5G NR Physical Layer

TP00005-V-1701 V0 - S02M01 Ed1

Learning objectives

Upon completion of this module, you should be able to:

- Describe the 5G New Radio Physical Layer
- List the different 5G New Radio Physical Channels and Signals

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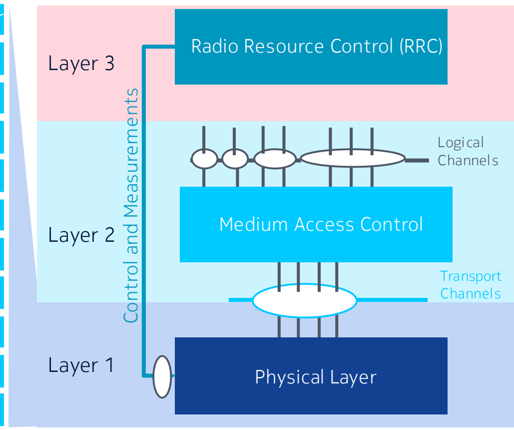
5G New Radio Physical Layer

5G Physical Layer
Physical Layer Functions

The NR physical layer (Layer 1) performs the following functions to provide the data transport service:

- Error detection on the transport channel and indication to higher layer
- FEC encoding/decoding of the transport channel
- Hybrid ARQ soft-combining
- Rate matching of the coded transport channel to physical channels
- Mapping of the coded transport channel onto physical channels
- Power weighting of physical channels
- Modulation and demodulation of physical channels
- Frequency and time synchronization
- Radio characteristics measurements and indication to higher layers
- Multiple Input Multiple Output (MIMO) antenna processing
- RF processing



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The physical layer offers a transport channel to MAC. The transport channel is characterized by how the information is transferred over the radio interface. The physical layer interfaces the Medium Access Control (MAC) sub-layer of Layer 2 and the Radio Resource Control (RRC) Layer of Layer 3.

The physical layer is expected to perform the following functions to provide the data transport service:

- Error detection on the transport channel and indication to higher layers;
- FEC encoding/decoding of the transport channel;
- Hybrid ARQ soft-combining;
- Rate matching of the coded transport channel to physical channels;
- Mapping of the coded transport channel onto physical channels;
- Power weighting of physical channels;
- Modulation and demodulation of physical channels;
- Frequency and time synchronization;
- Radio characteristics measurements and indication to higher layers;
- Multiple Input Multiple Output (MIMO) antenna processing;
- RF processing.

Physical layer procedures are:

- Cell search
- Power control
- Uplink synchronization and Uplink timing control
- Random access related procedures
- HARQ related procedures
- Beam management and CSI related procedures.

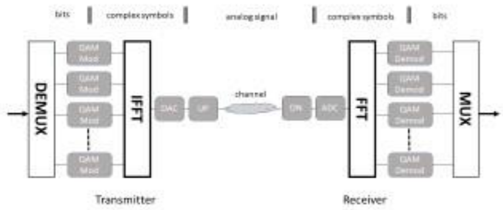
5G Physical Layer

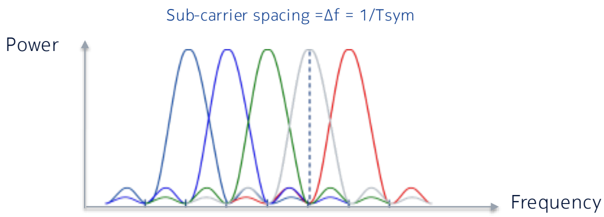
Physical Layer Functions

For the 5G Physical Layer, 3GPP proposes the following key components, among others:

- Modulation
- Waveform
- Multiple antenna systems – MIMO and beams
- Channel Coding

5G Physical layer
Modulation





Modulation is a telecommunications technique to mount a signal (to be transmitted) on top of a stronger/robust frequency (carrier), by modifying one of the physical properties of the carrier.

New Radio (5G) uses Orthogonal Frequency Duplex Modulation (OFDM) as the standard modulation format.

OFDM, combines the use of QPSK and QAM to allow a system that will broadcast high data rate messages over-the-air interface for both, uplink and downlink.

OFDM – Orthogonal Frequency Duplex Modulation

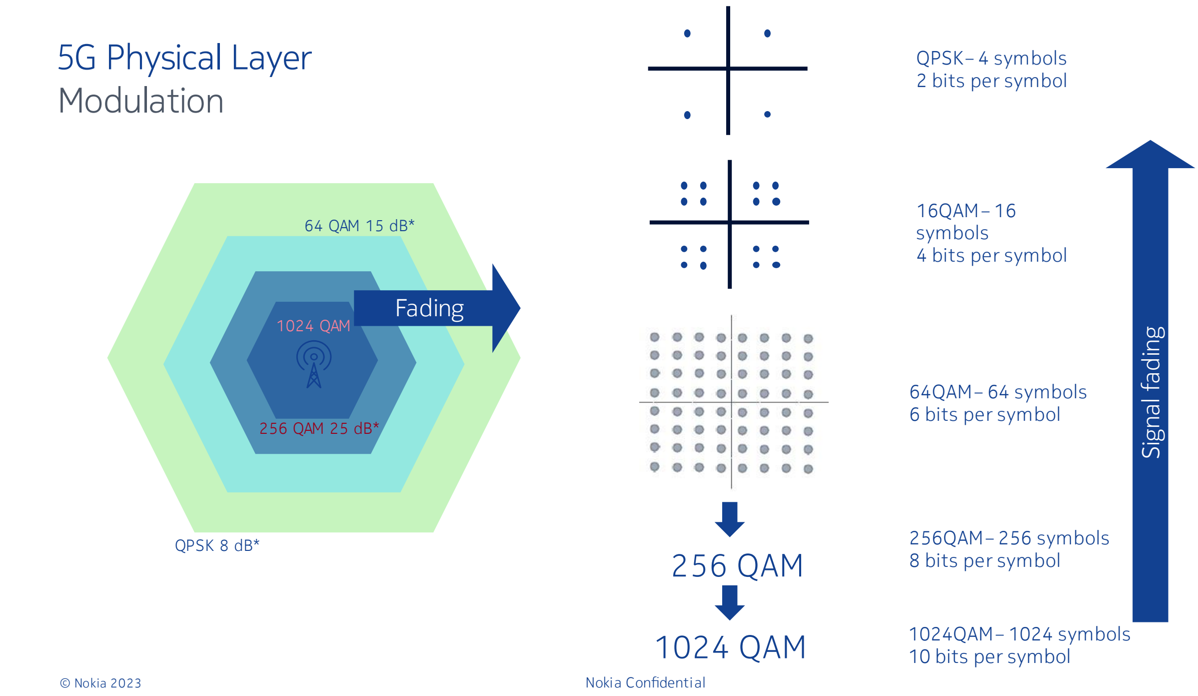
QPSK – Quadrature Phase Shit Keying

QAM – Quadrature Amplitude Modulation

OFDM is block transmission of N symbols in parallel on N orthogonal sinusoidal time-limited waveforms. Each sinusoidal frequency is called a subcarrier since one modulation symbol is mapped to one waveform per OFDM symbol time.

Each subcarrier is 15 kHz in bandwidth like LTE, but in NR Multiple sub-carrier spacings are supported including 15kHz, 30kHz, 60kHz and 120kHz for data.

The inter-subcarrier spacing is equally distributed over the channel. At the center frequency of each subcarrier, all the other subcarriers go to zero amplitude.



* - Values selected randomly

NR supports Quadrature Phase Shift Keying (QSPK), Quadrature Amplitude Modulation such as 64-QAM and 256 QAM for both Uplink and Downlink.

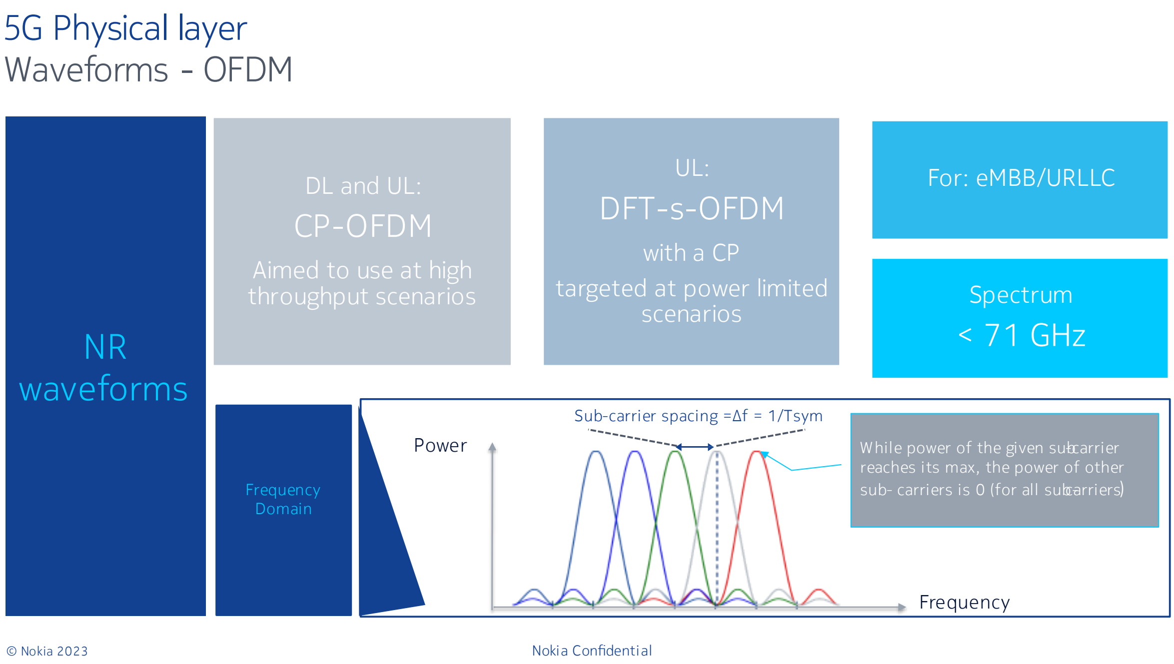
3GPP Release 17 specifies downlink 1024QAM for NR PDSCH operation in FR1, which provides higher downlink peak rate.

Depending on the modulation technique more bits per symbol may be carried out.

Modulation techniques are selected depending on their SNR (Signal-to-Noise-Ratio). This means users located at the cell border will need a more robust modulation scheme causing a lower throughput. All Modulation schemes feature an SNR threshold, this is due to the physical properties of the RF signals.

Signal quality is measured using Reference Signals, such as:

- Demodulation Reference Signal (DMRS)
- Phase Tracking Reference Signal (PTRS)
- Sounding Reference Signal (SRS)
- Channel State Information Reference Signal (CSI-RS)



Multiple numerologies are supported. The support of multiple numerologies and multiple subcarrier spacings is the most outstanding NR feature, when compared to LTE.

A Numerology corresponds to one subcarrier spacing in the frequency domain. By scaling a reference subcarrier spacing by an integer N, different numerologies can be defined.

LTE uses a fixed numerology of 15 kHz sub-carrier spacing (SCS), whereas NR Release-15 has a scalable numerology with sub-carrier spacings of 15, 30, 60 kHz, 120 kHz, and 240 kHz. Note that 240 kHz sub-carrier spacing can be used to provide broadcast signals at millimeter-wave.

Normal CP is supported for all sub-carrier spacings. Extended CP is supported for 60 kHz subcarrier spacing.

5G Physical layer
Waveforms - Numerology

	Numerology: Subcarrier spacing (kHz)						
Numerologies with normal CP	15	30	60	120	240	480	960
Numerologies with extended CP	60						

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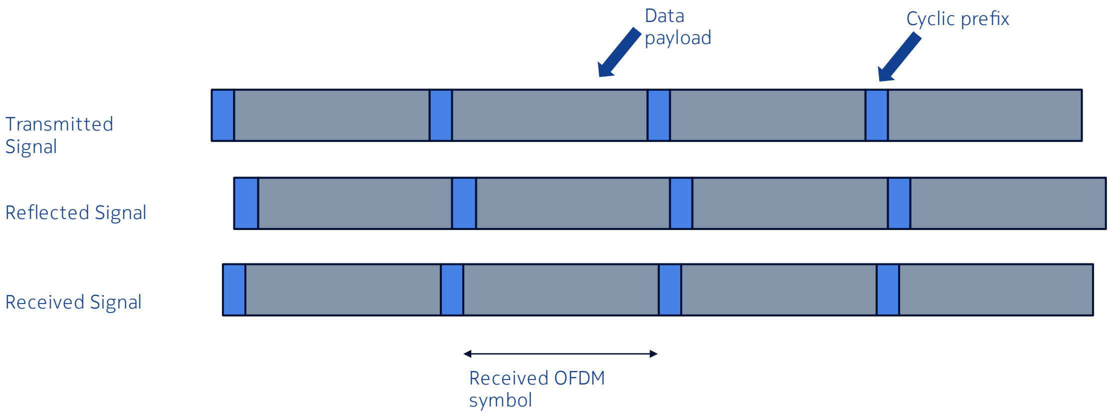
5G Physical layer
Waveforms - OFDM Cyclic Prefix



The cyclic prefix acts as a buffer region or guard interval to protect the OFDM signals from intersymbol interference.

The cyclic prefix performs two main functions.

- The cyclic prefix provides a guard interval to eliminate inter-symbol interference from the previous symbol.
- It repeats the end of the symbol so the linear convolution of a frequency-selective multipath channel can be modeled as circular convolution, so the result is that it may transform to the frequency domain via a discrete Fourier transform. This mechanism allows for simple frequency domain processing, such as channel estimation and equalization.

NR utilizes CP-OFDM in both, uplink and downlink up to a carrier level of 52.6 GHz.

5G Physical Layer
Waveforms – 5G Numerologies

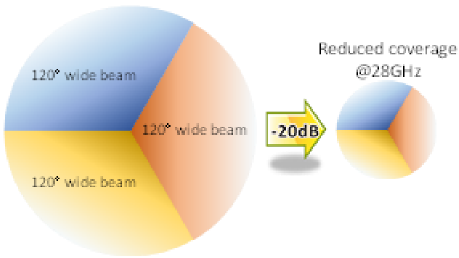
	15 kHz	30 kHz	60 kHz	120 kHz
Frequency band	0.41 – 7.125 GHz	0.41 – 7.125 GHz	0.41 – 7.125 GHz 24 – 52.6 GHz	24 – 52.6 GHz
OFDM Symbol duration	66.67 us	33.33 us	16.67 us	8.33 us
Cyclic Prefix duration	4.69 us	2.34 us	1.17 us	0.59 us
OFDM symbol with CP	71.35 us	35.68 us	17.84 us	8.91 us
Maximum Bandwidth	50 MHz	100 MHz	200 MHz	400 MHz

5G Physical layer
Multiple Antennas – MIMO and beams

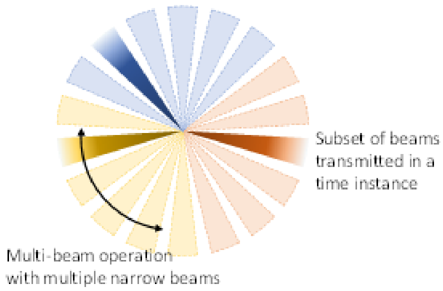
In lower frequencies, a single beam can be used to provide wide coverage

In higher frequencies, multiple beams can be used to extend coverage

Single beam per sector @2.8GHz



Multi-beam per sector @28GHz



Pathloss is proportional to the square of frequency

Pathloss of higher frequencies can be overcome by utilizing multi-antennas:

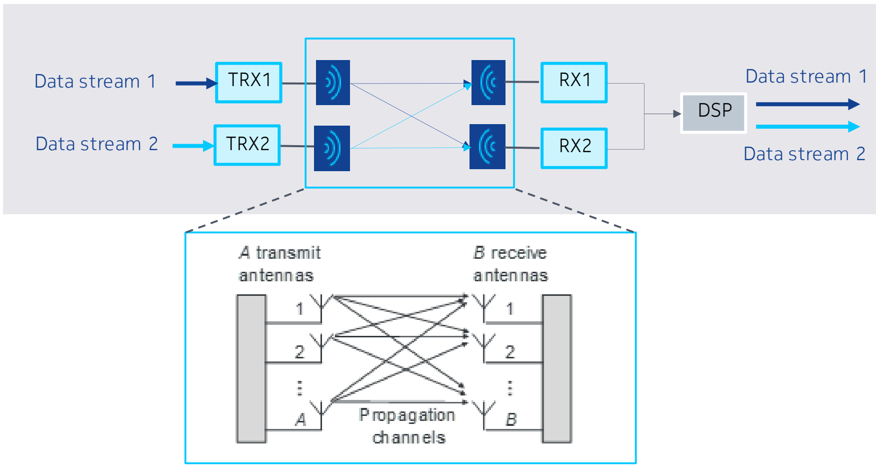
Multiple Rx antennas to effectively increase aperture size

Multiple Tx antennas to direct energy

5G Physical layer
Multiple Antennas – MIMO principle

Spatial multiplexing (MIMO)

MIMO principle with A transmit and B receive antennas



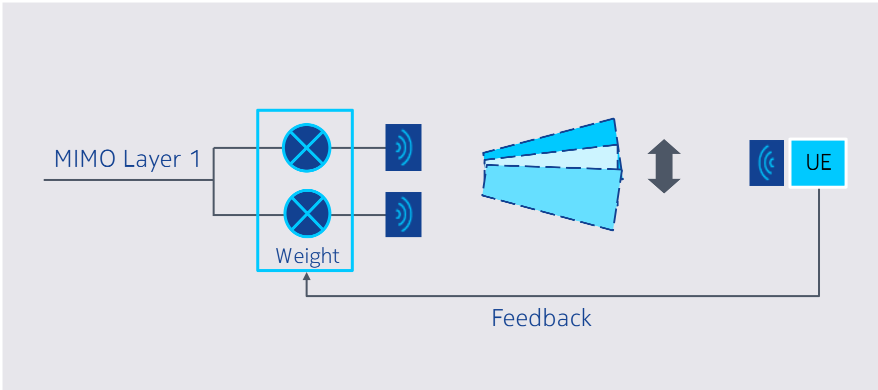
MIMO is a Multiple Input Multiple Output multi-antenna transmission and reception technique. MIMO basic concept is shown in this Figure. With MIMO, multiple spatially separated users are catered for by the antenna array in the same time and frequency resource. Data is divided into independent MIMO data streams that are transmitted simultaneously.

A x B MIMO refers to the case with A transmit antennas in the base station and B receive antennas in the device. Many current devices and networks utilize 2x2 MIMO where two parallel data streams can be transmitted. Some of the latest devices and networks support 4x4 MIMO (four receive antennas) which doubles the peak rate compared to 2x2MIMO and increases the average rates typically by +50%.

5G Physical layer
Multiple Antennas – Beamforming principle

Beamforming principle

Beam direction adjustments

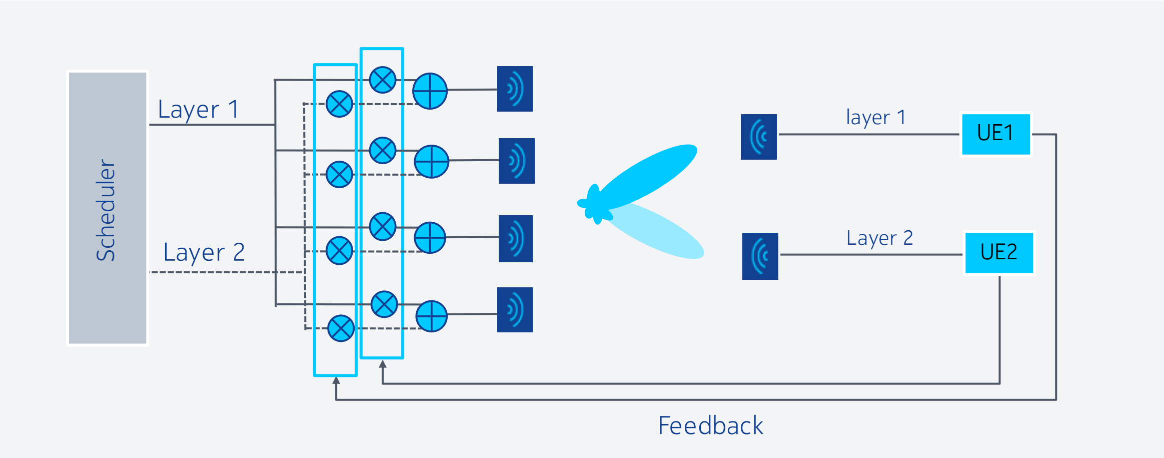


Beamforming is a signal processing technique used for directional signal transmission or reception. This is achieved by combining elements in an antenna array in such a way that signals at particular angles experience constructive interference while others experience destructive interference. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity.

There are several different ways to implement the beamforming. The most commonly used is Beamforming by Precoding : This is the technique that change the beam pattern (radiation form) by applying a specific precoding matrix.

Remember, Massive MIMO beamforming can increase spectral efficiency and network coverage substantially. Beamforming comes more practical at higher frequencies because the antenna size is relative to the wavelength. In practice, massive MIMO beamforming can be utilized at frequencies above 2 GHz in the base stations and at millimeter waves even in the devices.

5G Physical layer
MIMO and Beamforming combined for MU-MIMO



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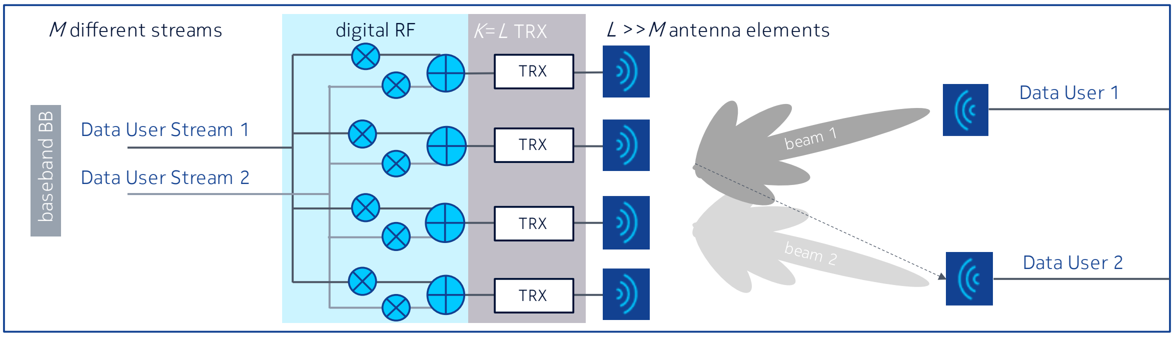
This figure shows user specific beamforming principle: Each user has its dedicated beam which is created in the digital domain based on the feedback from the device and/or based on the uplink channel measurements. The uplink measurements can be utilized for the downlink beamforming in TDD because the same frequency is used for uplink and for downlink

5G Physical layer
Digital RF Beamforming



Applicable to lower operating bands

Provides flexibility

Can generate many simultaneous beams
- Higher order MIMO
- Multi-user MIMO

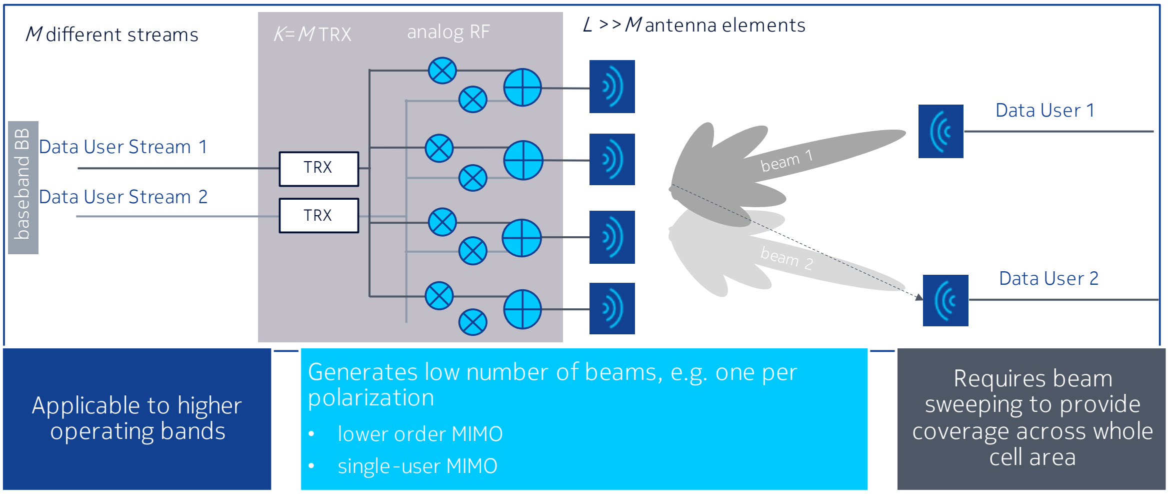
Has more costly hardware requirements

Beamforming can be implemented in different ways: Digital, analog, and hybrid Beamforming.

With Digital beamforming, beamforming is done completely in the digital domain which enables multiple beams and multiple streams out of the same antenna array. Digital beamforming supports many control schemes to increase capacity including user-specific beams and adaptive grid of beams. Each radiating element has separate transceiver in digital beamforming.

- Digital beamforming requires an RF chain ‘per antenna port’
- Becomes unpractical when the number of antenna ports becomes high
- Typical active antenna has up to 64 RF chains and 128 antenna elements, i.e. each TRX is connected to 2 antenna elements
- Digital beamforming provides flexibility in terms of being able to apply different phase shifts ‘per user’
- Phase shifts can also be applied ‘per Physical Channel

5G Physical layer
Analog RF Beamforming



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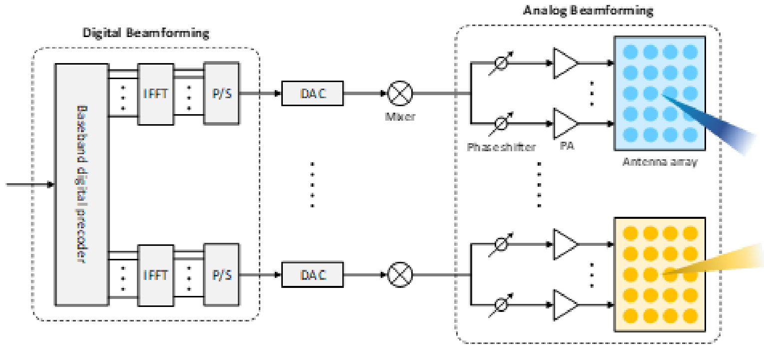
In case of Analog beamforming, beamforming is done in the analog domain by changing phase and amplitude of each antenna element. Each array has a single transceiver per polarization.

- Analogue beamforming requires an RF chain 'per beam'
- Reduces the requirement for RF hardware when large numbers of antenna elements are used
- Each beam contains the transmissions for all users, if multiple users are scheduled during the same slot

5G Physical layer
Hybrid beamforming

A combination of digital and analog beamforming, or ‘hybrid beamforming’ can be used to realize large BF gains without excessively increasing implementation complexity

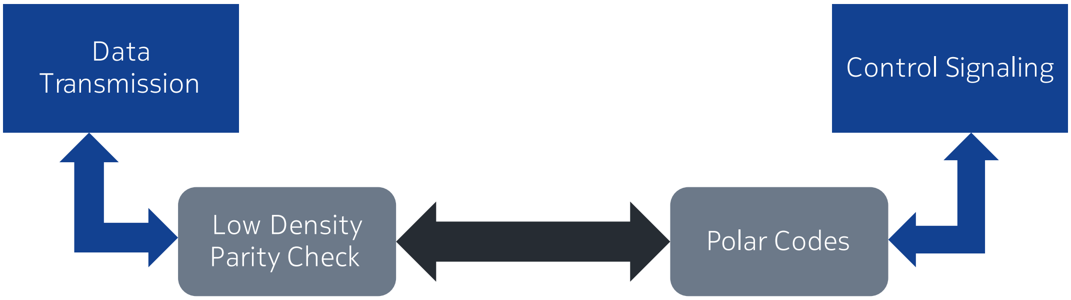


Hybrid
Adaptive TX/RX Weightings at both RF and Baseband
Single transceiver per RF beam
Combination RF / Baseband
Moderate Flexibility
Good power consumption & cost characteristics

In massive MIMO systems, the beamforming algorithms executed at the digital baseband can get very complex. At high frequencies and with large number of antenna elements, this can be very costly, increase loss and complexity in the system. Hybrid beamforming is an alternative solution where some of the beamforming is done using analog components and not digital.

Hybrid beamforming is a combination of analog and digital beamforming. When part of the beamforming is in analog domain, the number of transceivers is typically much lower than the number of physical antennas which can simplify the implementation especially at high frequency bands. This technique is suited for millimeter waves.

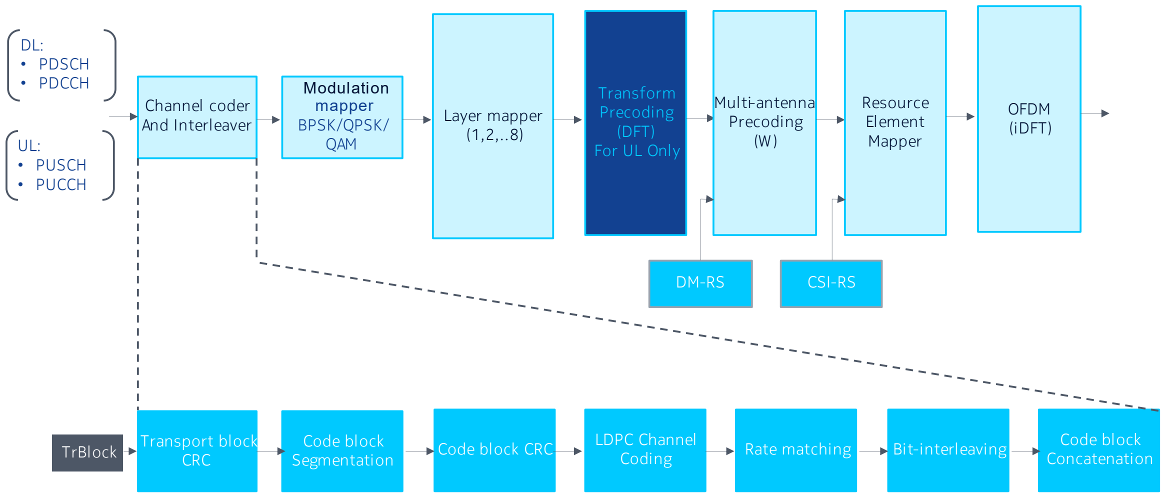
5G Physical layer
Channel Coding



5G/NR utilizes Low Density Parity Check coding for the data transmission of enhanced Mobile Broadband (eMBB) services and Polar coding for Control Signaling. LDPC codes for NR employ a rate-compatible structure which permits for transmission at different code rates and for HARQ operations using Incremental Redundancy.

NR employs Polar Codes for the physical layer control signaling where the information blocks are relatively small compared to data transmission. By concatenating the polar code with an outer code and by performing successive cancellation list decoding, good performance is achieved at shorter block lengths. Reed-Muller codes are used for the smallest control payloads.

NR Physical Layer
Transport-Channel Processing



The physical-layer processing of transport channels consists of the following steps:

1. Transport block CRC attachment (TBS above 3824 has 24 bit CRC, otherwise 16 bit CRC);
2. Code block segmentation and code block CRC attachment (24 bit CRC);
3. Channel coding: LDPC coding (base graph #1 or base graph #2);
4. Physical-layer hybrid-ARQ processing and rate matching;
5. Bit-interleaving;
6. Modulation: QPSK, 16QAM, 64QAM and 256QAM;
7. Layer mapping and pre-coding;
8. Mapping to assigned resources and antenna ports.

5G New Radio Physical Channels & Signals

5G New Radio Physical Channels & Signals
Downlink Physical Channels and Signals list

According to TS 38.211 v17.2, Physical channels are divided into Downlink and Uplink.

Downlink Physical channels:

- Physical Downlink Control Channel (PDCCH).
- Physical Broadcast Channel (PBCH).
- Physical Downlink Shared Channel (PDSCH).

Downlink Physical Signals:

- Demodulation reference signals (DM-RS)
- Phase-tracking reference signals (PT-RS)
- Positioning reference signal (PRS)
- Channel-state information reference signal (CSI-RS)
- Primary synchronization signal (PSS)
- Secondary synchronization signal (SSS)

PDCCH: which carries only L1 Downlink Control Information (DCI) and uses only QPSK modulation. There are 1 or more Control Channel Elements (up to 16 CCE's) used for PDCCH transmissions which allows one to adjust the amount of physical layer resources used for each PDCCH transmission. This enables link adaptation resources used for each PDCCH transmission upon the radio conditions.

PDSCH: it carries the user data as well as control information for higher layers. The PDSCH provides the physical layer to transport the Downlink Shared Channel, which carries information from higher layers. Additionally, the Paging channel (PCH) is carried on the PDSCH. Parameters related to PDSCH transmission such as allocation, are signaled on the PDCCH. The modulation techniques supported for the PDSCH are QPSK, 16-QAM, 64-QAM, 256-QAM.

PBCH: it conveys the required system information for the UE to be able to access the 5G network. In 5G, only the most necessary information is broadcasted periodically, while other system information is provided on a need basis. The upper layer Broadcast Channel is mapped on the PBCH and it features QPSK as the modulation scheme. The Synchronization Signal (SS) block is formed by using the BCH the Primary Synchronization Signal (PSS) and the Secondary Synchronization Signal (SSS).

DM-RS: is used to help on the channel estimation. DM-RS is used for both, downlink and uplink. The number of DM-RS signals can vary depending whether there are high-velocity UEs or not.

PT-RS: are used with high frequency bands when they are configured by the network. PT-RS is repeated periodically in the frequency-domain while continuing a sequence of known data. It allows the reduction of the common phase error on the receiver end. Like the DM-RS, PT-RS is used in both directions.

CSI-RS: on the downlink, helps the UEs to make a CSI measurement report. With know CSI-RS in the time and frequency domains, making feedback necessary for frequency domain scheduling in the gNB.

PSS and SSS: together the create the Physical Layer Cell Identity. There are 3 different sequences for the PSS and 336 for the SSS, therefore a maximum range of 1008 can be configured. Along with the PBCH, the form the so-called SS-Block.

PRS: is the main reference signal supporting downlink-based positioning methods, such as OTDOA Positioning Support, as listed on Release 16 TS 38.305.

5G New Radio Physical Channels & Signals
Uplink Physical Channels and Signals list

Uplink Physical Channels:

Physical Uplink Shared Channel (PUSCH)

Physical Uplink Control Channel (PUCCH)

Physical Random-Access Channel (PRACH)

Uplink Physical Signals:

Demodulation reference signals (DM-RS)

Phase-tracking reference signals (PT-RS)

Sounding reference signal (SRS)

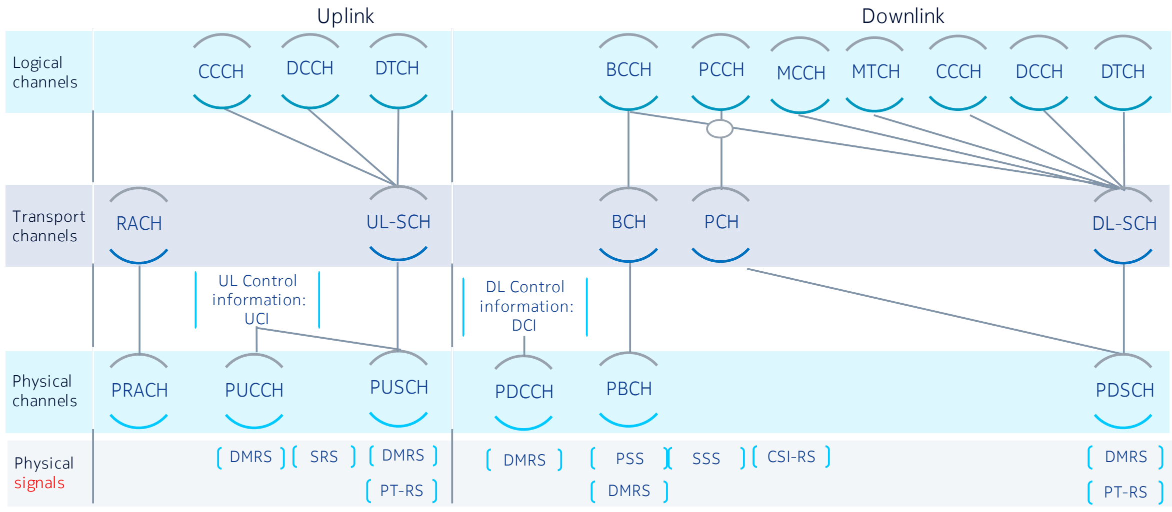
PUCCH: carries the L1 control information including the HARQ feedback as well as CSI. It uses QPSK as the modulation scheme, in some cases it can use BPSK. The PUCCH has different formats known as the short or long PUCCH.

PUSCH: carries the user data as well as higher layer and L1 control information. The Uplink Shared Channel (UL-SCH) is mapped on the PUSCH. It may use BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM.

PRACH: used to enable the Random-Access procedure. Random-Access Channel is mapped on the PRACH.

SRS: the SRS is transmitted by the UE to help the gNB obtain the channel state information (CSI) for each user. Channel State Information describes how the NR signal propagates from the UE to the gNB and represents the combined effect of scattering, fading, and power decay with distance. The system uses the SRS for resource scheduling, link adaptation, Massive MIMO, and beam management. It is also used for positioning on the uplink side, according to Release 16 TS 38.455.

5G NR Radio channels



5G NR radio channels mapping

5G NR Radio Channels (Physical, Transport and Logical Channels) as well as the physical layer signals are displayed on this slide. The slide shows the mapping between logical channels and transport channels and the mapping between transport channels and physical channels.

A downlink physical channel corresponds to a set of resource elements carrying information originating from higher layers. The following downlink physical channels are defined:

-the Physical Downlink Shared Channel (PDSCH),

-the Physical Downlink Control Channel (PDCCH),

-the Physical Broadcast Channel (PBCH),

An uplink physical channel corresponds to a set of resource elements carrying information originating from higher layers. The following uplink physical channels are defined:

-the Physical Random Access Channel (PRACH),

-the Physical Uplink Shared Channel (PUSCH),

-and the Physical Uplink Control Channel (PUCCH).

In addition to the physical channels above, Physical layer signals are defined, which can be reference signals, primary and secondary synchronization signals.

- DMRS associated with NR-PDSCH,
- DMRS associated with NR-PDCCH,
- DMRS associated with NR-PBCH,
- CSI-RS (UE specific, as Cell specific CSI-RS is not considered by 3GPP)
- Phase Tracking RS (PT-RS)
- DM-RS associated with NR-PUCCH,
- DM-RS associated with NR-PUSCH,
- Phase Tracking RS (PT-RS),
- SRS

The following transport channels, and their mapping to PHY channels, are defined:

In Uplink:

Uplink Shared Channel (UL-SCH), mapped to PUSCH and Random Access Channel (RACH), mapped to PRACH

In Downlink:

Downlink Shared Channel (DL-SCH), mapped to PDSCH, Broadcast channel (BCH), mapped to PBCH. And Paging channel (PCH), mapped to PDSCH

Logical channels are classified into two groups: Control Channels and Traffic Channels.

Control channels:

Broadcast Control Channel (BCCH): a downlink channel for broadcasting system control information.

Paging Control Channel (PCCH): a downlink channel that transfers paging information and system information change notifications.

Common Control Channel (CCCH): channel for transmitting control information between UEs and network.

Dedicated Control Channel (DCCH): a point-to-point bi-directional channel that transmits dedicated control information between a UE and the network.

Traffic channels: Dedicated Traffic Channel (DTCH), which can exist in both UL and DL.

In Downlink, the following connections between logical channels and transport channels exist:

BCCH can be mapped to BCH, or DL-SCH;

PCCH can be mapped to PCH;

CCCH, DCCH, DTCH can be mapped to DL-SCH;

In Uplink, the following connections between logical channels and transport channels exist:

-CCCH,DCCH, DTCH can be mapped to UL-SCH.

Wrap-up

In this module we have covered the following items

- Describe the 5G New Radio Physical Layer
- List the different 5G New Radio Physical Channels and Signals