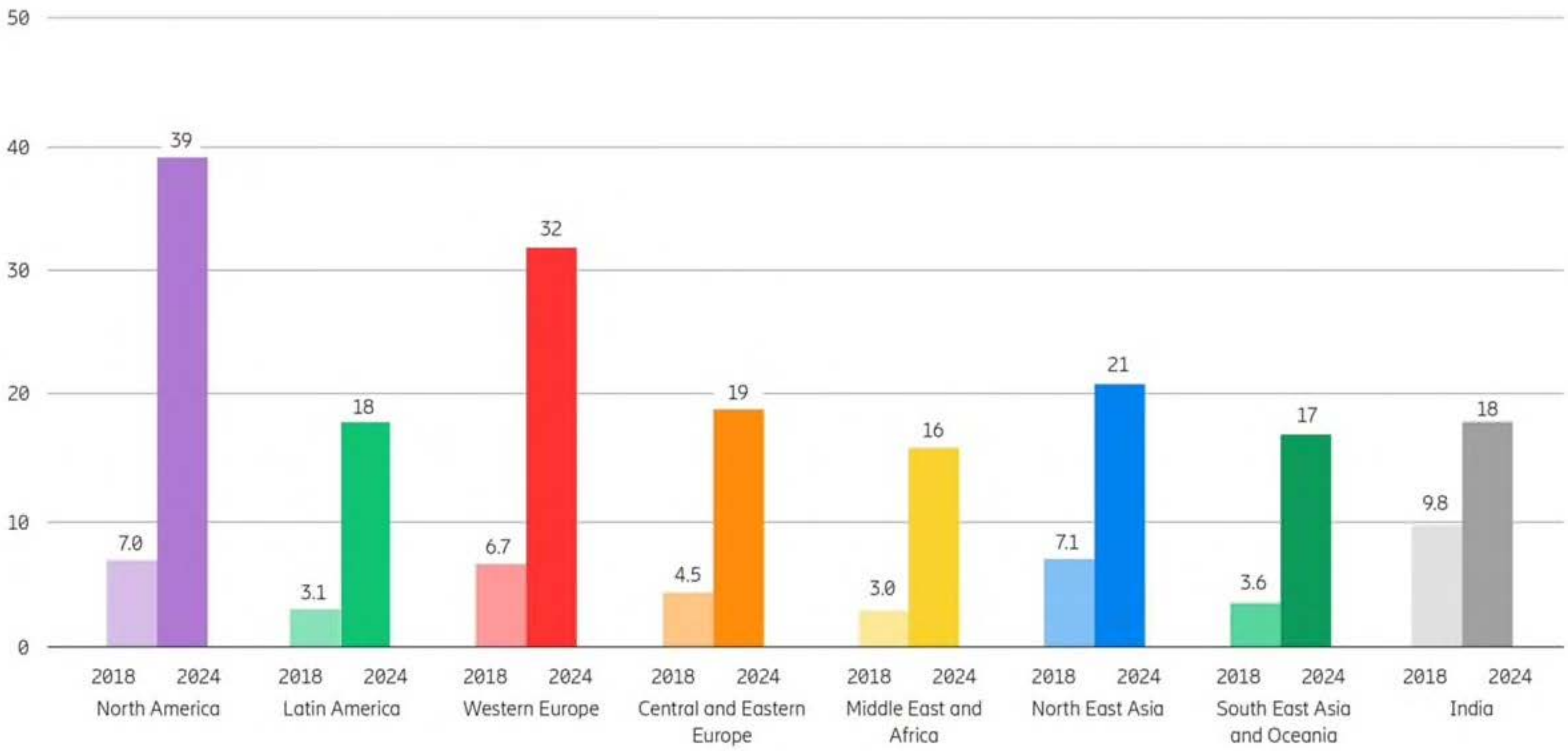
MU5EES08 - Unit IV
Advanced Physical Layer Concepts in 5G

by Julien Sarrazin, Sorbonne University

Introduction

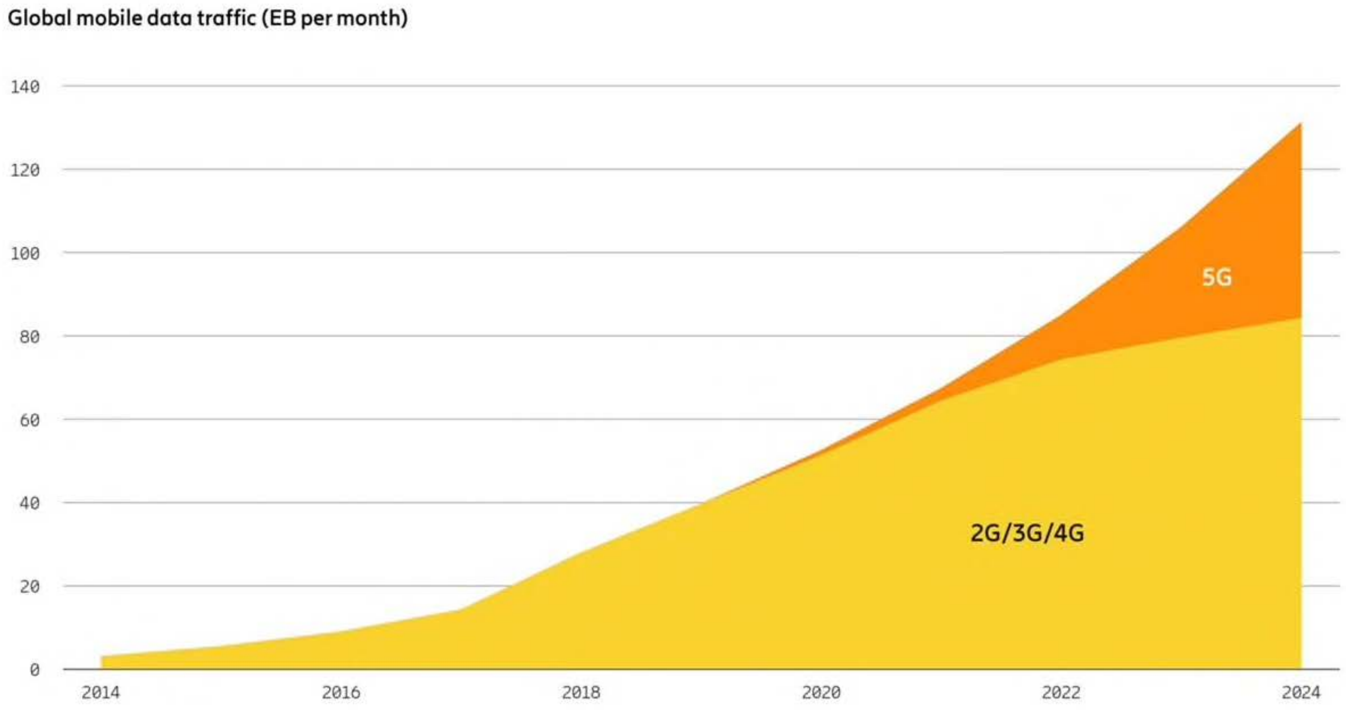
Mobile data traffic per smartphone (GB per month)



source: Ericsson

Introduction

5G: fifth generation wireless technology



source: Ericsson

- Total mobile data traffic continues to rise globally: expected to reach 131 exabytes (EB) per month by 2024 end
- The 5G infrastructure deployment is on-going

Introduction

5G: fifth generation wireless technology

- 5G will help in handling global data traffic
- but 5G will also provide new features:
  - **Enhanced Mobile Broadband** (eMBB):
  - **Ultra Reliable Low Latency Communications** (URLLC)
  - **Massive Machine Type Communications** (mMTC)

Introduction

5G introduces new key features (some already in LTE)

- Additional spectrum (below 6 GHz and above 24 GHz)
- Carrier aggregation
- Flexible frame structure
- Scalable numerology
- Massive MIMO
- Millimeter-wave band
- …

Introduction

Unit IV : Syllabus (10 hours)

1. 5G features and numerology: Overview of the main innovations of 5G at the physical layer
2. Channel diversity with multiple antenna systems
3. MIMO processing
4. Millimeter-wave array

Introduction

Evolution of mobile communication generations

- 1G: Analog mobile voice calls *(started in 1979)*
- 2G: Digital mobile voice calls and SMS *(started in 1991)*
- 3G: Digital mobile data (internet) *(started in 1998)*
- 4G: Digital mobile video consumption and higher data speed *(started in 2009)*

- 5G: *deployment started in 2019 in some countries*

How is 5G different from 4G?

- 4G/LTE focus was to enhance 3G's data rate
- 5G goal is broader, it aims to interconnect people, but also to interconnect and control machines, objects, and devices
  - 5G exhibits more feature than 4G
- Technological improvements:
  - 5G uses spectrum more efficiently than 4G
  - 5G exhibits higher data rate than 4G
  - 5G has more capacity than 4G (100x 4G traffic capacity)
  - 5G has lower latency than 4G (1-10ms)
  - 5G is more cost effective than 4G: 5G should enable 10 times lower cost per gigabyte than 4G networks

Introduction

5G NR (New Radio): use cases

- **Enhanced Mobile Broadband** (eMBB):

  Support high data rates (2 Gbps – 20 Gbps)

- **Ultra Reliable Low Latency Communications** (URLLC)

  Critical communications (autonomous vehicles, remote surgery…)

- **Massive Machine Type Communications** (mMTC)

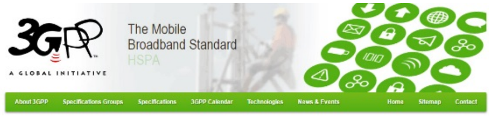
  support a massive number of devices (for Internet of Things - IoT…)

A defining capability of 5G is also the design for forward compatibility—the ability to flexibly support future services that are unknown today

Introduction

3GPP: 3rd Generation Partnership Project

- Standards organization (2G/3G/4G/5G…) composed of:
  - Organizational partners (7 telecommunications standard development organizations: ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC)
  - Market representation partners
- 3 Technical Specification Groups (TSG) in 3GPP:
  - Radio Access Networks (RAN)
  - Services & Systems Aspects (SA)
  - Core Network & Terminals (CT)
- 3GPP provides releases
  - Release 8: first release defining LTE
  - Release 10: LTE-Advanced



www.3gpp.org

Introduction

5G releases

3GPP release 15
5G phase 1

3GPP release 16
5G phase 2

3GPP release 17

2018-2019

2019-2020

2020-2021

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5G releases

Release 15

- NR
- The 5G System – Phase 1
- Massive MTC and Internet of Things (IoT)
- Vehicle-to-Everything Communications (V2x) Phase 2
- Mission Critical (MC) interworking with legacy systems
- WLAN and unlicensed spectrum use
- Slicing – logical end-2-end networks
- API Exposure – 3rd party access to 5G services
- Service Based Architecture (SBA)
- Further LTE improvements
- Mobile Communication System for Railways (FRMCS)

Release 16

- The 5G System – Phase 2
- **V2x Phase 3:** Platooning, extended sensors, automated driving, remote driving
- Industrial IoT
- Ultra-Reliable and Low Latency Communication (URLLC) enhancements
- NR-based access to unlicensed spectrum
- **5G Efficiency:** Interference Mitigation, SON, eMIMO, Location and positioning, Power Consumption, eDual Connectivity, Device capabilities exchange, Mobility enhancements
- Enhancements for Common API Framework for 3GPP Northbound APIs (eCAPIF)
- FRMCS Phase 2

3GPP Release 17:

- NR light (wearable devices…)
- MIMO enhancements
- Spectrum above 52.6GHz (including unlicensed spectrum at 60GHz…)
- Positioning enhancement
- Power saving enhancements
- …

New Spectrum

Additional frequency bands

New Spectrum

A look at the spectrum

- New spectrum dedicated to 5G is being considered
- FR1 bands: below 6-GHz bands (410MHz-7.125GHz)
- FR2 bands: above 24.5 GHz (24.25-52.6GHz+)

USA

3.5GHz

- 27.5 - 28.35GHz
- 37 - 38.6GHz
- 38.6 - 40GHz
- 37 – 43.5 GHz

Europe

- 3.4 – 3.8GHz
- 24.25 – 27.5GHz

China

- 3.3 – 3.6GHz
- 4.8 – 5.0GHz
- 24.25 – 27.5GHz
- 37 – 42.5GHz

Japan

- 3.6 - 4.2GHz
- 4.4 - 4.9GHz
- 27.5 - 29.5GHz

Korea

- 3.4 – 3.7GHz
- 26.5 – 29.5GHz

India

3.3-3.6GHz

3GPP TSG RAN WG4 Chairman (Samsung)

New Spectrum

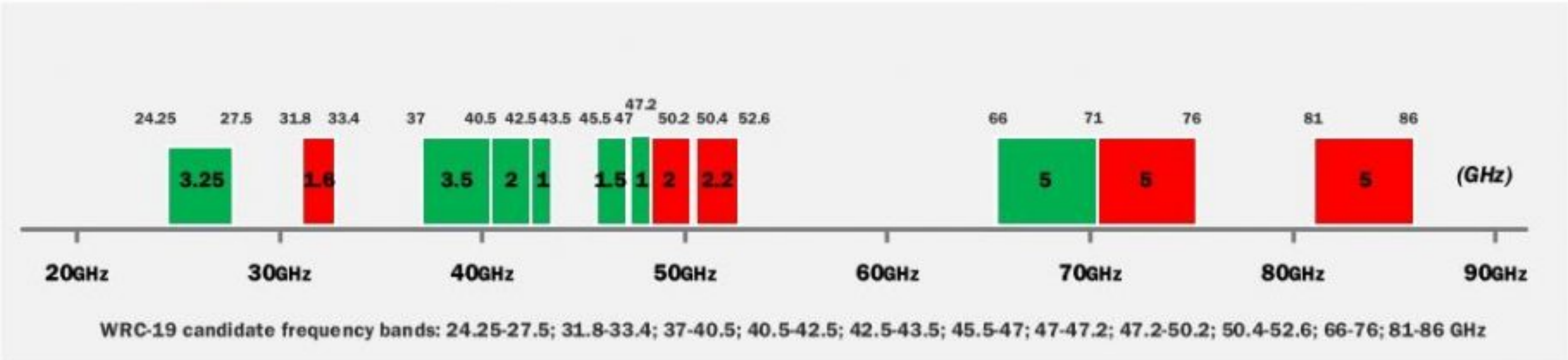
A look at the spectrum

- International Telecommunication Union (ITU) is the part of the United Nations (UN) that manages the use of both the RF Spectrum and space satellites among nation states. The Plenipotentiary Conference is the top policy-making body of the ITU, meeting every four years in order to set the Union's general policies.
- The World Radiocommunication Conference 2019 (WRC-19) identified frequency bands for International Mobile Telecommunications – IMT @ FR2 bands

New Spectrum

WRC-19 outcomes

- Identified frequency bands for International Mobile Telecommunications – IMT @ FR2 bands



Success of IMT identification	Failure of IMT identification
24.25 – 27.5 GHz (globally harmonized)	31.8 – 33.4 GHz
37 – 43.5 GHz (globally harmonized)	48.2 - 50.2 GHz
45.5 – 47 GHz	50.4 – 52.6 GHz
47.2 – 48.2 GHz	71 – 76 GHz
66 – 71 GHz (globally harmonized)	81 – 86 GHz

WRC-23: to come…

Frequency bands to be identified at WRC-23

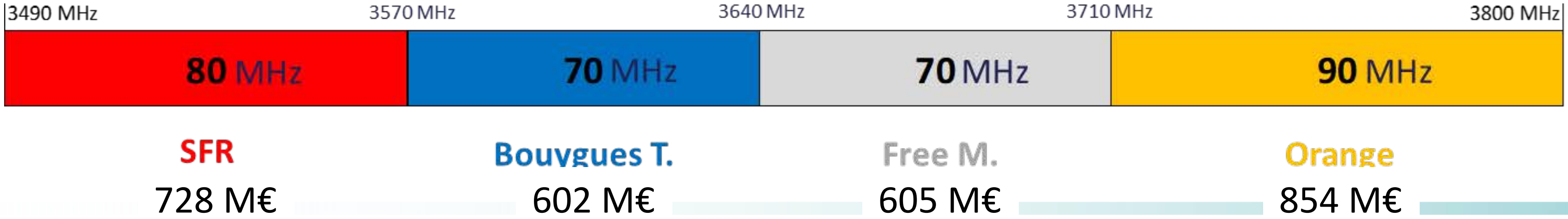
- **3400-3800 MHz:** This band is viewed as a core global 5G band and thus its IMT identification is key.
- **3300-3400 MHz:** This band is particularly attractive for future 5G deployments due to the vicinity to the aforementioned 3400-3800 MHz band.
- **6425-7125 MHz**: given the relative lack of large bandwidth allocations below 6 GHz and the coverage challenges associated to bands above 24GHz, this band is a good choice for the future 5G ecosystem.
- **10-10.5 GHz:** this band is also attractive for Fixed-Wireless Access service, with a better propagation than 26/28 GHz, especially in near or non-Line of Sight

NGMN 5G Whitepaper 2

New Spectrum

State regulation authority

- USA:
  - Federal Communications Commission (FCC)
  - Auctions of 70 MHz (10 MHz blocks) in the 3.55-3.65 GHz (total of 4 585 M€ raised)
- France
  - Arcep
  - Auctions for a 310MHz band (3.49-3.80 GHz) in October 2020
  - Results:



A look at the spectrum

5G new spectrum in the near future:

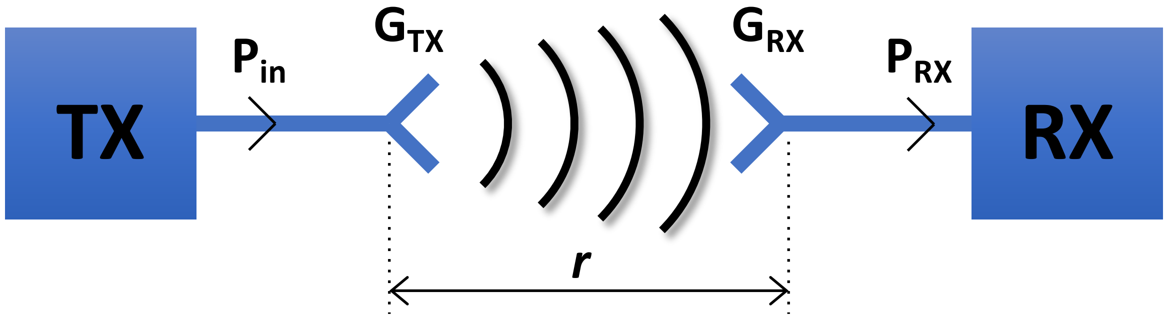
- FR1@ 3.5GHz: first band to introduce 5G in Europe (phase 1)
- FR2 @ 28GHz: first 5G band to make use of millimeter-waves for ultra-high data rate (phase 2)

+ evolution of LTE bands (refarming):

- 700 MHz
- 800MHz
- 1.8GHz
- 2.1GHz
- 2.6 GHz

➡ The frequency influences the attenuation

Friis Equation



$$P_{RX} = P_{in} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi r}\right)^2$$

where:

- $\left(\frac{\lambda}{4\pi r}\right)^2$ is the free space attenuation
- P_{RX} is the power received by the RX antenna
- P_{IN} is the input power accepted by the TX antenna
- G_{TX} and G_{RX} are the TX and RX gain, respectively, along the TX-RX axis

New Spectrum

Friis Equation

$$P_{RX_{dBW}} = P_{TX_{dBW}} + G_{TX_{dB}} + G_{RX_{dB}} + 20\log\left(\frac{\lambda}{4\pi r}\right)$$

where:

- $P_{TX/RX_{dBW}} = 10\log\left(P_{TX/RX}\right)$, in dBW (or dBm)
- $G_{TX/RX_{dB}} = 10\log\left(G_{TX/RX}\right)$, in dB

New Spectrum

Link budget

- Free space attenuation examples

$$P_{gain} = 20\log\left(\frac{\lambda}{4\pi r}\right) = 20\log\left(\frac{c}{4\pi r}\right) - 20\log(f)$$

@ 700MHz: $20\log(f)$ = -176.9dB
Δ=-9.1dB
@ 2GHz: $20\log(f)$ = -186dB
Δ=-4.9dB
@ 3.5GHz: $20\log(f)$ = -190.9dB
Δ=-18dB
@ 28GHz: $20\log(f)$ = -208.9dB
Δ=-6.7dB
@ 60GHz: $20\log(f)$ = -215.6dB

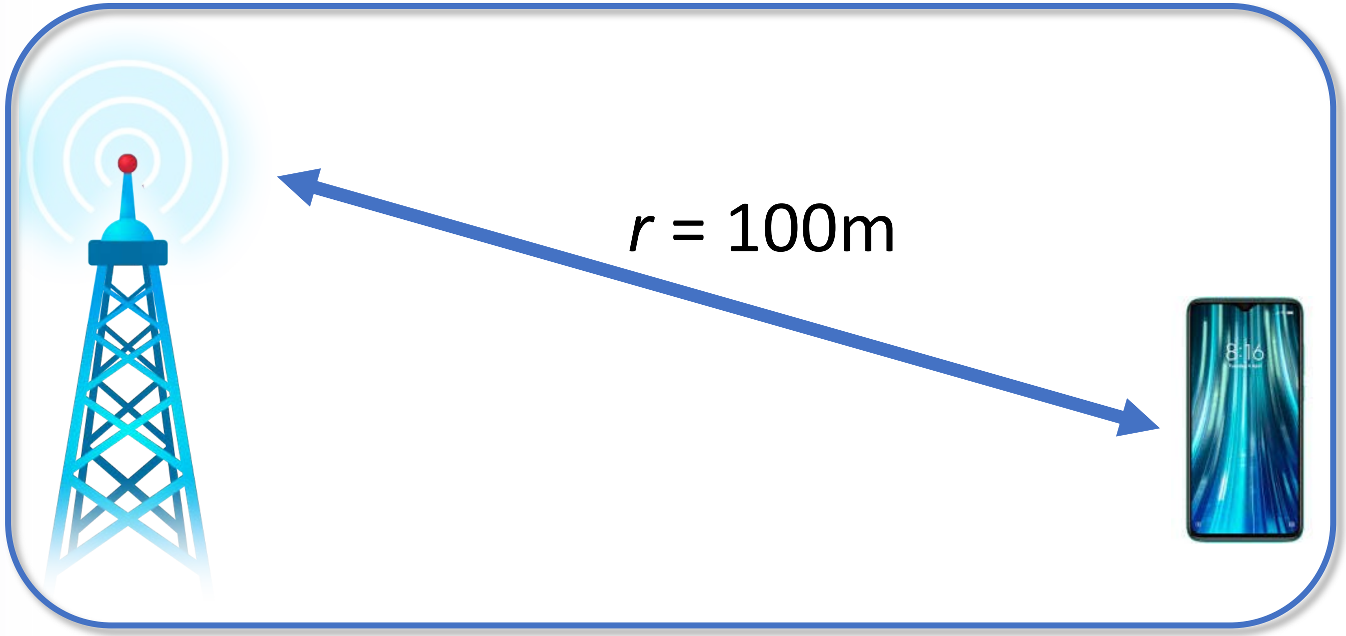
➡ Lower-frequency bands face much lower attenuations

New Spectrum

Link budget

- Free space attenuation examples

$$P_{gain} = 20\log\left(\frac{\lambda}{4\pi r}\right) = 20\log\left(\frac{c}{4\pi r}\right) - 20\log(f)$$



Frequency	P_{gain}
700 MHz	-69.3dB
2 GHz	-78.5 dB
3.5 GHz	-83.3 dB
28 GHz	-101.4 dB
60 GHz	-108 dB

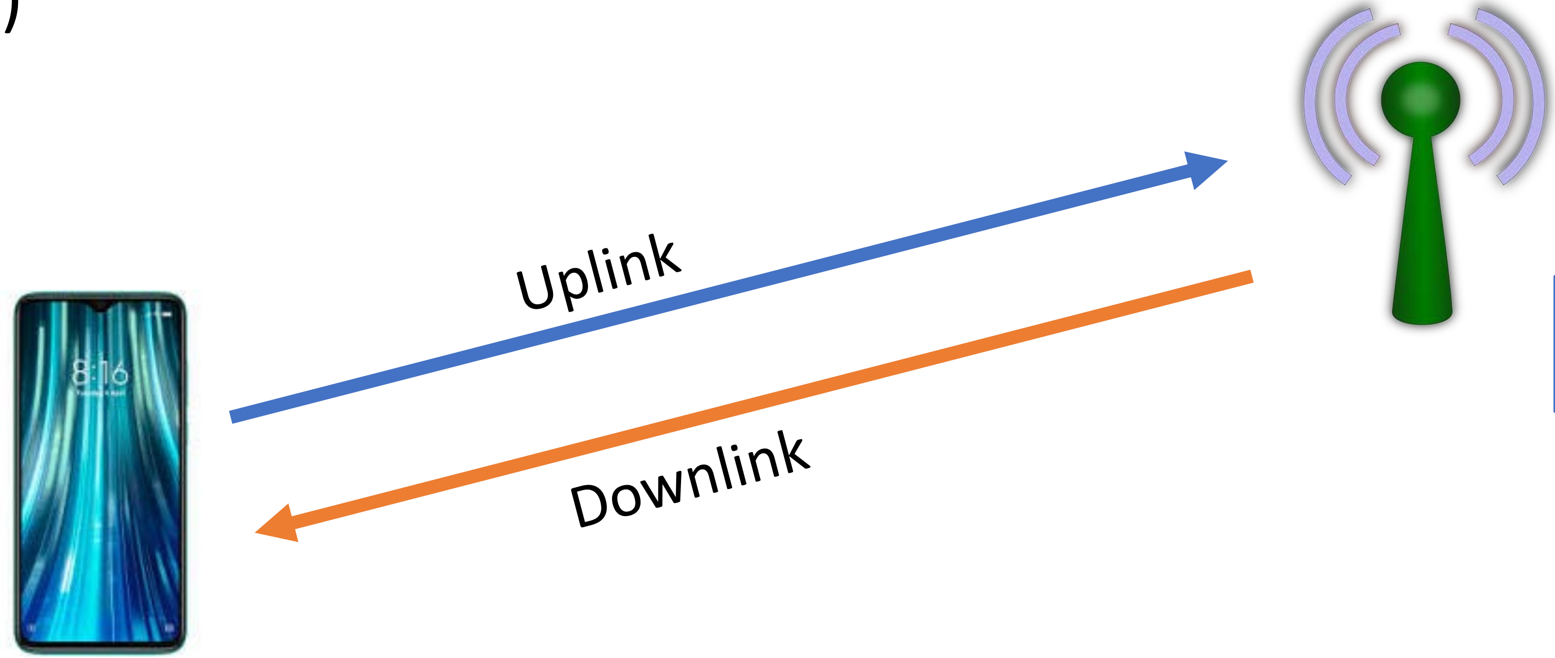
New Spectrum

Appropriate use of different frequency bands

- **700 MHz**: macro-cell, good coverage (rural area, Internet-of-Things…)
- **3.5 GHz**: small-cells, dense urban environment, high data rate
- **28/40 GHz**: hotspots (fixed access points), link at 10Gbps

Downlink and Uplink in the cellular network

- Communications between User Equipment (UE) and Base Stations (BS)



LTE BS: eNB
5G BS: en-gNB

2-way communications thanks to

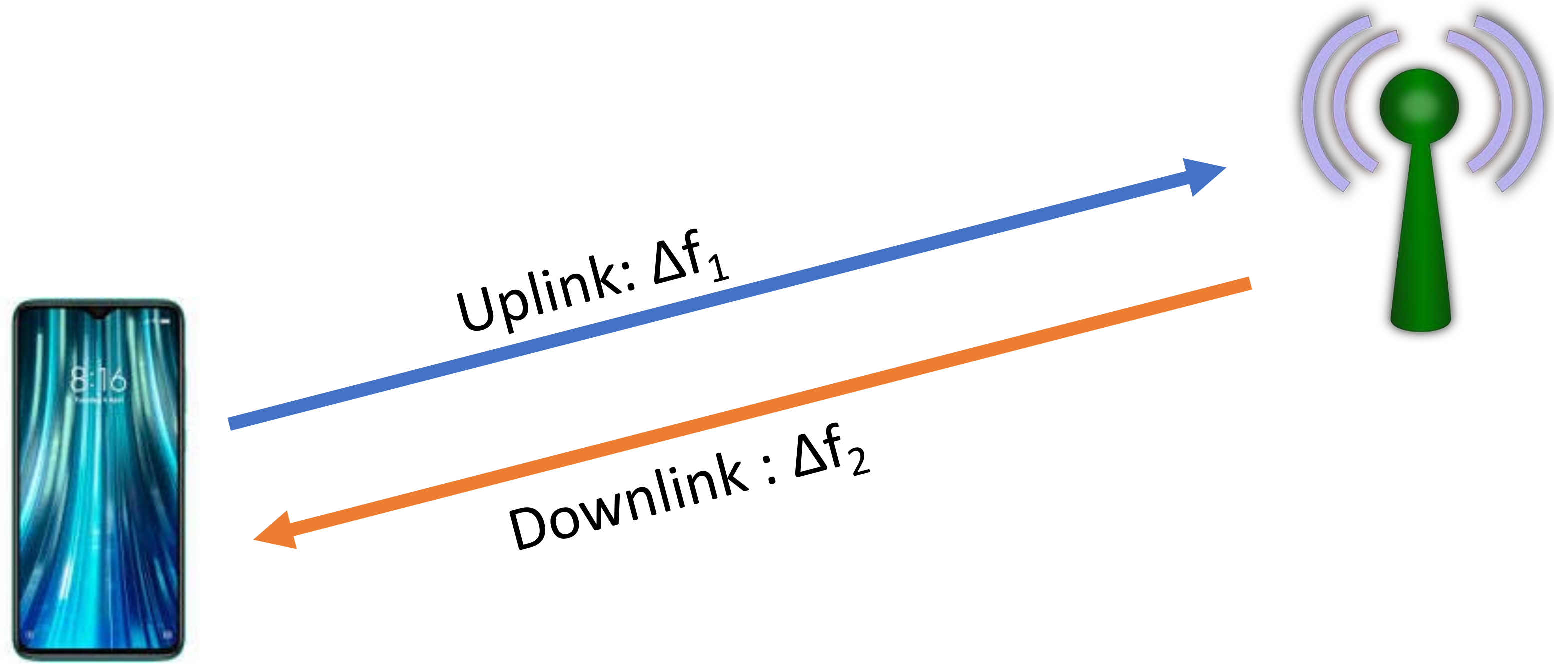
- **FDD**: Frequency Division Duplex
- **TDD**: Time Division Duplex

Both techniques are within 5G

New Spectrum

FDD in 5G

- FDD: Frequency Division Duplexing



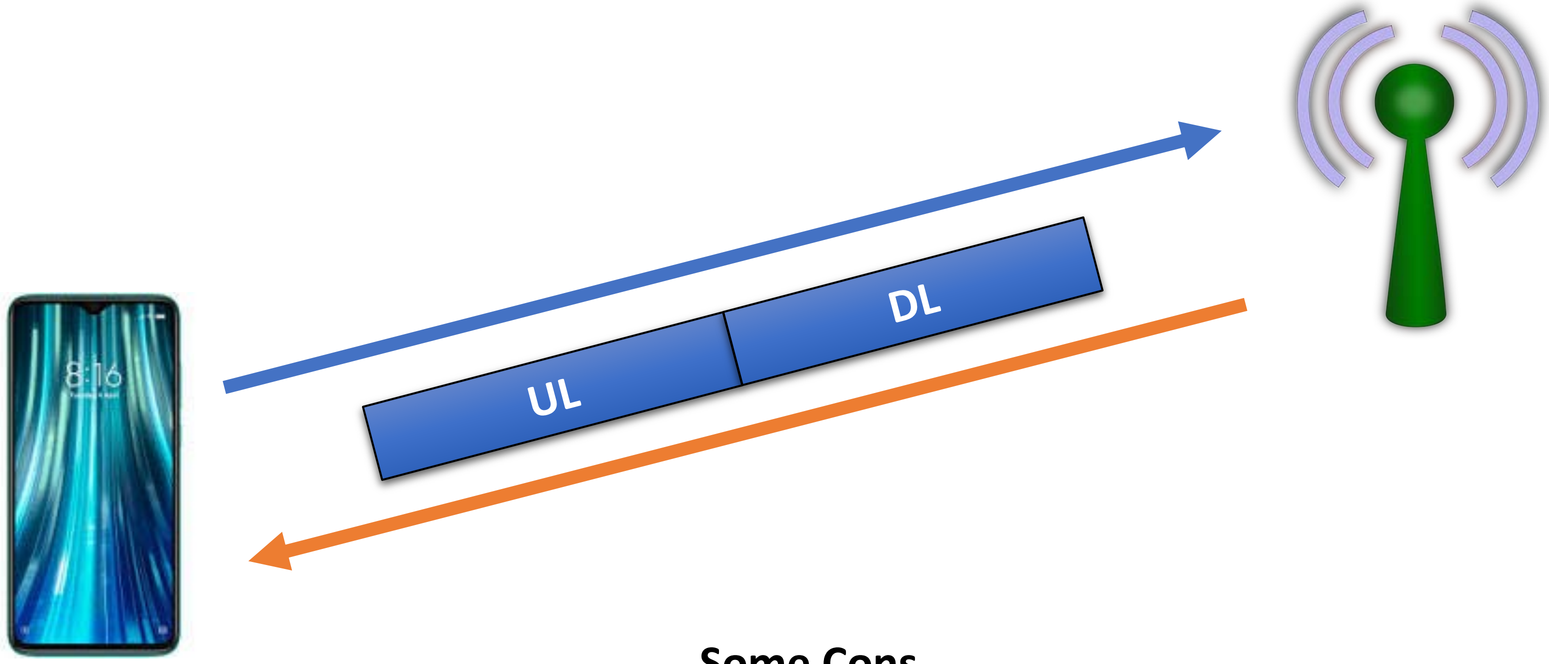
Some Pros
UL and DL can occur simultaneously
Continuous communication

Some Cons
FDD requires a paired spectrum
Costly duplexer is required to separate UL from DL
No channel reciprocity

New Spectrum

TDD in 5G

- TDD: Time Division Duplexing



Some Pros
TDD does not requires a paired spectrum
Channel reciprocity: channel estimation is easier
No spectrum is wasted as no guard bands are required

Some Cons
Synchronization is required between UE and BS
Guard time is required: decreases data rate
Calibrated RF hardware for CSI reciprocity

New Spectrum

Spectrum in 5G

- Frequency bands

5G Band	Uplink (UL) operating band	Downlink (DL) operating band	Duplex Mode
n1	1920MHz – 1980MHz	2110MHz-2170MHz	FDD
:	:	:	:
n77	3300MHz-4200MHz	3300MHz-4200MHz	TDD
:	:	:	:
n257	26.5GHz – 29.5GHz	26.5GHz – 29.5GHz	TDD
:	:	:	:
n512	:	:	:

LTE Refarming Bands

5G FR1 new bands

5G FR2 new bands

New Spectrum

5G frequency bands

NR operating band	Uplink (UL) operating band BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
n12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
n14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
n18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n29	N/A	717 MHz – 728 MHz	SDL
n30[3]	2305 Mhz – 2315 MHz	2350 MHz – 2360 MHz	FDD
n34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
n38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n48	3550 MHz – 3700 MHz	3550 MHz – 3700 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD

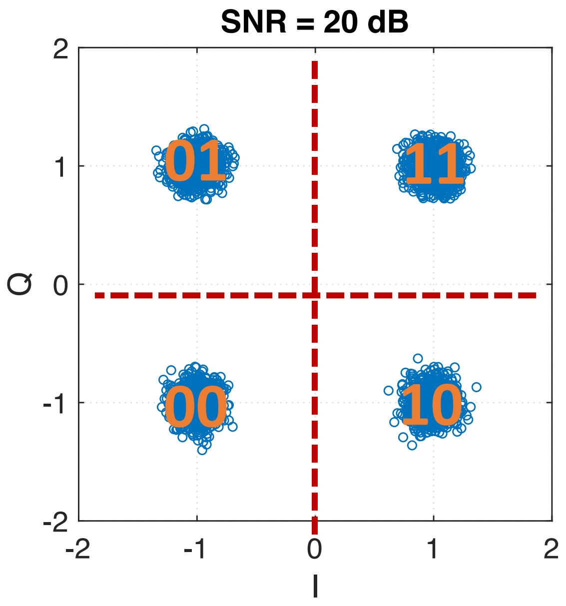
NR operating band	Uplink (UL) operating band BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n65	1920 MHz – 2010 MHz	2110 MHz – 2200 MHz	FDD[4]
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL
n76	N/A	1427 MHz – 1432 MHz	SDL
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n86	1710 MHz – 1780 MHz	N/A	SUL
n89	824 MHz – 849 MHz	N/A	SUL
n90	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD[5]
n91	832 MHz – 862 MHz	1427 MHz – 1432 MHz	FDD[9]
n92	832 MHz – 862 MHz	1432 MHz – 1517 MHz	FDD[9]
n93	880 MHz – 915 MHz	1427 MHz – 1432 MHz	FDD[9]
n94	880 MHz – 915 MHz	1432 MHz – 1517 MHz	FDD[9]
n95[8]	2010 MHz – 2025 MHz	N/A	SUL

SDL/SUL: Supplementary Down/Up Link

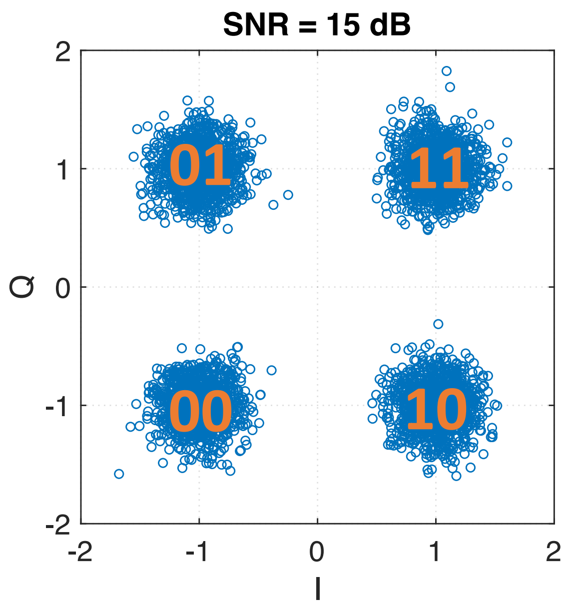
Modulations

Sensitivity to Signal-to-Noise Ratio (SNR)

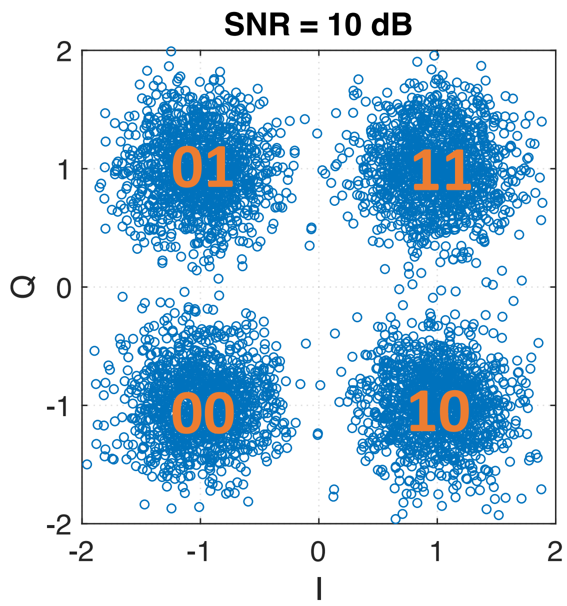
- QPSK example



BER ~ 7.6×10^{-24}



BER ~ 9.4×10^{-9}



BER ~ 7.8×10^{-4}

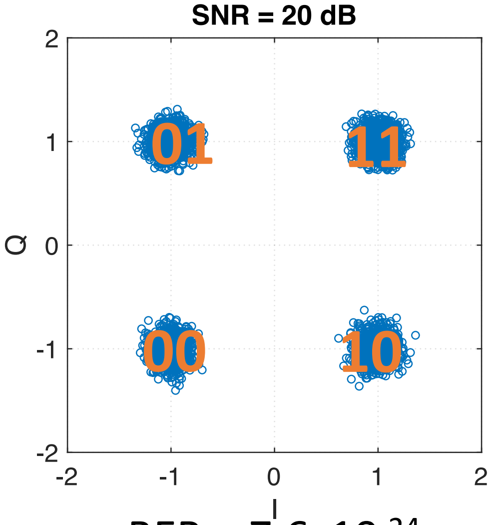
$$SNR = \frac{P_{signal}[W]}{P_{noise}[W]}$$

BER: Bit Error Rate

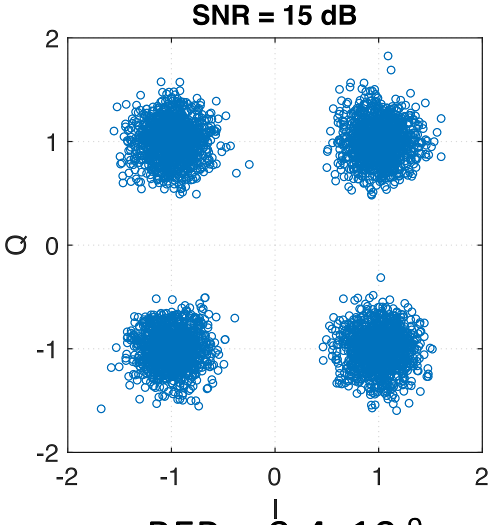
Modulations

Sensitivity to Signal-to-Noise Ratio (SNR)

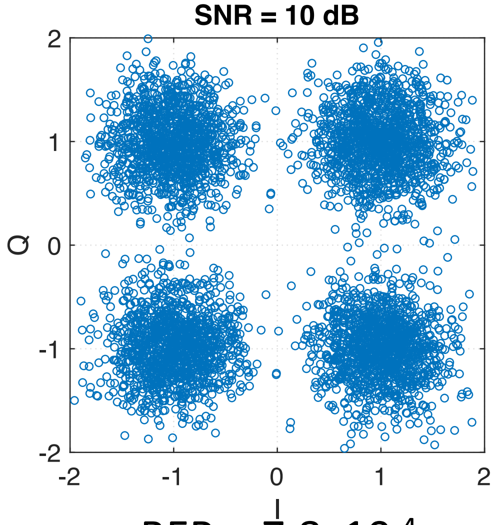
QPSK



BER ~ 7.6×10^{-24}

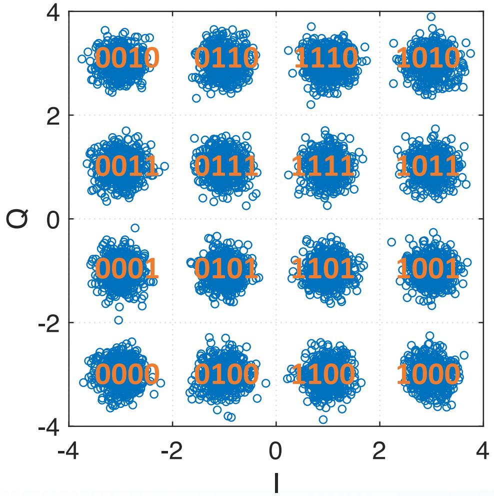


BER ~ 9.4×10^{-9}

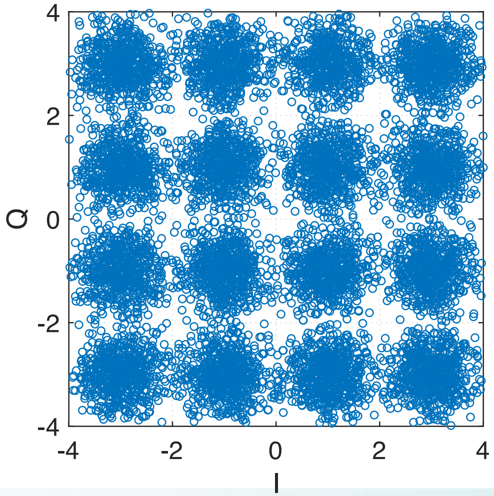


BER ~ 7.8×10^{-4}

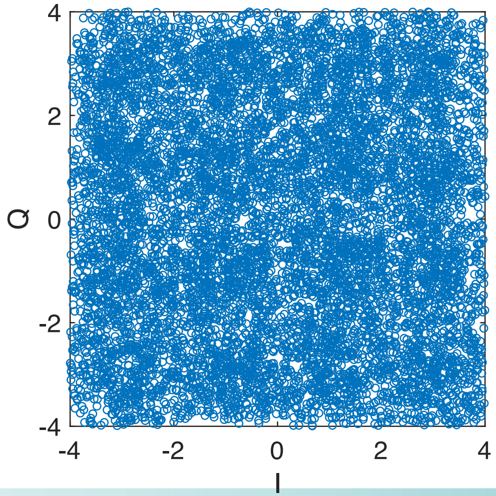
16-QAM



BER ~ 2.9×10^{-6}



BER ~ 4.5×10^{-3}

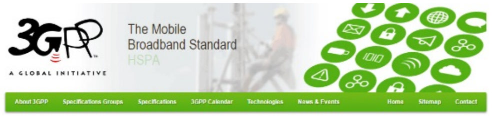


BER ~ 0.06×10^{-2}

Modulation schemes in 5G

- Downlink:
  - From QPSK up to 256-QAM
- Uplink:
  - From QPSK up to 256-QAM (if OFDM with Cyclic Prefix)
  - From BPSK up to 256QAM (if DFT-s-OFDM with Cyclic Prefix)
- Adaptive modulation based on channel quality

More details about modulation mapper in the 3GPP technical specifications document TS 38.211



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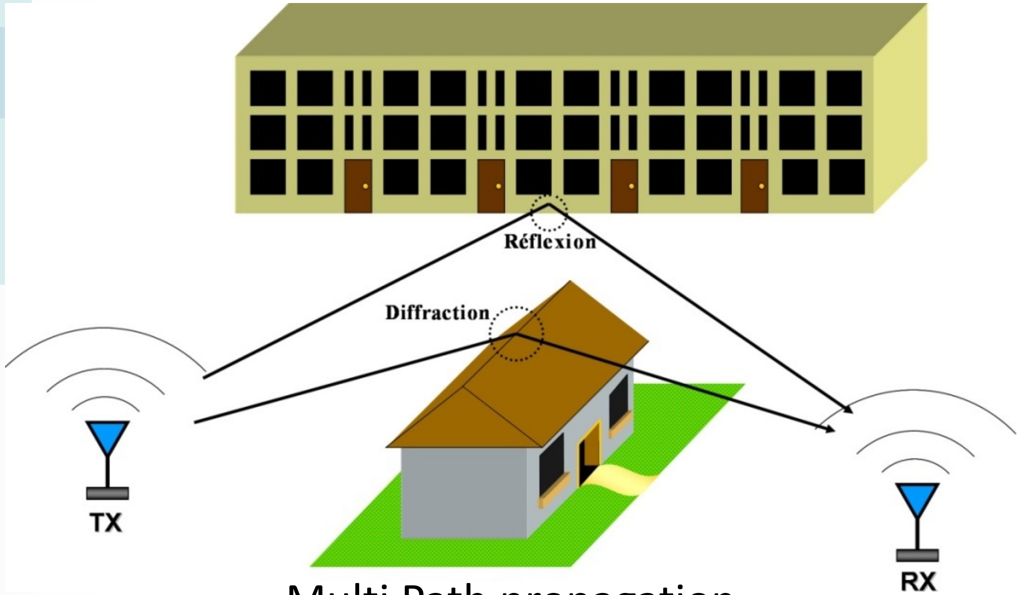
Modulations

The 5G waveform

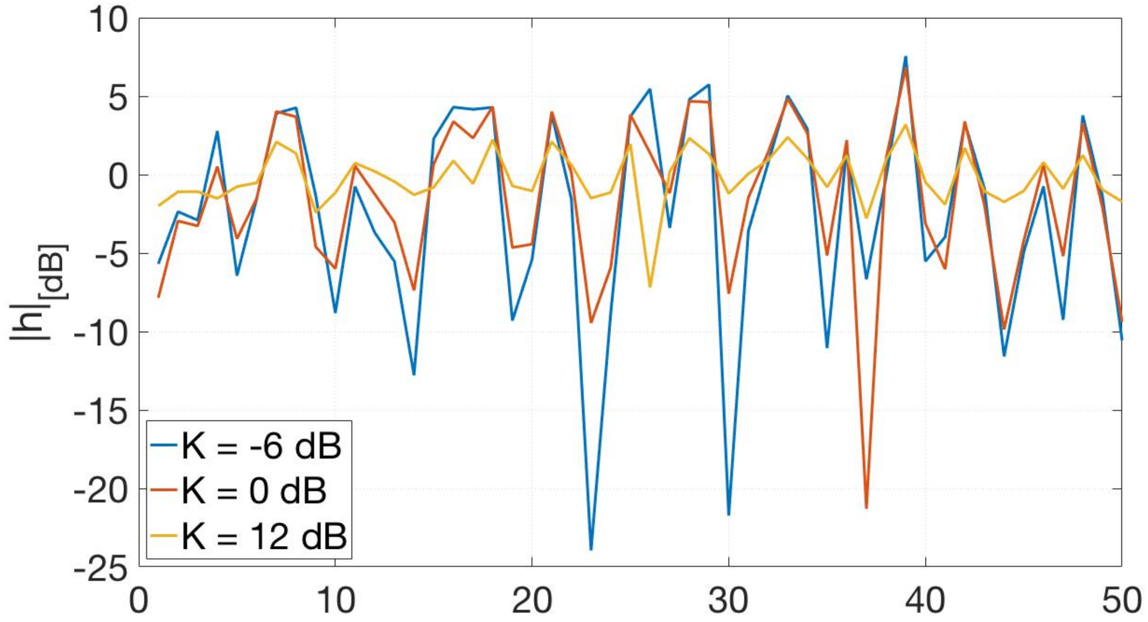
- Use of OFDM like in LTE
- OFDM: Orthogonal Frequency Division Multiplexing
  - Use of CP-OFDM
  - DFT-s-OFDM (eq. to SC-FDM(A))
- Reasonable resource consumption thanks to FFT-based implementation
- OFDM gives good spectral efficiency whilst providing resilience to selective fading

Modulations

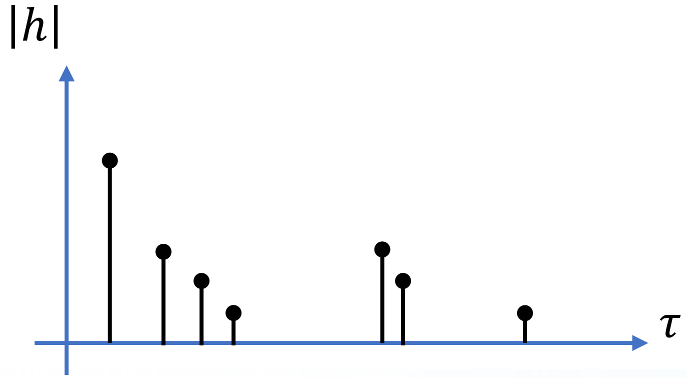
The propagation channel



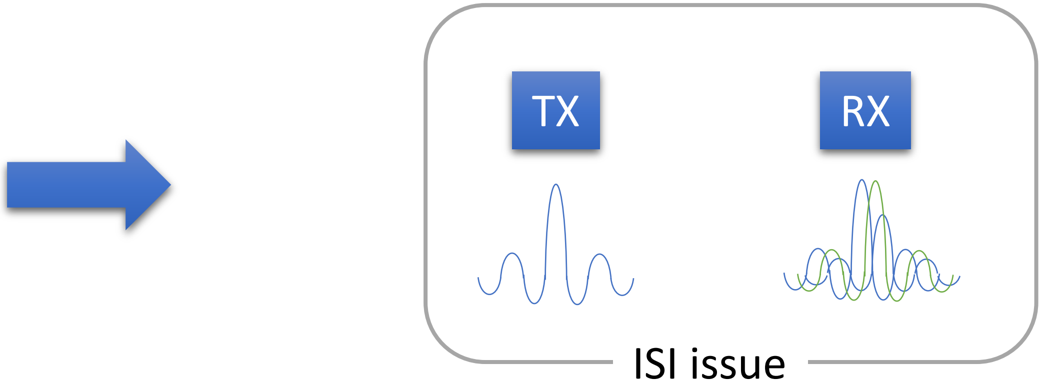
Multi Path propagation



Channel Frequency Response

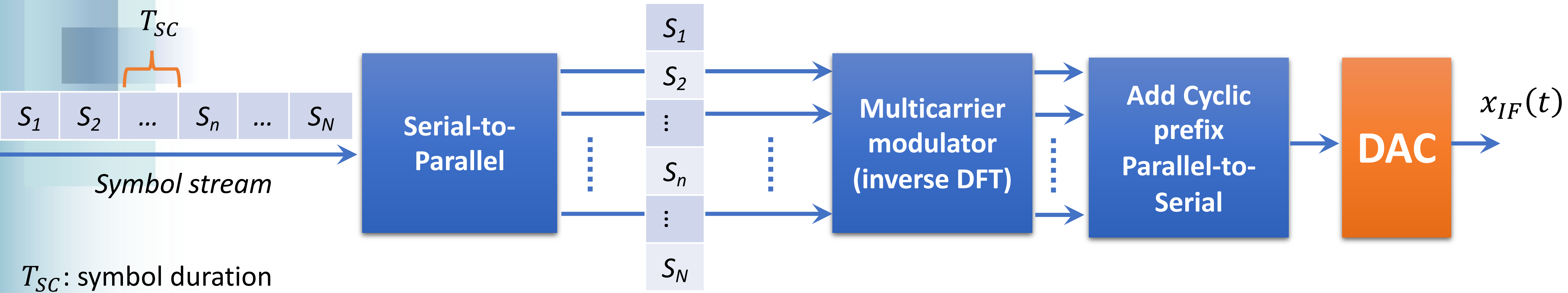


Channel Impulse Response (Time Domain)



ISI issue

OFDM TX architecture

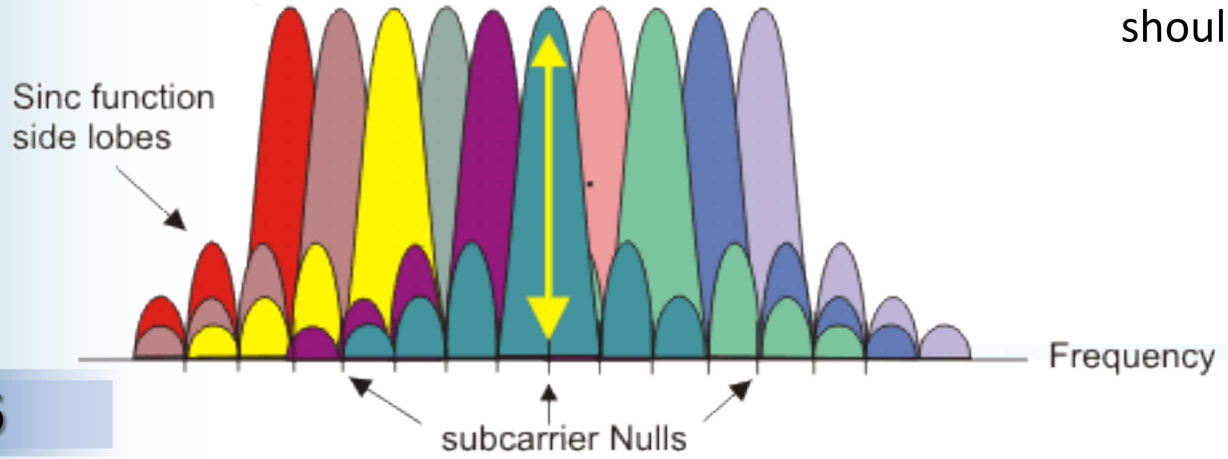


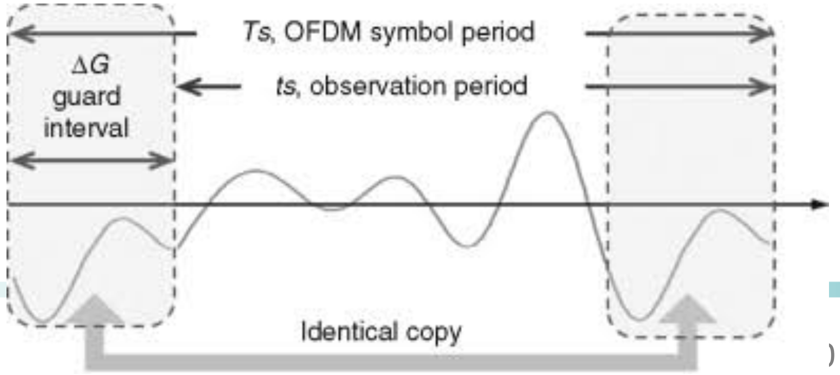
T_{SC}: symbol duration (if Single-Carrier)

$T = NT_{SC}$: OFDM symbol duration

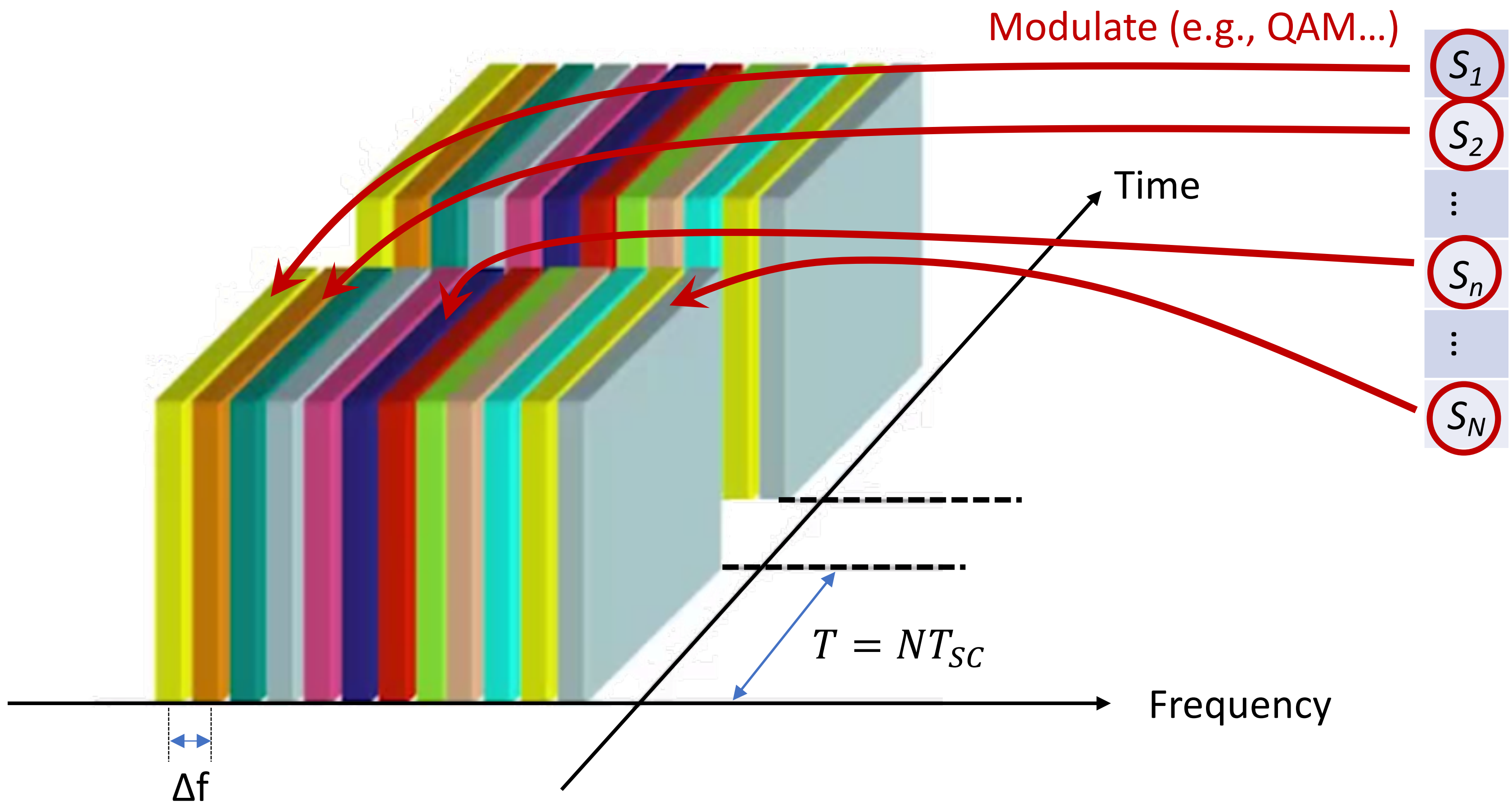
$\frac{1}{T} = \Delta\mathrm{f}$ ➡ orthogonal sub-carriers (with Δf the distance between subcarriers)

Cyclic prefix (CP): avoid ISI by acting as a time-guard (CP duration should be greater than channel duration)



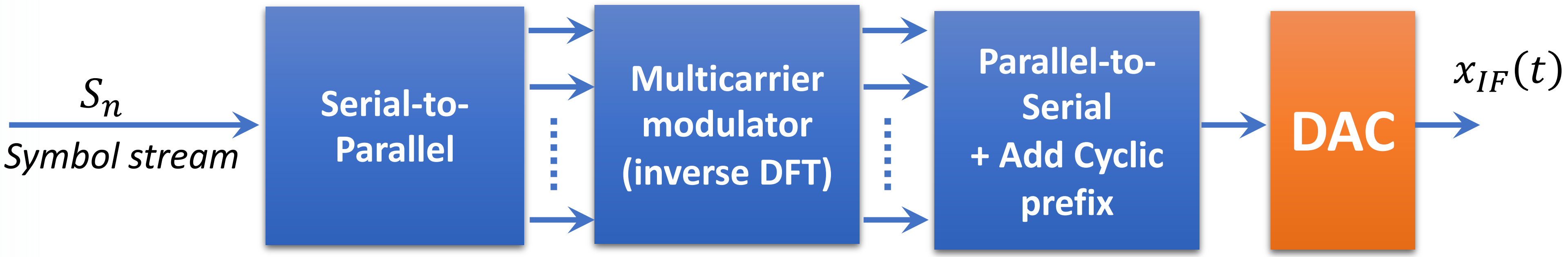


OFDM frame

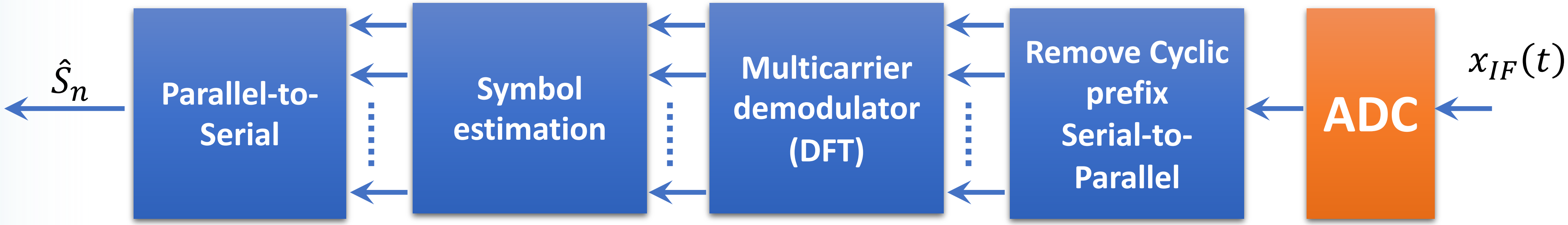


OFDM architecture

TX architecture



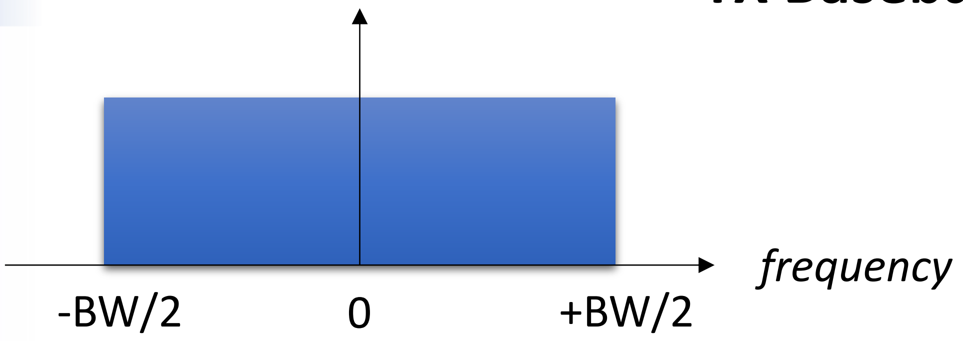
RX architecture



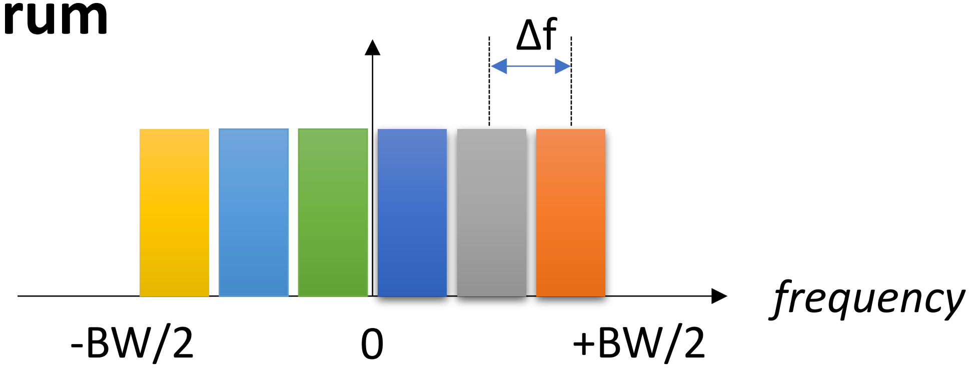
Modulations

OFDM: simple channel EQ, robustness to fading effect

TX Baseband spectrum

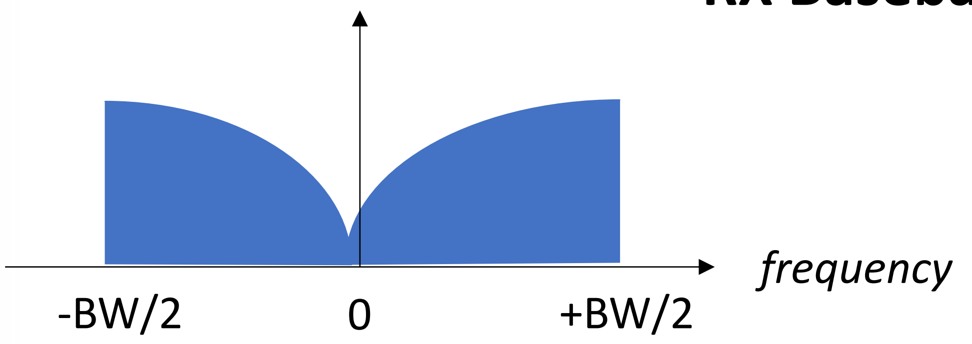


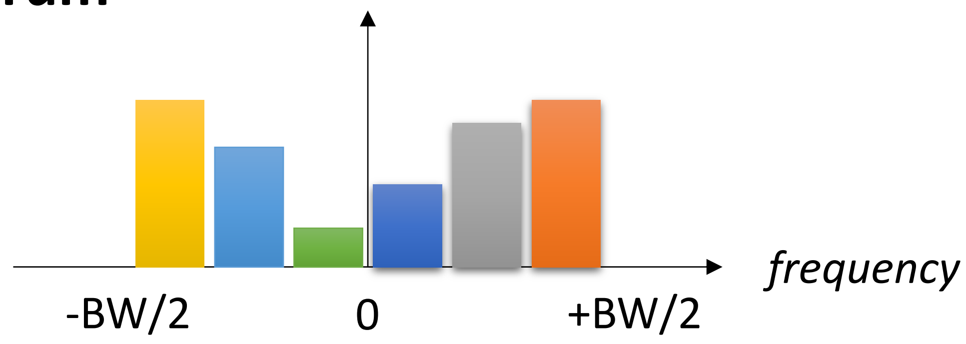
Single-Carrier-modulated signal



OFDM-modulated signal
(Multiple subcarriers)

RX Baseband spectrum





Frequency-selective channel: fading effect

OFDM side effect

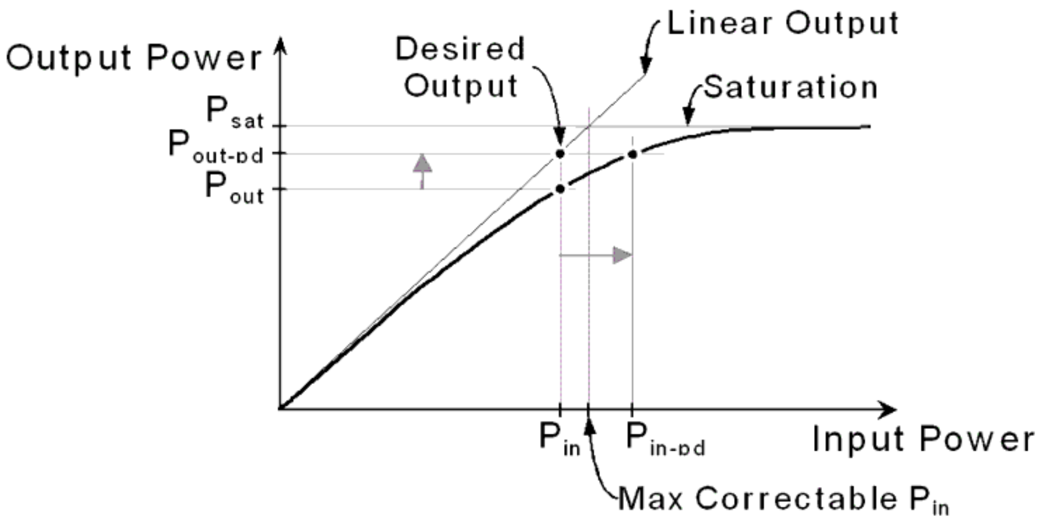
- OFDM signals have increases PAPR (Peak-to-Average-Power Ratio)

➡ May result in clipping of the signal voltage in DAC

➡ May saturate the Power Amplifier

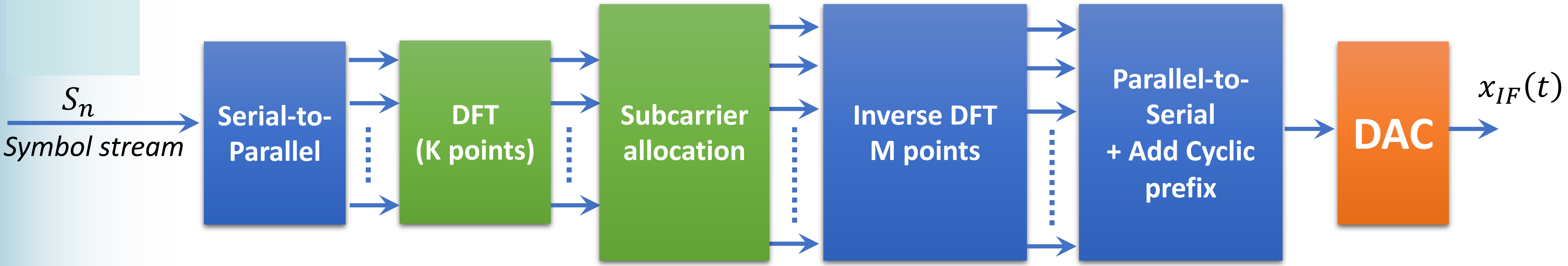
  ➡ Necessitate power backoff (decreases efficiency)

  ➡ Possible to reduce the PAPR by signal processing (random phase shift of different subcarriers…)



DFT-s-OFDM: DFT spread OFDM

- TX architecture



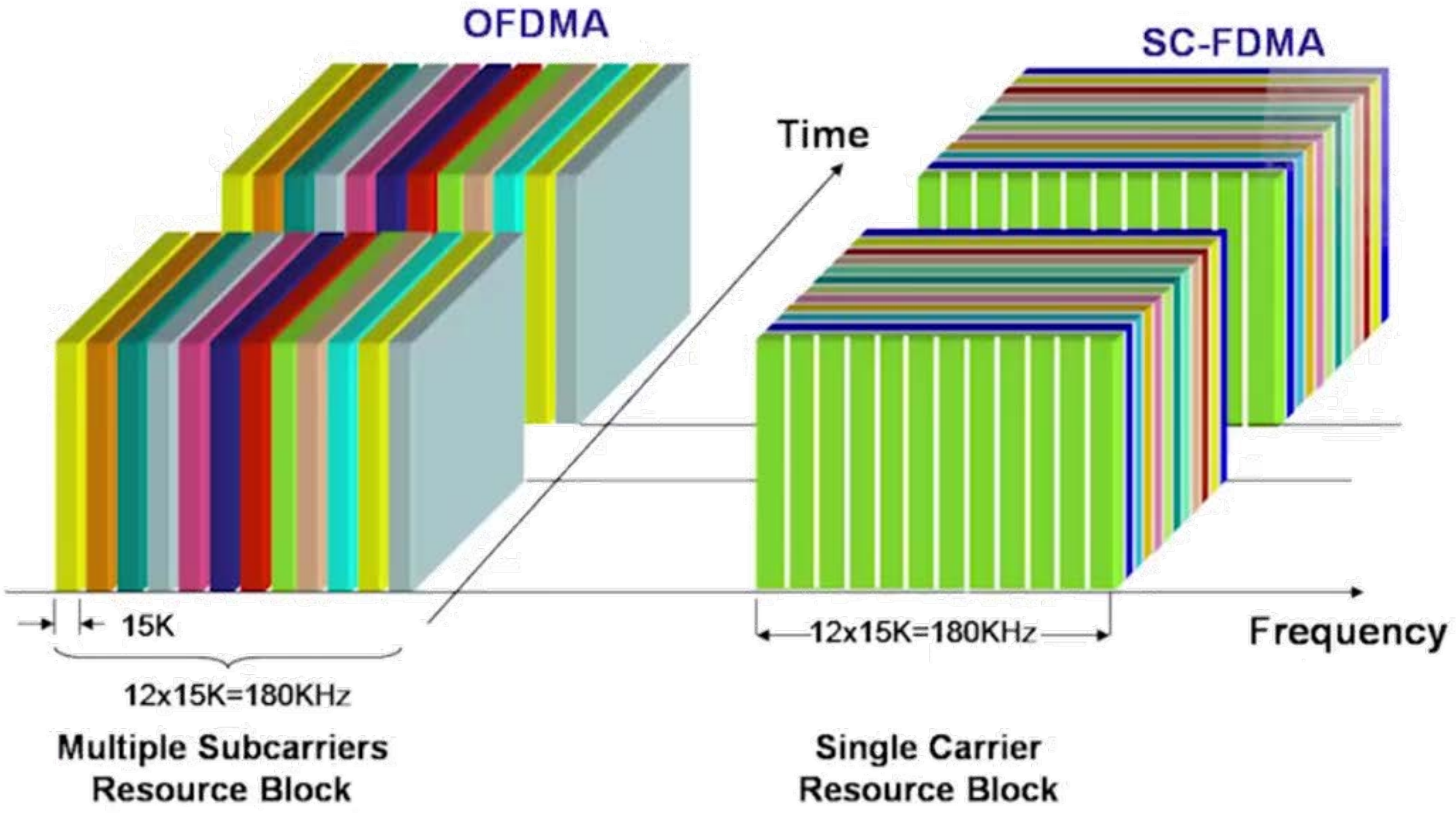
Unused subcarriers to 0
(can be used for other users)

- Reduces PAPR (well-suited to optimize power consumption at UE)
- Like OFDM it mitigates multipath degradation with Frequency Domain Equalization

But symbol duration are shorter => ISI issue

Modulations

DFT-s-OFDM frame

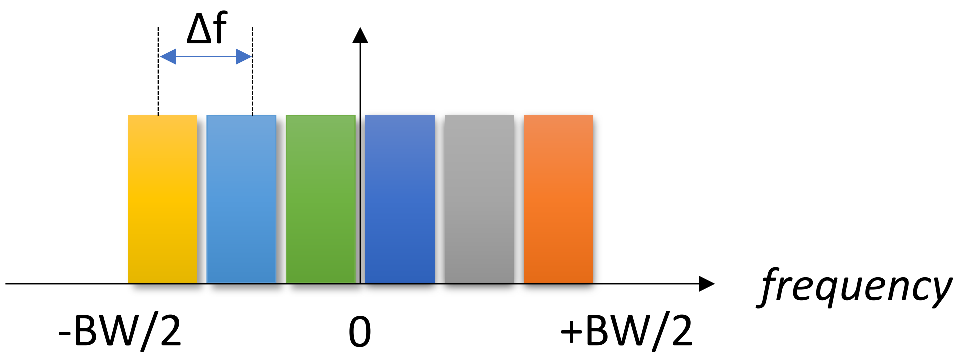


Flexible Numerology

Flexible Numerology

Numerology: flexible Sub-Carrier Spacing in OFDM

- SCS: Sub-Carrier Spacing



OFDM-modulated signal
(Multiple subcarriers)

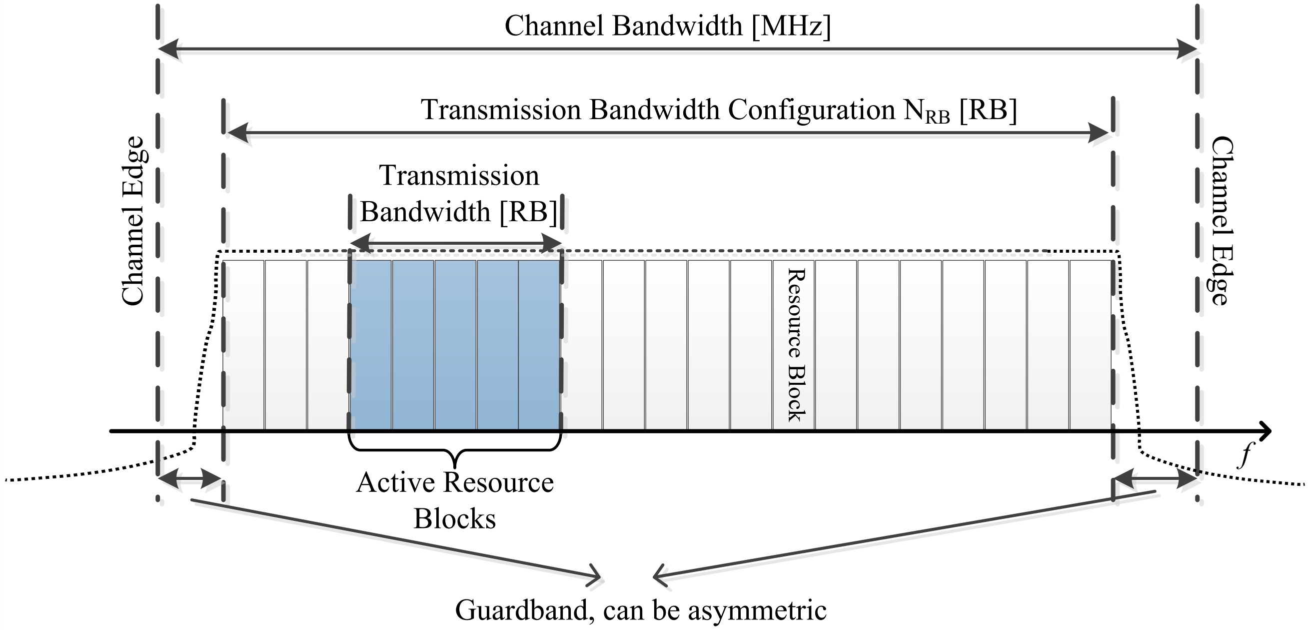
Flexible SCS in 5G

μ	$\Delta f = 2^{\mu}.15kHz$
0	15
1	30
2	60
3	120
4	240

(Fixed 15KHz SCS in LTE)

Numerology: flexible bandwidth

- **UE transmission bandwidth configuration**: Set of resource blocks located within the UE channel bandwidth which may be used for transmitting or receiving



- **1 Resource Block = 12 subcarriers**
- UE can operate with asymmetric UL and DL bandwidths

*Minimum guard-band = (CHBW – SCS*12*N_{RB})/2- SCS/2*

Numerology: flexible bandwidth

- Adjustable bandwidth

FR1

SCS (kHz)	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	30 MHz	40 MHz	50 MHz	60 MHz	70 MHz	80 MHz	90 MHz	100 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
15	25	52	79	106	133	160	216	270	N/A	N/A	N/A	N/A	N/A
30	11	24	38	51	65	78	106	133	162	189	217	245	273
60	N/A	11	18	24	31	38	51	65	79	93	107	121	135

FR2

SCS (kHz)	50 MHz	100 MHz	200 MHz	400 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}
60	66	132	264	N.A
120	32	66	132	264

n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz

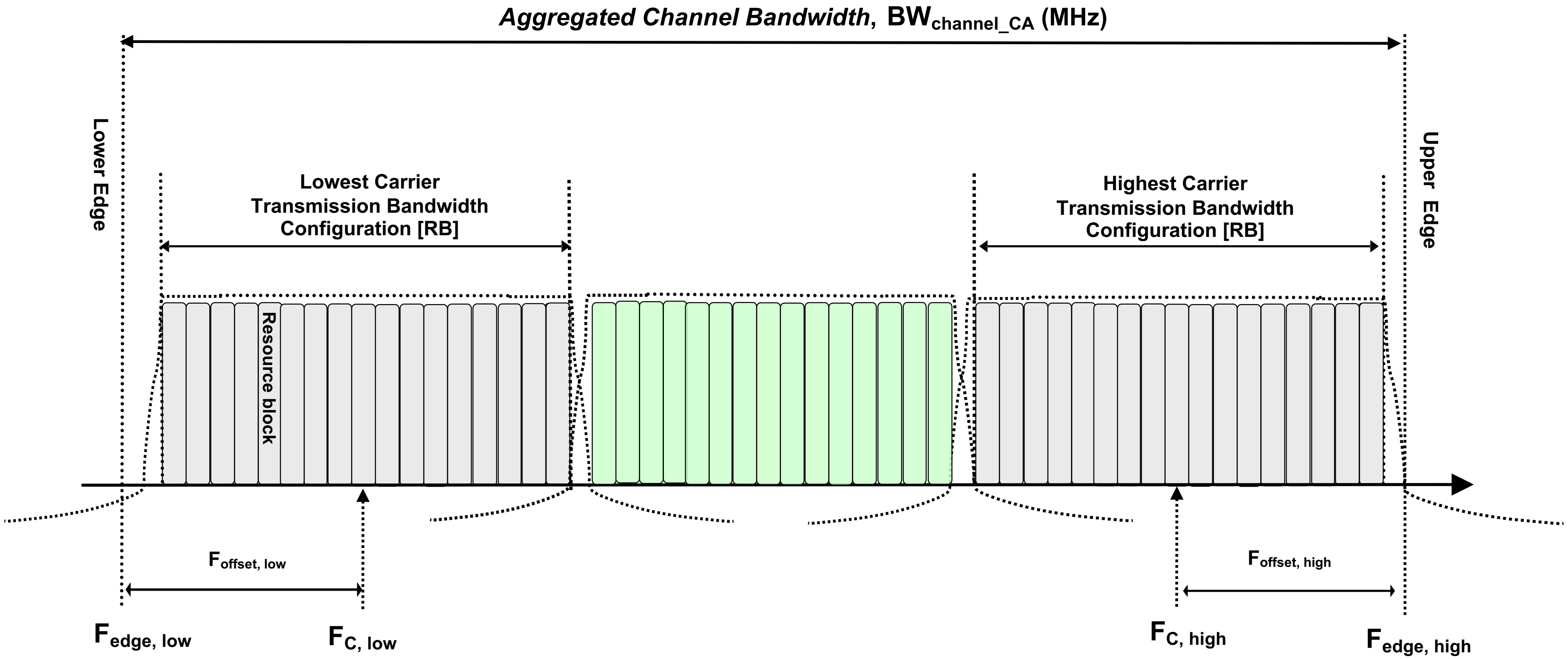
N_{RB}: Number of Resource Blocks
1 Resource Block = 12 subcarriers
Channel Bandwidth options availability depends on the frequency band considered (e.g., n1 band supports up to 20MHz Channel bandwidth, n7 band supports up to 50MHz)

More details about 5G frames in the 3GPP technical specifications document TS 38.101, 38.211

Flexible Numerology

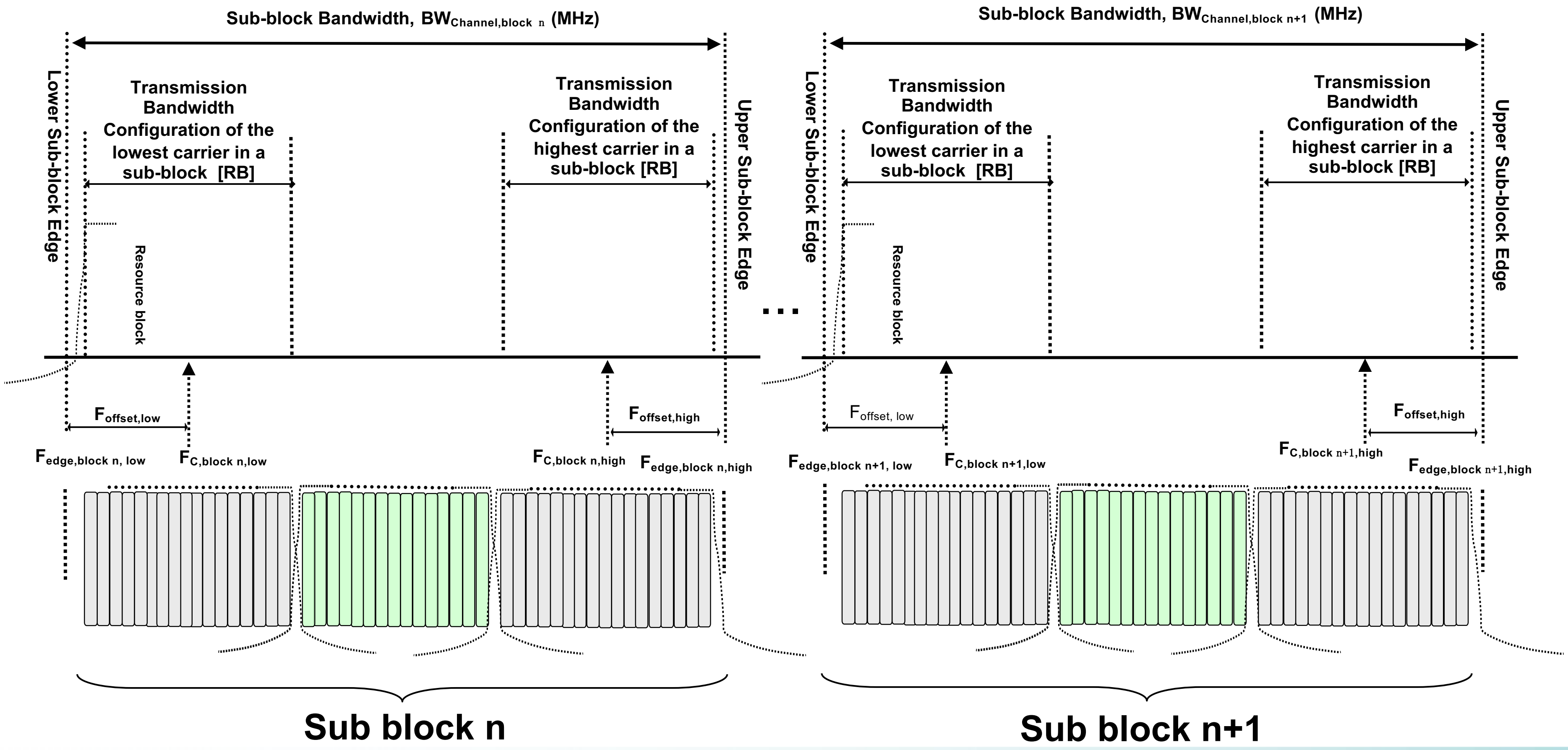
Numerology: flexible bandwidth

- Carrier Aggregation (CA): Intra-band Contiguous



Numerology: flexible bandwidth

- Carrier Aggregation (CA): Intra-band Non-Contiguous



Flexible Numerology

Numerology: flexible bandwidth

- Carrier Aggregation (CA): Inter-Band

NR operating band	Uplink (UL) operating band BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
n12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
n14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
⋮	…	…	…

2 bands

NR CA Band	NR Band (Table 5.2-1)
CA_n1-n3	n1, n3
CA_n1-n7	n1, n7
CA_n1-n8	n1, n8
⋮	…

3 bands

NR CA Band	NR Band (Table 5.2-1)
CA_n1-n3-n8	n1, n3, n8
CA_n1-n3-n28	n1, n3, n28
⋮	…

4 bands

NR CA Band	NR Band (Table 5.2-1)
CA_n1-n3-n8-n78	n1, n3, n8, n78
CA_n1-n3-n28-n78	n1, n3, n28, n78

Flexible Numerology

Numerology: flexible bandwidth

- Intra-band contiguous Carrier Aggregation (CA) @ FR1

NR CA bandwidth class	Aggregated channel bandwidth	Number of contiguous CC
A	$BW_{Channel} \leq BW_{Channel,max}$	1
B	20 MHz $\leq BW_{Channel\_CA} \leq$ 50 MHz	2
C	100 MHz $< BW_{Channel\_CA} \leq 2 \times BW_{Channel,max}$	2
D	200 MHz $< BW_{Channel\_CA} \leq 3 \times BW_{Channel,max}$	3
E	300 MHz $< BW_{Channel\_CA} \leq 4 \times BW_{Channel,max}$	4
F		2
G	100 MHz $< BW_{Channel\_CA} \leq$ 150 MHz	3
H	150 MHz $< BW_{Channel\_CA} \leq$ 200 MHz	4
I	200 MHz $< BW_{Channel\_CA} \leq$ 250 MHz	5
J	250 MHz $< BW_{Channel\_CA} \leq$ 300 MHz	6
K	300 MHz $< BW_{Channel\_CA} \leq$ 350 MHz	7
L	350 MHz $< BW_{Channel\_CA} \leq$ 400 MHz	8

CC: Carrier Component

…which can be again aggregated in an intra-band non-contiguous configuration or an inter-band configuration

$BW_{Channel,\ max}$ is maximum channel bandwidth supported among all bands in a release

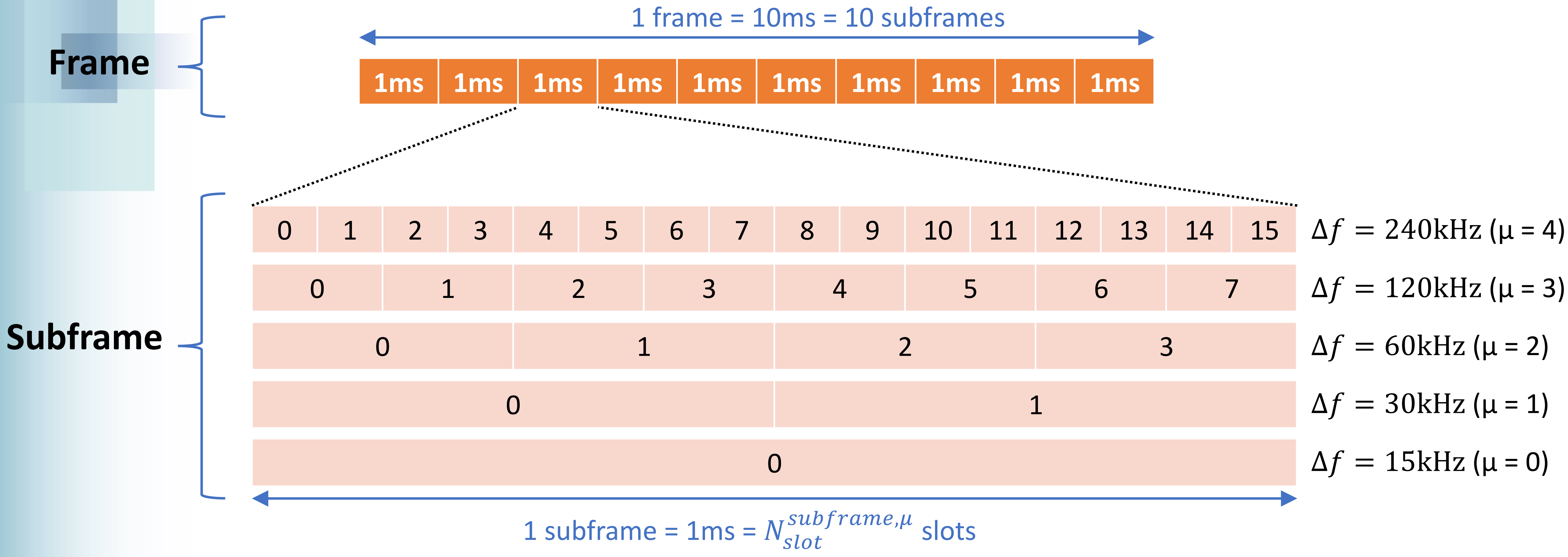
Flexible Numerology

Numerology: flexible bandwidth

- Carrier aggregation @ FR2
  - Intra-band contiguous aggregation up to 1.2GHz channel bandwidth
  - Intra-band non-contiguous aggregation up to 3GHz channel bandwidth (DL only)

Flexible Numerology

Numerology: flexible frame structure in 5G



- Number of OFDM symbols per slot is $N_{symb}^{slot} = 14$ (for normal cyclic prefix)
- Mini-slots of 2/4/7 OFDM symbols are considered for low-latency applications
- In 5G, each slot can be used either in UL or DL