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Multiplexing Techniques for Applications Based-on 5G Systems

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Abstract

Multiplexing is an important technique in modern communication systems that allows simultaneous transmission of multiple channels of information on the same transmission media. Fifth-generation (5G) mobile communication systems allow Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC). 5G has carrier frequency bands from sub-1 GHz to mid-bands and millimetre waves. The sub-1 GHz frequency band is for mobile broadband, broadcast and massive IoT applications. The mid-bands (between 1–6 GHz) offer wider bandwidths, focusing on mobile broadband and mission-critical applications. The frequency bands above 24 GHz (mmWaves) support super wide bandwidth applications over short, line-of-sight coverage. For each application on a corresponding frequency band, 5G allows defining of an optimized waveform from a family of waveforms. 5G uses massive MIMO, NOMA and network slicing techniques which allows spatial multiplexing and multibeam multiplexing. Multiplexing techniques play a major role in 5G systems in terms of data rate and bandwidth efficiency. This chapter presents multiplexing techniques for applications based-on 5G systems.

Keywords: 5G NR, duplexing schemes, spatial multiplexing, MIMO schemes, CSI framework, service-based multiplexing

1. Introduction

From the first generation (1G) that were introduced in 1979 by Nippon Telegraph and Telephone (NTT) to today's fifth generation (5G), mobile communication networks are constantly improving the speed and efficiency of bandwidth usage to support various applications with diverse requirements such as latency, high data rates and real-time support for random traffic demands [1].

The increasing number of not only smart phones, tablets and laptops but also the huge number of other devices such as IoT (Internet of Things) nodes, wearable devices for healthcare will demand significant challenges in 5G systems to manage a huge amount of devices and connections [2]. Besides, the exponential growth of mobile video services (e.g., live video streaming, online video gaming, mobile TV) requires wider bandwidth and higher spectral efficiency than that of 4G systems [3].

Such a huge volume of data traffic and connections will lead to 5G systems to use new and higher frequency bands [4]. Some other factors such as ultra-low latency (less than one millisecond), fast-tracking will also be considered in the design of 5G

system architecture. 5G systems support radio connections and end-to-end network connectivity at ultra-high speed, lower latency, higher reliability and massive connectivity [5].

1.1 Scope and contributions

This book chapter gives the reader an up-to-date multiplexing techniques that are implemented in 5G systems. The contributions of this book chapter are listed below:

- First, this book chapter provides a brief introduction of 5G system architecture for the readers to understand the components of 5G systems.
- Second, provides an overview of basic multiplexing techniques as a foundation for 5G systems to implement FDD, TDD modes.
- Finally, it describes MIMO service and data multiplexing operations from a mathematical background, physical antenna configurations, channels and signals, procedures for downlink and uplink MIMO schemes.

1.2 5G system architecture

Today we see the evolution of Industry 4.0 manifested in smart factories, where collaborative robots are instantly connected. The entertainment industry advances dramatically with AR/VR technologies. People are using Zero Search with intelligent personal digital assistants. The Intelligent Transportation Systems (ITS) require all cars connected via C-V2X protocol. The Industrial Internet of Things (IIoT) is used in smart cities and smart agriculture. This is the business ecosystem of 5G systems [6]. 5G systems enable people for living in an intelligently connected world. The 5G system architecture is illustrated in **Figure 1**. At the highest level, the 5G system consists of 5G NR RAN (gNB), 5G Core Network (5GCN)/EPC and different kinds of UEs for three kinds of service including Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (uRLLC), and Massive Machine Type Communications (mMTC) in a business ecosystem [7].

1.2.1 5G NR RAN (gNB)

5G NR (New Radio) is the global standard for the air interface of 5G networks developed by 3GPP with operation from below 1 GHz up to more than 40 GHz and massive MIMO beamforming capability [8].

Figure 1.
5G system architecture (vRAN approach).

RAN stands for Radio Access Network. RAN provides radio access and coordinates network resources across User Equipment (UE). For more general, the RAN is divided into two parts. The first part is the lower layer RAN split including the antenna integrated Radio Unit (RU) and the Distributed Unit (DU). The second part is the higher layer RAN split, a 3GPP standard F1 interface between the DU and the Centralized Unit (CU). DU and CU constitute Baseband Unit (BBU) [9].

Legacy LTE uses Evolved Node B (eNodeB or eNB) like Base Station (BTS) in GSM networks. Similarly, gNodeB (gNB – next generation Node B) is 5G Base Station. gNB features Software Defined Radio (SDR) with various MIMO options described in session 3 of this chapter [10].

In 5G NR, RU handles digital front end (DFE), part of the physical layer (low physical) and multiple beamforming operation. RU consists of a Remote Radio Head (RRH) and Active Antenna System (AAS) [11]. Antennas in AAS for 5G NR make use of the shorter element sizes at high frequencies to incorporate a larger count of radiating elements. These antenna arrays are essential for MIMO beamforming operations that play a vital role in 5G systems [12]. The RRH performs all RF functions like ADC/DAC, digital up/down-conversion, filtering and transmitting and receiving signals to the BBU including beamforming. RRH can also provide monitoring and control functions to optimize system performance.

In LTE systems, RRH is connected to the antenna by RF coaxial cable and is usually mounted near the antenna to reduce transmission line losses. In 5G NR, RRH and AAS are integrated in a small and compact form factor [6].

Common Public Radio Interface (CPRI) is the standardized interface that sends data from the RRHs to the Base Band Unit (BBU). CPRI is a very high-speed connection on fiber optic cable. eCPRI is enhanced CPRI which is used to reduce the burden on the fiber. The connection between the RUs and the DU is called fronthaul and it is fiber optic cable.

DU stands for Distributed Unit. DU is placed close to RU and runs RLC, MAC, parts of the Physical layer. This function consists of signal processing, network access. DU is controlled by CU (Centralized Unit). DU also supports FFT/IFFT functions [13].

CU provides support for the higher layers of the protocol stack such as SDAP, PDCP and RRC. Practically, there is a single CU for each gNB. A CU can control multiple DUs (can be more than 100 DUs). Each RU corresponds to one cell. Each DU can support one or more RUs, so in 5G systems, one gNB can control hundreds of cells. 5G NR cell can be femtocell, smallcell or macrocell [14]. 5G Small Cell Radio Nodes can be installed on walls or ceilings with network connectivity and power are provided over Ethernet. Midhaul connects the CU with the DU via F1 interface. Backhaul connects the 5G core to the CU. The 5G core may be up to 200 km away from the CU.

RIC is RAN Intelligent Controller which is responsible for all RAN operation and optimization procedures such as radio and resource connection management, mobility management, QoS management to support the best effective network operation.

There are three different approaches to design a RAN as abstracted in **Table 1** [15].

1.2.2 5G Core network

According to the definition of 3GPP, 5G has two networking modes: SA (Standalone) and NSA (Non-Standalone). 5G system Service-based

	Centralized/Cloud RAN (C-RAN)	Virtual RAN (vRAN)	Open-RAN (O-RAN)
RU	Proprietary		GPP COTS hardware (e.g., SDR)/ OEM vendor
BBU hardware	Centralized functionality, proprietary hardware, software	Generic hardware platforms (e.g., COTS Server with virtualized software), BBU splits into DU and CU.	
BBU software	Proprietary	Virtualized	Virtualized with open API
Interface	Proprietary		Open
Interoperability	Single vender for RU and BBU	Single vender for RU and software	Multiple venders

COTS: commercial-off-the-shelf.

Table 1.
RAN classification.

Figure 2.
5G system service-based architecture with core network functions.

architecture is illustrated in **Figure 2** and corresponding functions are described in **Table 2** [16].

The EPC (Evolved Packet Core) network consists of MME (Mobility Management Entity), S-GW (Service Gateway) and PDN gateway. EPC performs functions such as mobility management, IP connection, QoS management, and billing management.

1.3 Chapter structure and organization

The structure and organization of this book chapter are illustrated in **Figure 3**.

2. Basic multiplexing techniques

The term “multiplexing” refers to the sharing of a *system resource* (SR) to a set of users. There is a subtle distinction between multiplexing and multiple access, while multiplexing means the SR sharing is “fixed” (*static* multiplexing) or adaptive

Main functions		
NSSF	Network Slice Selection Function	Selects the Network Slice Instance (NSI) based on information provided during UE attach.
NEF	Network Exposure Function	Facilitates secure, robust, developer-friendly access to the exposed network services.
NRF	Network Repository Function	Provides a single record of all network functions.
UDM	Unified Data Management	Authentication Credential Repository, Access Authorization.
AUSF	Authentication Server Function	Authentication and Authorization.
PCF	Policy Control Function	Ensures policy and charging control, authorized QoS.
AMF	Access and Mobility Management Function	NAS Signaling TerminationMobility ManagementNetwork Slicing.
SMF	Session Management Function	Selection and control of UP function, UE IP address allocation and management.
UPF	User Plane Function	Packet routing and forwarding, QoS handling.
SMF	Session Management Function	Responsible for interacting with the decoupled data plane, creating updating and removing PDU sessions and managing session context with the UPF.

Table 2.
Core network functions.

Figure 3.
Structure and organization of the book chapter.

change (*dynamic* multiplexing), multiple access techniques are those techniques that enable multiple users to share limited SRs remotely.

Multiplexing allows multiple channels/users to share the same SR. Multiplexing helps to increase the efficiency of using the SR and the transmission capacity of the system. Dynamic multiplexing makes the allocation of the SR more efficient.

5G NR systems also use “duplexing schemes” for Uplink (UL) and Downlink (DL) data transmission.

The traditional multiplexing techniques are:

- 1.*Frequency Division Multiplexing (FDM)*: Specified subbands of frequency are allocated. Suitable for analog signal transmission, widely used in analog broadcast radio and television.

2. *Time Division Multiplexing (TDM)*: User data are assigned in periodically recurring timeslots. Suitable for digital signal transmission, commonly used in digital telephone systems.
3. *Code Division Multiplexing (CDM)*: Specified orthogonal spread spectrum codes are allocated.
4. *Wavelength Division Multiplexing (WDM)*: WDM is used in fiber-optic communications. In WDM, several optical carrier signals are multiplexed onto a single optical fiber by using different wavelengths.
5. *Space Division Multiplexing (SDM)*: Transmitting separate data streams in parallel using the same time/frequency resources. The receiver side also requires multiple antennas to the same level (degrees of freedom) as the number of streams or layers to spatially decorrelate, demodulate and decode.
6. *Polarization Division Multiplexing (PDM) or dual polarization frequency reuse*: Orthogonal polarizations are used to transfer signals, allowing for reuse of the same frequency band.

We are now considering basic multiplexing techniques.

2.1 Frequency division multiplexing

Frequency division multiplexing (FDM) is the division of total channel bandwidth into multiple, non-overlapping subbands. Each of these subbands is assigned to a user or a signal by modulating with the appropriate carrier frequency.

The multiplexer from the transmit side is responsible for multiplexing the modulated signals with different carrier frequencies into a total signal for transmission. The demultiplexer at the receiver is responsible for separating the total signal into signals of different users by different frequencies.

Example 1. Primary FDM system (**Figure 4**) with total frequency bandwidth from 60 kHz to 108 kHz is divided into 12 subbands, each subband has a bandwidth of 4 kHz. At the transmitter, the signal of a user is transmitted through a low pass filter (LPF) which is then a single side band (SSB) modulated with an appropriate carrier frequency. At the receiver, the total signal passes through a band pass filter (BPF) and a single side band demodulator to obtain a signal for the corresponding user.

FDM has some disadvantages:

- Analog system: noise accumulates in each hop if we use repeaters.
- Difficult to fabricate high-Q bandpass filters.
- Low multiplexing factor.

2.2 Time division multiplexing

Time Division Multiplexing (TDM) is a technique for the serial transmission of user data over a common medium such as a coaxial cable.

At a time, only one user's data are transmitted serially in a time slot. TDM allows each user to use the entire system bandwidth.

Figure 4.
Frequency division multiplexing.

Figure 5.
Time division multiplexing.

In addition to user data, signaling and frame alignment word (FAW) are inserted into the frame. At the receiver, there is clock recovery and frame synchronization to recover data for each channel (Figure 5).

2.3 Optical space-division multiplexing for MIMO systems

Space-Division Multiplexing (SDM) is a multiplexing technique for optical data transmission where multiple spatial channels are utilized. Figure 6 shows a generic optical MIMO-SDM system. At the transmitter, the user data signals are encoded, modulated, E/O converted and then multiplexed onto different wavelengths ($\lambda_1, \lambda_2 \dots \lambda_N$) in a WDM multiplexer [17].

At the receiver, the transmitted signals are recovered using MIMO digital signal processing consisting of an $N \times N$ array of equalizers by DSP (digital signal processor). First, the N channels signal is demultiplexed by an SDM demultiplexer. Then

Figure 6.
Space-division multiplexing for optical communications and application to 5G systems.

the separate signals $r_1 \dots r_N$ are fed into the $N \times N$ MIMO DSP block that is capable of eliminating all linear impairments of the transmission system and giving the reconstructed signals as output. Optical fibers are utilized at fronthaul, midhaul and backhaul of 5G systems. Data from RUs (at smallcells, for example) are multiplexed and transmitted to DU via fronthaul by optical fiber [18]. At present, a dense optical wavelength-multiplexing system has a transmission capacity of more than 1 Tera bit/s (1000 Gbit/s) per wavelength [19].

2.4 Code division multiplexing or code division multiple access

Code Division Multiple Access (CDMA) is a multiple access method that allows multiple users to share the same time and frequency resources.

In a CDMA system, each user is assigned with specific spreading code, and all users can send information simultaneously over a single communication channel. Since CDMA is based on the spread spectrum principle, each transmitter will use a pseudo-random code to modulate the data, and the receiver decodes the modulated signal using its own pseudo-random code. The principle of CDMA is illustrated in Figure 7.

2.5 Duplexing schemes in 5G NR

5G NR supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) schemes. TDD is the main duplexing mode for higher frequencies while FDD is used for lower frequencies as the interference problems with large cells is reduced by having different frequencies in UL and DL. FDD is similar to FDM, UL and DL use separate carrier frequencies. Data are transmitted in both directions simultaneously. TDD is similar to TDM, only one carrier frequency is used. Transmission/Reception in UL and DL is assigned by different time slots.

2.5.1 5G NR frame structure

Since TDD is the main duplexing mode of a 5G NR, we will discuss more detail about TDD. We start with 5G NR frame structure. Just like the TDM system, 5G NR is frame structured. A frame has a fixed duration of 10 ms which consists of 10 subframes of 1 ms duration. Each subframe can have 2ⁿ slots.

Figure 7.
Code division multiple access.

Figure 8.
5G NR frame structure.

Figure 8 shows the 5G NR frame structure. The number of slots per subframe (i.e., 2^μ), hence the slot duration depends on subcarrier spacing (SCS). 5G NR supports two frequency ranges FR1 (Sub 6GHz) and FR2 (millimeter wave range, 24.25 to 52.6 GHz). 5G NR uses flexible SCS derived from basic 15 KHz used in LTE to values of 30, 60, 120 KHz. For SCS of 15 KHz, a subframe has 1 slot of 1 ms duration. For SCS of 30 KHz, a subframe has 2 slots of 500 μ s duration as shown in **Table 3** and **Figure 9** [20].

Each slot is comprised of either 14 OFDM symbols or 12 OFDM symbols based on normal Guard Period (GP) and extended GP respectively. However, mini slots (2, 4, or 7 symbols) can be allocated for shorter transmissions. Slots can also be aggregated for longer transmissions.

SCS	μ	Number of slots per subframe	Slot duration	Number of slots in a frame	Guard Period
15 KHz	0	1	1 ms	10	Normal
30 KHz	1	2	500 μ s	20	Normal
60 KHz	2	4	250 μ s	40	Normal/Extended
120 KHz	3	8	125 μ s	80	Normal

Table 3.
Number of slots per subframe, slot duration, number of slots in a frame and guard period for reference SCS.

Figure 9.
5G NR scalable slot duration.

2.5.2 5G NR UL-DL pattern

Now we know the frame structure. When operating in TDD mode, we have to specify the exact timing for the uplink and downlink transmission. So, how do we define the time slots for uplink and downlink transmission?

Timeslots for uplink and downlink transmission are organized into DL-UL patterns. In LTE TDD, there are 7 predefined patterns for UL and DL allocation in a radio frame. There is no predefined pattern for 5G NR, but we can define a flexible pattern thanks to parameters in TDD UL/DL Common Configuration (*tdd-UL-DL-configurationCommon*) as shown in **Table 4** below.

You may ask yourself what is the difference between the DL-UL pattern and radio frame? The *dl-UL-TransmissionPeriodicity* parameter, for example 5 ms, defines the periodicity of the DL-UL pattern. So, a radio frame of 10 ms contains 2 DL-UL patterns.

From the above parameters, we can define TDD DL/UL configuration, aka. DL-UL pattern for 5G NR radio transmission as shown in **Figure 10**. In 5G NR, the slot

Field	Description
referenceSubcarrierSpacing	Reference SCS used to determine the number of slots in the DL-UL pattern. Only the values 15, 30 or 60 kHz (FR1), and 60 or 120 kHz (FR2) are applicable.
dl-UL-TransmissionPeriodicity	Periodicity of the DL-UL pattern in ms. This time results in even number of slots depending on the SCS. Possible values are: 0.5 ms, 0.625 ms, 1 ms, 1.25 ms, 2 ms, 2.5 ms, 5 ms and 10 ms.
nrofDownlinkSlots	Number of consecutive full DL slots at the beginning of each DL-UL pattern.
nrofDownlinkSymbols	Number of consecutive DL symbols in the beginning of the slot following the last full DL slot (as derived from nrofDownlinkSlots). The value 0 indicates that there is no partial-downlink slot.
nrofUplinkSlots	Number of consecutive full UL slots at the end of each DL-UL pattern.
nrofUplinkSymbols	Number of consecutive UL symbols in the end of the slot preceding the first full UL slot (as derived from nrofUplinkSlots). The value 0 indicates that there is no partial-uplink slot.

Table 4.
5G NR TDD DL/UL common configuration parameters.

Figure 10.
5G NR TDD UL/DL common configuration frame structure.

configuration is flexible and can be changed from time to time while maintaining the focus on inter-cell interference aspects [21].

Then, the next question is how to design a transmission pattern? We know that time slots allocation for UL and DL depends on UL and DL traffic. We call that UL/DL traffic load ratio. To adapt with actual traffic, 5G NR supports 3 different TDD configurations as follows:

Static TDD configuration: For static TDD, the UL/DL traffic ratio is usually decided by the statistical UL/DL traffic load ratio among multiple operators in a specific country or region. The slots and symbols are defined over a period of time that are dedicated to either the UL or DL based on the UL/DL traffic ratio.

Semi-Static TDD configuration: This configuration is more flexible than the static TDD. We have a certain number of UL and DL slots within a transmission periodicity (defined by *dl-UL-TransmissionPeriodicity*). The remaining slots, which are neither UL nor DL, can be considered ‘Flexible’ with the help of another IE *TDD-UL-DL-ConfigDedicated*.

Dynamic TDD configuration: This is the most flexible configuration for UL/DL transmission for dynamic assignment and reassignment of time-domain resources between the UL and DL transmission. Dynamic TDD is used to adapt to actual traffic but requires coordination to avoid interference between cells, so that there is no fixed UL/DL allocation. With the popularity of video streaming increasing, it is forecast that the proportion of DL content will grow even further in the future, hence it is natural that more resources should be allocated to the DL.

Example 2. The DL-UL pattern design. Assuming SCS = 30 kHz and the carrier is FR1 with 100 MHz bandwidth.

Field name	Value
dl-UL-TransmissionPeriodicity	2.5 ms
nrofDownlinkSlots	3
nrofDownlinkSymbols	10
nrofUplinkSlots	1
nrofUplinkSymbols	2

Since slot duration for reference SCS of 30 kHz is 0.5 ms, the number of slots in DL-UL periodicity would be

$$\text{NumSlotsDLULPeriodicity} = \frac{\text{dl-UL-TransmissionPeriodicity}}{\text{Slot length}} = \frac{2.5\text{ms}}{0.5\text{ms}} = 5\text{ slots, and}$$

$$\begin{aligned} &\text{NumberOfGuardSymbols} \\ &= \text{TotalSymbolsInPattern} - \text{TotalSymbolsWithTypeSpecified} \\ &= (14 * \text{NumSlotsDLULPeriodicity}) \\ &\quad (\text{numDLSlots} * 14 + \text{numDLSyms} + \text{numULSyms} + \text{numULSlots} * 14) \\ &= 2\text{ symbols.} \end{aligned}$$

This DL-UL pattern is illustrated in **Figure 11**. This pattern repeats itself in the timeline.

3. 5G NR MIMO multiplexing operation

Perhaps the most challenging part of the 5G NR system is the MIMO operation modes. Let us start with SU-MIMO and MU-MIMO. SU-MIMO stands for Single-

Figure 11.
Example on design a TDD downlink frame structure.

User MIMO. In Single User MIMO, both the base station and UE have multiple antennas, and the base station can transmit multiple data streams simultaneously to the UE using the same time/frequency resources. By doing so, it doubles (2×2 MIMO), or quadruples (4×4 MIMO) the peak throughput of a single user.

MU-MIMO stands for Multi User MIMO. The base station serves more than 2 UEs simultaneously. Since in MU-MIMO, the base station sends multiple data streams, one per UE, using the same time-frequency resources, MU-MIMO mode increases the total cell throughput, i.e., cell capacity. MU-MIMO is not a new concept. We have MU-MIMO in LTE (Transmission Mode 5 - TM5) and WLAN (802.11ad). However, in 5G NR the scale of MU-MIMO will be much larger and deployment will also be more common. 5G NR uses massive MIMO.

Massive MIMO employs a large number of transmit and receive antennas, improves spectral efficiency and increases the transmission data rate through spatial multiplexing to deliver multiple streams of data within the same resource block (time and frequency). Massive MIMO is also called Large Scale MIMO.

By now, you may ask a question: *Why massive MIMO, and how many antenna elements are needed to be called massive MIMO?* In conventional 4G LTE using a normal MIMO, the maximum number of the antenna is 2×2 or 4×4 and even 8×8 is mentioned. We know that the larger the number of antennas, the narrower the beam width. It means the coverage of a specific beam would be smaller. We need a more precise beam control algorithm, but in return, the achievable data rate will be higher. The number of antennas in massive MIMO should be $\gg 8$ [22].

3.1 Mathematical background

Figure 12 shows a typical MIMO system equipped with N_T transmit antennas and N_R receive antennas. The data are encoded in both space and time domains and then transmitted by N_T transmit antennas through a MIMO propagation channel.

The relationship between the input and output of a MIMO system can be written as follows

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (1)$$

where.

$\mathbf{x} = [x_1, x_2, \dots, x_{N_T}]^T$ is transmitted signal,

$\mathbf{y} = [y_1, y_2, \dots, y_{N_R}]^T$ is received signal,

$\mathbf{n} = [n_1, n_2, \dots, n_{N_R}]^T$ is AWGN,

Figure 12.
 System and channel model for spatial multiplexing.

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_T} \\ h_{21} & h_{22} & \dots & h_{2N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R1} & h_{N_R2} & \dots & h_{N_RN_T} \end{bmatrix} \text{ is channel matrix,}$$

where $h_{i,j}$ is an element of the i^{th} row and the j^{th} column in the matrix $\mathbf{H}$, denotes a channel from the j^{th} TX antenna to the i^{th} RX antenna.

If the channel matrix $\mathbf{H}$ is known at both base station (gNB) and UE (i.e., Channel state information - CSI) then we could take *singular value decomposition* (SVD) on channel matrix $\mathbf{H}$ as

$$\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{W}^*, \quad (2)$$

where $\mathbf{U} \in \mathbb{C}^{N_R \times N_R}$ and $\mathbf{W} \in \mathbb{C}^{N_T \times N_T}$ are orthogonal unitary matrices and $\mathbf{D} \in \mathbb{R}^{N_R \times N_T}$ is diagonal matrix, whose diagonal elements are non-negative real numbers and whose off-diagonal elements are zero. The diagonal elements of matrix $\mathbf{D}$ $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_r$ are the ordered singular values of channel matrix $\mathbf{H}$, where $r = \min \{N_T, N_R\}$ is rank of $\mathbf{H}$.

Assume the receiver knows the $\mathbf{U}$ matrix and the transmitter knows the $\mathbf{W}$ matrix. The transmitted data $\mathbf{x}$ is precoded by $\mathbf{W}$ matrix and the received data $\mathbf{y}$ is equalized by $\mathbf{U}$ matrix, we have

$$\begin{aligned} \tilde{\mathbf{y}} &= \mathbf{U}^* \mathbf{y} = \mathbf{U}^* [\mathbf{H}\tilde{\mathbf{x}} + \mathbf{n}] = \mathbf{U}^* [(\mathbf{U}\mathbf{D}\mathbf{W}^*)\mathbf{W}\mathbf{x} + \mathbf{n}], \\ \tilde{\mathbf{y}} &= \underbrace{[\mathbf{U}^* \mathbf{U}]}_{\mathbf{I}} \underbrace{[\mathbf{D} \mathbf{W}^* \mathbf{W}]}_{\mathbf{I}} \mathbf{x} + \mathbf{U}^* \mathbf{n}, \\ \tilde{\mathbf{y}} &= \mathbf{D}\mathbf{x} + \mathbf{U}^* \mathbf{n}, \\ \tilde{\mathbf{y}} &= \mathbf{D}\mathbf{x} + \tilde{\mathbf{n}}, \end{aligned} \quad (3)$$

where $\tilde{\mathbf{n}} \in \mathcal{CN}(0, N_0 \mathbf{I}_{N_R})$ has the same distribution as $\mathbf{n}$. Thus, we have an equivalent representation as a parallel Gaussian channel

$$\tilde{y}_i = \lambda_i \tilde{x}_i + \tilde{n}_i, i = 1, 2, \dots, r. \quad (4)$$

$\mathbf{W} = [\mathbf{w}_1 | \mathbf{w}_2 | \dots | \mathbf{w}_{N_T}]$ is a precoding matrix. Each symbol x_i is precoded by precoding vector $\mathbf{w}_i$.

From the Eq. (4), we can see that the base station can transmit simultaneously maximum of r data streams to the target UE, increasing the channel throughput. This is called spatial multiplexing (SM). MIMO spatial multiplexing takes advantage of multipath effects, where a transmitted signal arrives at the receiver through several different paths. Each path can have a different time delay, and the result is that multiple instances of a single transmitted symbol arrive at the receiver at different times [23].

If SNR is high, the number of data streams and data rate for each stream is chosen by the *waterfilling* algorithm [24]. In the opposite case, with low SNR, the best thing to do is to simply choose one subchannel with the highest singular value. This is called beamforming [25, 26]. We can rewrite the Eq. (3) as

$$\tilde{y}_1 = \mathbf{u}_1^* \mathbf{H} \mathbf{w}_1 x_1 + \mathbf{u}_1^* \mathbf{n}. \quad (5)$$

Instead of transmitting a vector of symbols, we just transmit a single symbol at a time. The $\mathbf{w}_1$ vector defines the beamforming weights and $\mathbf{u}_1$ here defines the receive beam.

Now we know how to transmit multiple data streams to a UE. We consider the way 5G NR implement MIMO modes.

Clearly, to implement SM, the network (gNB and UEs) should know the channel matrix $\mathbf{H}$ then calculate the 3 matrixes $\mathbf{U}$, $\mathbf{D}$, $\mathbf{W}$ out of $\mathbf{H}$. The transmitter applies $\mathbf{W}$ as a precoder and the receiver apply $\mathbf{U}$ for processing of the received signal. For downlink transmission, gNB is a transmitter and UE is receiver and vice versa for uplink transmission.

3.2 Basic terminologies

The first thing we have to know is the codebook. The **codebook** is a set of predefined precoders (precoding matrices). Why codebook? Consider DL transmission, gNB has to calculate a precoder from a reference signal or selects a predefined precoder with a requested index from UE before transmitting data. The first case is called non-codebook and the second is called codebook-based precoding.

Codebook type in 5G NR: There are two types of codebooks specified in 5G NR. Type I is designed for SU-MIMO and selected by UE report and RRC Configuration. Type II is designed mainly for MU-MIMO and is based on a more detailed CSI report. Type I codebook has predefined matrices based on the number of layers and CSI-RS ports. Type II codebooks contain mathematical formula for selecting a set of beams and then specifying relative amplitudes and phases to generate a weighted combination of beams for each layer of transmission.

The requested index into a set of predefined matrices, a so-called codebook is a **precoding matrix indicator** (PMI). PMI is used for DL transmission, conditioned on the number of layers indicated by the RI. In the uplink direction, the PMI is denoted by **Transmit Precoder Matrix Indicator** (TPMI) to differentiate it from the downlink PMI.

Together with the codebook, **the number of layers** is the number of simultaneous data streams. The number of layers is less than or equal to the rank of the channel matrix that we mentioned before. The number of layers depends upon the channel condition between receiver and transmitter antennas. Low correlation propagation paths increase rank and the number of layers and vice versa. **Rank indicator** (RI) defines the number of possible transmission layers for the downlink and uplink transmission under specific channel conditions. However, gNB does not need to transmit RI as requested by the UE.

Channel state information (CSI) are parameters related to the state of a channel including the channel quality indicator (CQI), precoding matrix indicator (PMI) and rank indicator (RI). UE reports CSI parameters to gNB as feedback in CSI-RS mode.

Channel quality indicator (CQI) is an indicator of channel quality. The CQI index is a scalar value from 0 to 15 representing the highest modulation-and-coding scheme (MCS) to achieve the required block error rate (BLER) for given channel conditions.

CSI-RS resource indicator (CRI), used in conjunction with beamformed CSI reference signals. The CRI indicates the beam the device prefers in case the device is configured to monitor multiple beams.

SRI is an SRS resource indicator.

3.3 Physical antenna configuration versus antenna ports

It is very important to understand the physical antenna configurations, the antenna port and the relationship between them. The antenna system in 5G NR is an Active Antenna System (AAS). Typical active antennas are made up of a matrix of subarrays. Each subarray consists of individual dual-polarized elements. Each polarization is controlled by a beamforming (BF) coefficient. Therefore, the number of columns is doubled.

For example, **Figure 13a** shows 8T8R configuration with 4 columns, 1 row (4x1) consisting of 4 (1x8) subarrays. **Figure 13b** shows 64T64R configuration which is made up of 8 columns, 4 rows of (1x2) subarrays.

Figure 14a shows single panel antenna. 5G NR supports both single panel and uniform (b) and non-uniform multi-panel (c). In 5G NR, logical antenna configuration is described by 3 parameters: N_g is the number of panels, N_1 is number of columns and N_2 is the number of rows in a panel.

In association with N_1 and N_2 , 3GPP defines DFT oversampling factors O_1 and O_2 to determine the sweeping steps of a beam during the beam management (beam tracking). O_1 determines the sweeping step in the horizontal direction and O_2 determines the sweeping step in the vertical direction.

We have:

- Number of polarizations = 2,
- Number of CSI-RS antenna ports = $(2 * N_1) * N_2$,

Figure 13.
Physical antenna configuration.

Figure 14.
Single panel and multi panel antenna configurations.

- Number of beams in a column = $N_1 * O_1$,
- Number of beams in a row = $N_2 * O_2$,
- Number of beams = $(N_1 * O_1) * (N_2 * O_2)$ = from 8 to maximum 256 beams.

Antenna port: This is a logical concept and different from the physical one that you see on the antenna tower. You can find the definition of antenna port from the 3GPP specification as “an antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed” [27]. We can understand the antenna port like socket and port concept which is used on Internet. For example, port 80 is used for the HTTP protocol, port 20 for FTP, port 22 is for SSH, port 25 is for SMTP. We use “antenna ports” to transmit and receive data. Why the definition of antenna port of 3GPP is related to the channel because we have to estimate the channel model before decoding transmitted data. The channel model has estimated thanks to reference signals. Each antenna port is assigned by a dedicated reference signal. Each antenna port represents a specific and unique channel model. The receiver can use a reference signal transmitted on an antenna port to estimate the channel model for this antenna port and this channel model can subsequently be used for decoding data transmitted on the same antenna port.

Each antenna port carries its own resource grid. One resource grid is transmitted on a given antenna port, subcarrier spacing configuration and transmission direction (downlink or uplink). The resource grid consists of a number of RBs (Resource Blocks) for one subframe.

3.4 Physical channels and signals

Physical Channels and Signals for DL, UL and corresponding antenna port addresses are as follows (Table 5):

Downlink channels		Function	Antenna port starting from:
PDSCH	Physical downlink shared channel	Carry user data in the downlink direction	1000 (1000 Series)
PDCCH	Physical Control Channel	Carry DCI (Downlink Control Information) e.g., downlink scheduling assignments and uplink scheduling grants.	2000 (2000 Series)
CSI-RS	Channel State Information - Reference Signal	For DL CSI acquisition. CSI-RS is configured specifically to UE. But multiple users can also share the same resource.	3000 (3000 Series)
SS-Block/PBCH	Physical broadcast Channel	The combination of SS and PBCH is known as SS-Block (SSB). PBCH carries very basic 5G NR system information for Use (Downlink System BW, Timing information in the radio frame, SS burst set periodicity, System frame number).	4000 (4000 Series)
Uplink Channels		Function	Antenna port starting from:
PUSCH/DMRS	Physical Uplink Shared Channel / Demodulation Reference Signal	It is used by a 5G NR receiver to produce channel estimates for demodulation of the associated physical channel.	1000 (1000 Series)
SRS, precoded PUSCH	Sounding Reference signal	It is used for UL channel sounding. In contrast to LTE, it is configured specifically to UE.	1000 (1000 Series)
PUCCH	Physical Uplink Control Channel	transport UCI (Uplink Control Information) e.g., HARQ feedback, SR (Scheduling Request) and CSI report (CQI, PMI, RI, Layer Indicator LI).	2000 (2000 Series)
PRACH	Physical Random Access	Carry random access preamble from UE towards gNB (i.e., 5G NR base station). It helps gNB to adjust the uplink timings of the UE in addition to other parameters.	4000 (4000 Series)

Table 5.
Physical channels and signals and corresponding antenna port addresses.

3.5 Mapping antenna ports to physical antennas

There is no strict mapping of antenna ports to physical antenna ports. **Figure 15** indicates the mapping between antenna ports and physical antennas. One antenna port can be mapped to single or multiple physical antenna(s). Due to each antenna port representing a specific and unique channel model, the number of layers in the physical layer may reach the number of antenna ports. The number of layers may range from a minimum of one layer up to a maximum number of layers equal to the number of antenna ports. The layers are then mapped to the antenna ports.

3.6 Downlink MIMO schemes

Legacy LTE supports 9 transmission modes (TM). To avoid sophisticated transmission mode handover for different scenarios, 5G NR uses the term *unified transmission mode* [28]. However, according to the channel state information (CSI) acquisition method, downlink MIMO schemes are categorized into (**Figure 16**):

Figure 15.
Mapping antenna ports to physical antennas.

Figure 16.
Downlink MIMO schemes.

Single User MIMO (SU-MIMO):

- SRS-based (sounding reference signal)
- CSI-RS-based (CSI - reference signal, codebook type I, Single / Multi panel)

Multi User MIMO (MU-MIMO):

- CSI-RS without Beamforming (codebook type II Single Panel)
- CSI-RS Beamformed (codebook type II Port Selection)

DL and UL channels are considered reciprocal. From a channel calculation perspective, in SRS-based Single User MIMO scheme, channel calculation obligation belongs to gNB, the remaining schemes rely on UE's CSI report from its channel calculation. The device's capability and channel condition decide the best MIMO mode among the above schemes.

3.7 Single user MIMO schemes

3.7.1 Procedure for SRS-based single user MIMO

- 1. UE transmits sounding reference signals through each of its antenna ports.
- 2. gNB estimates the channel (e.g., downlink precoding weights) based on received sounding reference signals
- 3. gNB transmits PDSCH using a calculated precoder.

This scheme is illustrated in **Figure 17a**, and very simple but due to size and power at the UE are limited, the number of the antenna of UE is smaller than that of gNB and adding more RF chains to UE is difficult, SRS resources are transmitted on antenna ports one by one by transmit antenna switching (TAS).

3.7.2 CSI-RS based single user MIMO

Figure 18 shows a typical downlink transmission CSI-RS based SU/MU-MIMO scheme. First of all, UE needs to know the **H** matrix. The gNB is obligated to transmit CSI-RS ports so that UE can observe the full MIMO channel matrix. UE calculates the channel matrix and reports PMI, RI and CQI to gNB.

In the equivalent MIMO channel, we have N_L data streams, corresponding to N_L layers. Each i -th diagonal element of **D**, λ_i , represents the i -th layer's channel magnitude; $\mathbf{w}_i$, the i -th column vector of **W**, is the beamforming weights for the i -th layer.

UE reports gNB is its preferred PMI but gNB is not obligated to apply the precoding indicated by the PMI, and the gNB does not provide the UE with explicit

Figure 17.
Downlink single user MIMO operation.

Figure 18.
CSI reporting and equivalent channel for SU-MIMO.

information regarding the precoding procedure. The UE relies upon using the Demodulation Reference Signal (DMRS) when decoding the PDSCH.

CSI-RS single user MIMO scheme uses type I codebook which is based upon a specific set of assumed antenna configurations. The antenna configurations are Single Panel and Multi Panel as described in **Tables 6** and **7**.

For codebook type I single panel: MIMO ranks: 1 to 8; CSI RS Ports: 2, 4, 8, 12, 16, 24, 32.

For codebook type I multi panel: MIMO ranks: 1 to 4; CSI RS Ports: 8, 16, 32.

3.7.3 Procedure for CSI-RS based single user MIMO

1. gNB transmits **32** CSI-RS ports to UE (**Figure 17b**). If DL antenna ports for CSI measurement is limited to ≤ 8 , for example = 8, gNB has to transmit 4 CSI-RS sets of resources of 8 ports (**Figure 17c**)
2. UE estimates the channel based on the received CSI-RS resources, selects the best PMI.
3. UE reports PMI, RI, CQI to gNB.
4. gNB decides a precoder to transmit PDSCH.

3.8 Multi-user MIMO schemes

In Multi User MIMO schemes, gNB tries to communicate simultaneously with a set of UE through the same time/frequency resources. MU-MIMO schemes uses Type II codebook to provide more details about Channel State Information. MU-MIMO schemes support to a maximum of 2 layers per UE. This is smaller than that of SU-MIMO (up to 8 layers for type I single panel) but the maximum number of layers per cell is higher to allow multiple UE to use 2×2 MIMO simultaneously.

DL MU-MO Type II codebook allocates a set of beams to each UE. Each set of the beam is the weighted combination of beams with relative amplitudes and co-phasing phase shifts.

Beamformed CSI-RS relies upon the gNB having some advanced information to allow beamforming of the CSI Reference Signal transmissions.

Procedure for beamformed CSI-RS as follows: gNB transmits one or more CSI-RS, each in different “directions”. UE computes and reports CRI/PMI/CQI to gNB.

Number of CSI-RS antenna ports	4	8	12	16	24	32
(N_1, N_2)	(2,1)	(2,2) (4,1)	(3,2) (6,1)	(4,2) (8,1)	(4,3) (6,2) (12,1)	(4,4) (8,2) (16,1)
(O_1, O_2)	(4,1)	(4,4)	(4,4)	(4,1) (4,4)	(4,4)	(4,1) (4,4) (4,4) (4,1)

Table 6.
Single panel antenna configuration.

Number of CSI-RS antenna ports	8		16		32			
(N_g, N_1, N_2)	(2,2,1)	(2,4,1)	(4,2,1)	(2,2,2)	(2,8,1)	(4,4,1)	(2,4,2)	(4,2,2)
(O_1, O_2)	(4,1)	(4,1)	(4,1)	(4,4)	(4,1)	(4,1)	(4,4)	(4,4)

Table 7.
Multi panel antenna configuration.

3.9 Uplink transmission modes

5G NR supports uplink PUSCH precoding up to 4 layers. However, in the case of DFT-based transform precoding, only single-layer transmission is supported. The transmitted symbols are layer mapped and then precoded at the UEs.

If gNB instructs UE on PDCCH regarding the choice of precoding matrix selected from a codebook: codebook based (**Figure 19a**). Otherwise, UE measure DL CS-RS signal to determine precoding weights (not constrained to a codebook): Non-codebook based (**Figure 19b**).

3.9.1 Procedure for non-codebook-based transmission mode

- 1. UE measures DL SCI-RS signal to design suitable precoders for the SRS transmission.
- 2. UE transmits up to four SRS resources where each resource has one antenna port.
- 3. gNB determines one or multiple SRIs based on the received SRSs, number of layers for PUSCH. In this example, SRS1 and SRS3 are selected. TRI is equal to the number of SRIs.

Figure 19.
Uplink MIMO operation.

4. UE uses selected resources to transmit PUSCH.

3.9.2 Procedure for codebook-based transmission mode

1. UE transmits SRS from each of its antenna ports.
2. gNB estimates UL channel based on the received SRSs to select the best SRS for antenna port, appropriate rank and precoding matrix. gNB transmits SRI (SRS resource indicator), RI and TPMI to UE.
3. UE uses selected resources to transmit PUSCH from the indicated antenna port, the number of layers and precoding matrix.

4. Service-based multiplexing

4.1 Principle

5G networks are designed for a wide variety of use cases including urban mobile broadband, massive machine-type communications, ultra-reliable low latency communications, applications such as remote surgery, autonomous driving, a massive number of sensors communicating with the network, 3D video streaming.

The problem is that the physical infrastructure resources are limited. The need for data, services and operators working on the same network increase. The solution is network slicing (NS). NS will create virtual network segments for the different services within the same 5G network. NS will divide the physical network into independent logical subnets for different kinds of services, each of which has a size and structure suitable for dedicated service [29].

NS is one of the key features of 5G NR. NS allows operators to support efficiently different use cases and enterprise customers on a dedicated 5G network. NS leverages the running of multiple logical subnets on top of physical network, multiplexes data services over physical infrastructure.

The concept of network slicing is illustrated in **Figure 20** showing two slices. One slice supports smartphones with 3D streaming, virtual reality (VR) connections with guaranteed throughput slice, the other supports automotive connectivity, IIoT for smart factory with low latency slice on the same network infrastructure [30].

Figure 20.
Service multiplexing by network slicing.

4.2 5G network slicing implementation

An End-to-End (E2E) Network Slice consists of RU, RAN and Core Transport subnets. Basically, we have to designed Slice Profiles (for RAN, Core and Transport subnets) including the slice characteristics and requirements needed to support the service requested by the UE. Procedure for slicing is as follows:

1. Create slice profile:

The customer will provide their service requirements they want to run on a network slice including bandwidth, capacity, and latency. The operator creates a service level agreement, and allocates the necessary capacity and bandwidth for the slice by NSSAI (Network Slice Selection Assistance Information). NSSAI consists of up to 8 S-NSSAI (Single –NSSAI). The S-NSSAI contains two components: the SST (Slice/Service Type) and an optional SD (Slice Differentiator).

2. UE gathers information for slices when registering for the network:

The UE gathers information for the available slices when registering for the network via NAS signaling. A single UE may be assigned up to eight difference slices [31].

3. Determines the candidate AMF(s) or AMF Set to be used to serve the UE:

Once a PDU session is set up, the UE is then signaled to the NSSAI, assuming this has been provided earlier to the UE.

4. Selects which slices the UE can connect:

Based on required NSSAI and registered information, the network will select the appropriate slice instance and related resources, with the AMF coordinating the actions in the 5G core network. There is one AMF that is common for all the slices a single UE has.

5. Conclusion

This chapter presented multiplexing techniques utilized in 5G systems. Duplexing is one of the key factors affecting the performance of 5G NR in terms of their wide-area coverage. The Frequency Division Duplex (FDD) and Time Division Duplex (TDD) schemes utilized in 5G NR are inherited from FDM and TDM, providing flexibility for designing UL/DL patterns.

Spatial multiplexing supports multi layer transmission. Multiple beamforming will transmit data through targeted beams and advanced signal processing that could speed up data rates and boost bandwidth and reduce interference for nearby users. 5G NR permits to use different waveforms on subbands with scalable subcarrier spacing and transmission time interval operating on one frequency band. Network slicing creates independent logical subnets for different kinds of services.

With these multiplexing techniques, 5G systems could provide data rate up to 20 Gbps and capacity increase by 1000 times and flexible platform for the services like massive Industrial Internet of Things (IIoT), connected society, smart factories.

It is expected that 5G combined with artificial intelligence can improve social life, make life better, more productivity, and safety.

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