Beam Management and Inter Numerology Interference in 5G NR

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **Beam Management and Inter Numerology Interference in 5G NR**, submitted by **K R Avyakta**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Beamforming, Beam management, Precoding, Inter-Numerology Interference

The aim of this thesis is to present a low complexity algorithm for Hybrid beamforming in 5G systems. We assume a MISO system, but the algorithm can easily extended to MIMO as well. We also present a brief analysis of the Inter Numerology interference problem arising in the Multi numerology OFDM systems.

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CHAPTER 1

INTRODUCTION

The following thesis consists of two parts. In Chapter 1, we will talk about Beam management in 5G NR and propose a new algorithm to implement hybrid beamforming in MISO systems.
In Chapter 2, we will discuss the concept of Inter-Numerology interference. Due to the various use cases in 5G, Multi-numerology transmission is proposed. But this comes with the disadvantage of Inter-Numerology interference. We will analyse the suggested solutions by various authors to this issue and present our observations.

CHAPTER 2

BEAM MANAGEMENT IN 5G NR

2.1 Beam Management

The primary goal in beam management is to establish and retain a suitable beam pair, i.e., to find a transmitter side beam direction and a receiver side beam direction which provide good connectivity. In cases where there is beam correspondence (the best beam pair in DL is also the suitable beam pair in UL) it is sufficient to determine the beam pair in one transmission direction.

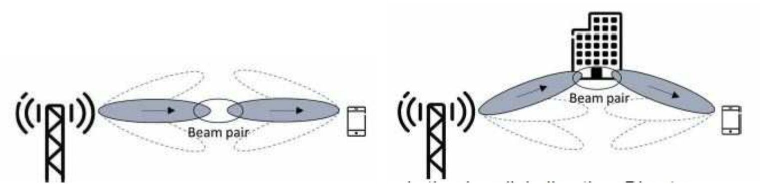


Figure 2.1: Establishing a beam pair

- Beam Management can be divided into - Initial Beam establishment , Beam adjustment and Beam recovery.
- For initial access, SS Blocks are used and for tracking, both CSI-RS and SS Blocks are used in the Downlink.
- The NR specifications include a set of basic beam-related procedures for the control of multiple beams at frequencies above 6 GHz.
  - **Beam Sweeping** :Covering a spatial area with a set of beams transmitted and received according to pre-specified intervals and directions.
  - **Beam Measurement** :Evaluation of the quality of received signal using quantities like SINR, RSRP etc.
  - **Beam Determination** : Selecting the beam according to beam measurements.
  - **Beam Reporting** : Procedure at the UE to send beam quality and beam decision information to RAN
- These procedures are periodically repeated to update the optimal transmitter and receiver beam pair over time.

2.1.1 Beam Failure and Recovery

Beam failure/recovery consists of the following steps:

- Beam-failure detection, that is, the device detecting that a beam failure has occurred (based on measures L1-RSRP of CSI-RS and SS block)
- Candidate-beam identification, that is, the device trying to identify a new beam or, more exactly, a new beam pair by means of which connectivity may be restored
- Recovery-request transmission, that is, the device transmitting a beam recovery request to the network
- Network response to the beam-recovery request

2.2 Multi-antenna Transmission Model

2.2.1 Beamforming in LTE

If no knowledge of the Downlink channels of different transmit antennas is available, then multiple transmit antennas can only provide diversity but not beamforming. For such a case, it is necessary to have low mutual correlation between the antennas. In general, beamforming can increase signal strength at the receiver upto a factor of N_T i.e., the number of transmit antennas. We have two cases - 1) high antenna correlation and 2) low antenna correlation

High antenna correlation: Configured with small inter-antenna distance. In this case, the channels between different antennas and a receiver are the same, except a few direction dependent phase differences.

The overall beam can be steered by applying different phase shifts to the signals to the signals on the different antennas. This is called *Classical Beamforming*.

Due to small antenna distance, the overall beam is relatively wide and adjustments in the direction will be carried out relatively slowly.

Adjustments can be based on estimates of direction from UL measurements.

Low antenna correlation Implies either sufficiently large antenna distance or different antenna polarisation directions.

Beam-forming principle : In contrast to classical beam-forming, the antenna weights should take complex values, implying that both phase and amplitude of the signals can be adjusted.This can be expressed in vector notation, as a precoding vector v to the transmitted vector

$$s_T = vs$$

Classical beam-forming can also be described in this way but weights are limited to unit gain and only provide phase shifts.

For low correlation case, there is a need for more detailed channel knowledge, including estimates of the instantaneous channel fading. In case of FDD, fading is uncorrelated between UL and DL.So the terminal would report an estimate of the channel via UL or may select a suitable precoder from the codebook and report this to the BS.

In TDD, there is a high fading correlation between UL and DL, so, the BS could determine instantaneous DL fading from measurements on UL. (However, this assumes that the terminal continuously transmits on the uplink)

2.2.2 Multi-Antenna transmission in NR

Antenna panels : In mobile communications, an extension of Rx antenna area, enabling higher directivity transmission can be achieved by means of an antenna panel. The dimension of each antenna element and the distance between antenna elements is proportional to the wavelength. So, as frequency increases, the dimension of antenna elements and the distance between them proportionally decreases, but this can be compensated by increasing the number of antenna elements.

Advantage : Instead of using one single antenna, we can use the antenna panel to adjust the direction of Tx beam by separately adjusting the phase of signals applied to each element.

Multi-antenna transmission model : N_L spatial layers mapped to N_T transmit antennas using a matrix W of dimension $N_T \times N_L$

$$y = Wx$$

Two cases -

1) W is applied within the analog part, i.e., after DAC

2) W is applied within the digital part, i.e., before DAC is applied

Drawback with digital beamforming - implementation complexity with the need of

1 DAC per antenna element. In case of higher frequencies, analog processing will be most common.In this case, multi -antenna transmission will be limited to per antenna phase shifts providing beamforming.

Analog Processing - Beamforming is carried out on a per-carrier basis.For DL, this means itâĂŹs not possible to frequency multiplex beam formed transmissions to devices located in different directions. So, beamformed transmissions in different directions must be separated in time.

Digital Processing(precoding)

- Used in case of smaller number of antenna elements and lower frequencies.
- Enables much higher flexibility - each element in W matrix(precoder) may include both phase shift and scale factor.
- Also allows for independent multi-antenna processing for different signals within the same carrier. That is, simultaneous beamformed transmissions to multiple devices in different directions is possible by means of frequency multiplexing.

2.3 Hybrid Beamforming

An important requirement in mmWave systems is the use of large arrays at the transmitter and receiver to provide a reasonable link budget. It has been proposed to enable gigabit per second communication for next generation cellular systems and local area networks. A key difference relative to lower frequency solutions is that in mmWave systems, precoding/combining can not be performed entirely at digital baseband, due to the high cost and power consumption of some components of the radio frequency (RF) chain. Therefore, we develop a low complexity algorithm for finding hybrid precoders that split the precoding/combining process between the analog and digital domains.

2.4 Proposed Algorithm for HBF

2.4.1 Defining the Problem Statement

The problem is to compute the avg. capacity for each sector (users are randomly located) for the 16 port and the 8 port hybrid precoders across different terrains and for different dopplers, and compare the results with the 32 port fully digital case. Analyse the results and list the suitable conditions to implement the respective hybrid precoders.

2.4.2 System Model

We assume a single cell multi user MISO system, that is, each user is assumed to have only a single receiver antenna. The Base station is located at the centre of the cell, and the users are randomly located scattered across the sector with some specified velocities. The transmitter has a 8x8 cross polarised antenna array (128 elements) mapped to 32 ports. Each 4x1 vertical array in the antenna array is mapped to 1 TxRU port.

2.4.3 Codebook-based Hybrid Beamforming

To solve our problem, we model the hybrid precoder as a product of two precoder vectors - $F = F_{RF}F_{BB}$, where F_{BB} is obtained from the codebook and F_{RF} is matrix containing analog weight vectors as columns.

For the fully digital case the F_{RF} matrix boils down to an identity matrix, and the precoder is just obtained from the 32-port codebook.
The receiver equation (before combining) is given as -

$$r = \sqrt{\rho} H F_{RF} F_{BB} s + n.s$$

So, instead of obtaining the best F_{RF} and the best F_{BB} simultaneously, we can as well evaluate the equivalent channel in the hybrid cases and then obtain the best codebook precoder. To explain this further, let us consider the 16-port hybrid precoding case. Here, the F_{BB} is obtained from the 16-port codebook. This hybrid case is obtained when we combine two adjacent digital ports (from the 32-port case) in an analog manner to obtain two wide beams spanning the width of the sector with the digital precoders defining the narrow beams within these wide beams.
So, if the set of 32-port precoders spanned across the entire width of the sector, the 16-port ones are meant to cover only the wider analog beam. Here, we have a set of precoders for each beam. So, in order to simplify the problem, we find the equivalent channels for each beam, and find the best precoder in a similar way we found the best

precoder in the fully digital case.

2.4.4 Algorithm to find the best precoder

As we have seen in the previous section, we need to find the best precoder in order to compute the overall capacity of the BS. We divide the bandwidth into subbands, each of width approximately equal to the coherence bandwidth. This is to assume flat fading over each subband. So for every slot and every subband, we first generate the channel (considering 32-port). Now using this channel, we can compute the capacity obtained using each precoder from the codebook. The precoder delivering the best capacity is labelled as the best precoder for that subband in that slot. We try to maximise capacity by just maximising SNR as we ignore other interferences and assume AWGN noise. Once this is done, the average is calculated over the entire bandwidth and over all users.

CHAPTER 3

INTER NUMEROLOGY INTERFERENCE

The upcoming 5G technologies are expected to support three major user cases with diverse requirements -

1. **eMBB** (enhanced Mobile BroadBand) is expected to support 20Gbps in DL and 10Gbps whose performance is significantly affected by channel characteristics. For fast fading channel, a larger subcarrier spacing is preferrable for highly mobile users to counter the Doppler spread. Smaller subcarrier spacing can achieve robustness for channel with long delay spread.
2. **mMTC** (massive Machine Type Communications) prefers smaller subcarrier spacing i.e., larger symbol spacing to support delay-tolerant devices.
3. **URLLC** (Ultra-Reliable and Low Latency Communications) needs high reliability and low end-to-end delay.A larger subcarrier spacing is hence required to meet the latency requirements.

To achieve the required flexibility in 5G systems, mixed numerologies are proposed. For conventional OFDM multiplexing which is well-localised in time domain, aligning different numerologies in time domain can maintain orthogonality between consecutive blocks. However, frequency domain multiplexing has better forward compatibility and inclusive support for different latency services.A viable way is to divide the bandwidth into several subbands and assign different numerologies to different subbands.
It is important to note here that only the subcarriers within one numerology are orthogonal to each other.Subcarriers of one numerology interfere with subcarriers of other numerologies since energy leaks outside the subcarrier bandwidth and is picked up by the subcarriers of the other numerology.We consider a time-domain windowing approach to reduce the inter-numerology interference due to it's low complexity implementation and superior performance.
In *transmitter windowing*, the edges of OFDM symbols are multiplied with smooth slopes in time domain - an increasing slope the beginning of CP, and a decreasing slope after the core OFDM symbol within a cyclic suffix. Since the receiver keeps only the core OFDM symbols, transmitter windowing is transparent to the Rx.
Receiver windowing : A standard OFDM receiver uses a rectangular window in the time

domain to obtain the desired core OFDM symbols. This is equivalent to convolution with a sinc function in frequency domain which leads to high interference pickup from adjacent non-orthogonal signals such as the OFDM signals from other numerologies. To reduce this, the rectangular window is replaced with a smooth window function.The following figure depicts Tx-Rx windowing over one symbol period.

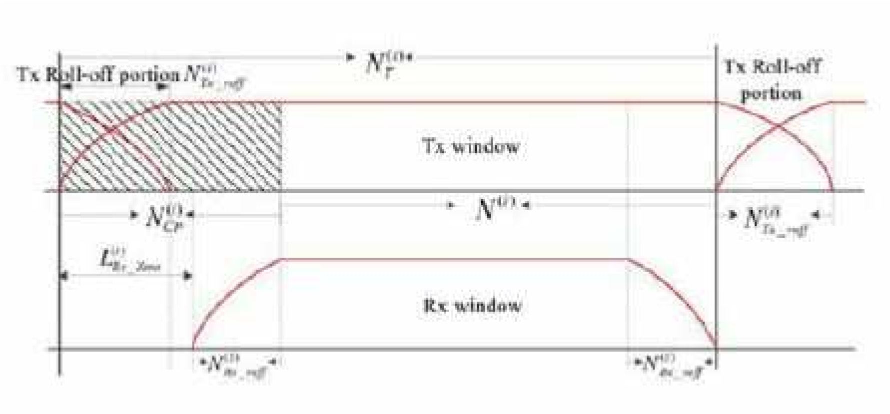


Figure 3.1: Caption

The amount of INI can vary with Δf , BW, guards, TCP, the number of different numerologies, alignment of different numerologies in frequency domain, filtering/windowing usage, frequency bands, user powers, and so on. The reference (7) develops a model for the INI in windowed OFDM systems and proposes an OSIC algorithm for INI mitigation. In this paper the subcarrier spacing and CP are defined as -

$$\Delta f^{(i)} = n_i \Delta f^{(i-1)}, N_{CP}^{(i)} = \frac{N_{CP}^{(i-1)}}{n_i}$$

where $n_i = 2^K, K = integer$, and $\Delta f^{(i)}$ is the subcarrier spacing for the ith numerology.Two adjacent subbands using two different numerologies with a guard band F_{GB} are considered for the following analysis. The received signal can be written as

$$y(n) = y^{(1)}(n) + y^{(2)}(n) \tag{3.1}$$

For the arbitrary subband using numerology i, the subchannel of each subcarrier is assumed to be flat fading in the considered use case scenario.When y(n) is demodulated by the receiver with numerology i, the demodulated signal on the kth subcarrier of the mth W-OFDM symbol can be written as -

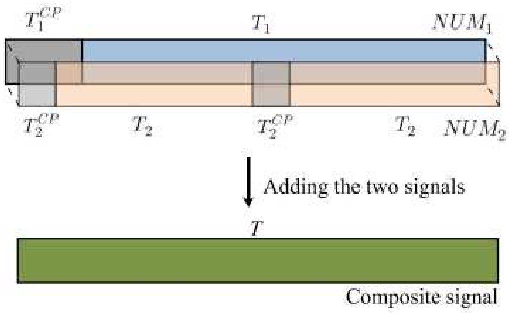
$$\hat{y}^{(i)}_{k,m} = \sum_{n} y(n)\overline{q^{(i)}_{k,m}(n)}$$
$$= \rho^{(i)} x^{(i)}_{k,m} H^{(i)} + \rho^{(j)} \sum_{u=0}^{Z^{(j)}-1} \sum_{v=-\infty}^{\infty} x^{(j)}_{u,v} \sum_{l=0}^{L^{(j)}_{CH}-1} h^(j)(l) \times \sum_{n} g^{(j)}_{u,v}(n-l)\overline{q^{(i)}_{k,m}(n)} + w^{(i)}(k) \tag{3.2}$$

Here, the first term is the desired signal, second term the INI caused by subband using numerology j and the last term the Gaussian noise.

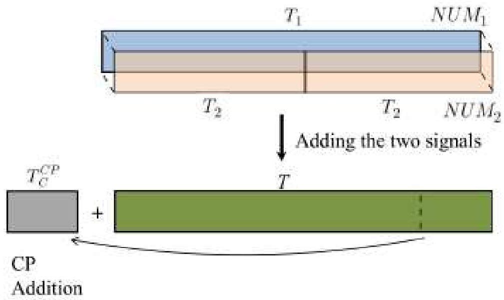
$\rho^{(i)}$ = power adjusting factor for numerology i
$x^{(i)}_{k,m}$ = information symbol
$H^{(i)}$ = Channel frequency response
$Z^{(i)}$ = Number of subcarriers in the subband using numerology$i$
$L^{(i)}_{CH}$ = channel delay spread

The later part of the paper analyses INI experienced by each of the numerologies and proposes an INI cancellation algorithm. Finally, it is observed that the proposed Soft-OSIC algorithm can achieve better MSE performance compared with that of SoftZF and SoftMMSE.
In the reference (6), it is pointed out that the varying symbol lengths caused due to the usage of different subcarrier spacing(ScS) makes the whole system unsynchronised in the time domain. This difficulty in achieving synchronisation is one of the major drawbacks of the multi-numerology systems.Now, if one ScS is an integral multiple of another, an LCM symbol duration can be considered and synchronisation can be achieved by using either individual CP or common CP (3.2). INI affecting multi-numerology signals is studied using the figures 3.3 and 3.4.

At transmitter : NUM_1 ($\Delta f = 15kHz$) causes no interference at any of the NUM_2 ($\Delta f = 30kHz$)subcarriers, while NUM_2 imparts some interference on one out of every two subcarriers of NUM_1. Number of NUM_1 subcarriers affected by INI from NUM_2 depends on the ratio $\Delta f_1/\Delta f_2$ of the two numerologies.



(a) Synchronization with individual CP



(b) Synchronization with common CP

Figure 3.2: Sychronisation of the two numerologies for one subcarrier

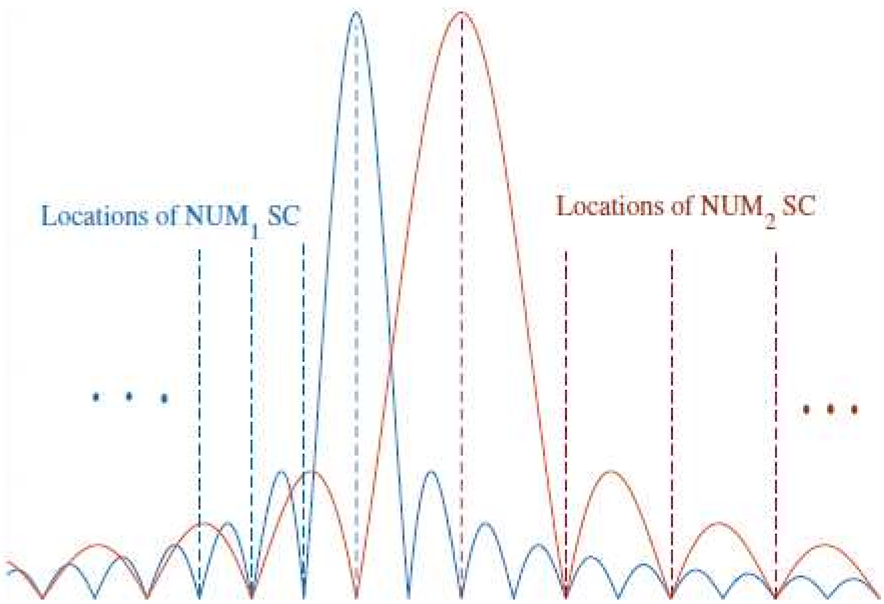
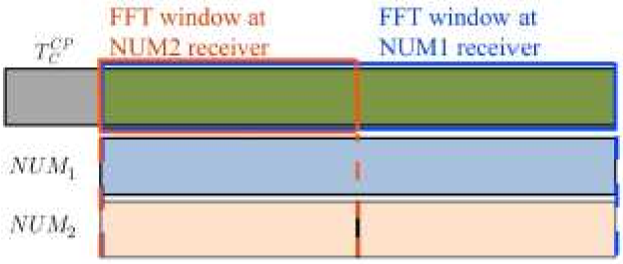
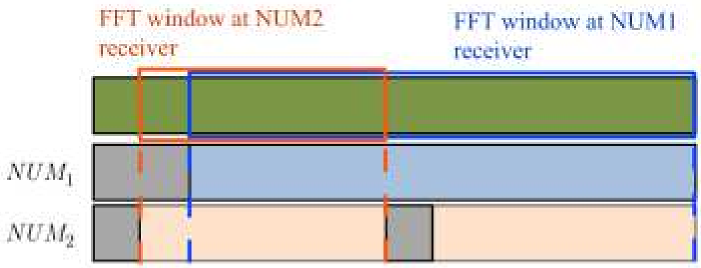


Figure 3.3: Multiplexed subcarriers of NUM_1 (Δf_1 = 15 kHz) and NUM_2 (Δf_2 = 30 kHz) at the transmitter



(a) Common CP case



(b) Individual CP case

Figure 3.4: Illustration of FFT-window at the receiver of each numerology

At receiver : In the **common CP** case, interference on NUM_1 is the only one that was created at the transmitter while all the subcarriers of NUM_2 are affected by INI even though they were interference-free at the transmitter. In the **individual CP** case, FFT process at NUM_1 receiver causes interference from NUM_2 to all subcarriers of NUM_1, and FFT process at NUM_2 receiver causes interference from NUM_1 to NUM_2.

Further, in this paper, a detailed analysis about the factors affecting INI - *Inter-Numerology Subcarrier Spacing Offset, Number of Subcarriers, Power Offset, Windowing, Guard Band* - is provided aong with appropriate simulations and their results.

In reference (9), an study of multi numerology systems is presented. In NR, the concept of Bandwidth Part is introduced.Bandwidth Part (BWP) defines a fixed band over which the communication taking place uses the same numerology throughout the existence of the BWP.BWPs are controlled at BS based on UE needs and network requirements.5G UEs need not monitor the entire transmission bandwidth.They scan only the BWP assigned to them.BWPs serve as an useful tool as the BS can modify UE numerologies by changing it BWPs.

NR allows overlapping of BWPs using different numerologies in time-frequency grid(10).

Numerology-domain NOMA system designs can be developed to exploit this gap(11). The paper discusses about the effects of having guard bands, guard intervals, filtering and windowing on INI. Simulations for interference estimations are done and the following observations are made :

- There is more INI at the edge subcarriers of the different numerologies.
- INI present at each subcarrier decreases as the guard band between different numerologies increases.
- Effect of guard bands are more prominent for the edge subcarriers.
- CP addition causes additional interference for the numerology with smaller subcarrier spacing.
- Subblocks of second numerology are constituted by dividing the composite signal. $\Longrightarrow$ Symbols of first numerology cause an extra interference on those of second numerology.
- INI on every 2^kth subcarrier is less than that of the other subcarriers for the numerology with a smaller subcarrier spacing.

REFERENCES

[1] Erik Dahlman, Stefan Parkvall,Johan Skold. *4G - LTE/LTE-Advanced for Mobile Broadband*.

[2] Erik Dahlman, Stefan Parkvall,Johan Skold. *5G NR- The next generation wireless access technology*.

[3] *3GPP TR 37.840 V12.1.0*. (2013-12).

[4] Li Xiaohui1, Lin Yingchao1, Meng Meimei1, Hei Yongqiang1 *Gram-Schmidt based hybrid beamforming for mmWave MIMO systems*. The Journal of China Universities of Posts and Telecommunications

[5] Cristian Rusuy, Roi MÂt'endez-Rialy, Nuria GonzÂt'alez-Prelcicy, and Robert W. Heath Jr.z *Low Complexity Hybrid Sparse Precoding and Combining in Millimeter Wave MIMO Systems*.

[6] Abuu B. Kihero, Muhammad Sohaib J. Solaija, Ahmet Yazar and Huseyin Arslan *Inter-Numerology Interference Analysis for 5G and Beyond*. (2018).

[7] Xiaoying Zhang , Lei Zhang, Pei Xiao, Senior Member, IEEE, Dongtang Ma, Jibo Wei, and Yu Xin *Mixed Numerologies Interference Analysis and Inter-Numerology Interference Cancellation for Windowed OFDM Systems*. IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, **VOL. 67,**, NO.8 (August 2018).

[8] Ali A. Zaidi, Robert Baldemair, Hugo Tullberg, Hakan BjÃűrkegren, Lars SundstrÃűm, Jonas Medbo, Caner Kilinc, and Icaro Da Silva *Waveform and Numerology to Support 5G Services and Requirements*.

[9] Ahmet Yazar, Berker Pekoz and Huseyin Arslan , *Flexible Multi-Numerology Systems for 5G New Radio*. (2018)

[10] J. Jeon, *NR wide bandwidth operations*, IEEE Communications Magazine, **vol. 56**, no. 3,pp. 42-46, Mar. 2018.

[11] A. A. Sabah, H. Arslan, *NOMA for multi-numerology OFDM systems*, accepted for publication in Wireless Communications and Mobile Computing, 2018.