

Uplink Signal Generation and Analysis of 5G NR

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Abstract— The telecommunication standard organization, third generation partnership project (3GPP) has come up with New Radio (NR) 5G which has different kinds of physical channels for downlink and uplink communication, these channels will have communication between mobile station, base station and 5G core network and they will help in exchanging of data and control messages. The 5G NR uses Discrete Fourier Transform Spread Orthogonal Frequency Division Multiplexing and Orthogonal Frequency Division Multiplexing based waveform in uplink, which are different from 4G-LTE and has the advantage of Low Peak-to-Average Power Ratio, Delay-Sensitive, Avoiding Interference and Spectral Efficiency. In this paper, it describes how to build, generate and analyse of 5G NR uplink waveform for a baseband component carrier by using MATLAB 5G Toolbox.

Keywords—Uplink Waveform, PUSCH, PUCCH, MATLAB 2021a

I. INTRODUCTION

The 5G wireless cellular network makes use of two frequency bands one known as FR1 (between 4.1GHz to 7.125GHz) and it is also called as low frequency band as well as Sub6 band, and FR2 (between 24.25GHz to 52.5GHz) is a millimeter wave (mmwave) also called as high frequency band. The FR1 frequency range bands are used by some of technologies like 4G/4G-LTE, and others for wireless and cellular communication services [1]. The frequency bands have been divided into two groups: frequency and time division duplex. Two frequency bands are necessary for FDD use, one for uplink and one for downlink. TDD uses a single channel for the link: time slots rather than multiple frequencies are allocated to the uplink as well as downlink. As a result, TDD requires single communication band [2].

The 5G NR FR2 range band is already beginning to gain traction with new technology development in order to make microwave links available for the large-scale deployment that will be required [3]. Allocations are being made in various portions of the spectrum more than 20 GHz, as it is moderately utilized now. The new 5G mobile communication system comes with three different

data access channels for uplink and downlink such as logical, transport & physical channel as expressed in fig. 1 and fig. 2. The 5G digital cellular communication system consist of several different parameters for frequency bands and these parameters are varied according to the needs for the transmissions of the 5G NR signal. In the table 1 and 2, shows the signal features and distinguishes them according to their use of FR1 and FR2 [4].

Table 1: 5G NR FDD Frequency Band (FR1) [3]

5G NR Band	Uplink Frequency	Downlink Frequency	Bandwidth
n1	1920 -1989 MHz	2110 - 2170 MHz	60 MHz
n2	1850 - 1910 MHz	1930 - 1990 MHz	60 MHz
n3	1710 - 1785 MHz	1805 - 1880 MHz	75 MHz
n5	824 - 849 MHz	869 - 894 MHz	25 MHz
n7	2500 - 2670 MHz	2620 - 2690 MHz	70 MHz
n8	880 - 915 MHz	925 - 960 MHz	35 MHz
n12	699 - 716 MHz	729 - 746 MHz	17 MHz
n14	788 - 798 MHz	758 - 768 MHz	20 MHz
n18	815 - 830 MHz	860 - 875 MHz	15 MHz
n20	832 - 862 MHz	791 - 821 MHz	30 MHz
n25	1850 - 1915 MHz	1930 - 1995 MHz	65 MHz
n28	703 - 748 MHz	758 - 803 MHz	45 MHz

Table 2: 5G NR TDD Frequency Band (FR2) [3]

5G NR Band	Band Alias	Uplink / Downlink Band	Bandwidth
n257	28 GHz	26.5 - 29.5 GHz	3 GHz
n258	26 GHz	24.250 - 27.5 GHz	3.250 GHz
n259	-	39.5 - 43.5 GHz	4 GHz
n260	39 GHz	37 - 40 GHz	3 GHz
n261	28 GHz	27.5 - 28.35 GHz	850 MHz

This paper proves, finding out in what way to parameterize and produce a baseband component carrier waveform divided into categorized by bandwidth parts (BWPs) and multiple subcarrier spacings. we can create several cases of the physical uplinks shared (PUSCHs) and control channels (PUCCHs), and the channel state information reference signal over the different bandwidth parts. In order to map the PUCCHs, we need to configure the set of control resource called as CORESETs and search space [5].

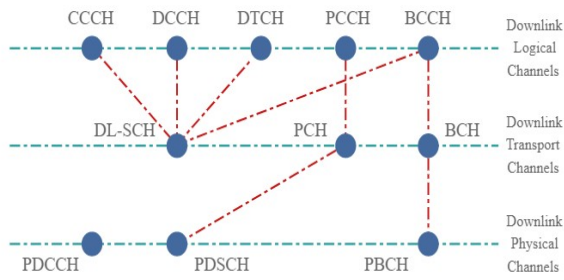


Fig. 1: The 5G NR downlink logical, transport & physical channel aligning [2].

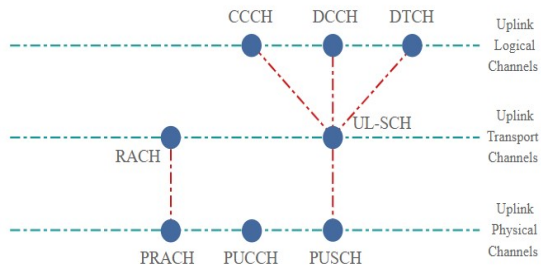


Fig. 2: The 5G NR uplink logical, transport & physical channel aligning [2].

The mobile devices use primary and secondary synchronization signals (uplink) to get frame timing and cell identity. The user equipment uses the demodulation-reference signal and the channel state information reference signal to assist measurements and aid in channel estimation [6].

II. 5G NR UPLINK WAVEFORM GENERATION

The 5G network uses orthogonal frequency-division multiplexing based waveforms in both the uplink and downlink to utilise the wide carrier bandwidths efficiently; however, it allows more flexibility in subcarrier spacing for deployment in different frequency bands. It is anticipated that up to 16 carriers can be aggregated, making it suitable to offer bandwidths in the gigahertz range to a single device [7].

A. Uplink physical layer functions and procedures

The protocols and functional blocks that are present in 5G NR uplink physical layer are organized according to its channel features, deployment scenario and use cases. In the figure 3 shown, the communication of data and its processing takes place from higher layer like MAC Protocol Data Unit (PDU) to physical layer of user equipment. The main function includes

error detection, that is the cyclic redundancy check calculations and attachment, channel encoding (low density parity check and Polar) and decoding (LDPC) of the transport layer, rate matching of the coded transport to physical channels, Quadrature amplitude modulation (QAM) modulation and demodulation. Mapping of data to physical resources and, MIMO array antennas. It also supports the HARQ-related signaling and layer-1 control operations [8].

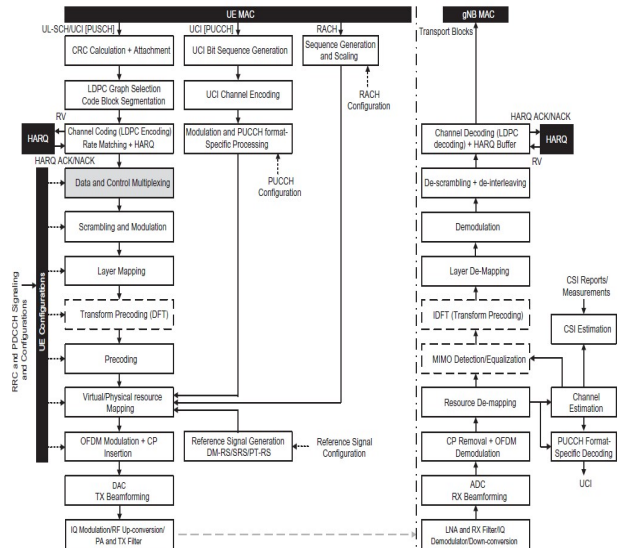


Fig. 3: Complete downlink physical layer processing [5].

The physical RACH preamble format, which consists of a cyclic prefix, a preamble, and a guard duration during which no signal is sent, establishes the physical-layer structure for RACH transmission.

B. Waveform and Carrier Configuration

In order to generate baseband waveform, following parameters are required and configured is shown in fig. 4,

- Label for the uplink carrier waveform configuration (UL carrier 1).
- Subcarrier spacing carrier bandwidth in resource blocks, for example 50MHz, 100MHz, 200MHz, 400MHz.
- Carrier Cell Identity, Default value is ‘0’.
- Generally, the wireless frames in 5G NR are of the length ‘10ms’ and it is divided into number of subframes of ‘1ms’, and each slot has 14 OFDM symbols.
- Assigning the overall sampling rate for OFDM Modulated signal.

- Defining the windowing percentage, related to fast fourier transformation length.
- Setting subcarrier frequency (for example 15KHz, 30KHz, 60KHz etc).

```

waveconfig = nrULCarrierConfig(1); % Create an instance of the waveform's parameter object
waveconfig.Label = 'UL carrier 1'; % Label for this uplink waveform configuration
waveconfig.NCellID = 0; % Cell identity
waveconfig.ChannelBandwidth = 50; % Channel bandwidth (MHz)
waveconfig.FrequencyRange = 'FR1'; % 'FR1' or 'FR2'
waveconfig.NumSubframes = 10; % Number of 1ms subframes in generated waveform (1,2,4,8 slots per 1ms subframe)
waveconfig.WindowingPercent = 0; % Percentage of windowing relative to FFT length
waveconfig.SampleRate = []; % Sample rate of the OFDM modulated waveform
waveconfig.CarrierFrequency = 0; % Carrier frequency in Hz. This property is used for symbol phase
                                % compensation before OFDM modulation, not for upconversion
    
```

Fig. 4: Frame, subframe and slot at different numerology [1].

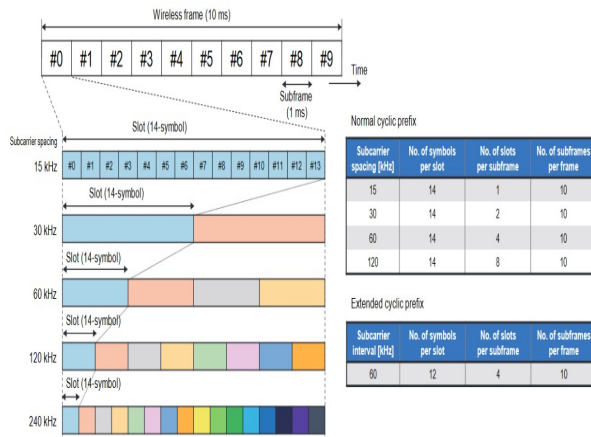


Fig. 5: Frame, subframe and slot at different numerology [4].

In the figure 5 shown, describes about 5G NR frame structure with multiple slots and OFDM symbols, and different subcarrier spacing.

C. Bandwidth Parts

The bandwidth parts are also referred to as total carrier bandwidth, each bandwidth part is allied with its own numerology (subcarrier frequency spacings and cyclic prefix). To have proper battery consumption of user equipment, it is necessary to use only one bandwidth part in the downlink and one in uplink, and they are active at a given time on an active serving cell.[10][11] While the wideband receiver is only utilized dynamically when necessary to handle extremely high data rates, the limited bandwidth portion is used for monitoring control channels and receiving low/medium data rates. 3GPP Release 15 only supports a one active bandwidth segment. The user equipment can be mapped with

up to 4 bandwidths in downlink and 4 bandwidths in the uplink with a one downlink bandwidth part active at a given time. For each bandwidth part, it is necessary to assign the bandwidth, subcarrier spacing and cyclic prefix length. In fig. 6, it consists of 2 Bandwidth Part (BWP) of 15KHz and 30KHz subcarrier spacing with normal cyclic prefix (CP) length [9].

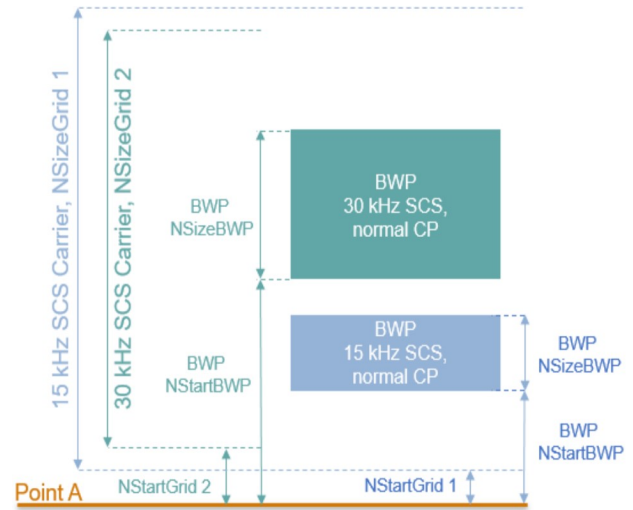


Fig. 6: Different Bandwidth Parts [1]

D. PUSCH Instances Configuration

In this part shows, the parameters defined for the PUSCH sequence instance are defined into the waveform. Each one element defines a PUSCH sequence instance in the structure array. Here in this part two PUSCH sequence instances are defined.[12] In the fig. 12 shows the generation of PUSCH signal and following are the parameters to be set for PUSCH sequence instance (As shown in fig. 7),

- Activate or deactivate PUSCH sequence.
- Label specification for the PUSCH instance and activate or deactivate.
- Downlink shared control information channel coding can be activated or deactivated.
- Defining a bandwidth part conveying the PUSCH. The subcarrier spacing supplied for this bandwidth part is used by the PUSCH.
- Activate or deactivate the uplink-shared channel transport channel coding.
- Assigning the symbol modulation and overhead parameters values.

- Activate or deactivate the interleaving of the virtual to physical resource block mapping.
- Setting radio network temporary identifier to PUSCH.
- Set the target code rate which helps to evaluate transport block sizes.
- Assigning the modulation scheme such as “QPSK, 16QAM, 64QAM, 256QAM”.
- Setting the number of PUSCH Layers and antenna ports.

```
pusch = (nrWavegenPUSCHConfig());
pusch{1}.Enable = 1; % Enable PUSCH sequence
pusch{1}.Label = 'PUSCH @ 15 kHz'; % Label for this PUSCH sequence
pusch{1}.BandwidthPartID = 1; % Bandwidth part of PUSCH transmission
pusch{1}.Power = 0; % Power scaling in dB
pusch{1}.Coding = 1; % Enable the UL-SCH transport channel coding
pusch{1}.NID = 1; % Scrambling for data part
pusch{1}.RNTI = 0; % RNTI
pusch{1}.TransformPrecoding = false; % Transform precoding
pusch{1}.TargetCodeRate = 0.47; % Code rate used to calculate transport block sizes
pusch{1}.Overhead = 0; % Rate matching overhead

% Transmission settings
pusch{1}.TransmissionScheme = 'codebook'; % 'codebook', 'nonCodebook'
pusch{1}.Modulation = 'QPSK'; % 'pi/2-BPSK', 'QPSK', '16QAM', '64QAM', '256QAM'
pusch{1}.NumLayers = 2; % Number of PUSCH layers
pusch{1}.NumAntennaPorts = 4; % Number of antenna ports
pusch{1}.TPMI = 0; % Transmitted precoding matrix indicator (0...27)
pusch{1}.RVSequence = [0,2,3,1]; % RV sequence to be applied cyclically across the PUSCH
pusch{1}.FrequencyHopping = 'InterSlot'; % Intra-slot frequency hopping ('enabled', 'disabled')
pusch{1}.SecondHopStartPRB = 10; % Resource block offset for second hop

% Data source
pusch{1}.DataSource = 'PN9'; % Channel data source
```

Fig. 7: PUSCH Specification [1]

E. PUSCH Instances Configuration

In this unit, the parameters defined for the PUSCH sequence instance are defined into the waveform. Each one element defines a PUSCH sequence instance in the structure array [13]. Here in this part two PUSCH sequence instances are defined. In the fig. 12 shows the generation of PUSCH signal and following are the parameters to be set for PUSCH sequence instance (As shown in fig. 8),

- Activate or deactivate PUSCH sequence.
- Label specification for the PUSCH instance and activate or deactivate.
- Downlink shared control information channel coding can be activated or deactivated.
- Defining a bandwidth part conveying the PUSCH. The subcarrier spacing supplied for this bandwidth part is used by the PUSCH.
- Activate or deactivate the uplink-shared channel transport channel coding.
- Assigning the symbol modulation and overhead parameters values.

- Activate or deactivate the interleaving of the virtual to physical resource block mapping.
- Setting radio network temporary identifier to PUSCH.
- Set the target code rate which helps to evaluate transport block sizes.

```
pusch = (nrWavegenPUSCHConfig());
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pusch{1}.BandwidthPartID = 1; % Bandwidth part of PUSCH transmission
pusch{1}.Power = 0; % Power scaling in dB
pusch{1}.Coding = 1; % Enable the UL-SCH transport channel coding
pusch{1}.NID = 1; % Scrambling for data part
pusch{1}.RNTI = 0; % RNTI
pusch{1}.TransformPrecoding = false; % Transform precoding
pusch{1}.TargetCodeRate = 0.47; % Code rate used to calculate transport block sizes
pusch{1}.Overhead = 0; % Rate matching overhead

% Transmission settings
pusch{1}.TransmissionScheme = 'codebook'; % 'codebook', 'nonCodebook'
pusch{1}.Modulation = 'QPSK'; % 'pi/2-BPSK', 'QPSK', '16QAM', '64QAM', '256QAM'
pusch{1}.NumLayers = 2; % Number of PUSCH layers
pusch{1}.NumAntennaPorts = 4; % Number of antenna ports
pusch{1}.TPMI = 0; % Transmitted precoding matrix indicator (0...27)
pusch{1}.RVSequence = [0,2,3,1]; % RV sequence to be applied cyclically across the PUSCH
pusch{1}.FrequencyHopping = 'InterSlot'; % Intra-slot frequency hopping ('enabled', 'disabled')
pusch{1}.SecondHopStartPRB = 10; % Resource block offset for second hop

% Data source
pusch{1}.DataSource = 'PN9'; % Channel data source
```

Fig. 8: PUSCH Specification [1]

F. Allocation

The parameters that are required for the allocation to PUSCH is as shown in fig. 9, In order to control the PUSCH distribution some of the parameters are to be set and these parameters are associated to BWP.

- Setting up mapping type for PUSCH
- Allocation of symbol within the slot of frame to each PUSCH sequence.
- OFDM symbols in a slot of frame assigned to every PDSCH instance.
- The duration of the slot allotment. An empty period signifies that there will be no recurrence.
- Assigning the PRBs relative to the Bandwidth parts.

```
pusch{1}.MappingType = 'A'; % PUSCH mapping type ('A'(slot-wise)
pusch{1}.SymbolAllocation = [0,14]; % First symbol and length
pusch{1}.SlotAllocation = [0 1]; % Allocated slots indices for PUSCH
pusch{1}.Period = 5; % Allocation period in slots
pusch{1}.PRBSet = 0:10; % PRB allocation
```

Fig. 9: PUSCH Allocation [1]

G. PUSCH DM-RS and PT-RS Configuration

Setting up the Demodulation-Reference Signal (DM-RS) parameters and it is used by 5G NR receiver to find channel estimates for demodulation of associated physical channel. The following variables are to be set (as shown in Fig. 10),

- Assigning the DM-RS configuration type such as 1 or 2.
- Setting of total number of antenna port used for DM-RS.
- Defining type position and length of DMRS symbol.
- Initialization and identification of scrambling for DFT-s-OFDM and CP-OFDM.
- Configuring group and sequence hopping as true or false.

```
% Antenna port and DM-RS configuration (TS 38.211 section 6.4.1.1)
pusch(1).DMRSPower = 0; % Additional power boosting in dB

pusch(1).DMRSConfigurationType = 1; % DM-RS configuration type (1,2)
pusch(1).DMRSNumCDMGroupsWithoutData = 2; % Number of DM-RS CDM groups without data. The value can be one of the set {1,2,3}
pusch(1).DMRSNumPortsSet = [0 2]; % DM-RS antenna ports used ([]) gives port numbers 0:NumLayers-1
pusch(1).DMRSTypePosition = 2; % Mapping type A only. First DM-RS symbol position (2,3)
pusch(1).DMRSLength = 1; % Number of front-loaded DM-RS symbols (1(single symbol),2(double symbol))
pusch(1).DMRSAdditionalPosition = 2; % Additional DM-RS symbol positions (max range 0...3)
pusch(1).DMRSNIDNSCID = 1; % Scrambling identity for CP-OFDM (0...65535). Use empty ([]) to use physical layer cell identity
pusch(1).DMRSNID = 0; % Scrambling initialization for CP-OFDM (0,1)
pusch(1).DMRSNID0 = 0; % Scrambling identity for DFT-s-OFDM DM-RS (0...1007). Use empty ([]) to use physical layer cell identity

pusch(1).DMRSGroupHopping = true; % Group hopping configuration. This property is used only when transform precoding is enabled
pusch(1).DMRSSequenceHopping = false; % Sequence hopping configuration. This property is used only when transform precoding is enabled
```

Fig. 10: PUSCH DM-RS [1]

The phase of the local oscillator at the receiver and transmitter is tracked using Phase Tracking Reference signal (PT-RS).[14] This allows for the reduction of common phase error and phase noise, which is especially significant at high carrier frequencies like millimeter wave.

- Activate or deactivate the PT-RS.
- Assigning time and frequency density of PT-RS for CP-OFDM and DFT-s-OFDM.
- Setting the number of PT-RS samples and groups for DFT-s-DFM.
- Defining PT-RS antenna ports and scrambling identity for DFT-s-OFDM and CP-OFDM.
- Setting of PT-RS resource element offset for CP-OFDM such as “00,01,10,11”.

```
% PT-RS configuration (TS 38.211 section 6.4.1.2)
pusch(1).EnablePTRS = 0; % Enable or disable the PT-RS (1 or 0)
pusch(1).PTRSPower = 0; % Additional PT-RS power boosting in dB for CP-OFDM

pusch(1).PTRS.TimeDensity = 1; % Time density (L_PT-RS) of PT-RS (1,2,4)
pusch(1).PTRS.FrequencyDensity = 2; % Frequency density (K_PT-RS) of PT-RS for CP-OFDM (2,4)
pusch(1).PTRS.NumPTRSSamples = 2; % Number of PT-RS samples (NGroupSamp) for DFT-s-OFDM (2,4)
pusch(1).PTRS.NumPTRSGroups = 2; % Number of PT-RS groups (NPTRSGroup) for DFT-s-OFDM (2,4,8)
pusch(1).PTRS.REOffset = '00'; % PT-RS resource element offset for CP-OFDM ('00','01','10','11')
pusch(1).PTRS.PTRSPortSet = 0; % PT-RS antenna ports must be a subset of DM-RS ports for CP-OFDM
pusch(1).PTRS.NID = 0; % PT-RS scrambling identity for DFT-s-OFDM (0...1007)
```

Fig. 11: PT-RS Configuration [1]

H. SRS Instances Configuration

SRS is an abbreviation for Sounding Reference Signal, which is a reference signal broadcast by the UE in the uplink direction and utilized by the eNodeB to evaluate the uplink channel quality over a larger bandwidth [15].

- For each SRS sequence, set the following parameters:

- This SRS sequence can be enabled or disabled.
- Give this SRS sequence a label.
- Provide the BWP that contains this SRS sequence. The SRS sequence configuration makes use of the SCS for this BWP.
- Enter the power scaling in decibels (dB).

```
srs(1).NumSRSPorts = 1; % Number of SRS ports (1,2,4)
srs(1).NumSRSymbols = 4; % Number of SRS symbols in a slot (1,2,4)
srs(1).SymbolStart = 10; % Time-domain position of the SRS in the slot. (8...13) for normal CP and (6...11) for extended CP
srs(1).SlotAllocation = 2; % Allocated slots indices
srs(1).Period = 5; % Allocation period in slots
srs(1).FrequencyStart = 0; % Frequency position of the SRS in BWP in RBs
srs(1).NPRB = 0; % Additional offset from FreqStart specified in blocks of 4 PRBs (0...67)
srs(1).CSRS = 13; % Bandwidth configuration C_SRS (0...63). It controls the allocated bandwidth to the SRS
srs(1).BSRS = 2; % Bandwidth configuration E_SRS (0...3). It controls the allocated bandwidth to the SRS
srs(1).BWP = 1; % Frequency hopping configuration (0...3). Set BWP < BSRS to enable frequency hopping
srs(1).KTC = 2; % Comb number (2,4). It indicates the allocation of the SRS every KTC subcarriers
srs(1).KBarTc = 0; % Subcarrier offset of the SRS sequence (0...KTC-1)
srs(1).CyclicShift = 0; % Cyclic shift number (0...NCSmax-1). NCSmax = 8 for KTC = 2 and NCSmax = 12 for KTC = 4.
srs(1).Repetition = 1; % Repetition factor (1,2,4). It indicates the number of equal consecutive SRS symbols in a slot
srs(1).GroupHopping = 'neither'; % Group or sequence hopping ('neither', 'groupHopping', 'sequenceHopping')
srs(1).SRSID = 0; % Scrambling identity (0...1003)
srs(1).SRSPositioning = false; % Enable SRS for user positioning
```

Fig. 12: PUSCH Allocation [1]

J. Waveform Generation

This part allocates all channels and signal parameters to the primary uplink carrier configuration object, creates the waveform, which is shown as in Fig. 13, Fig. 14 and Fig. 15,

```
waveconfig.SCSCarriers = scsCarriers;
waveconfig.BandwidthParts = bwp;
waveconfig.PUSCH = pusch;
waveconfig.SRS = srs;

% Generate complex baseband waveform
[waveform,info] = nrWaveformGenerator(waveconfig);
```

Fig. 13: Waveform Generation [1]

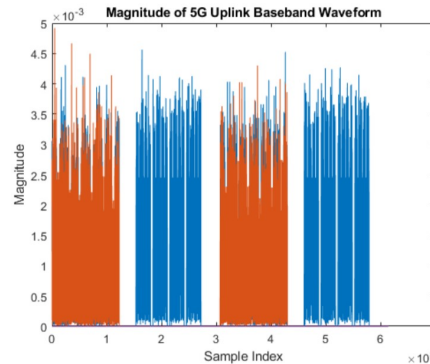


Fig. 14: Waveform Generation [1]

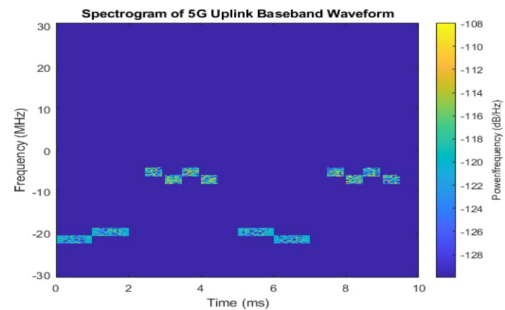


Fig. 15: 5G Uplink waveform [1]

III. CONCLUSION

The upcoming new 5G/6G wireless and cellular communication network make use of millimeter or terahertz frequency signals and the data rate is increased by using multiple array antennas. These MIMO antennas exist within each hexagonal cells and they communicate with wireless devices; thus, multiple bit streams of data will be sent concurrently in parallel. This paper has provided an attempt to understand the generation of uplink waveform and its configuration parameters by using 5G MATLAB toolbox to extend the data rate transmission more than the 4G and 4G LTE configurations. The MATLAB toolbox offers typical compliant functions and references for the modelling, verification, and simulation of communication system. It gives us more knowledge and understanding of generation, transmission, and reception of 5G signals. whole world is waiting to experience this fastest technology which make the life of people much easier.

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