Technical Principles and Simulations of the 5G NR Physical Layer Standard

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Abstract—**Development of 5G products is accelerating, with the first device and network deployments in 2019. 5G New Radio (NR) technology introduces a flexible architecture that will enable the ultra-fast, low-latency communications needed for next-generation mobile broadband networks and applications such as connected autonomous cars, smart buildings and communities, digital health care, and industrial IoT. The flexibility of the 5G NR standard will make design and test more complex. Engineers developing 5G enabling technologies and connected devices need a solid understanding of the fundamental concepts behind the 5G NR specification as well as standard compliant functions and reference examples. In this paper, we introduce the key 5G physical layer technologies and concepts. You will learn about the structure of 5G waveforms; how the waveforms are constructed, modulated, and processed; beam management in massive MIMO systems; and methods for simulating and measuring link-level performance.**

Keywords—5G; New Radio; Physical Layer; Simulation

I. INTRODUCTION TO KEY CONCEPTS IN THE 5G NEW RADIO PHYSICAL LAYER STANDARD

First, we will review the requirements and use cases for 5G, followed by an overview of key 5G physical layer features. Finally, we will introduce 5G Toolbox$^{\text{TM}}$, which implements the 5G physical layer specification for simulation and waveform generation.

A. 5G Use Cases

5G is meant to support multiple use cases. The specification is designed to enable mobile networks and devices that support an ambitious range of applications, including:

- Enhanced mobile broadband (eMBB) requiring extremely high mobile broadband data rates and increased bandwidth efficiency
- Massive machine type communications (mMTC) needing support for a large number of connections and energy efficiency and low-power operation
- Ultra-reliable and low-latency communications (URLLC) needed, for example, for autonomous vehicles or remote surgery

B. Main Physical Layer Differences between 5G and LTE

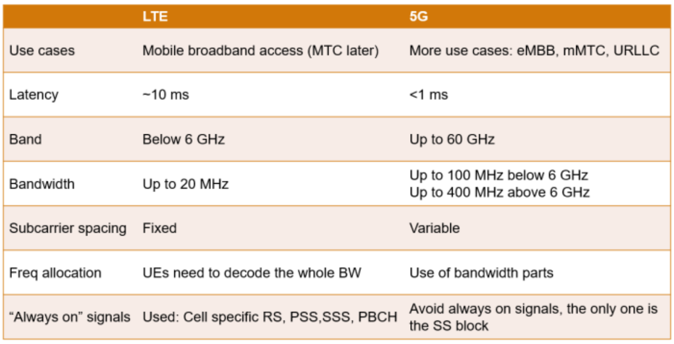
While 5G retains some similarities to LTE, you can see in Figure 1 that these requirements have resulted in significant differences. Several have a direct impact on the physical layer. For example, 5G will operate in higher frequency bands and use larger bandwidths than LTE, which affects the design of RF front ends as well as baseband operation. 5G is significantly more flexible than LTE to accommodate the range of use cases, data rates, and latency. This is accomplished by using variable subcarrier spacing and bandwidth parts to make more efficient use of the available bandwidth under different circumstances.

5G NR is defined from the start to support more use cases than LTE was initially conceived for, and the latency requirement is much more stringent. This leads to several key changes in the organization of the resource grid for 5G NR that are explained below:

- Delay requirements: 5G NR supports a physical layer roundtrip latency of 1 ms for URLLC cases.
- Spectral and throughput requirements: 5G NR requires higher throughput. More throughput is achieved by either more bandwidth or more spectral efficiency. Higher bandwidth requires frequency bands with large “contiguous” bandwidths. That is available only at carrier frequencies as high as 60 or 70 GHz, whereas LTE is deployed only below 6 GHz. Here again, this has significant consequences for the design of the physical layer, as beamforming becomes required to support those higher frequencies. At higher

frequencies, more spectrum is available, and 5G NR is set to take advantage of this spectrum with up to 400 MHz of bandwidth. Moving on to more detailed points of the physical layer, the subcarrier spacing, fixed in LTE at 15 kHz, can now take values between 15 and 240 kHz.

- Efficient signaling: Regarding frequency allocation, an LTE UE, placed in a 20 MHz cell, is required to decode the whole bandwidth, and signals of interest can span the whole bandwidth. On the other hand, 5G UEs do no need to support the whole bandwidth. Remember that the bandwidth in 5G NR can be much larger, which would have compounded that problem. Signals of interest can be confined to a subsection of the bandwidth, and bandwidth parts are one of the new concepts that help with this capability.
- Energy/power efficiency: Finally, the number of always-on signals has been reduced in 5G NR in order to save energy. The main casualty is the cell-specific reference signals, or CRSs, which are provided in LTE as a cell-wide reference for demodulation and channel-quality estimation. CRSs are no longer present in 5G NR. Another motivation for that change is that, at higher carrier frequencies, signals need to be beamformed in order to overcome propagation losses. As a result, it is both difficult and not useful to provide cell-wide reference signals: the signal strength would be low and each channel is beamformed anyway, which means that the UE would need to be informed of the precoding matrix separately. Instead, UEs in 5G rely on reference signals that undergo the same beamforming as the associated channel.



	LTE	5G
Use cases	Mobile broadband access (MTC later)	More use cases: eMBB, mMTC, URLLC
Latency	~10 ms	<1 ms
Band	Below 6 GHz	Up to 60 GHz
Bandwidth	Up to 20 MHz	Up to 100 MHz below 6 GHz Up to 400 MHz above 6 GHz
Subcarrier spacing	Fixed	Variable
Freq allocation	UEs need to decode the whole BW	Use of bandwidth parts
"Always on" signals	Used: Cell specific RS, PSS,SSS, PBCH	Avoid always on signals, the only one is the SS block

Fig 1: Comparison of 5G and LTE physical layer parameters

II. 5G PHYSICAL LAYER FEATURES

We have produced a series of educational videos that explain all components and features of the 5G physical layer. This paper provides a lighter treatment of the following topics:

- Transport channels, physical channels, and physical signals
- 5G waveforms, frame structure, and numerology
- Downlink data
- Uplink data

Additional information is available on the topics mentioned above as well as the following features of the 5G physical layer [1]:

- Downlink control
- CORESETs
- Uplink control
- DMRS
- Synchronization signal block
- Initial acquisition procedures: cell search and RACH
- Signals for channel sounding
- Hybrid beamforming

A. 5G Transport Channels, Physical Channels, and Physical Signals

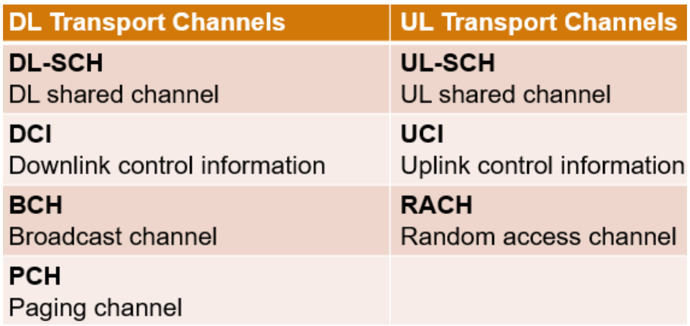
The 5G PHY, like LTE, is organized into a set of channels and signals that serve specific purposes, such as establishing connections between UEs and base stations, carrying information, and implementing control functions. The 5G standard defines different channels that are used to provide different kinds of data transfer and control services in the MAC layer of the 5G protocol stack.

In the next paragraphs, we provide a quick overview of the relevant terminology. For a complete discussion of these topics, please view the "5G Explained" page on mathworks.com [1].

1) Transport Channels

Transport channels in 5G have several different functions:

- Provide information transport services from the physical layer to the MAC layer (broadcast channel).
- Carry control and signaling information and data in the downlink and uplink information.
- Define scrambling, channel coding, interleaving, and rate matching to apply to information in each direction.
- Establish an uplink connection from a UE to 5G base stations (RACH, or random-access channel).



DL Transport Channels	UL Transport Channels
DL-SCH DL shared channel	**UL-SCH** UL shared channel
DCI Downlink control information	**UCI** Uplink control information
BCH Broadcast channel	**RACH** Random access channel
PCH Paging channel	

Fig 2: Downlink and uplink transport channels

2) Physical Layer Channels and Signals

Physical layer channels in 5G define the mechanism for mapping data messages to specific time and frequency locations. There are three types of physical layer channels for downlink and uplink: shared, control, and broadcast.
Shared, control, and broadcast channels are DL-SCH/PDSCH, PDCCH, BCH/PBCH for Downlink and UL-SCH, PUSCH, PUCCH for Uplink

The synchronization and reference signals enable the USE and base station to establish a connection, coordinate the time location of information, and demodulate signals.
Synchronization and reference signals are PSS, SSS, and DM-RS.

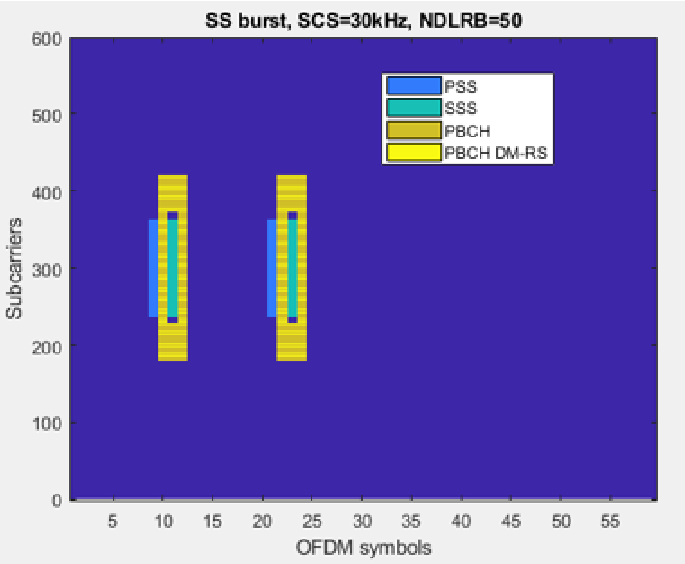


Fig 3: Example of channels mapped onto the 5G OFDM grid

B. *5G Waveforms, Frame Structure, and Numerology*

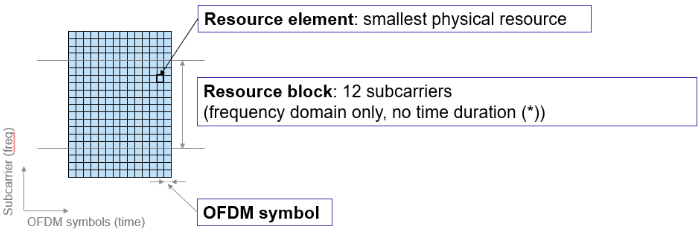
This section provides a brief overview of the structure of 5G waveforms and numerology. While the structure has many similarities to LTE, there are important differences to note.

1) *Waveforms*

5G waveforms, like LTE, use OFDM waveforms with cyclic prefix (CP-OFDM). However, there are many more details and greater flexibility in 5G. These features include mixed-frame numerology, multiple bandwidth parts, multiple shared channels, fully parameterizable SS bursts, and multiple CORESETs (control resource sets) and search spaces.

a) *Resource Elements and Resource Blocks*

Information in 5G is mapped onto a time vs. frequency grid. The unit of time is an OFDM symbol, and the unit of frequency is a subcarrier.
Within this grid, information-carrying physical layer resources are divided into resource blocks (a collection of 12 subcarriers in the frequency domain), which in turn consist of resource elements. A resource element is one OFDM symbol within one subcarrier.



(*) unlike LTE: 1 RB = 12-by-7

Fig 4: Resource elements and blocks are mapped onto a time-frequency grid

2) *Frame Structure*

The 5G frame structure is conceptually like LTE, but it is more flexible to accommodate the different requirements for high-speed and low-latency operation.
5G frames are 10 ms in duration, with 10 subframes per frame. There can be a variable number of slots per subframe, with 14 OFDM symbols per slot.
As a result, there can be a variable number of OFDM symbols per subframe.

a) *Variable Subcarrier Spacing*

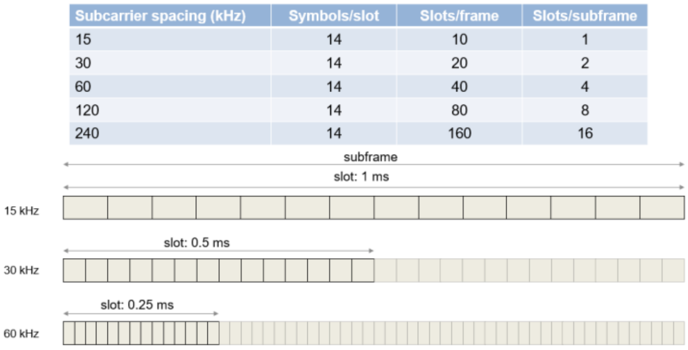
One of the main innovations in the 5G standard is the concept of flexible numerology and subcarrier spacings to enable a range of bandwidths and latency. In the 5G standard, subcarrier spacing can be a power-of-two multiple of 15 kHz, so spacings can vary from 15 to 240 kHz. 5G waveforms can contain variable subcarrier spacings. That means that within a 5G waveform, different time and frequency resource blocks can be specified.
One of the requirements of 5G is to increase the maximum supported bandwidth. By providing for a larger subcarrier spacing as well as a higher number of downlink resource blocks, we can achieve a larger overall bandwidth compared with LTE. In LTE, the maximum bandwidth is 20 MHz, while in 5G the bandwidth can be 397.4 MHz.
This flexibility is designed to meet the requirements of different services in 5G (enhanced mobile broadband, massive machine type communications, and ultra-reliable and low-latency communications). The increased subcarrier spacing can also - help operation at millimeter-wave frequencies.

	Slot configuration 0				
Subcarrier spacing (kHz)	15	30	60	120	240
Symbol duration (no CP) (µs)	66.7	33.3	16.6	8.33	4.17
Nominal max BW (MHz)	49.5	99	198	396	397.4
Min scheduling interval (ms)	1	0.5	0.25	0.125	0.0625

Fig 5: Flexible numerology and subcarrier spacing in 5G standard

b) Slots and OFDM Symbols

As the resolution in frequency is changed by varying the subcarrier spacing, the frame or time domain duration also is affected. In the 4G LTE standard, one subframe has a duration of 1 ms. In 5G, at 15 kHz, 1 ms corresponds to one slot. As you increase the spacing by power-of-two multiples, the slot duration is also divided by 2, 4, and so on.



Subcarrier spacing (kHz)	Symbols/slot	Slots/frame	Slots/subframe
15	14	10	1
30	14	20	2
60	14	40	4
120	14	80	8
240	14	160	16

Fig 6: A change in subcarrier spacing corresponds to a change in the number of time slots per frame

3) Bandwidth Parts

Another important aspect of flexibility in 5G is the ability to divide the bandwidth into bandwidth parts (BWPs), which are sets of consecutive resource blocks characterized by their own subcarrier spacing and cyclic prefix.

The availability of BWPs helps to address two issues. First, some devices may not be able to receive the full bandwidth. Second, BWPs permit bandwidth adaptation to reduce energy consumption when only narrow bandwidth is required. 5G UEs can be configured with up to four bandwidth parts, but only one can be active at a time. UEs are not expected to receive data outside of the active bandwidth part.

C. Downlink Data in 5G NR

In this section, we take a closer look at downlink data transmission in 5G New Radio.

1) Downlink Shared Channel

The downlink shared channel, or DL-SCH, is the channel that carries user data. It also carries other pieces of information, such as the different types of system information blocks, or SIBs.

The coding chain includes the usual steps, such as CRC, code block segmentation, rate matching, and concatenation. All of these steps are already known from LTE. The main difference with LTE is the use of LDPC coding. The output of the coding chain is a codeword.

5G supports transmission of up to eight layers to a single user on the downlink. This means that there can be up to eight streams transmitted in parallel. Those streams are coming for one or two codewords: one codeword for the first four layers and a second one for the next four.

The coded data is then mapped to the physical downlink shared channel, or PDSCH.

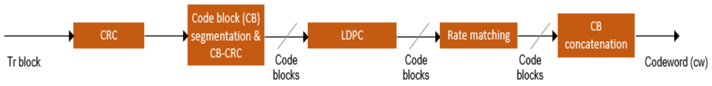


Fig 7: Coding chain for the downlink shared channel

2) Physical Downlink Shared Channel

The physical downlink shared channel is highly configurable—much more than in LTE—and we will see some of the detail in the next paragraphs. It is configured by both downlink control information, which can change from slot to slot, and radio resource control, which can set up some parameters as well. This is very similar to LTE. In this channel, we find scrambling, modulation, layer mapping, precoding for MIMO processing, resource mapping, and mapping to physical antennas.

While those are all known blocks, there are a few differences worth pointing out. The precoding step is not specified explicitly in the standard, although it is fully expected to be present. NR uses the exact same list of modulations on the downlink as LTE: from QPSK through 256 QAM.

3) PDSCH Multi-antenna Precoding

After one or two codewords are mapped to between one and eight layers, the layers undergo precoding, which, interestingly, is not specified in the standard for downlink.

Precoding is the operation that maps the layers to as many or more antenna ports, using a matrix multiplication with the precoder. A special case of precoding is mapping one layer to multiple antennas, which enables beamforming. For line-of-sight transmission, this would likely mean targeting a specific direction. Another case of precoding is mapping several layers to multiple antennas. This more general case is sometimes referred to as spatial multiplexing.

One key aspect of precoding in 5G is that the associated demodulation reference signals, or DMRSs, must undergo the same precoding. As a result, the UE doesn't need to be made aware of the precoder, as the effect of the precoder is included in channel estimation.

The precoder output is then mapped to physical resource blocks, as we will see in the next paragraph. Downlink channels and signals, including the PDSCH and associated DMRS, share the OFDM grid.

4) PDSCH Allocation

Here we see examples of PDSCH resource allocation in time. The PDSCH may span the whole slot, as shown at the bottom of the grid in Figure 8). It may also use only part of a slot. This is sometimes referred to as partial slot allocation, and it is a new capability in 5G New Radio compared with LTE. As you may remember, LTE always allocates a full subframe of 1 ms for PDSCH.

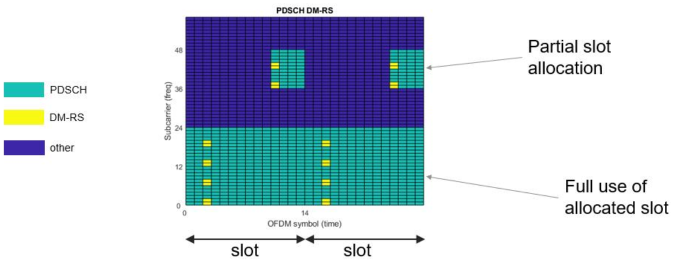
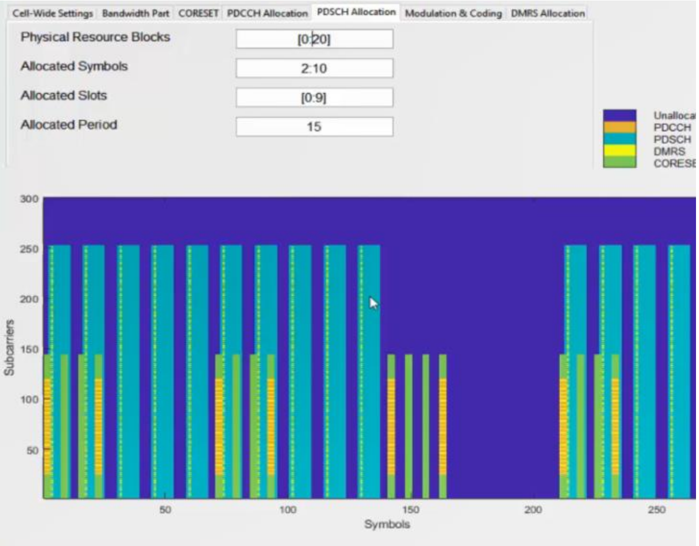


Fig 8: Partial and full slot allocation on the OFDM grid

It is possible to explore some of those allocation options interactively with a user interface that uses 5G Toolbox from MathWorks.

Figure 9 shows 10 subframes with 30 kHz subcarrier spacing, which means a total of 20 slots. The PDSCH is shown in greenish blue.

Resource block allocation does not have to be contiguous, although it is easier to signal when it is. If it is contiguous from 0 to 20, there will be PDSCH transmission in the first 10 slots, followed by five empty slots. This is because we allocated slots 0 through 9 with a periodicity of 15 slots.



Physical Resource Blocks [0:20]
Allocated Symbols 2:10
Allocated Slots [0:9]
Allocated Period 15

Fig 9: Allocation of slots 0 through 9 with a periodicity of 15 slots leads to a PDSCH transmission in the first 10 slots, followed by five empty slots

If the allocation is changed to something different (for example, i[0:5 to 8]), slots 6, 7, and 9 will not have PDSCH transmission.

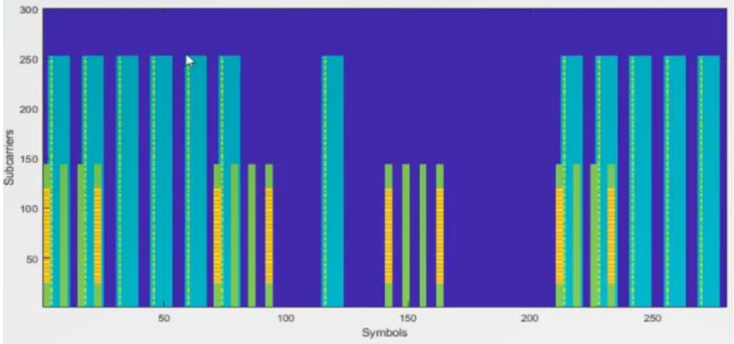


Fig 10: If the allocation is changed to i[0:5 to 8], slots 6, 7, and 9 will not have PDSCH transmission

Notice that, within each slot, the PDSCH uses only symbols 2 through 10. This is called partial slot allocation. You can choose to allocate the full slot, in which case there is no break between PDSCH transmissions.

Notice also that the reference signals for PDSCH are shown in yellow. Those locations are not available for PDSCH mapping.

III. METHODS FOR SIMULATING 5G PHYSICAL LAYERS AND PERFORMANCE MEASURING

The best way to understand 5G PHY is to explore it by running simulations as you can do with 5G Toolbox in the MATLAB® environment.

The proposed simulation environment addresses three primary use cases:

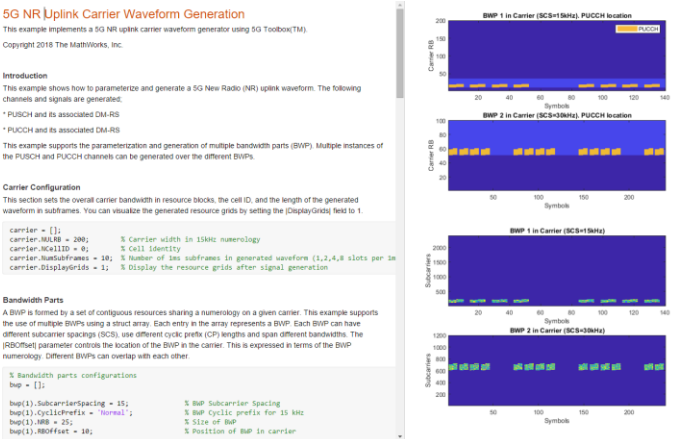
- End-to-end link simulation, enabling you to model the full transmitter/channel/receiver chain to analyze system performance, including BER and throughput.
- Waveform generation and analysis, including the NR subcarrier spaces and frame numerologies. You can use the waveforms to test designs of RF transceivers and other components, and to provide I/Q samples for over-the-air testing with RF instruments.
- Golden reference design verification. 5G Toolbox is customizable and editable MATLAB code, so you can see how the algorithms work, modify them for your own design, and verify the behavior of your design.

Functions to model all aspects of the physical layer discussed in this paper are available. These functions mirror the structure of 5G waveforms, uplink and downlink channels, and physical signals, and give you access to the details of the processing subsystems. In addition, the channel models specified in the 5G standard are available [2].

All functions in 5G Toolbox are open, editable, and customizable. This allows to see the implementation and understand the mathematics of 5G algorithms. They provide an excellent starting point for the verification of user-specific implementations.

The MATLAB code provided with the tool can be automatically translated into C/C++ code to accelerate simulations and to use in external simulation and test environments.

To help the user get started, comprehensive reference examples covering NR synchronization procedures, downlink processing, and uplink processing are available and ready for use [3].



5G NR Uplink Carrier Waveform Generation

This example implements a 5G NR uplink carrier waveform generator using 5G Toolbox(TM).

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Introduction

This example shows how to parameterize and generate a 5G New Radio (NR) uplink waveform. The following channels and signals are generated;

* PUSCH and its associated DM-RS

* PUCCH and its associated DM-RS

This example supports the parameterization and generation of multiple bandwidth parts (BWP). Multiple instances of the PUSCH and PUCCH channels can be generated over the different BWPs.

Carrier Configuration

This section sets the overall carrier bandwidth in resource blocks, the cell ID, and the length of the generated waveform in subframes. You can visualize the generated resource grids by setting the |DisplayGrids| field to 1.

```
carrier = [];
carrier.NULRB = 200;        % Carrier width in 15kHz numerology
carrier.NCellID = 0;        % Cell identity
carrier.NumSubframes = 10;  % Number of 1ms subframes in generated waveform (1,2,4,8 slots per 1m
carrier.DisplayGrids = 1;   % Display the resource grids after signal generation
```

Bandwidth Parts

A BWP is formed by a set of contiguous resources sharing a numerology on a given carrier. This example supports the use of multiple BWPs using a struct array. Each entry in the array represents a BWP. Each BWP can have different subcarrier spacings (SCS), use different cyclic prefix (CP) lengths and span different bandwidths. The |RBOffset| parameter controls the location of the BWP in the carrier. This is expressed in terms of the BWP numerology. Different BWPs can overlap with each other.

```
% Bandwidth parts configurations
bwp = [];

bwp(1).SubcarrierSpacing = 15;              % BWP Subcarrier Spacing
bwp(1).CyclicPrefix = 'Normal';             % BWP Cyclic prefix for 15 kHz
bwp(1).NRB = 25;                            % Size of BWP
bwp(1).RBOffset = 10;                       % Position of BWP in carrier
```

Fig 11: Comprehensive reference examples covering NR synchronization procedures, downlink processing, and uplink processing are available and ready for use

IV. CONCLUSIONS

In this short paper we introduced key concepts in the complex 5G physical layer, explaining how 5G features are related to specific application requirements for future mobile communication systems. Also, we introduced an efficient environment for modeling and simulating 5G New Radio systems.

REFERENCES

[1] https://de.mathworks.com/videos/series/5g-explained.html

[2] https://de.mathworks.com/help/5g/referencelist.html?type=function&s_cid=doc_ftr

[3] https://de.mathworks.com/help/5g/examples.html?&s_tid=CRUX_gn_example

ACRONYMS

BCH	Broadcast Channel
BER	Bit Error Rate
BWP	Bandwidth Part
CORESET	Control Resource Set
CP-OFDM	Cyclic Prefix-OFDM
CRC	Cyclic Redundancy Check
CRS	Cell Reference Signal
DL-SCH	Downlink Shared Channel
DM-RS	Demodulation Reference Signal
eMBB	Enhanced Mobile Broadband
IoT	Internet of Things
I/Q	In-Phase and Quadrature
LDPC	Low Density Parity Check
LTE	Long-Term Evolution
MIMO	Multiple Input Multiple Output
mMTC	Massive Machine Type Communications
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RS	Reference Signal
SIB	System Information Block
SS	Synchronization Signal
SSS	Secondary Synchronization Signal
UE	User Equipment
UL-SCH	Uplink Shared Channel
URLLC	Ultra-Reliable and Low-Latency Communications