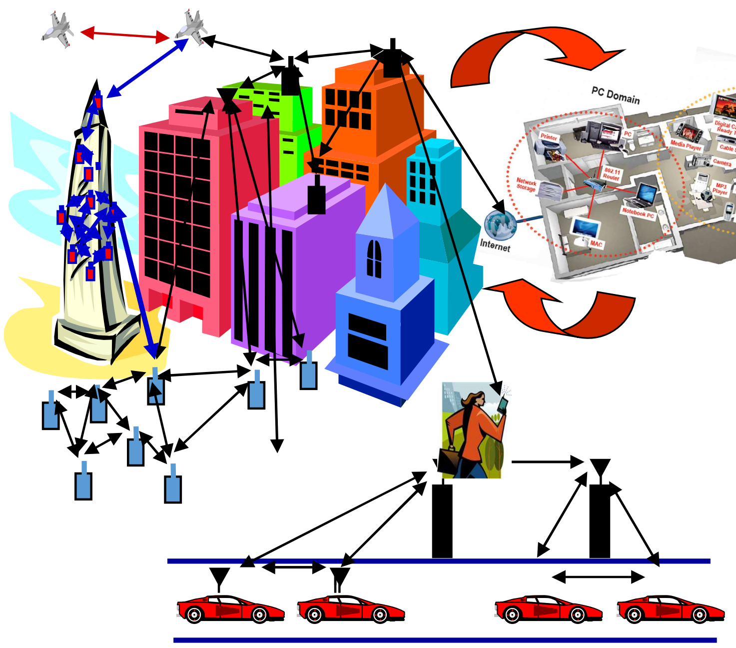
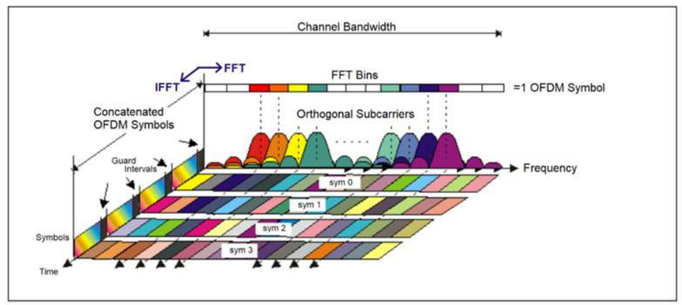
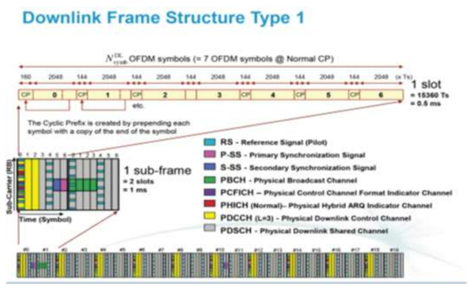
IEE2650: Cellular Communication Technologies

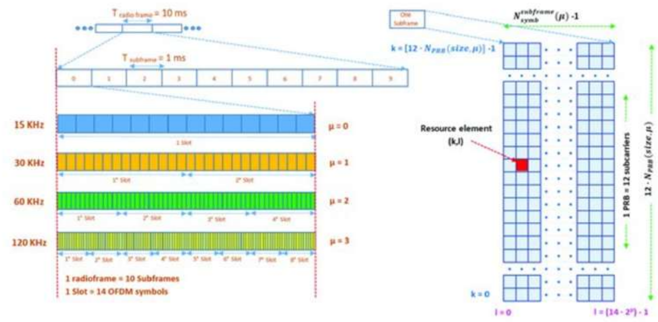
Muhammad Mahtab Alam, Professor





Frequency-Time Representative of an OFDM signal

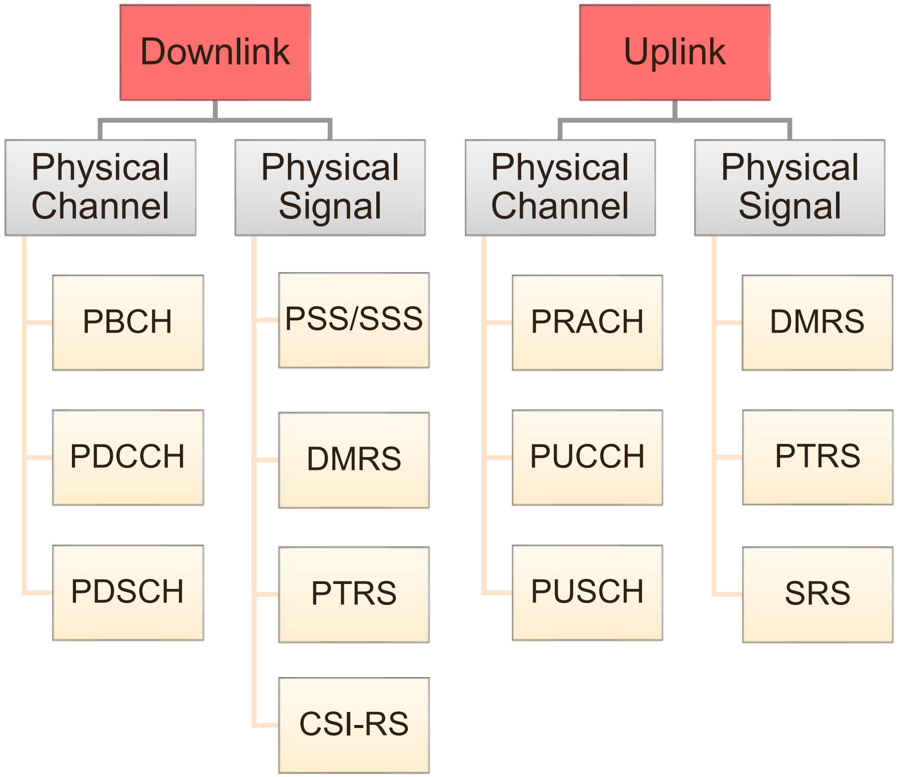




1 Overview

2 Details about 5G NR Channels and Signals

NR Physical Channels and Signals Overview

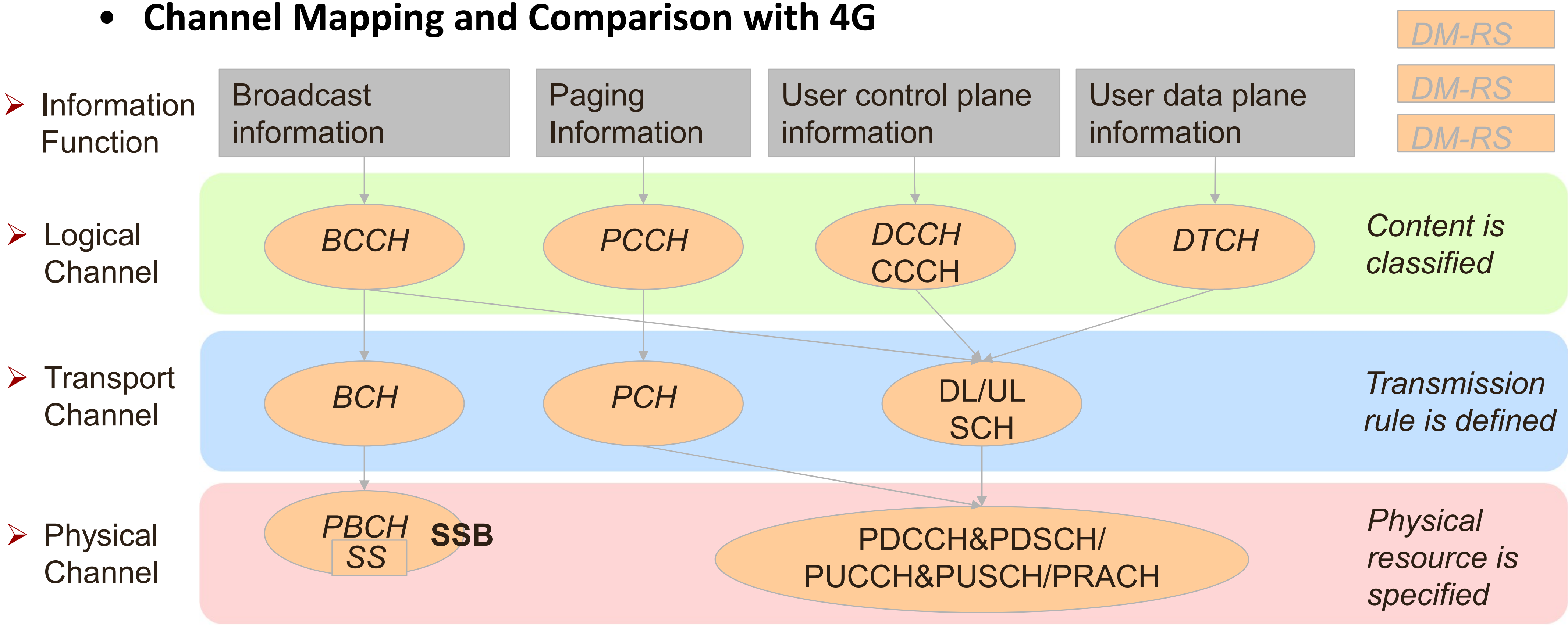


Downlink Physical Channel/Signal Functions	
SS	Used for time-frequency synchronization and cell search.
PBCH	Carries system information to be broadcast.
PDCCH	Transmits control signaling, such as signaling for uplink and downlink scheduling and power control.
PDSCH	Carries downlink user data.
DMRS	Used for downlink data demodulation and time-frequency synchronization.
PTRS	Tracks and compensates downlink phase noise.
CSI-RS	Used for downlink channel measurement, beam management, RRM/RLM measurement, and refined time-frequency tracking.

Uplink Physical Channel/Signal Function	
PRACH	Carries random access request information.
PUCCH	Transmits L1/L2 control signaling, such as signaling for HARQ feedback, CQI feedback, and scheduling request indicator.
PUSCH	Carries uplink user data.
DMRS	Used for uplink data demodulation and time-frequency synchronization.
PTRS	Tracks and compensates uplink phase noise.
SRS	Used for uplink channel measurement, time-frequency synchronization, and beam management.

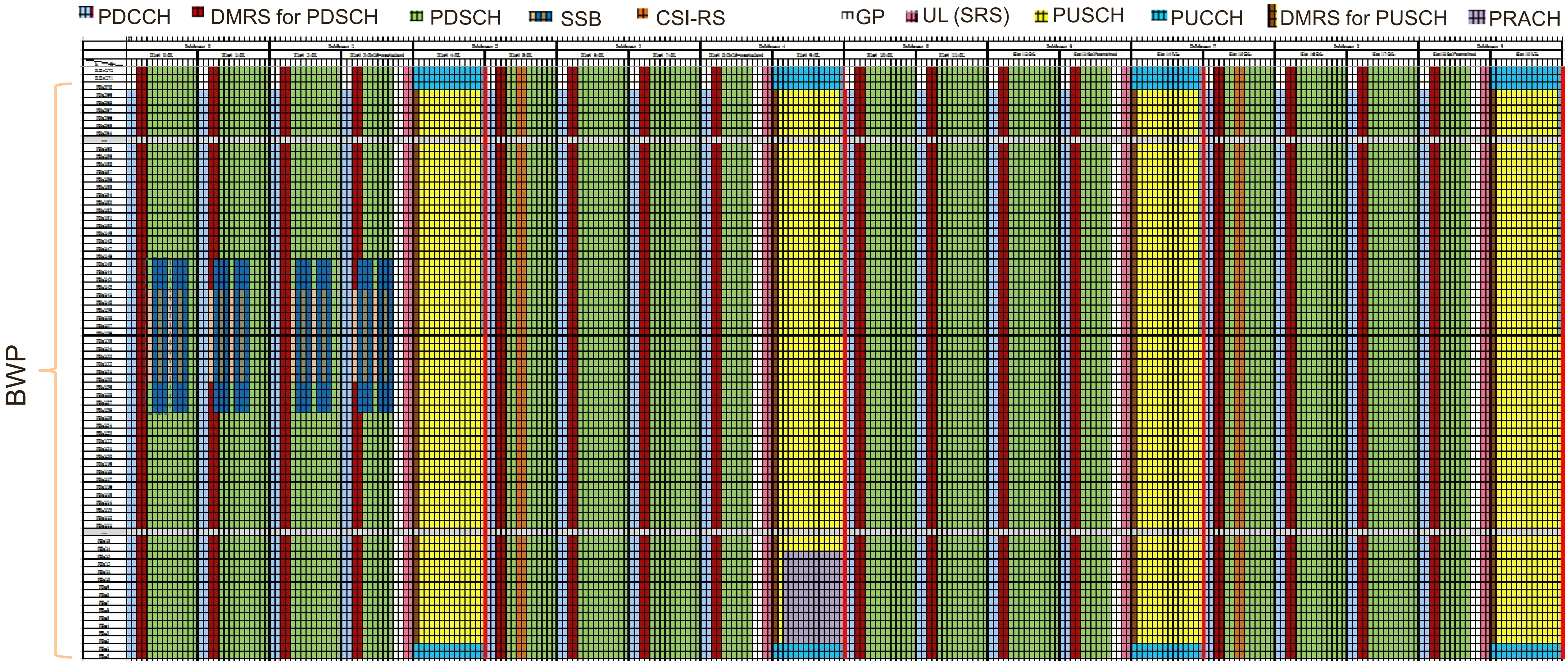
The Basic Functions of NR Air Interface

- **Channel Mapping and Comparison with 4G**



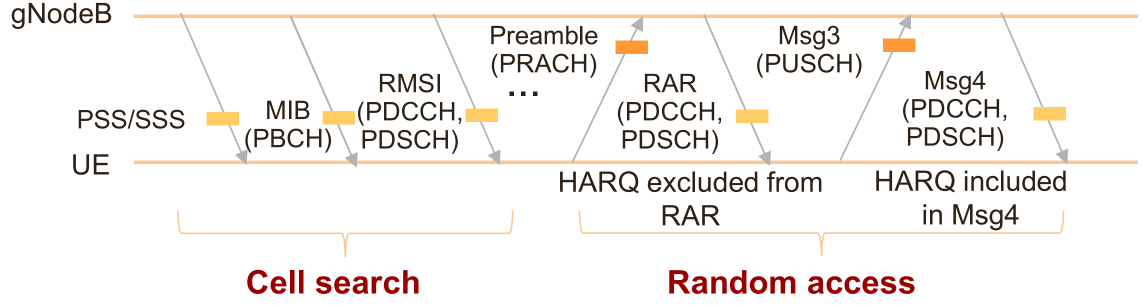
Time-Frequency Domain Distribution

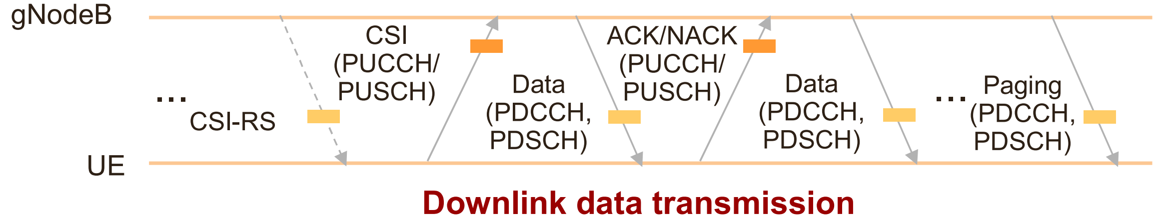
- **Schedulable and configurable resources** **through flexible physical channel and signal design**.

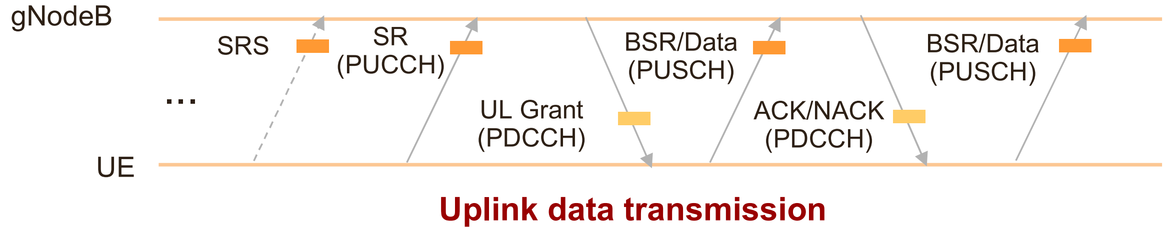


Application of NR Physical Channels

- **Physical channels involved in cell search**
  - PSS/SSS -> PBCH -> PDCCH -> PDSCH
- **Physical channels involved in random access**
  - PRACH -> PDCCH -> PDSCH -> PUSCH
- **Physical channels involved in downlink data transmission**
  - PDCCH -> PDSCH -> PUCCH/PUSCH
- **Physical channels involved in uplink data transmission**
  - PUCCH -> PDCCH -> PUSCH -> PDCCH







Some Definitions

- A CORESET (Control Resource Set) in 5G NR is a configurable, localized set of time-frequency resources used to transmit the Physical Downlink Control Channel (PDCCH) and Downlink Control Information (DCI)

- **RMSI stands for Remaining Minimum System Information** in 5G New Radio (NR) networks. It refers specifically to **System Information Block 1 (SIB1)**, which is crucial for a User Equipment (UE) to access a cell.
  - While the Master Information Block (MIB) provides the absolute minimum information to find the network, the RMSI (SIB1) provides the detailed parameters required for a device to initiate communication, such as random access channel (RACH) configuration

- **Bandwidth Part (BWP)** is a subset of the UE-specific bandwidth, defined by its starting resource block and size
  The minimum size of a BWP must be at least as large as the SSB (Synchronization Signal Block) bandwidth, to ensure initial access and broadcast are always possible.
  The maximum BWP size is limited by the configured carrier bandwidth and the UE's capability.

Some Definitions

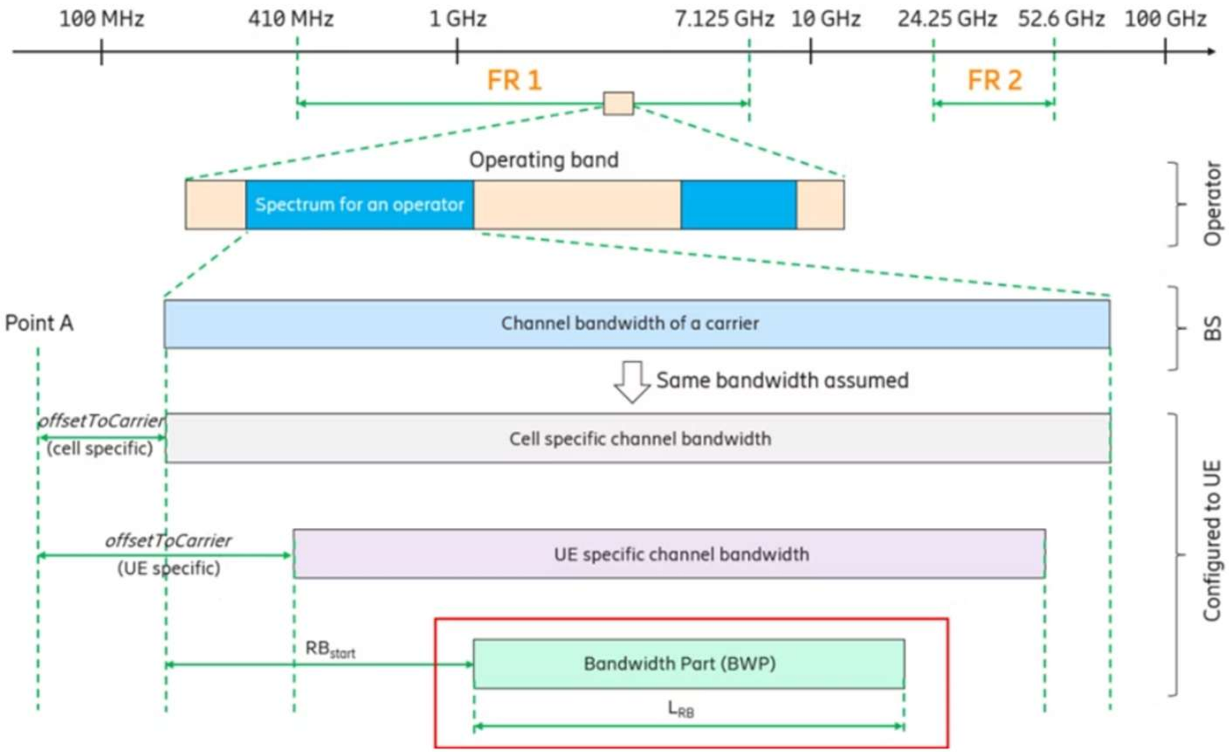
"Point A" in 5G NR is a critical,
1- common frequency reference point used for resource block (RB) numbering across the entire carrier bandwidth, facilitating efficient resource allocation.
2- It defines the starting position for the frequency grid and is used to determine the exact location of the initial bandwidth part (BWP) and CORESET0 (Common Resource Set).

Key Details Regarding Point A:

- **Definition:** It acts as the anchor (Subcarrier 0 of Common Resource Block 0) from which all other resource blocks are indexed.
- **Location Method:** During initial access, the UE discovers Point A by decoding the Master Information Block (MIB) in the SS/PBCH block, specifically using the parameter offsetToPointA.
- **Frequency Reference:** It represents the lowest subcarrier of the lowest resource block in the grid.
- **FR1 vs. FR2:** For Frequency Range 1 (sub-6 GHz) offsetToPointA is measured in 15 kHz RB units; for Frequency Range 2 (mmWave), it uses 60 kHz units.
- **Role in CORESET:** The initial CORESET (CORESET#0) location is defined relative to this point, allowing the UE to find the PDCCH and decode system information (SIB1).

Point A is not necessarily inside the actual operating carrier band, but it serves as a universal reference to ensure consistent frequency allocation for UEs

Point A, BWP ..

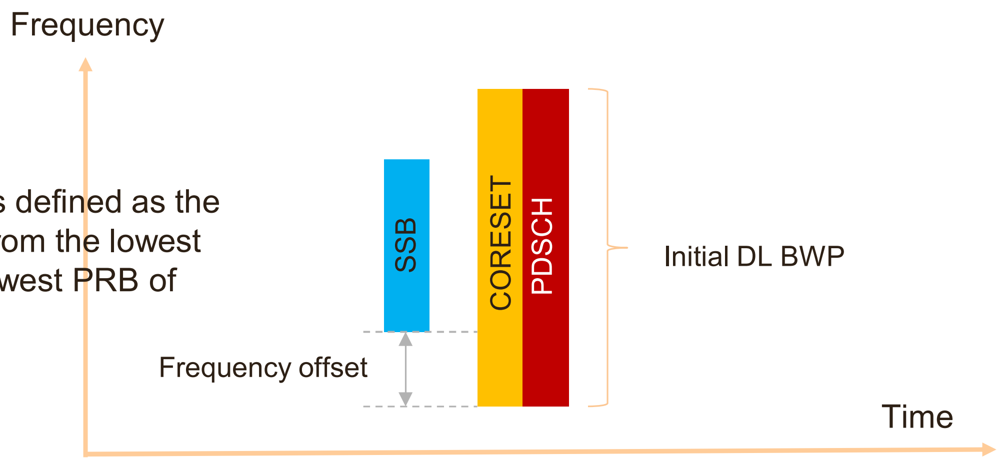


Reference: *A Primer on Bandwidth Parts in 5G New Radio, Xingqin Lin, Dongsheng Yu, Henning Wiemann*

Initial BWP and CORESET

- **Initial DL BWP configuration**
  - The initial BWP equals the frequency-domain location and bandwidth of RMSI CORESET.
  - The frequency-domain location of the initial BWP is determined by the SSB location and the bandwidth of RMSI CORESET, and is sent to UEs through the MIB and SIB1.

The frequency offset is defined as the frequency difference from the lowest PRB of RMSI to the lowest PRB of SS/PBCH block.



First, after obtaining the PCI, the SSB reads the MIB and obtains the pointA, thereby configuring the Coreset to obtain the SI. Then, through the coreset, the SIB1 can be received, thereby reading the initial BWP, that is, the part of the PDSCH. That is, the bandwidth of the initial BWP includes coreset.

- **Procedure for UEs to determine the downlink initial BWP**

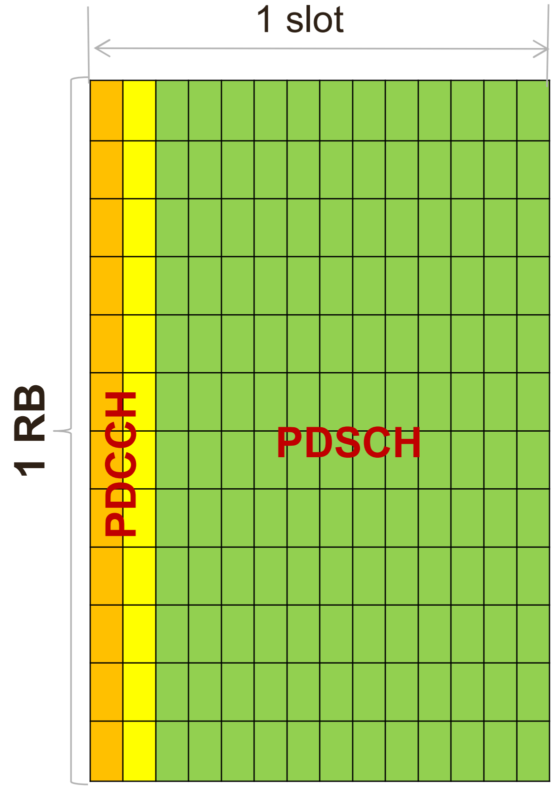
UEs obtain the SSB frequency-domain location through SI (MIB). → UEs read SI to obtain the frequency offset and CORESET bandwidth. → The frequency-domain location and bandwidth of RMSI CORESET are determined. → UEs obtain information about the frequency-domain location and bandwidth of the initial BWP.

PDCCH&PDSCH Working Mechanism

CCE: User scheduling granularity

1 CCE = 6 REG = 1 RB

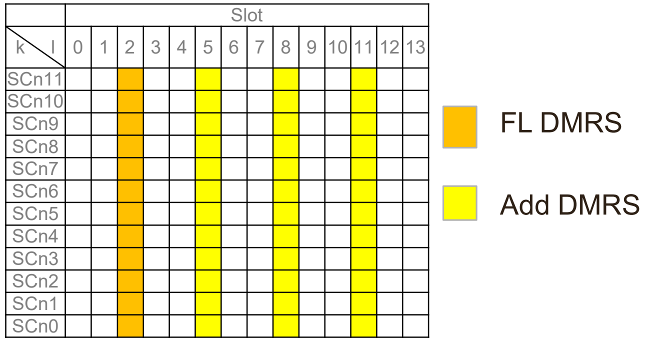
In 5G New Radio (NR), the relationship where 1 Resource Block (RB) is equivalent to 6 Resource Element Groups (REGs) specifically refers to the **Control Resource Set (CORESET)** structure used for the Physical Downlink Control Channel (PDCCH).

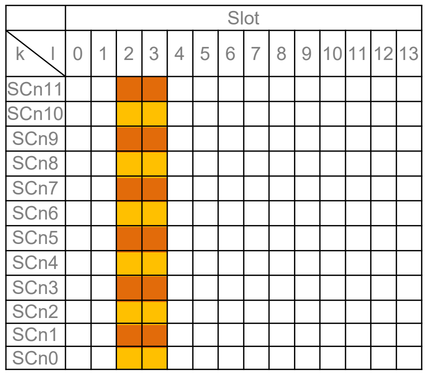


- **RNTIs used by DCIs**
  - P-RNTI (*paging message*)
  - SI-RNTI (*system message*)
  - RA-RNTI (*RAR*)
  - Temporary C-RNTI (*Msg3/Msg4*)
  - C-RNTI (*UE uplink and downlink data*)
  - SFI-RNTI (*slot format*)
  - INT-RNTI (*resource pre-emption*)
  - TPC-PUSCH-RNTI (*PUSCH power control command*)
  - TPC-PUCCH-RNTI (*PUCCH power control command*)
  - TPC-SRS-RNTI (*SRS power control command*)

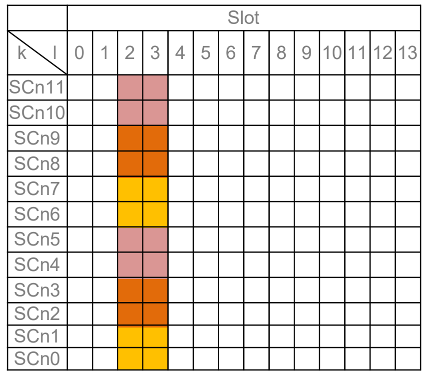
DMRS for PDSCH Introduction

- **DMRS category: Different in low-speed and high-speed scenarios**
  - Front Loaded (FL) DMRS: Occupies 1 to 2 symbols
  - Additional (Add) DMRS: Occupies 1 to 3 symbols, used in high-speed scenarios for anti- Doppler spread.
- **DMRS type: Different DMRS types allow different maximum numbers of ports.**
  - Type1: Single-symbol: 4, dual-symbol: 8
  - Type2: Single-symbol: 6, dual-symbol: 12
- **DMRS time-frequency mapping position**
  - Mapping type A: Staring from the 3rd or 4th symbol in the slot.
  - Mapping type B: Staring from the 1st symbol on the scheduled PDSCH.





Type1, dual-symbol



Type2, dual-symbol

CSI-RS: Main Functions

- The main functions and types of the CSI-RS are as follows:

Function		Description
Channel quality measurement	**CSI obtaining**	Used for channel state information (CSI) measurement. The UE reports the following content: CQI, PMI, rank indicator (RI), layer Indicator (LI)
	Beam management	Used for beam measurement. The UE reports the following content: L1-RSRP and CSI-RS resource indicator (CRI)
	RLM/RRM measurement	Used for radio link monitoring (RLM) and radio resource management (handover). The UE reports the following content: L1-RSRP
Time-frequency offset tracing (TRS)		Used for precise time-frequency offset tracing.

- Design principles and features of the CSI-RS:
  - Sparsity: The density of the time and frequency domains is low and the domain resource consumption is low. The maximum number of ports is 32.
  - Sequence generation and cell ID decoupling: The scrambling code ID is configured by higher layer parameters.
  - Flexible resource configuration: UE-specific configurations for time-frequency resources are supported.

18B DL User Peak Throughput@3.5GHz 100MHz TDD

- DL Peak throughput =
- **Effective REs per DL slot** × **Bits for modulation order** × **Coding rate** × **Layers/ Slot length (s)** × **DL ratio** × (1-**BLER**)

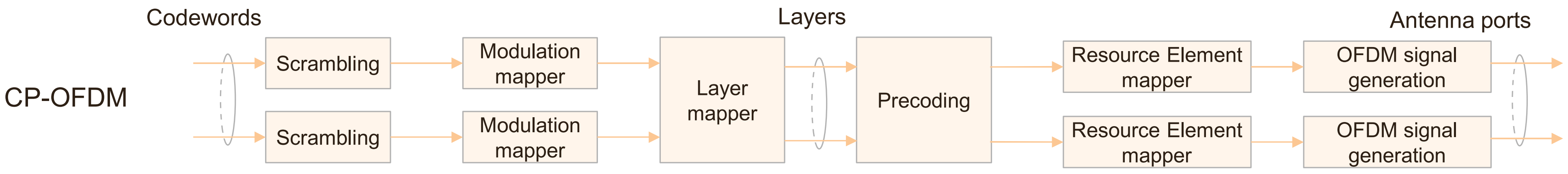
DL effective RE ratio calculation	
Total RB number	273
OFDM symbol number per slot	14
SCS number per RB	12
Total REs Per slot (Includes overhead)	45864
Effective REs per DL slot	33200
DL Effective RE ratio	72.4%
DL Effective RE ratio (excludes UL at Self-contained slot)	76%

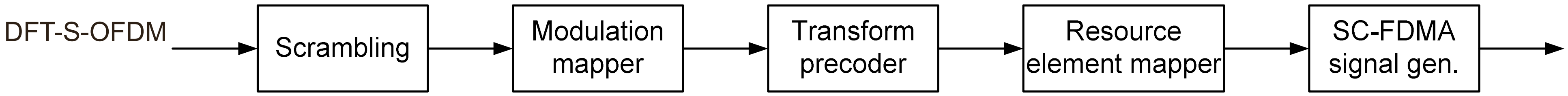
Overhead Estimation (average to per DL slot)		
SS Block	For sync and MIB and beam sweeping	20.4%
CSI-RS (Channel State Information RS)	For DL channel measurement	
PDCCH	Control channel for DL grant and UL grant	
RMSI (remaining minimum system information)	System information transmitted in PDSCH	
DMRS (Demodulation RS)	For data coherent demodulation	
TRS (Tracking RS)	For doppler shift tracking	
GP at Self-contained slot	For TDD system DL/UL conversion	3.6% (2 symbols)
UL at Self-contained slot	For UL transmission	3.6% (2 symbols)

- DL Peak throughput = **33200** * **8** (256QAM) * **0.92** * **8** / **0.0005** * **0.8** (DL/(UL+DL))* **90%** ≈ **2.8G**

2 Waveforms Supported in PUSCH

- **Waveform**: Unlike PDSCH, PUSCH supports 2 waveforms.
  - **CP-OFDM**: a multi-carrier waveform that supports MU-MIMO.
  - **DFT-S-OFDM**: a single-carrier waveform that supports only SU-MIMO and improves the coverage performance.
- **Physical layer procedures**

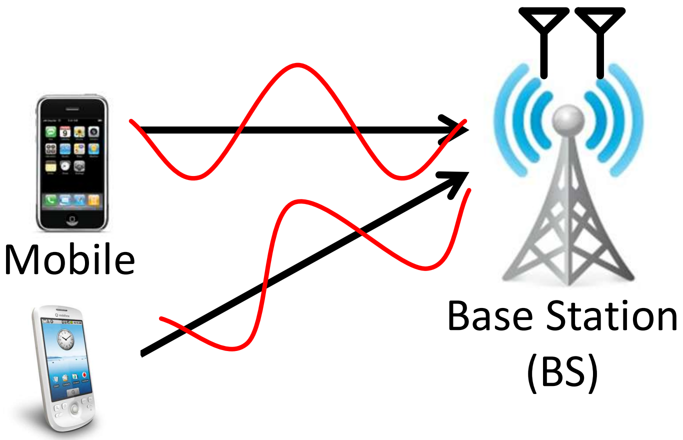




Waveform	Modulation mode	Codeword	Number of Layers	RB Resource Allocation	PAPR	Application Scenario
CP-OFDM	QPSK, 16QAM, 64QAM, 256QAM	1	1–4	Contiguous/ non-contiguous	High	At/near the cell center
DFT-S-OFDM	π /2-BPSK, QPSK, 16QAM, 64QAM, 256QAM	1	1	Contiguous	Low	At the cell edge (achieving gain by using a low PAPR)

Past Challenges in Wireless

Example: cellular network



1. Fading ✓
2. Multiplexing ✓
   (Multiple Access)

Past 15 years:

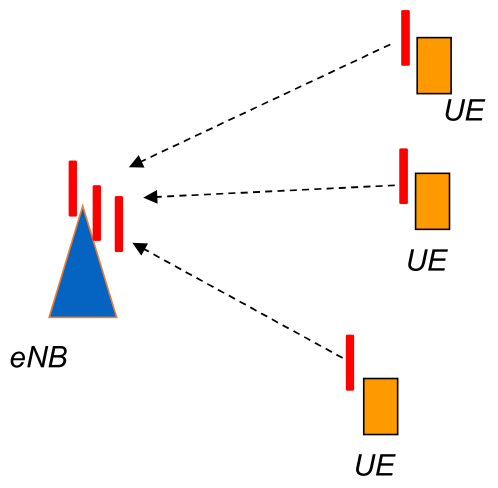
- MIMO
- Opportunistic communication
- Wideband Systems
  - ✓ CDMA, OFDMA

System Gain:
pertains to point-to-point/single-cell performance

Cooperation in MIMO system

- **In general, cooperation in MIMO system aims to realize a single multiple-input multiple-output scheme by involving more than one transmitter and a receiver.**
  In other words, *M* terminals with N_T antennas each (for example with $N_T = 1$) cooperate for forming a unique «virtual» multiple antennas terminal with $M \times N_T$ antennas.

Example 1



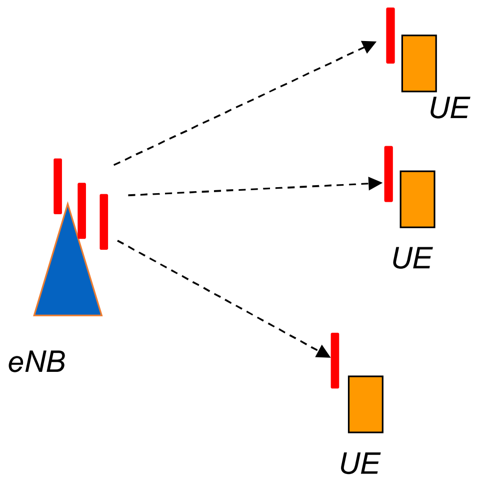
Uplink virtual MIMO: M terminals with a single antenna transmit simultaneously and in the same band to a base station with multiple antennas. The *M* terminals can be seen as a «virtual multiple antenna» with *M* elements and the entire system can be seen as a MIMO system (3 x 3 in this picture).

The advantage is clearly given by the increase of the throughput or capacity of a factor M (spatial multiplexing gain).

The disadvantage is given by the complexity of the system and by the need of additional signaling for the coordination. Of course the coordination is typically managed by the base station.

Cooperation in MIMO system

Example 2



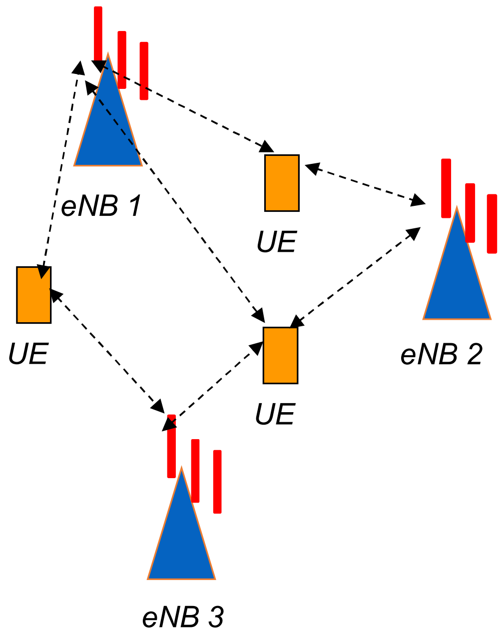
Downlink multi-user MIMO: the same concept of uplink virtual MIMO can be used in the downlink for exploiting the spatial multiplexing gain (a factor 3 also in this example).

Since here the decoding will be done at the terminals, which have less computational capability, *it is very important that the base station send signals properly encoded for helping the terminals in the detection of their interfered signal with reasonable complexity*.

Also, the terminals involved in virtual MIMO have to be selected carefully according to their channel conditions (CSI).

Cooperation in MIMO system

Example 3



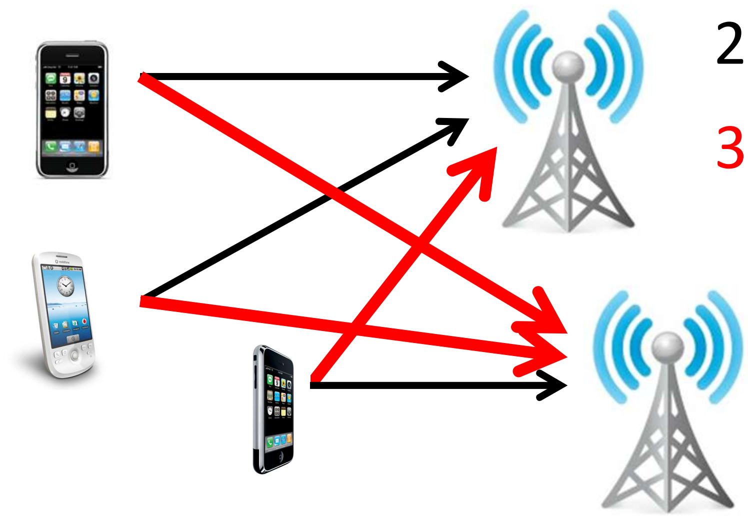
Network MIMO: the cooperation can be extended, in principle, to multiple base stations and multiple terminals, all creating an extended virtual MIMO system. We often denote this scheme, involving more BS, as Network or Distributed MIMO.

Of course complexity and challenges, due to the necessity of a strong coordination among many nodes, increase remarkably.

In mobile standards (4G, 4.5G), these configurations are also referred as examples of **Coordinated Multipoint** (CoMP) schemes.

A Current Key Challenge

As # of mobile & BS ↗⑤



1. Fading ✓
2. Multiplexing ✓
3. **Interference**

Signal not intended to the receiving terminal (intercell)

Bad news: capacity of two-user **interference channel** remains open for 35+ years

Performance of today's wireless system is majorly limited by **interference***!*