX) and Power Saving Mode (PSM), which allow devices to enter low-power states when not actively transmitting or receiving data. It is also noteworthy that mMTC devices typically transmit small amounts of data infrequently, with data rates ranging from a few bits per second to a few kilobits per second. [8] To support this, 5G NR employs narrowband transmission schemes and optimized radio resource allocation for small payloads. Furthermore, mMTC devices may be deployed in challenging radio environments, such as deep indoors or in remote areas. To ensure reliable connectivity, 5G NR includes coverage enhancement techniques, such as the repetition of transmissions and advanced coding schemes, which improve the link budget and extend the coverage area. To reduce device complexity and cost, mMTC devices can have simplified radio designs with reduced bandwidth and processing capabilities and this is made possible by the usage of single antenna devices, Bandwidth Parts, and flexible numerology. And also, similar to URLLC, mMTC can also benefit from network slicing. A dedicated network slice can be created for mMTC applications, ensuring that they receive the necessary resources and priority over other types of traffic. Lastly, To reduce

Table: Importance of various requirements for each Use Case

	Maximum Connection Throughput	Average Connection Throughput	Spectrum Efficiency	Area Traffic Capacity	Connection Density	Latency	Mobility	Network Energy Efficiency
eMBB	High Importance	High Importance	High Importance	High Importance	Medium Importance	Medium Importance	High Importance	High Importance
URLLC	Low Importance	Low Importance	Low Importance	Low Importance	Low Importance	High Importance	High Importance	Low Importance
mMTC	Low Importance	Low Importance	Low Importance	Low Importance	High Importance	Low Importance	Low Importance	Medium Importance

Fig. 6: 3GPP defined focus areas for different use cases

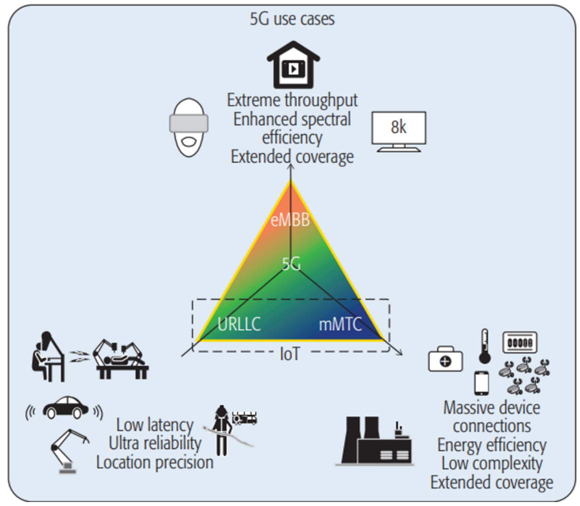

Fig. 7

signaling overhead and improve network efficiency, 5G NR supports grant-free access for mMTC devices. This allows devices to transmit data without the need for explicit scheduling grants from the network, simplifying the communication process and reducing latency.

D. MBSFN - Multicast-Broadcast Single Frequency Network

MBSFN or Multicast-Broadcast Single Frequency Network is a feature in 5G NR that enables efficient delivery of multicast and broadcast services. MBSFN allows the simultaneous transmission of the same content to multiple users within a specific area, making it suitable for applications such as live video streaming, emergency alerts, and digital signage. Foremostly, MBSFN operates as a Single Frequency Network, meaning that all base stations (gNBs) involved in the multicast or broadcast transmission use the same frequency and transmit the same content synchronously. This approach helps to improve signal quality and coverage, as the signals from multiple base stations can be constructively combined at the receiver. [9] Importantly, In 5G NR, MBSFN transmissions are allocated specific resources within the radio frame structure. These resources, known as MBSFN subframes, are reserved for multicast and broadcast services, ensuring that they do not interfere with unicast transmissions which can dynamically be configured. Also, MBSFN provides a scalable solution for delivering content to a large number of users simultaneously. By using multicast and broadcast transmissions, the network can efficiently distribute the same content to multiple users without the need for individual unicast connections, reducing the overall network load and improving spectral efficiency. MBSFN benefits from coverage enhancement techniques, such as higher-order modulation and coding schemes, transmission repetition, and beamforming. These techniques help to improve the link budget and extend the coverage area, ensuring that users in challenging radio environments can still receive the multicast or broadcast content. Overall, MBSFN services can be delivered more efficiently and with lower latency compared to traditional unicast transmissions. [4]

V. Numerology Design Constraints

A. Symbol Alignment and Mini Slot Transmission

A lot of this was discussed during the frame structure and use cases, but this is an important design aspect to be kept in mind and we will try to distill all the relevant information now. So far we have discussed and learnt that given a numerology n, the subcarrier spacing is equal to $15 * 2^n$, we have 2^n number of slots, and based on the channel hostility and delay spread (shall be spoken about in detail later), we have a fixed, corresponding Cyclic Prefix, whose length decreases with increasing n. Now upon looking at figure 3, we can see that there is a need to have a few symbols with an extended Cyclic Prefix so that we can fit an integer number of slots within a subframe and the mathematics behind it is also fairly simple. This Time Domain Alignment of the slot is important to allow time-aligned uplink and downlink transmission. [2]

3GPP has designed 5 numerologies, 0, 1, 2, 3, and 4. Negative numerologies (-1 and -2) although not part of the 3GPP 5G NR standard, have been proposed in the research literature to explore the potential benefits of using smaller subcarrier spacings for specific use cases, such as low-frequency bands and narrowband IoT (NB-IoT) applications. [12]

Negative Numerology with μ = -1, the subcarrier spacing becomes 15 kHz × $2^{(} - 1)$ = 7.5 kHz. This smaller subcarrier spacing can potentially improve spectral efficiency and reduce the impact of inter-symbol interference (ISI) in low-frequency bands. It may also provide better coverage and penetration for indoor and deep-indoor environments.

Negative Numerology with μ = -2, the subcarrier spacing becomes 15 kHz × $2^{(} - 2)$ = 3.75 kHz. This even smaller subcarrier spacing can further enhance the benefits mentioned for μ = -1. However, it also increases the symbol duration, which may result in higher latency and reduced capacity.

Another important concept introduced in 5G was a mini-slot transmission. [7] This arises due to the longer 14 OFDM symbol configuration, and also for meeting the latency needs of low latency applications such as URLLC. Mini-slot transmission is a method of Time division/domain multiplexing, in which we can service multiple services at the same time, in which we don't need to schedule and wait for an entire slot, but we can schedule at symbol level within each slot. Technically speaking, In front loaded DM-RS, and PDSCH type b type communication we can schedule for 2, 4, 6 symbols or 2, 4, 7 symbols in case of extended CP case. From the table (Figure 10), we can see the various types of configurations and from the diagram, we can see how it looks at the symbol level.

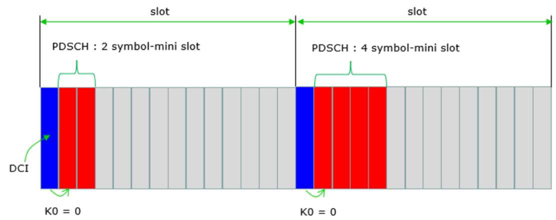

Fig. 8: High level overview of Mini-Slot transmission

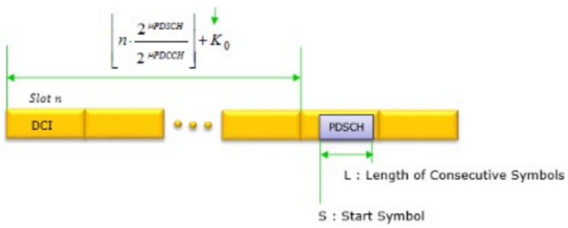

Fig. 9: Symbol offset for Mini Slot transmission

There is symmetricity for Uplink, where we have UCI instead of DCI and PUSCH instead of PDSCH (Figure 8 and 9).

B. Phase Noise

Phase noise is defined as the noise arising from the rapid, short-term, random phase fluctuations that occur in a signal. [14] These random fluctuations are caused by time domain instabilities called phase jitter. It is very easily visualisable in the frequency domain.

As you can see from Figure 11, there is a spread in the phase or frequency component. Ideally, a local oscillator would produce a sinusoidal signal, whose power spectrum is a delta function at the carrier frequency, but in reality, its output power appears also in a band around the desired frequency.

Causes:-

1) As already discussed, **Phase jitter**: This is caused by fluctuations in the local oscillator that produces the local carrier and also the one at the receiver.
2) **Thermal noise:** This is termed as the noise that is generated by the random motion of electrons in a conductor due to temperature fluctuations. In wireless communication, this can be observed at the circuitry of the receiver.
3) **Flicker Noise and other nonlinear noises** in the circuitry of the receiver add to the phase noise as well. Flicker noise has a special property of having high power at low frequencies which is contrary to the normal behavior of phase noise having a proportional positive relation with carrier frequency, in general, there is a 6dB gain in phase noise for doubling of carrier frequency. [14]

PDSCH mapping type	Normal cyclic prefix			Extended cyclic prefix		
	S	*L*	*S+L*	*S*	*L*	*S+L*
Type A	{0,1,2,3} (Note 1)	{3,…,14}	{3,…,14}	{0,1,2,3} (Note 1)	{3,…,12}	{3,…,12}
Type B	{0,…,12}	{2,4,7}	{2,…,14}	{0,…,10}	{2,4,6}	{2,…,12}
Note 1: S = 3 is applicable only if *dmrs-TypeA-Position* = 3						

Fig. 10: Possible values of S and L in SLIV (Type B allows Mini-slot transmission)

Effects:-

1) **Common Phase Error (CPE):-** CPE [1] describes the average of the phase noise sequence spanning an OFDM symbol. This causes imperfect synchronization between the transmitter and receiver and therefore, can impact system performance and increase BER. Although, this effect is fairly easy to mitigate and there are 2 ways: -
   a) Through the use of a phase-locked loop (PLL) at the receiver. A PLL is a feedback system that adjusts the phase of the receiver's clock to match the phase of the incoming signal. By continuously tracking and correcting for CPE, the PLL can help to improve the accuracy of demodulation and decoding.
   b) Through the use of pilot subcarriers to estimate channel noise. Let's recall the example from class, MCS-16 case, In 1 Physical Resource Block (PRB) spanning 14 OFDM symbols, there were 162 data subcarriers, and 6 pilot subcarriers. Those subcarriers are used to transmit bits that the receiver expects. The receiver can then statistically estimate the channel and make use of PT-RS [13] to statistically estimate the noise and using these measurements, we generate de-noised received input.
2) **Inter Carrier Interference (ICI):-** In OFDM systems, as we already know, the signal is divided into multiple subcarriers that are modulated with data symbols and these subcarriers are closely spaced in frequency and are orthogonal to each other, which means that they do not interfere with each other in ideal conditions. But due to phase noise, they do, and this deteriorates the system performance as the receiver won't be able to detect the signal error-free. In some cases, the receiver can mitigate the effects of ICI through techniques such as equalization or frequency and phase synchronization. However, in severe cases, where the interference is too strong, the receiver may not be able to fully compensate for the ICI, and the overall system performance may be significantly degraded. The way to avoid ICI is by choosing a higher subcarrier spacing so that the orthogonal frequency components are spaced sufficiently apart.

Now to see the effect of phase noise on numerology, we make use of simulations. From our own simulation result as seen in Figure 12, which is based on the mmMagic project [1], we can see that for a given SIR (Signal to Interference ratio), the Power Spectral density decreases for phase noise for increasing subcarrier spacings or frequency offset (experimented with 6, 28 and 82 GHz oscillator frequencies with the fixed bandwidth of 100 MHz). Figure 13 is from a simulation done by the referenced paper [1], which again was based on the mmMagic project, which actually motivated us to simulate the previous result. It's clearly visible that, with an increasing subcarrier spacing, the Signal-to-Interference ratio increases, regardless of the oscillator frequency used. [21] [22]

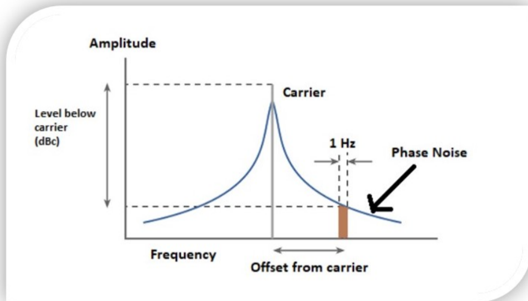

Fig. 11: Frequency domain visualisation of Phase Noise

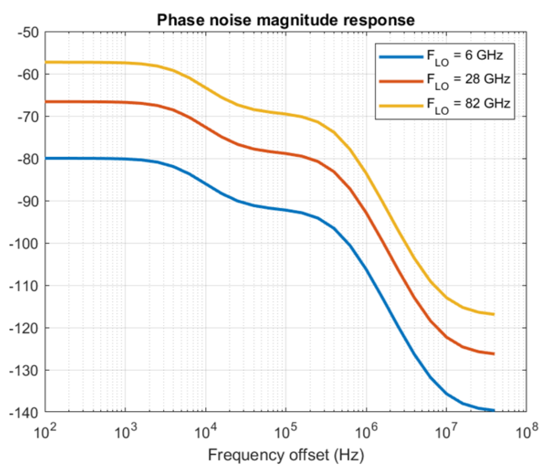

Fig. 12: Our simulation of Phase Noise PSD vs different sub-carrier spacings at different carrier frequencies

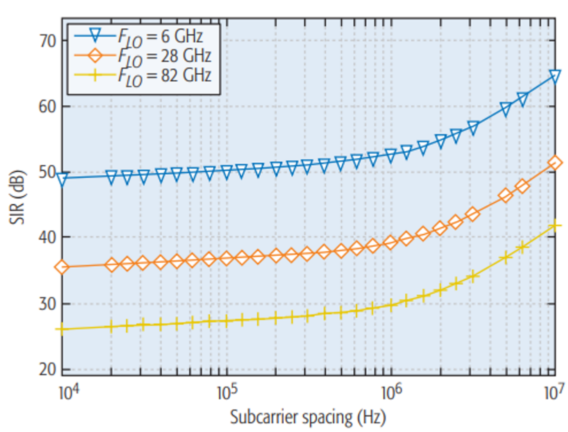

Fig. 13: Simulation of SIR vs different sub-carrier spacings at different carrier frequencies [1]

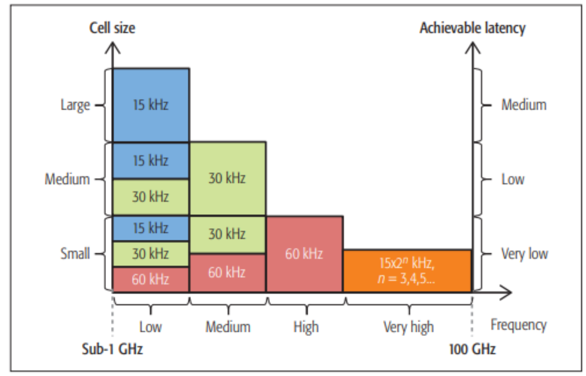

Fig. 14: Cell size vs achieveable latency vs carrier frequency with respect to different numerologies

C. Delay Spread

Delay spread is the difference in arrival times of different copies of a transmitted signal at the receiver due to multipath propagation in a wireless channel (Figure 15). When a signal is transmitted in a wireless channel, it can reach the receiver by multiple paths, each path having a different length and hence a different propagation delay. These multiple copies of the signal can overlap and interfere with each other, causing ISI (inter-symbol interference) which can degrade the quality of the received signal. [15]

The way we overcome the delay spread is by choosing a cyclic prefix that is longer than the delay spread so that there is enough spacing between the symbols.

Typically, the delay spread reduces with the cell size, Therefore, the required cyclic prefix length also drops. Therefore, to find common ground with preventing phase noise, we can choose a big enough carrier frequency, which directly correlates to a smaller cell size so the delay spread also drops, and the cyclic prefix is larger than the delay spread and choose a subcarrier spacing high enough to avoid ICI. Figure 14 beautifully describes the relations between the cell size, latency achievable, and carrier frequency varying with respect to the numerology or sub-carrier spacing. Higher sub-carrier spacings correspond to small cell sizes due to hostile channels, lower achievable latencies, and lower carrier frequencies. Whilst, lower sub-carrier spacings correspond to big cell sizes, relatively higher latency, and relatively higher carrier frequency. [15]

D. Doppler Spread

In an OFDM system, relative mobility between a user and an access node causes Doppler Effect (Figure 16). This may lead to both ISI as well as loss of orthogonality or ICI. Doppler effect also increases with the carrier frequency. But at small cell sites, it can be negligible. As we have already seen, cell size decreases with higher carrier frequencies/sub-carrier spacings, therefore, doppler spread may impose a lower limit on the choice of numerology as by choosing a higher sub-carrier spacing we are increasing the distance between the sub-carriers in the frequency domain making them less susceptible to ICI. [16] One thing to keep in mind is that choosing higher

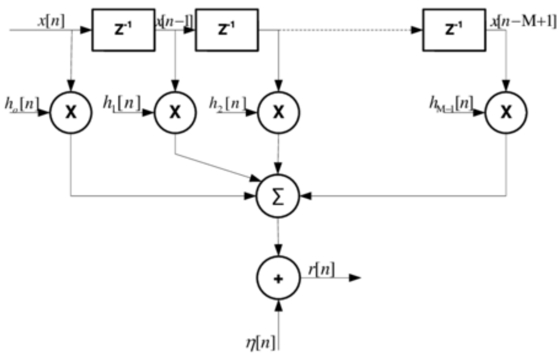

Fig. 15: Delay Spread from a multipath system

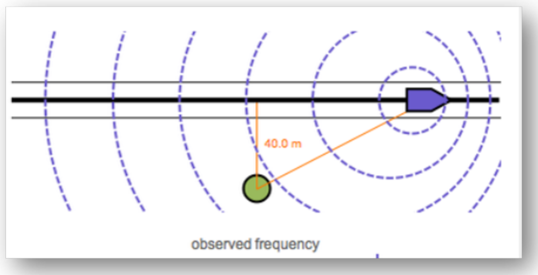

Fig. 16: Doppler spread arising from relative velocity between gNB and UE

sub-carrier spacings may be alluring, but there is a tradeoff with spectral efficiency, as we are reducing the number of sub-carriers within a given bandwidth.

E. Multiplexing different services

By now we have seen that there are numerous different aspects to keep in mind before deciding upon our numerology, as we have to keep in mind the limits set by the phase noise, delay spread, and Doppler spread and all the imperfections posed by the channel. Now we would like to talk about another scenario that needs to be kept in mind for deciding the numerology for a particular service. As we have already discussed, different services (URLLC, eMBB, mMTC, MB-SFN) have different requirements. Therefore if we want to serve them simultaneously in one carrier, there are two ways we can do that, a.) Mini-slot transmission and b.) Multiplexing in the frequency domain. We have already spoken about Mini Slot Transmission, therefore, we would like to now focus on Multiplexing different numerologies in the frequency domain [17]

It is easy to implement in FDM, but there are numerous drawbacks. Firstly, as we have seen in all the cases of phase noise etc., there will be a loss of orthogonality, and in this case, there will be a loss of orthogonality between different numerology subcarriers, as the subcarriers are only orthogonal to each other in the same numerology. There will be energy leaks outside the subcarrier bandwidth and it will be picked up by other subcarrier filters of different numerology. This interference with each other leads to the phenomenon of inter-numerology interference(INI). [11]

To mitigate the effect of INI, we first have to perform spectral confinement, (which we will elaborate on in much greater detail), add guard bands between numerologies to restrict their interference, [11] and the guard band would usually be 8 times the smaller subcarrier spacing width. And also we may have to add extended CP to the higher subcarrier spacing numerology which has a smaller CP length.

Spectral Confinement [17] is an important tool to reduce out-of-band emissions, which are nothing but energy leaks outside of the bandwidth allocated for the subcarriers for each numerology. To measure Out of Bands emissions, we make use of Spectral Roll Off, which refers to the rate at which the power of a signal decreases as the frequency moves away from the carrier frequency. It is a measure of how quickly the power of the signal decreases as the frequency increases or decreases. Simply put, a steeper spectral roll-off indicates that there is a rapid reduction of power outside the carrier frequency, and therefore it contributes lesser to out-of-band emissions. Therefore, we should try to have a steep Spectral Roll-Off. As you can see from Figure 17, which we have simulated on our own, there is a steeper spectral roll-off for a lower sub-carrier spacing. And in general, there is an increase in steepness for lower subcarrier spacing and numerology. Therefore, this sets an upper limit on numerology.

Also, in Figure 18a.), you can see the effects of having a higher subcarrier spacing. [1] In the diagram, there are two cases, in which both of them have the multiplexing of a higher aggressor numerology(dash-dotted lines), and a victim, lower numerology(bold lines). The red line case is the one where there is no filtering applied at the transmitter or receiver, and the blue line case indicates when filtering is applied. As we have already discussed, higher numerology or aggressor numerology has a higher spectral roll-off, and therefore, the victim numerology catches a lot of interference from the aggressor numerology's out-of-passband emissions. And we can see in the filtered case, where filtering is applied at the aggressor transmitter and victim receiver, there is much lesser INI and ideal behavior. The filter designs are seldom complicated, but we can use band-pass, Butterworth filters, Chebyshev filters, and Elliptic filters. Our choice of filter would depend on the specific requirements of the system, such as attenuation requirements, and transmission bandwidth.

There is however another less complex solution to spectral confinement with filtering, which is windowing as shown in Figure 18b.). [1] The setup is a TLD-A tapped channel model with a 1000ns RMS Delay Spread model, we multiplex a 15kHz numerology with 60kHz and plot its throughput. The blue line represents the windowed technique used for Spectral confinement in the multiplexed environment with a guard subband of 8*15kH = 120kHz, and the red line demarcates a simple non-windowed single numerology OFDM case, and we can see, even with a huge, greater than normal delay spread, due to guard banding and windowing, we are able to achieve near ideal transmission throughput while servicing two numerologies in the same carrier. Just as in filtering, we have multiple choices of windows, Hann, Blackman, and Kaiser

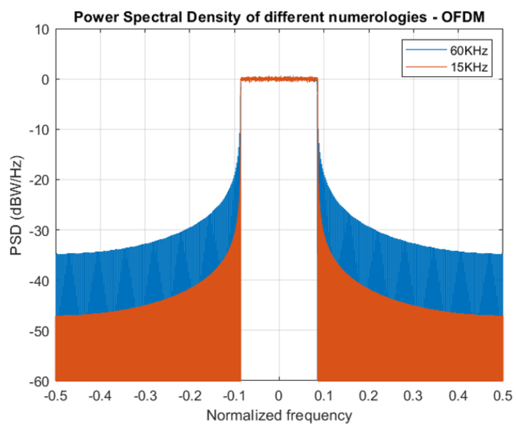

Fig. 17: Our simulation results for Spectral Roll-off with 15 and 60 kHz sub-carrier spacing's

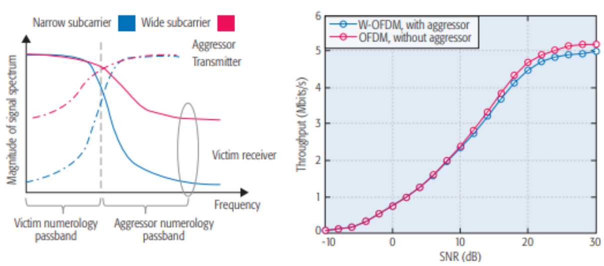

Fig. 18: Simulation results of FDM multiplexing services. a.) Example of filtering. b.) Example of Windowing [1]

windows. [18] The difference between windowing and filtering also lies in the domain in which they function, windowing works in the time domain, and filtering works in frequency. Also, windowing is performed after the signal is transmitted, while filtering happens after transmission. And windowing is usually easier for large bandwidths, which benefits us, as this is more important for wider, aggressive numerologies. Therefore, windowing is a less complex and equally viable alternative to Filtering.

VI. Conclusion and Future Aspects

In this paper, we have seen from the bottom up how the 5G frame structure is, how it is different from 4G LTE, and what are the various 3GPP guidelines which drive the innovation of this technology forward. We have taken a look at how 5G has enabled scalable sub-carrier spacing and frame structures with the numerology parameter. We then saw why this scalability is important after taking a deep dive into the small intricacies of various important use cases which have a high significance in the current day and age.

The main and most significant part of the paper was to understand the implementations and consequences of choosing a numerology given particular constraints. We saw how different numerologies affect the subframe at the time domain and we have to perform alignment, and we introduced the concept of Mini-Slot transmissions so that we can meet low latency requirements and also service multiple numerologies or services within a slot or with a single carrier. We were able to see with the help of our simulations how phase noise affects different sub-carrier settings at various carrier frequencies and how it applies a lower limit on numerology if we want to retain the SIR. We were also able to look at how theoretically Doppler and delay spread affect our numerology selection.

Multiplexing in the frequency domain, its challenges (INI), and its mitigation with Spectral Confinement were also seen in detail.

However, this was not an exhaustive paper and we feel this can be extended to the following ideas:-

1) **Dynamic Adaptive Numerologies:-** The following publication referenced [19] is a statistical and analytical approach towards solving the problem of numerology design. The publication is a Python simulation of a fully 5G compliant model, with a dynamically adapting numerology to the channel conditions, etc.
2) **Machine Learning solutions for numerology design:-** The following publication references are a reinforcement learning-based solution for network-aware slicing for deterministic and non-deterministic traffic. The crux is, during simulations and using a reinforcement learning framework, the node can understand and learn how to design the numerology given the channel parameters, and owing to multiple runs and its structure has the capability to learn very deep correlations in data on the fly and then work well in test time as well. [20]

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