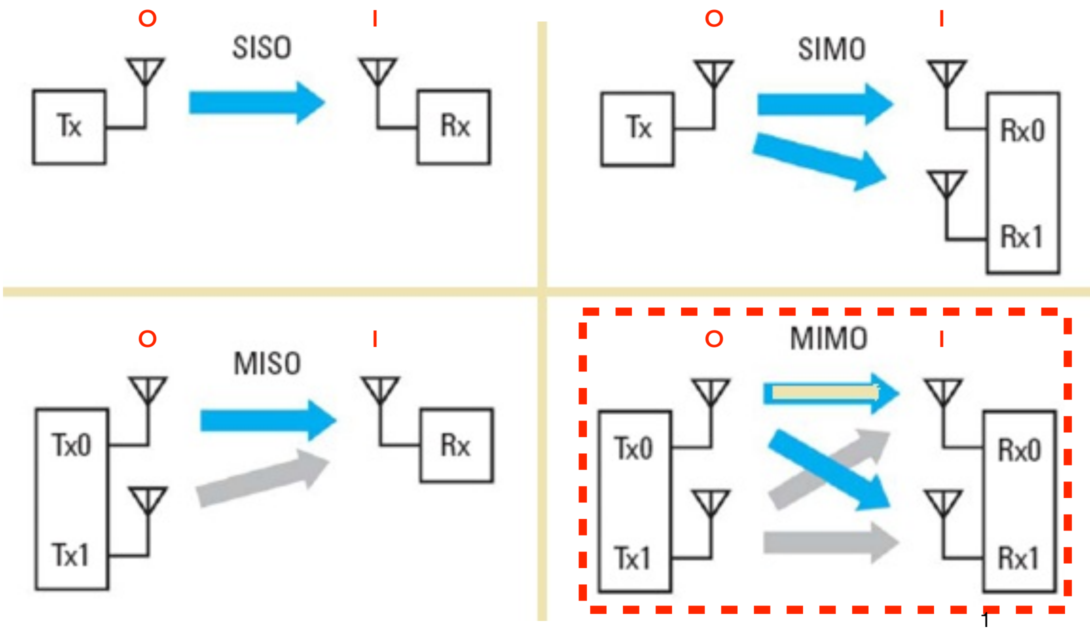
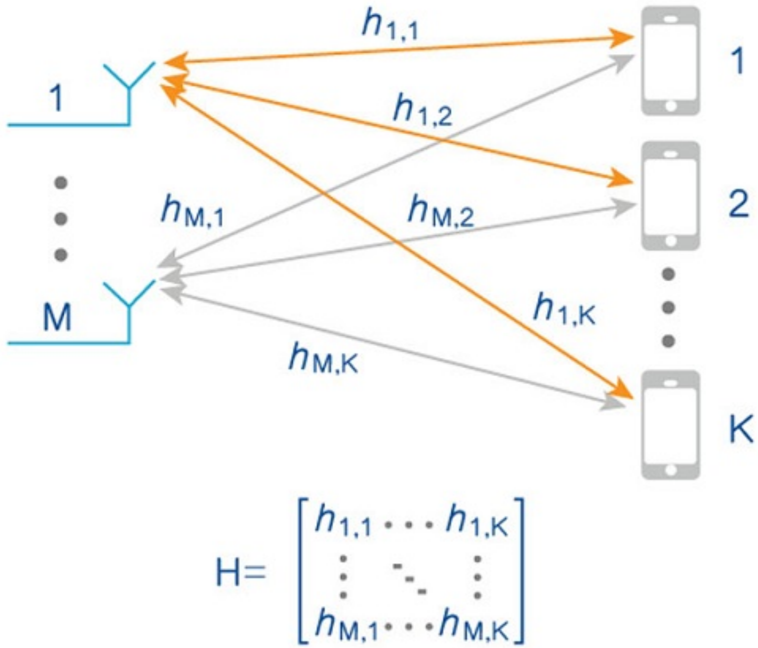
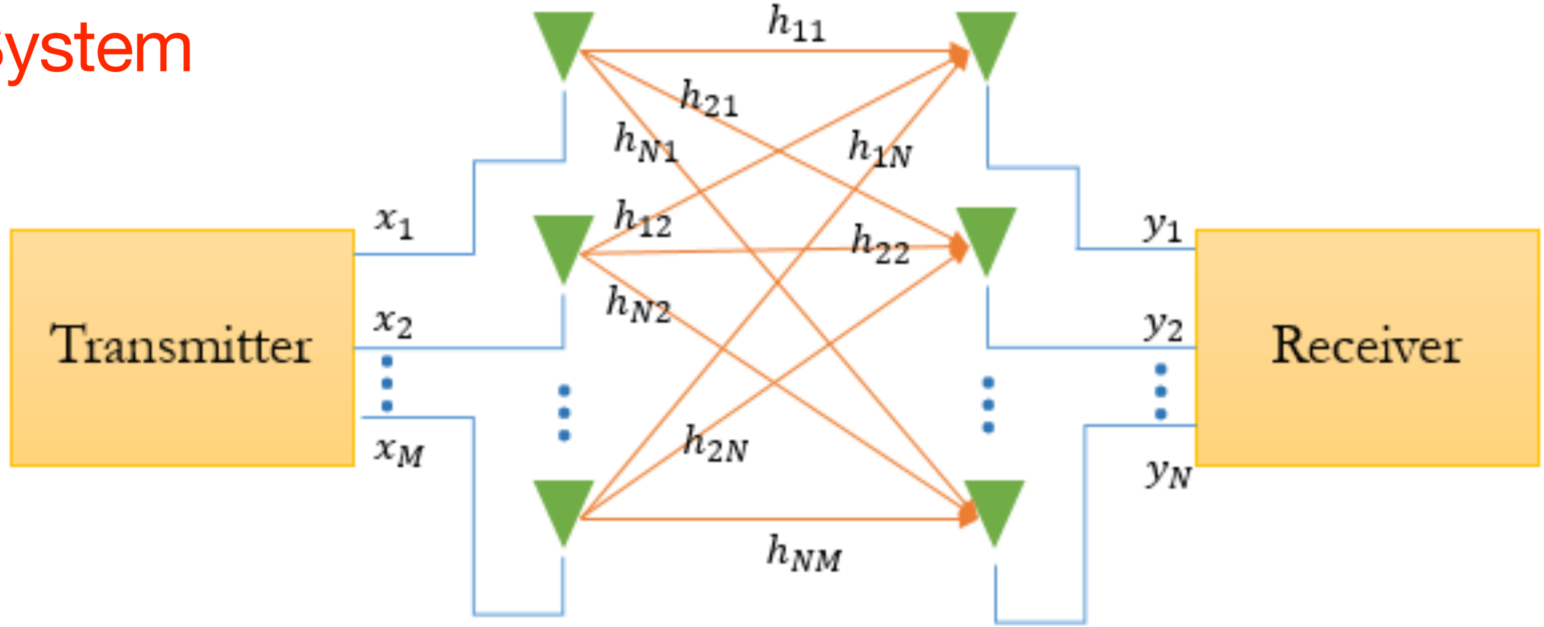
MIMO

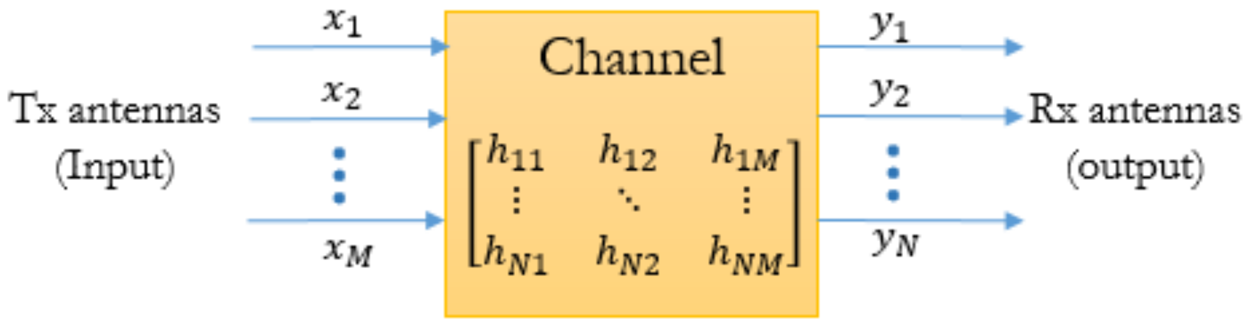
- MIMO terminology refers to the channel
    - Transmitter (T_x) is the channel input (I)
    - Receiver (R_x) is the channel output (O)





MIMO System

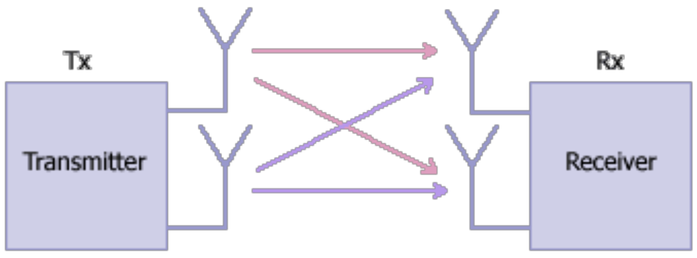




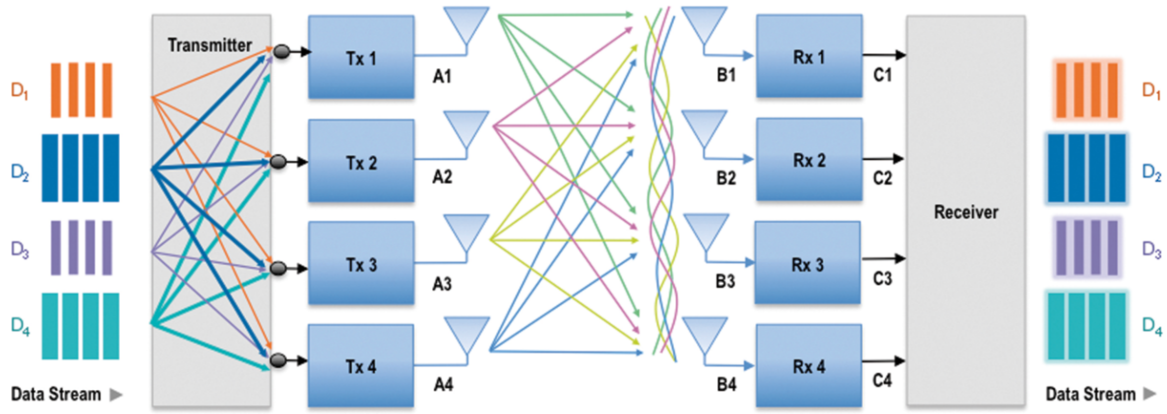
MIMO from channel perspective

Massive Antenna

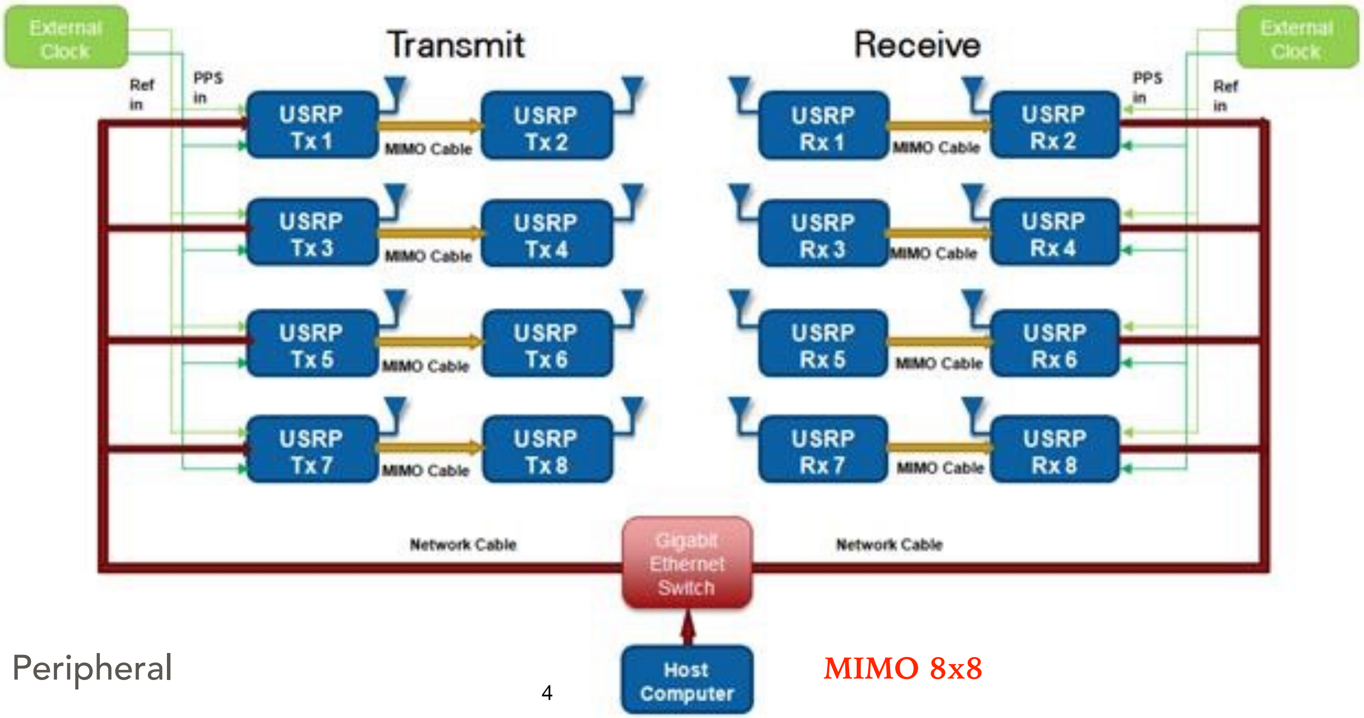
MIMO



MIMO 2x2



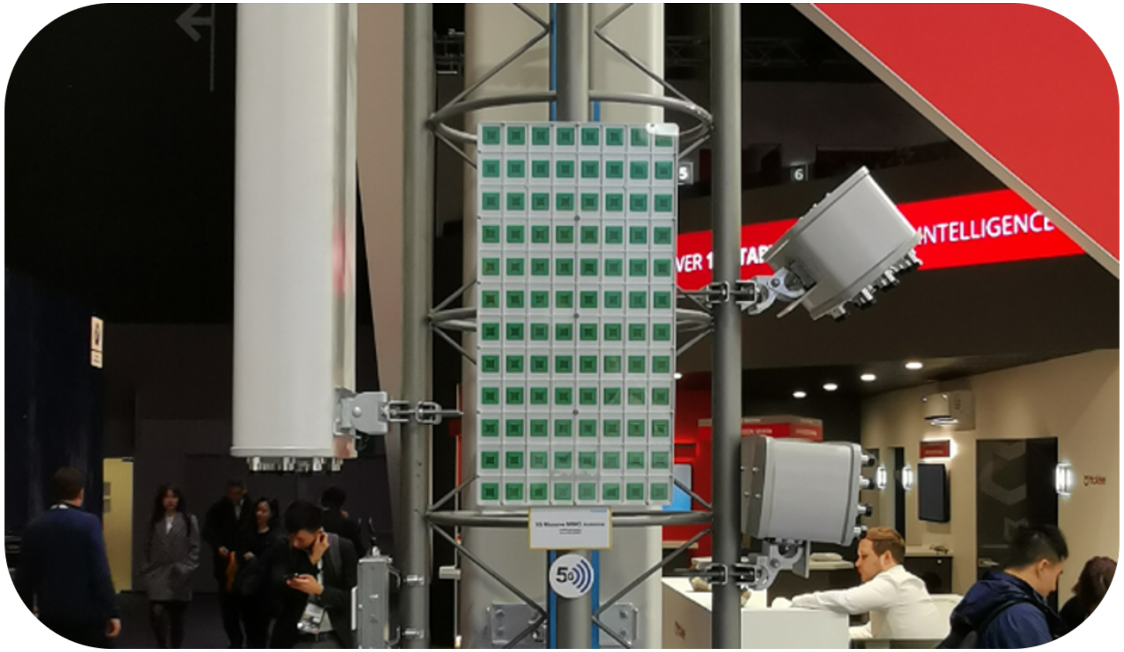
MIMO 4x4



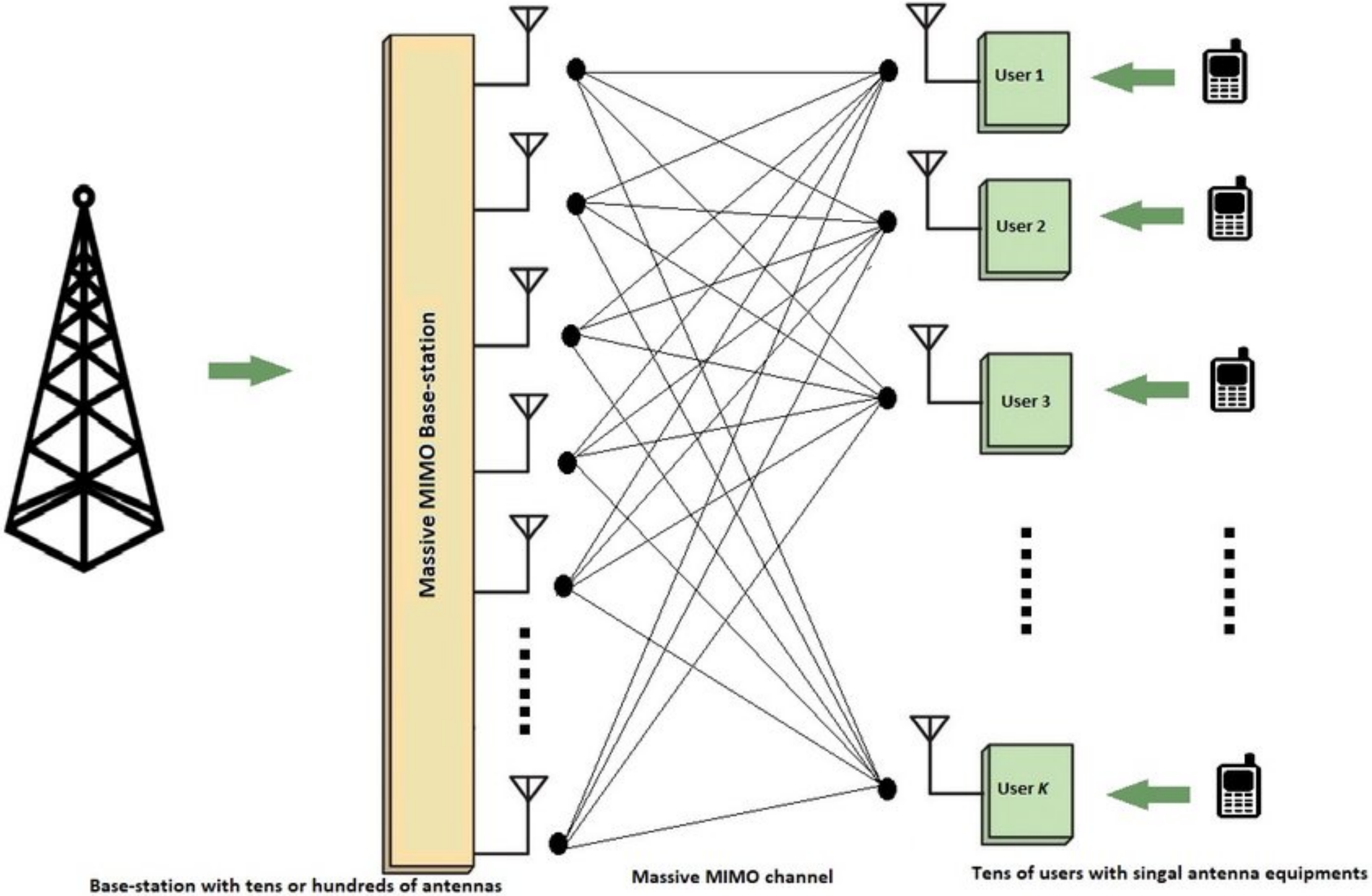
USRP: Universal Software Radio Peripheral

MIMO 8x8

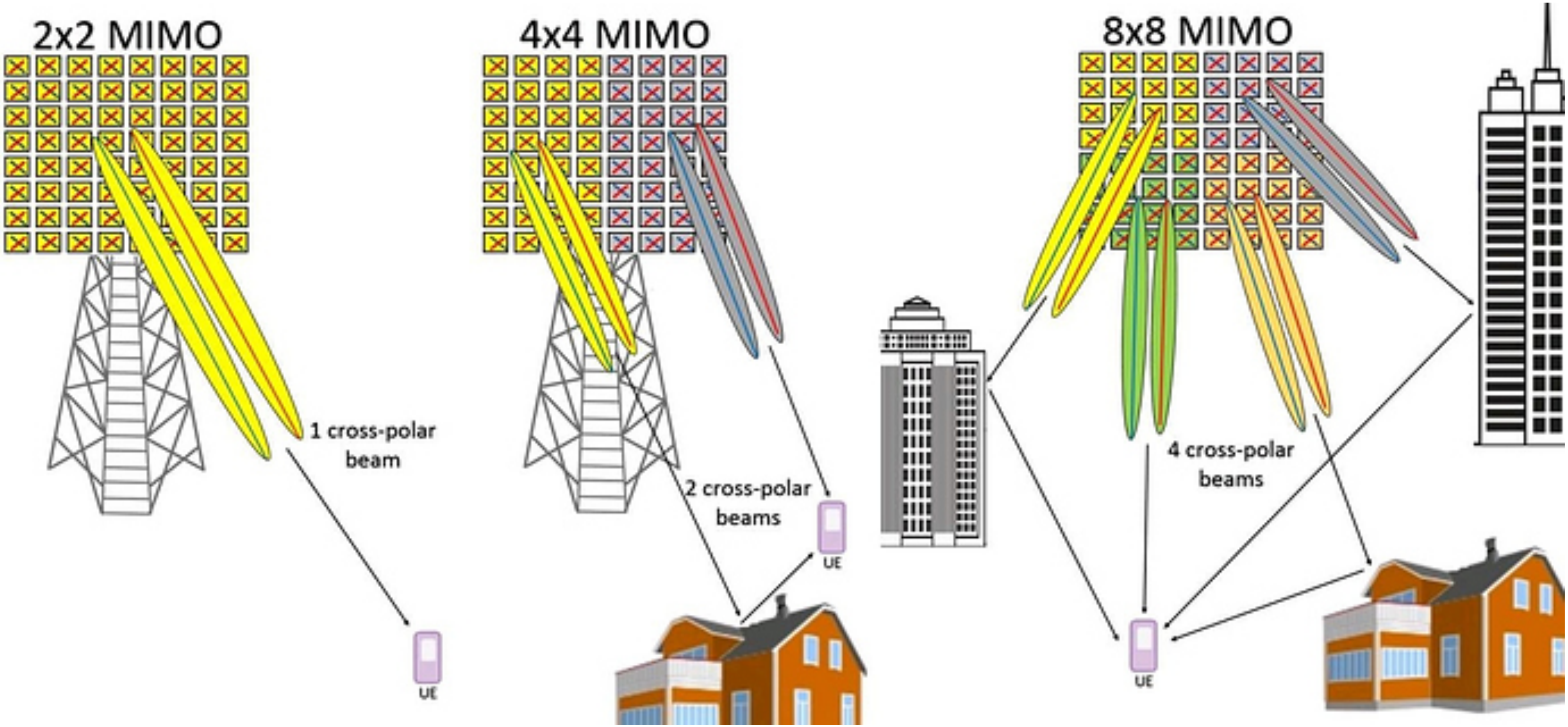
5G Massive MIMO



Massive MiMO Architecture

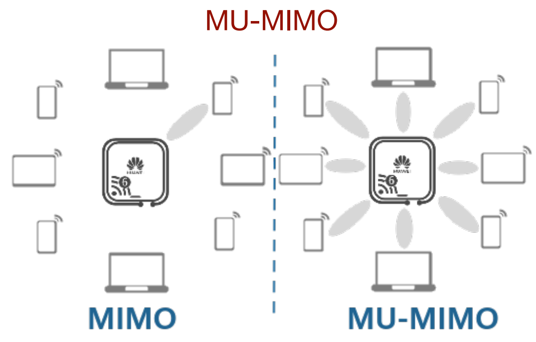


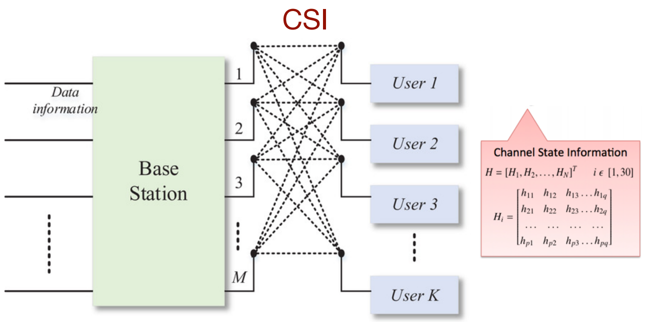
NR MIMO

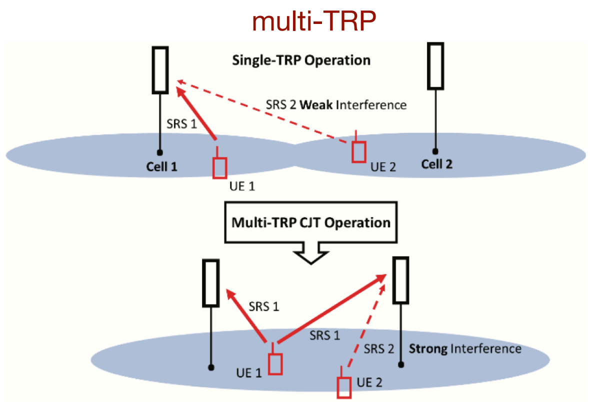


2x2 MIMO
1 cross-polar beam
UE
4x4 MIMO
2 cross-polar beams
UE
8x8 MIMO
4 cross-polar beams
UE

- **NR MIMO features**
  - High-resolution CSI (Channel State Information) for efficient MU-MIMO operation
  - Beam management for enabling mmWave communications
  - Support for multi-TRP (Multiple Transmission and Reception Point) transmissions

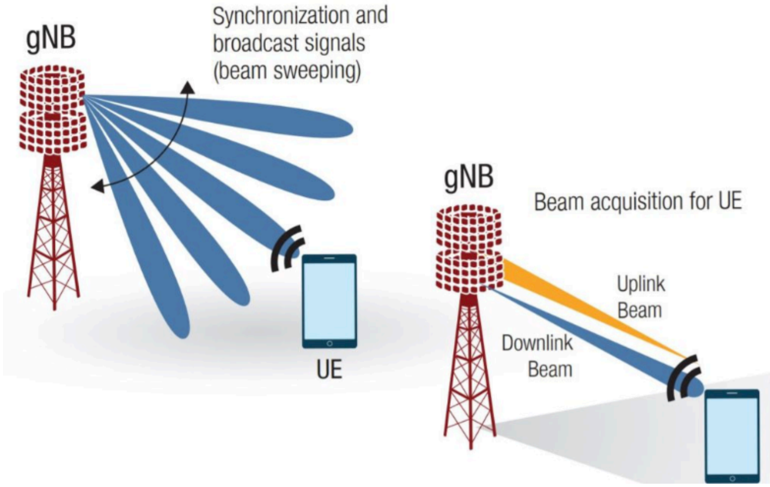




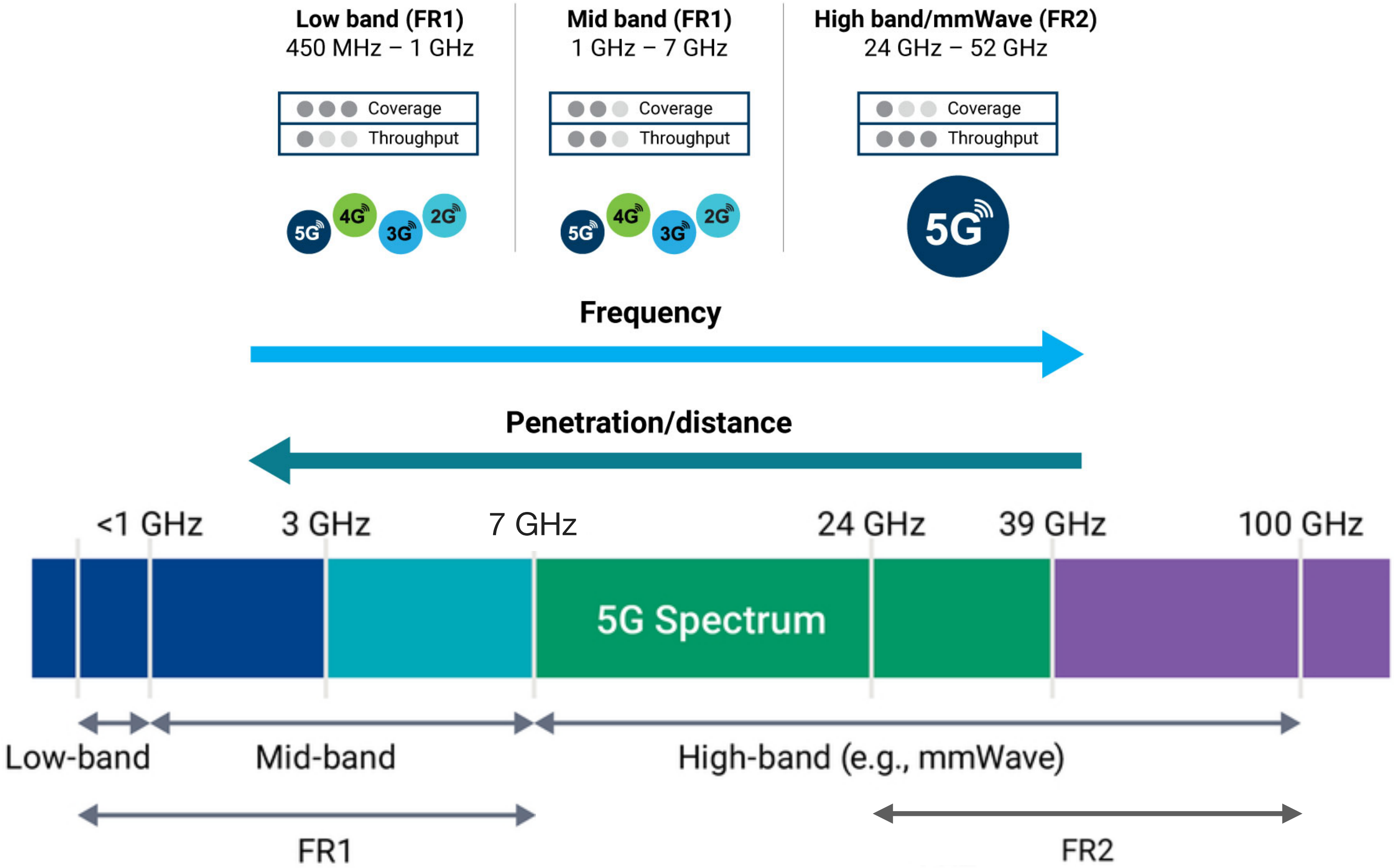


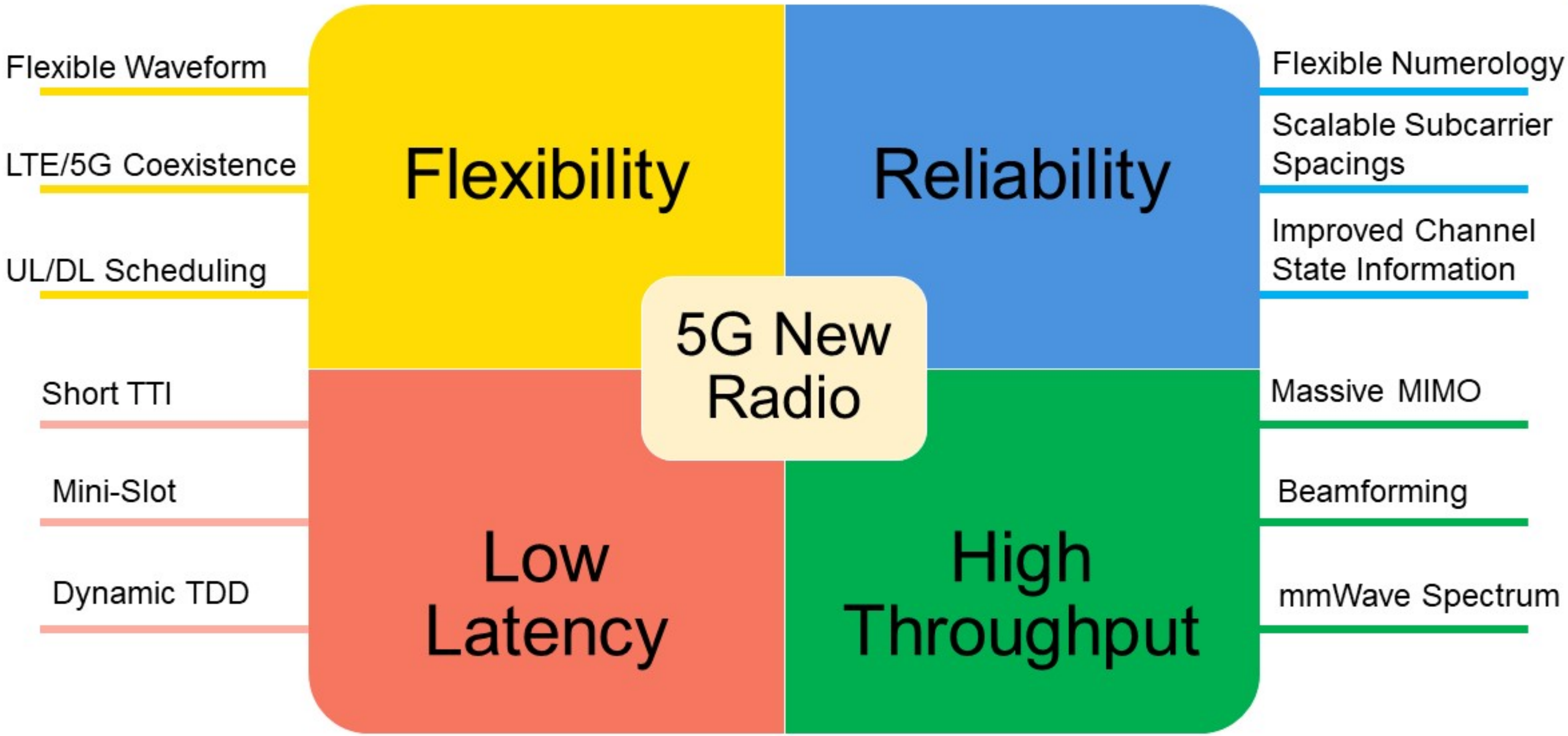
- Enabling energy-efficient transmission and reliable channel measurement
- Enabling new use cases and commercial deployment scenarios such as lower and higher frequency bands, non-terrestrial networks, and industrial Internet of Things (IIoT)
- Extension of beam management for enhancing inter-cell user mobility

- **Beam tracking**
  - Uses vehicle locations and channel quality indicators as features to predict beam power
  - Deep learning model for predicting beamforming vectors directly from signals received



5G-New Radio (NR)



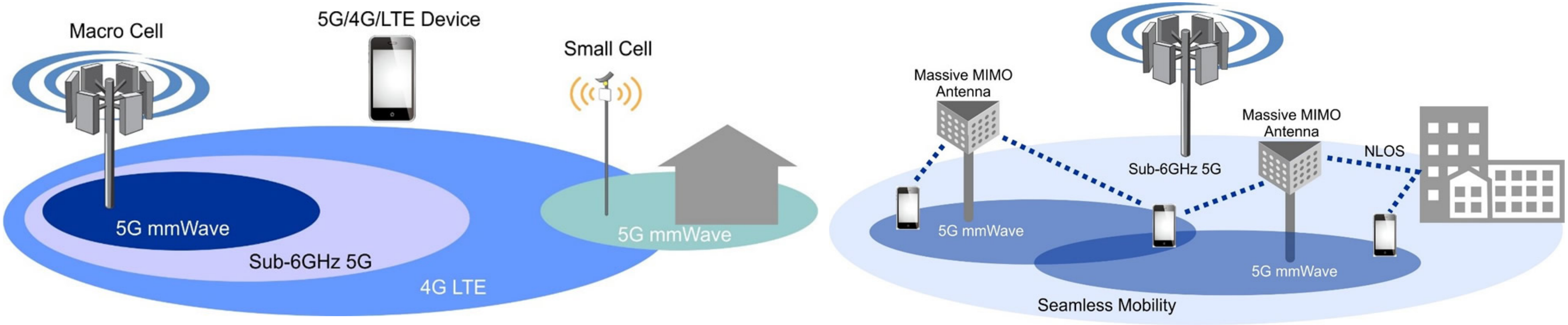


TTI：Transmission Time Interval

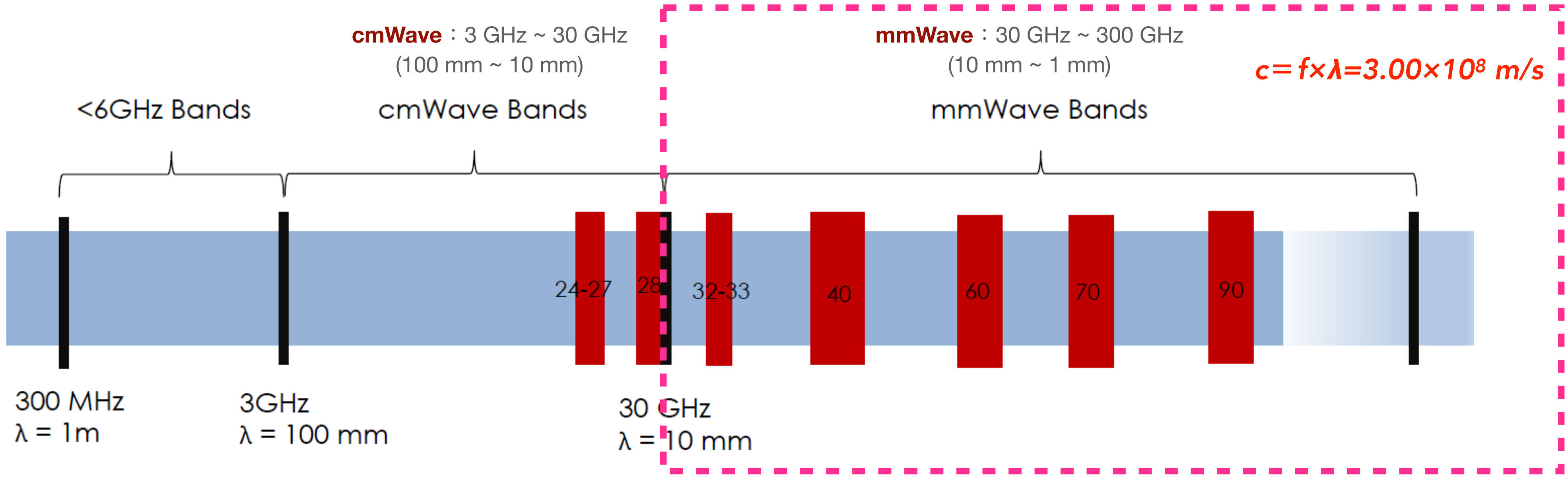
Millimeter Waves (mmWave)

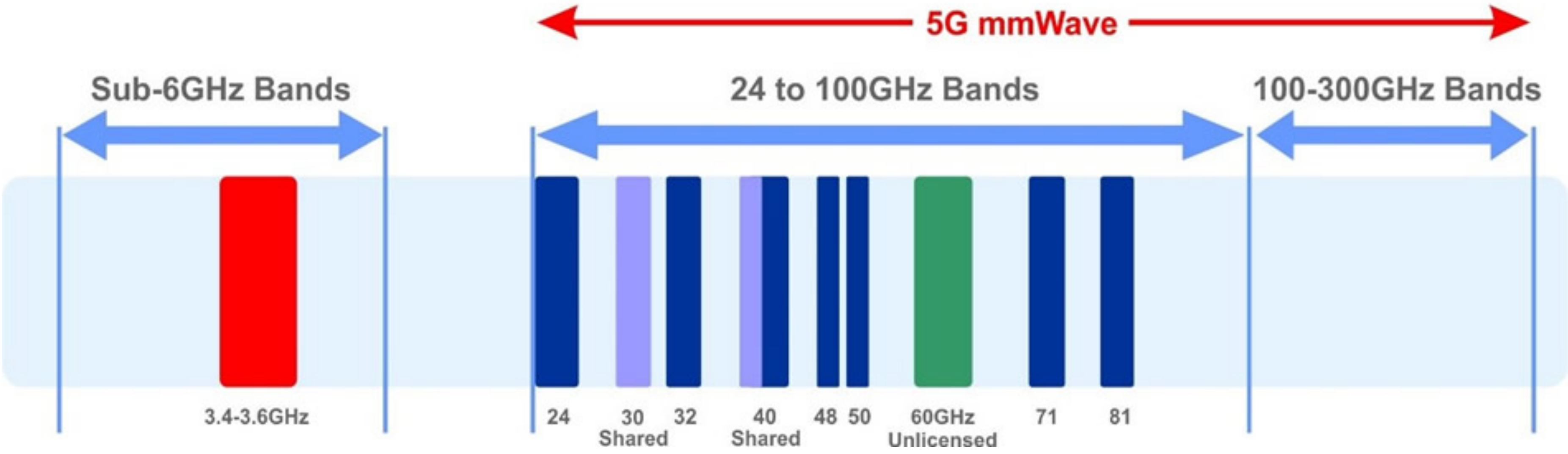
$c = f \times \lambda = 3.00 \times 10^8$ m/s
mmWave：30 GHz ~ 300 GHz
(10 mm ~ 1 mm)

- Have a <u>short wavelength</u>, possible to pack a large no. of <u>antenna</u> elements into a small area
- Help realize **massive MIMO** (Multiple Input Multiple Output) at both the base stations and user devices



https://www.accton.com/Technology-Brief/the-emergence-of-5g-mmwave/





https://www.accton.com/Technology-Brief/the-emergence-of-5g-mmwave/

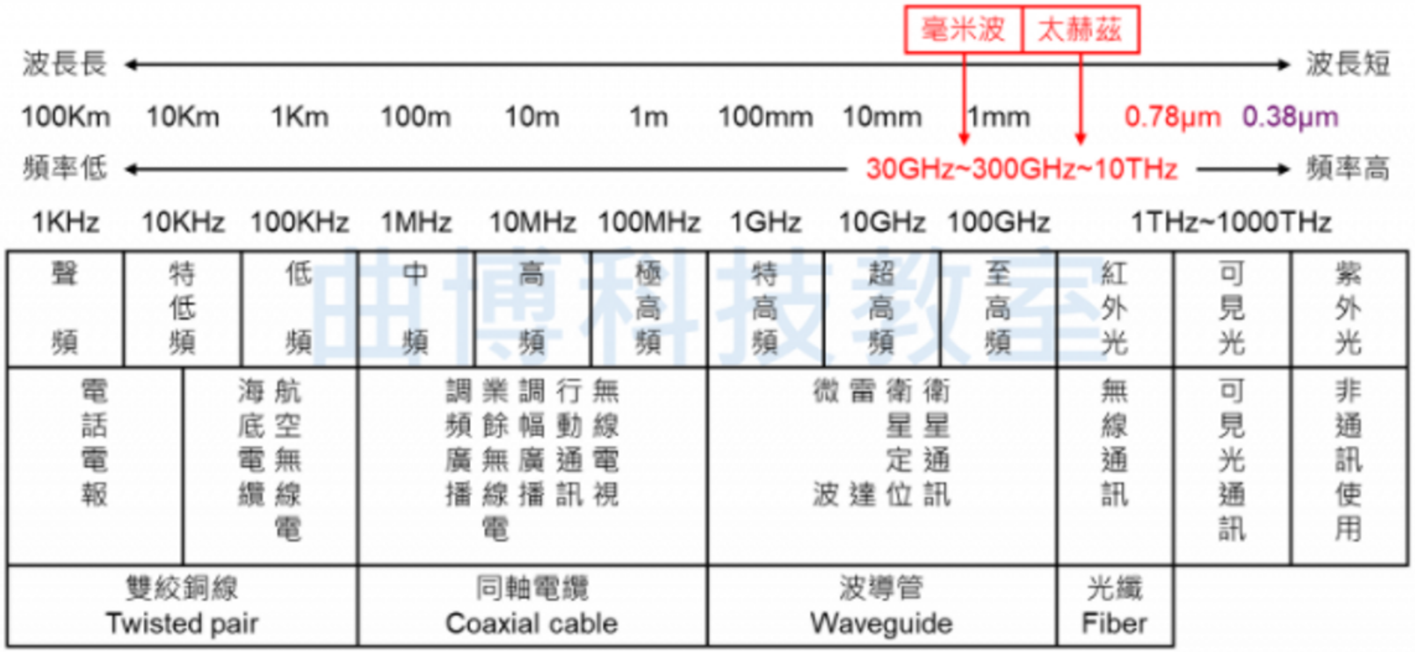
- **Shannon's Theorem**
  - Gives an upper bound to the capacity (***C***) of a link, in bits per second (bps), as a function of the available bandwidth (***B***) and the signal-to-noise ratio (***S/N***, ***SNR***) of the link

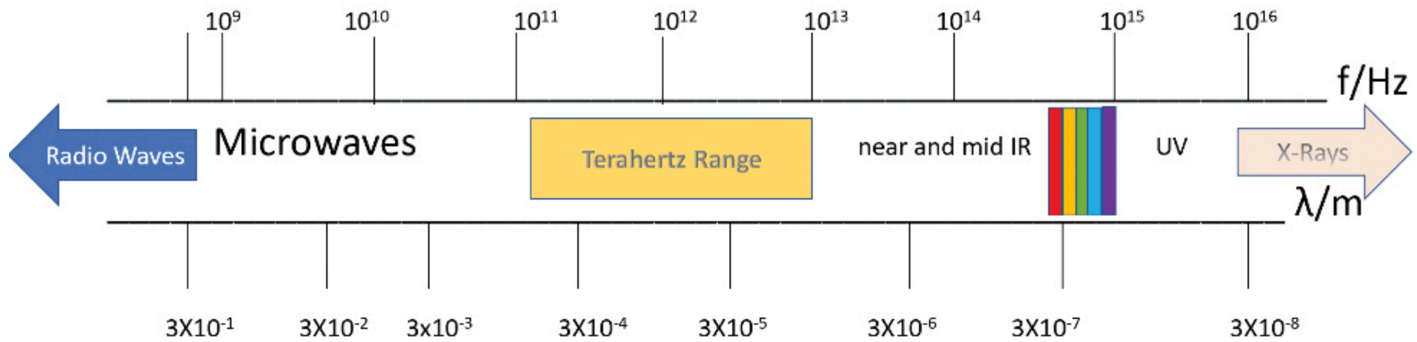
$$C = B * \log_2(1 + S/N)$$

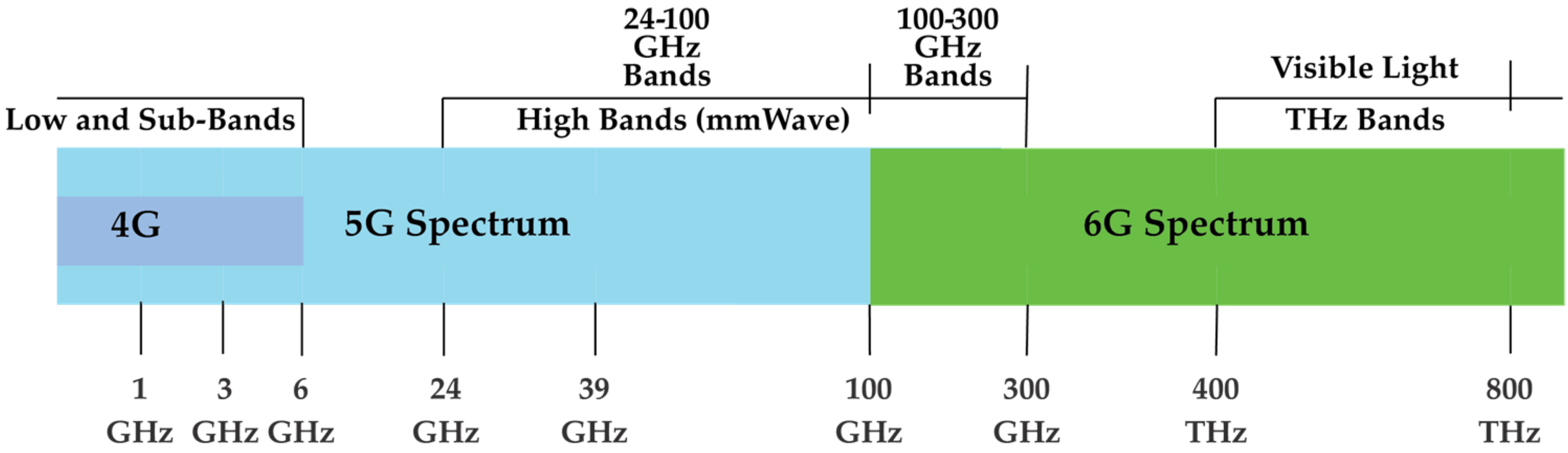
    - C: the achievable channel capacity (bps)
    - B: the bandwidth of the line (Hz)
    - S: the average signal power
    - N: the average noise power

Spectrum Bands for 5G & 6G

Terahertz
—spectrum: 0.3~3 THz,
— wavelentg: 1mm~0.1mm (or 100μm)

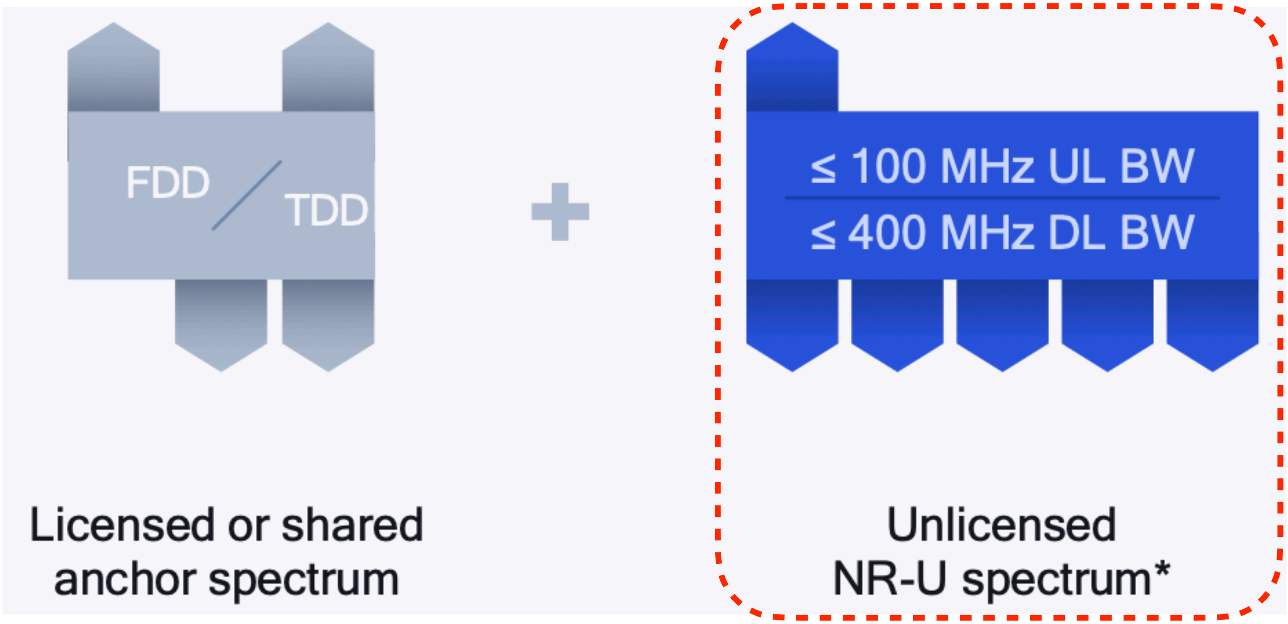




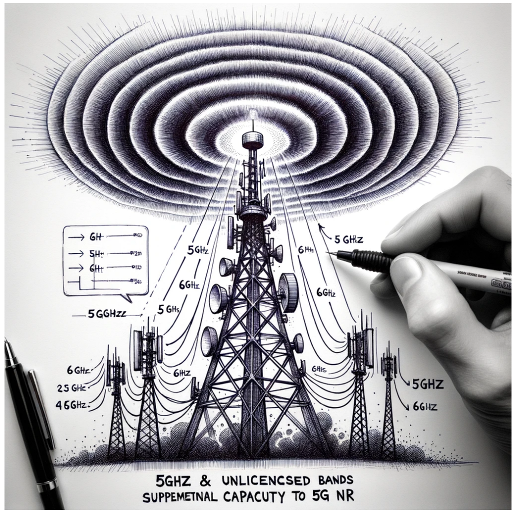

24-100 GHz Bands
100-300 GHz Bands
Visible Light
Low and Sub-Bands
High Bands (mmWave)
THz Bands
4G
5G Spectrum
6G Spectrum
1 GHz
3 GHz
6 GHz
24 GHz
39 GHz
100 GHz
300 GHz
400 THz
800 THz

NR Unlicensed (NR-U)

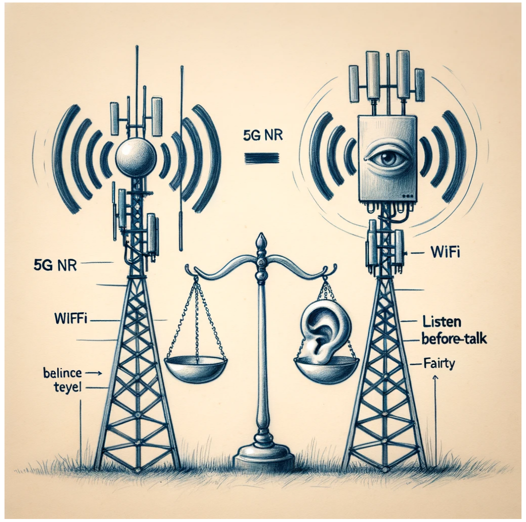
- Extend 5G ecosystem to unlicensed spectrum to provide supplemental capacity for various use cases while ensuring fair coexistence with other technologies



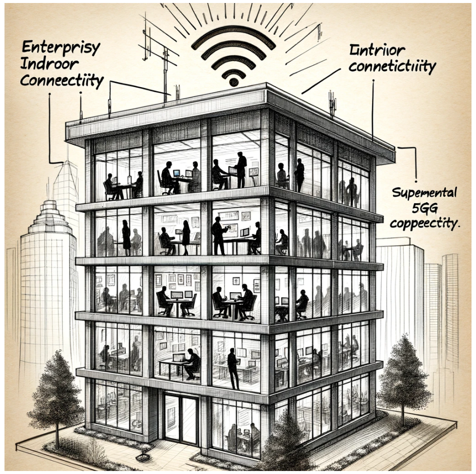
- **Spectrum bands**
  - Initial focus is on 5GHz and 6GHz <u>unlicensed</u> bands
  - Offer wide bandwidths for <u>supplemental capacity</u> to licensed 5G NR



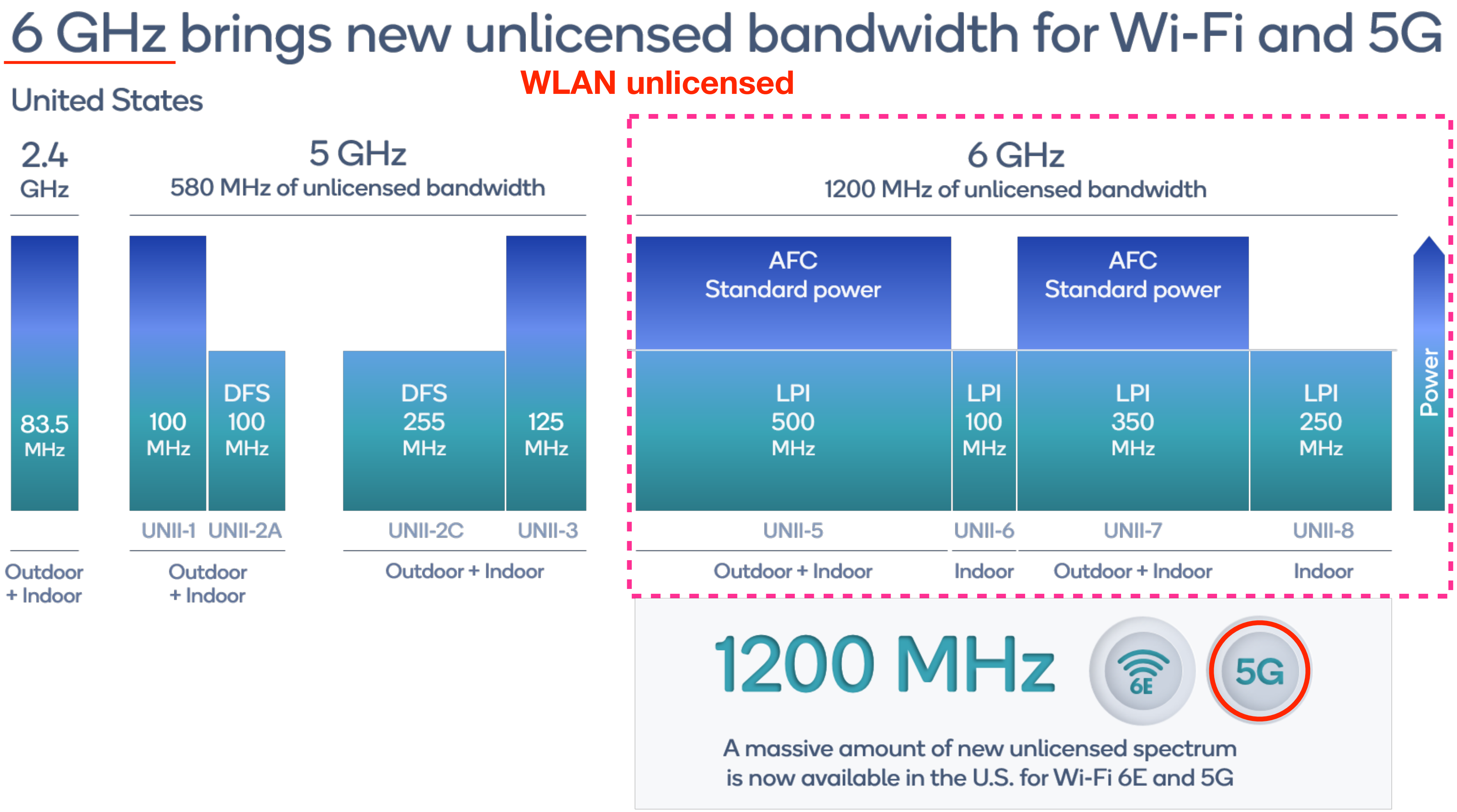
- **Coexistence**
  - Incorporate <u>listen-before-talk</u> (LBT) and <u>fairness</u> mechanisms for coexistence with WiFi and other technologies



- **Use cases**
  - Enterprise/indoor connectivity
  - Urban hotspots
  - Residential broadband etc.
- **Dual connectivity**
  - 5G devices can leverage both licensed and unlicensed spectrum simultaneously through dual connectivity to licensed anchor bands



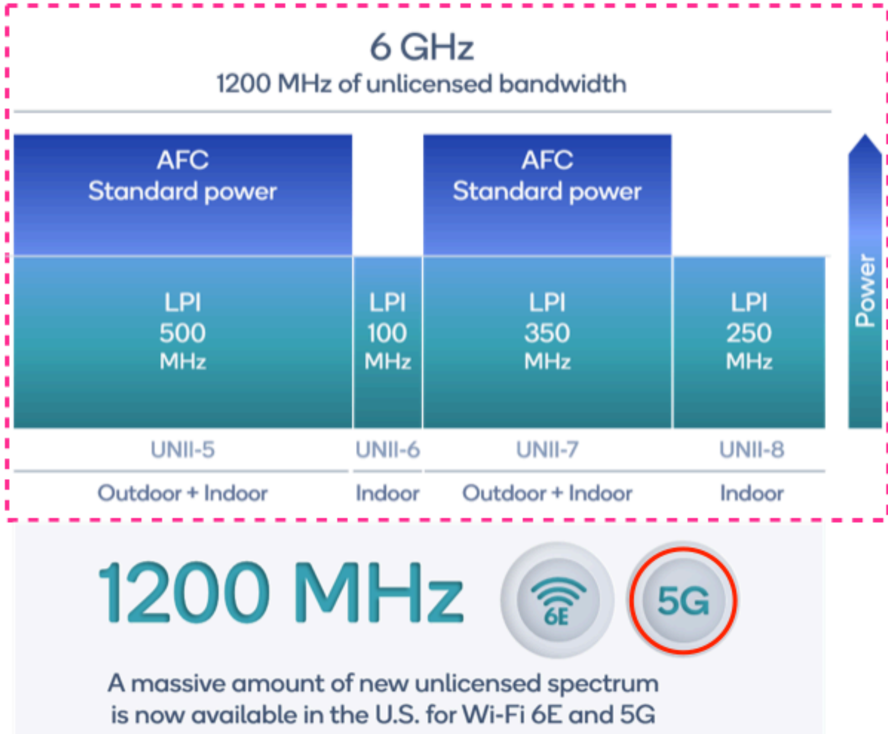
WLAN Unlicensed Spectrum Use



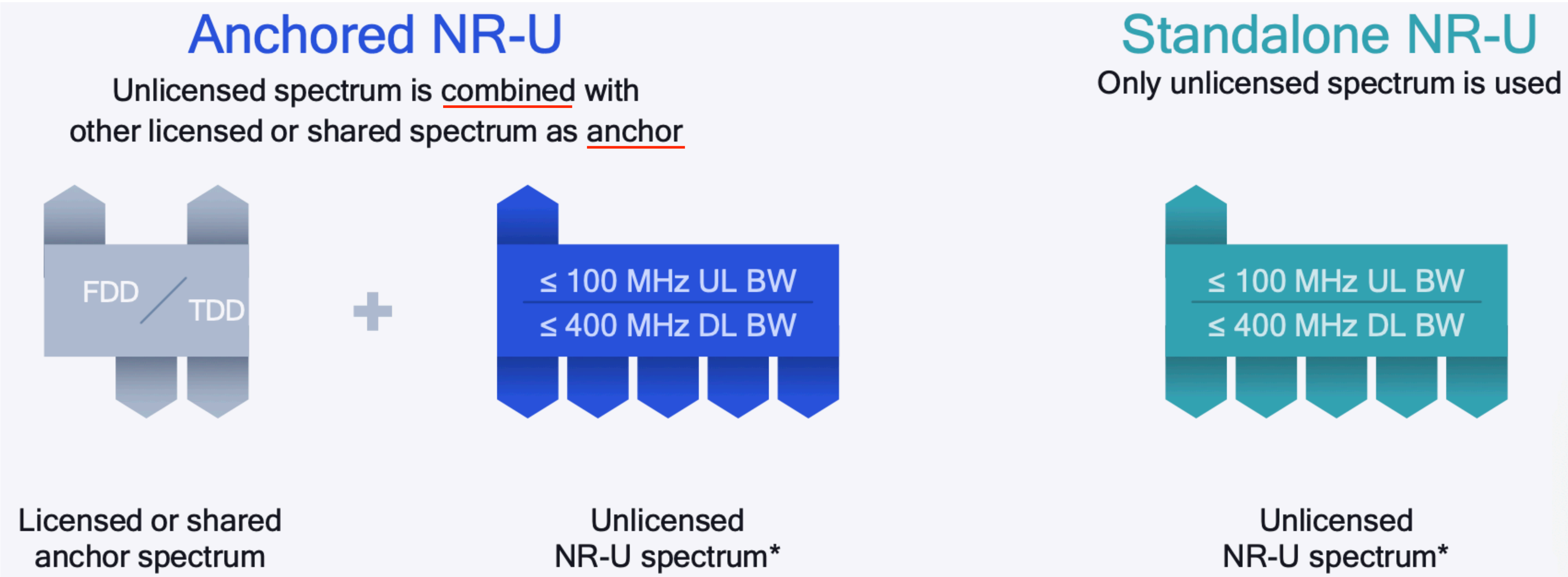
AFC= Automated frequency control, DFS= Dynamic Frequency Selection, LPI= Low power indoor

WFi 6E: WiFi 6 Extended to 6GHz

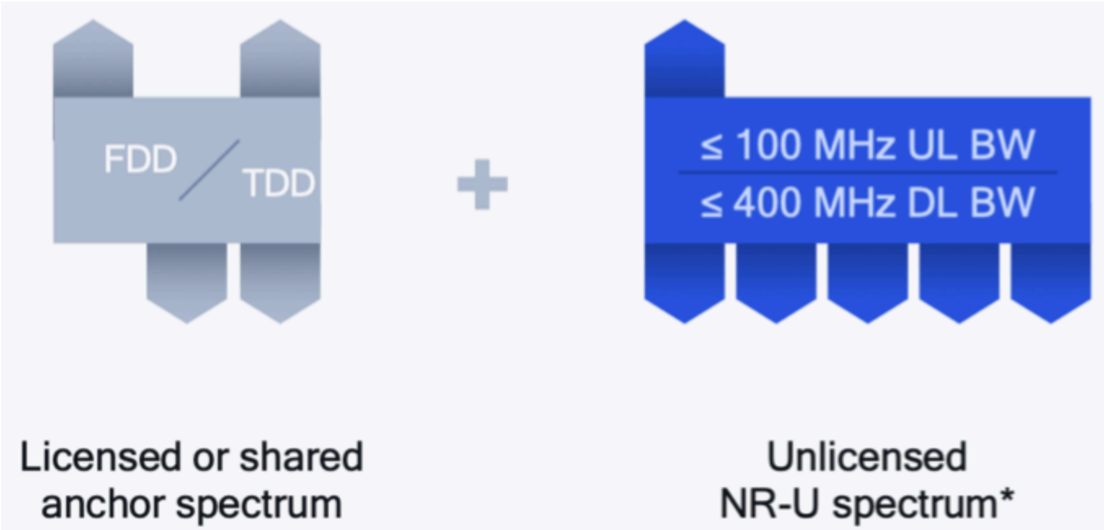
- The 6 GHz band has up to 1200 MHz of spectrum and can be opened up for unlicensed use under WiFi 6E and 5G NR-U standards
- For **WiFi 6E**, wider 160 MHz channels in 6 GHz allows multi-gigabit speeds while retaining backward compatibility with WiFi 5/6
- For **5G NR-U**, 6 GHz will be a key band for supplemental capacity aggregated with licensed anchor bands



NR in Unlicensed Band (NR-U)

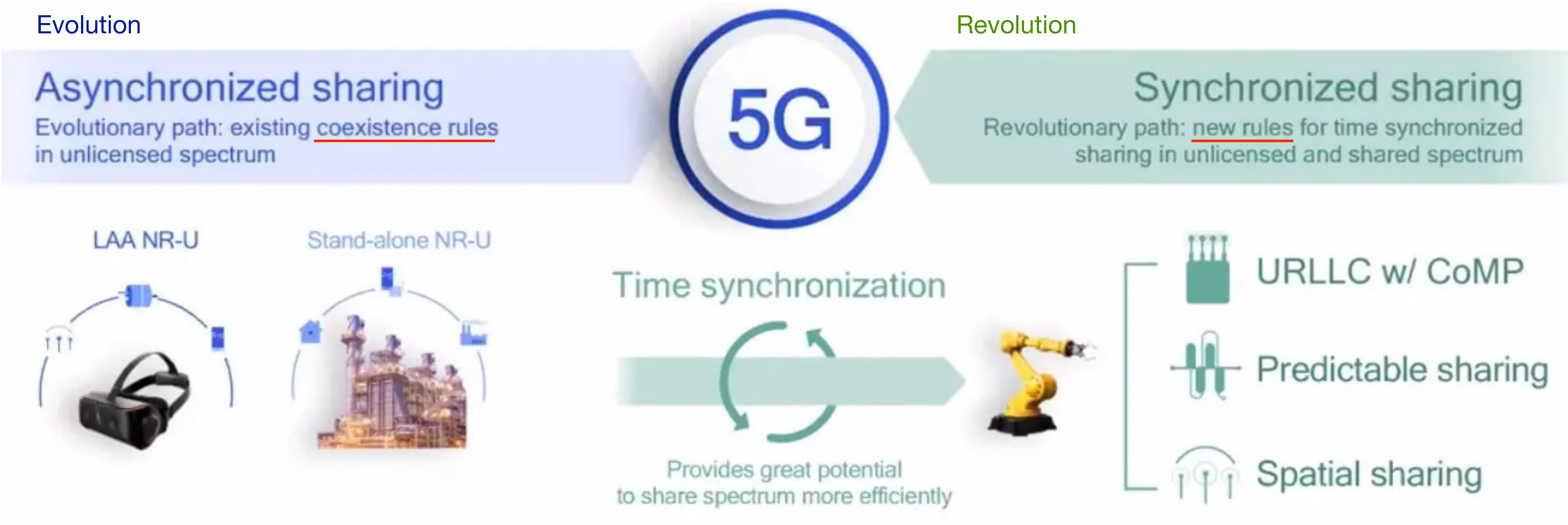


- **Anchored NR-U**
  - Rely on a licensed spectrum for control and signaling
  - Enhances overall system performance by leveraging unlicensed spectrum for data transmission
  - Connection stability is maintained by the licensed anchor carrier



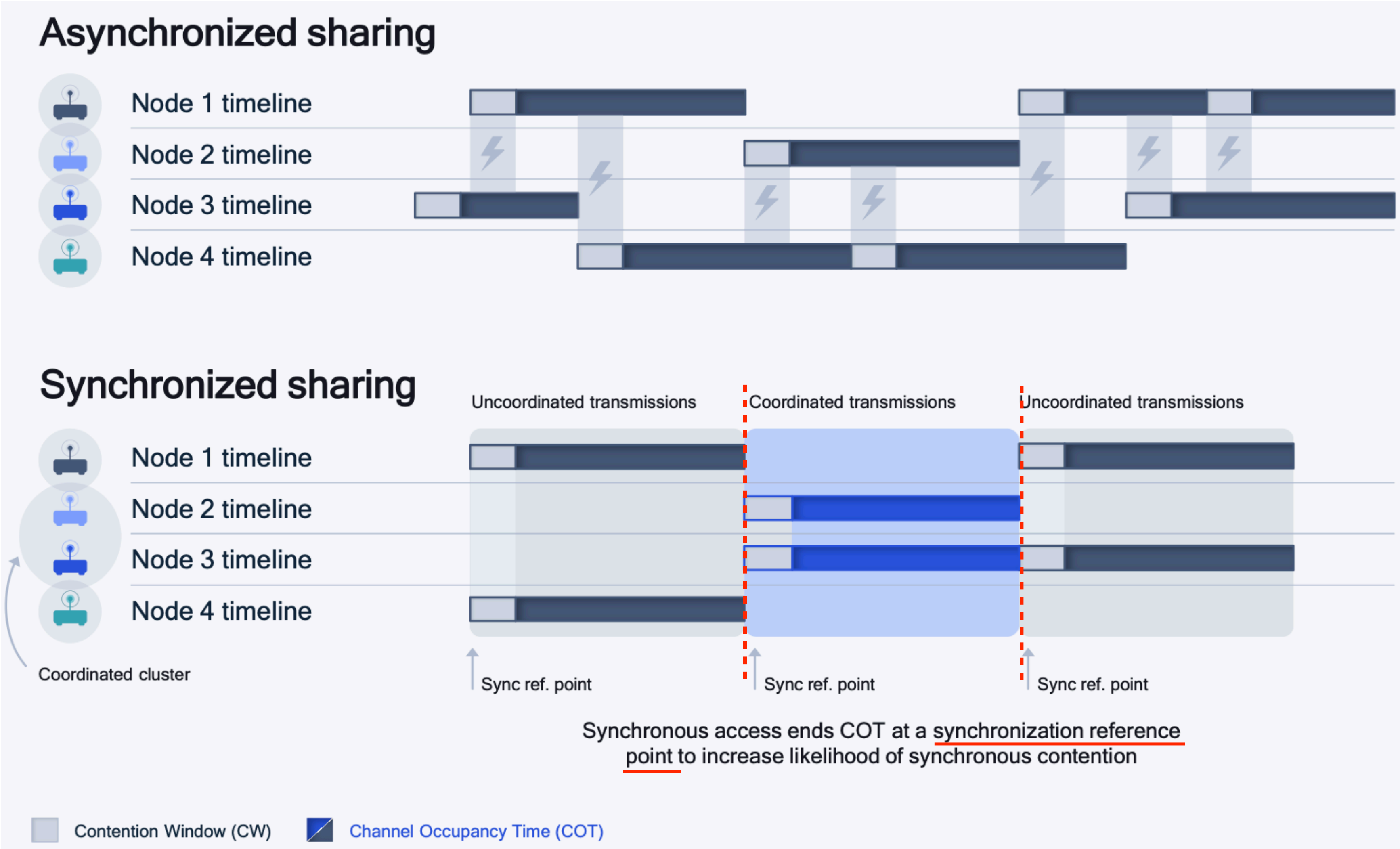
- **Standalone NR-U**
  - Operate solely in unlicensed bands
  - Both control signaling and data transmissions are managed in the unlicensed spectrum
  - Suitable for deployments in areas without licensed spectrum availability

NR-U Async. Vs. Synch.

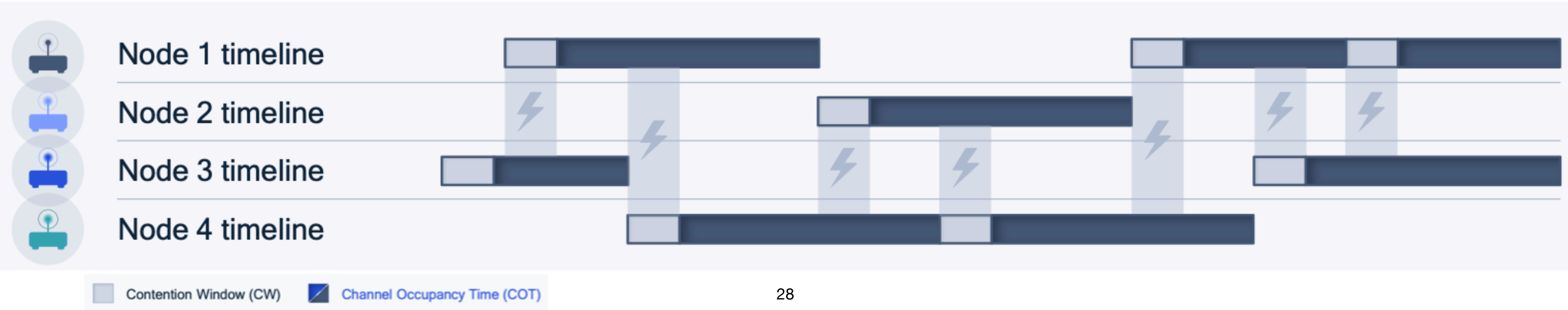


LAA：License-Assisted Access

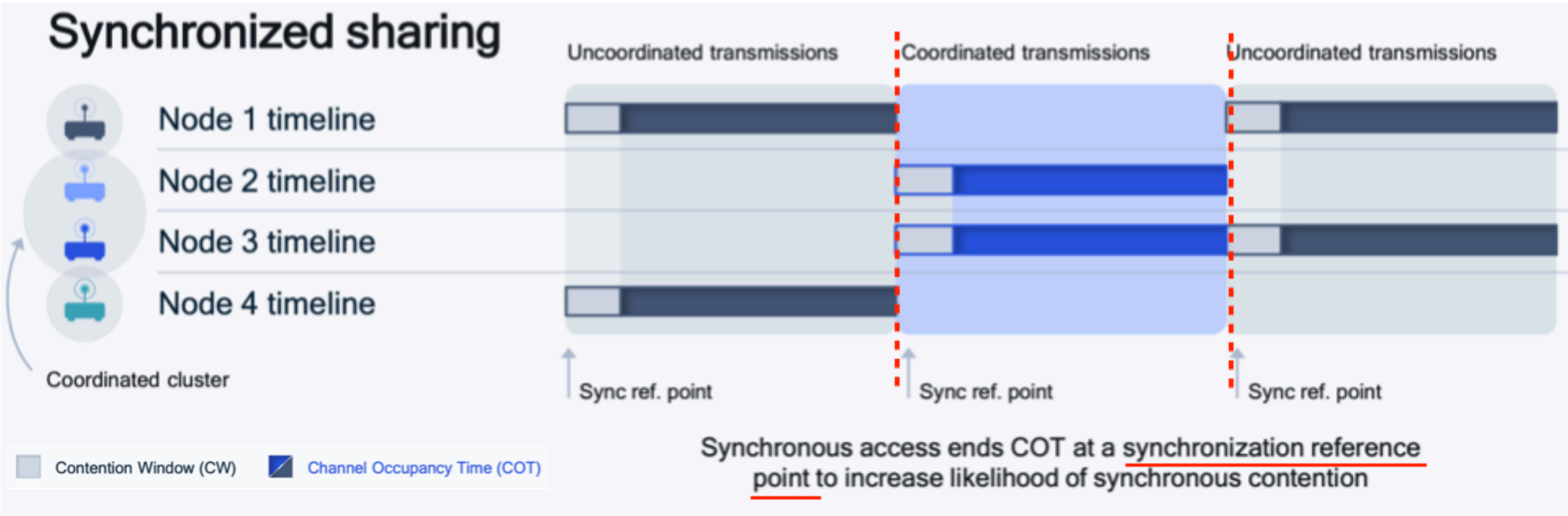
NR-U Synchronized Sharing brings Higher Performance



- **Asynchronous NR-U** (Evolution)
    - Does <u>not synchronize</u> its timing with the timing of <u>licensed</u> 5G networks
    - Asynchronous NR-U devices can transmit and receive data at <u>any time</u>, without having to wait for a synchronization signal
    - Examples: LAA NR-U, stand-alone NR-U

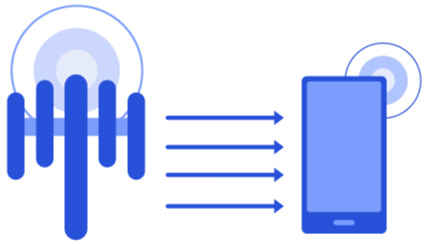


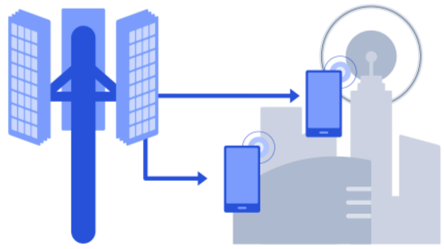
- **Synchronous NR-U** (Revolution)
  - <u>Synchronizes</u> its timing with the timing of <u>licensed</u> 5G networks
  - Synchronous NR-U devices can only transmit and receive data at <u>specific times</u>, which are aligned with the timing of the licensed 5G networks
  - Examples: URLLC w/ CoMP, predictable sharing, spatial sharing

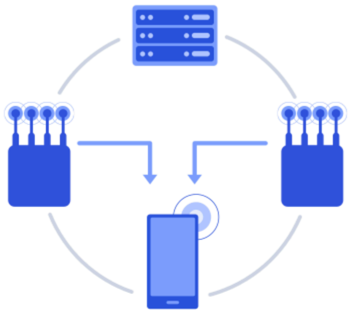


Characteristic	Asynchronous NR-U	Synchronous NR-U
Synchronization	Not synchronized with licensed 5G networks	Synchronized with licensed 5G networks
Timing	Transmits and receives data at any time	Transmits and receives data at specific times, aligned with the timing of licensed 5G networks
Performance	Can achieve higher performance than synchronous NR-U	Can achieve lower latency than asynchronous NR-U
Complexity	More complex to deploy and manage than synchronous NR-U	Less complex to deploy and manage than asynchronous NR-U
Ecosystem	Supported by a narrower range of devices and infrastructure than synchronous NR-U	Supported by a wider range of devices and infrastructure than asynchronous NR-U

Coordinated Multi-Point (CoMP)







LTE MIMO

2 Gbps peak-rates with 4x4 MIMO[1], carrier aggregation and higher order modulation

Example: 2 or 4 antennas for transmit and receive

5G Massive MIMO

Multi-user MIMO and 3D beamforming for better capacity and cell edge performance

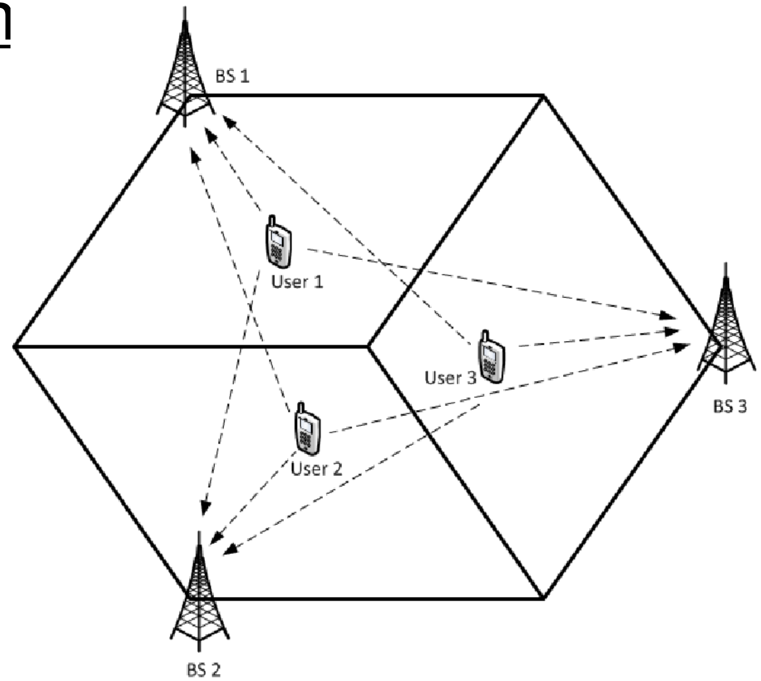
Example: 128 or 256 antenna elements for macro deployments

5G CoMP

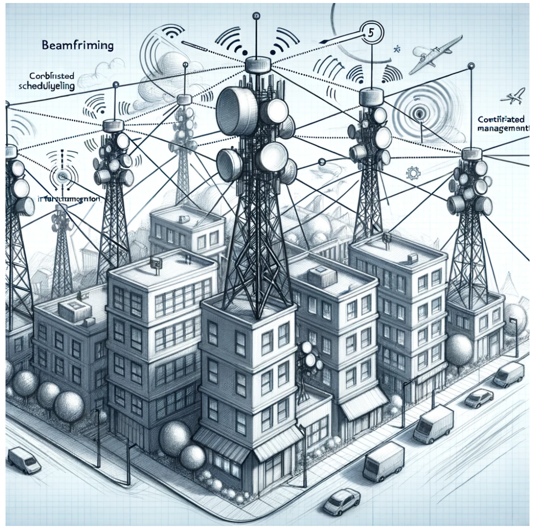
Leveraging CoMP[2] diversity and multiplexing to extend 5G to new use cases and verticals

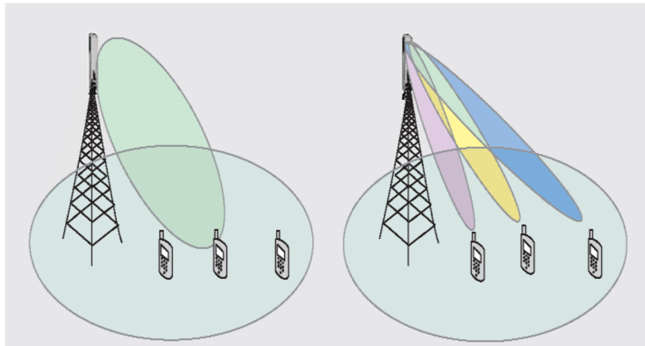
Example: Multiple small-cells with 4 antennas

- CoMP is used in cellular networks to improve coverage, throughput, and system capacity by coordinating transmissions across multiple geographically separated BSs
  - **Coordination between cells**: multiple geographically separated cells/BSs coordinate their transmission and reception dynamically based on channel conditions and UE location
  - **Joint processing**: data for a UE can be jointly processed and transmitted from multiple cells/points to improve received signal quality



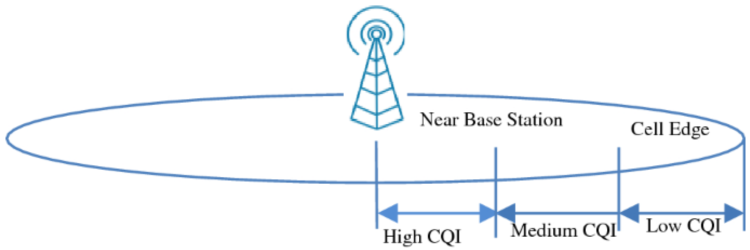
- **Interference management**: coordinated scheduling and beamforming to manage interference between coordinated cells
- **Additional throughput and coverage**: improve cell-edge performance and overall throughput
- **Faster handovers**: allow faster handovers and reduce signal drops



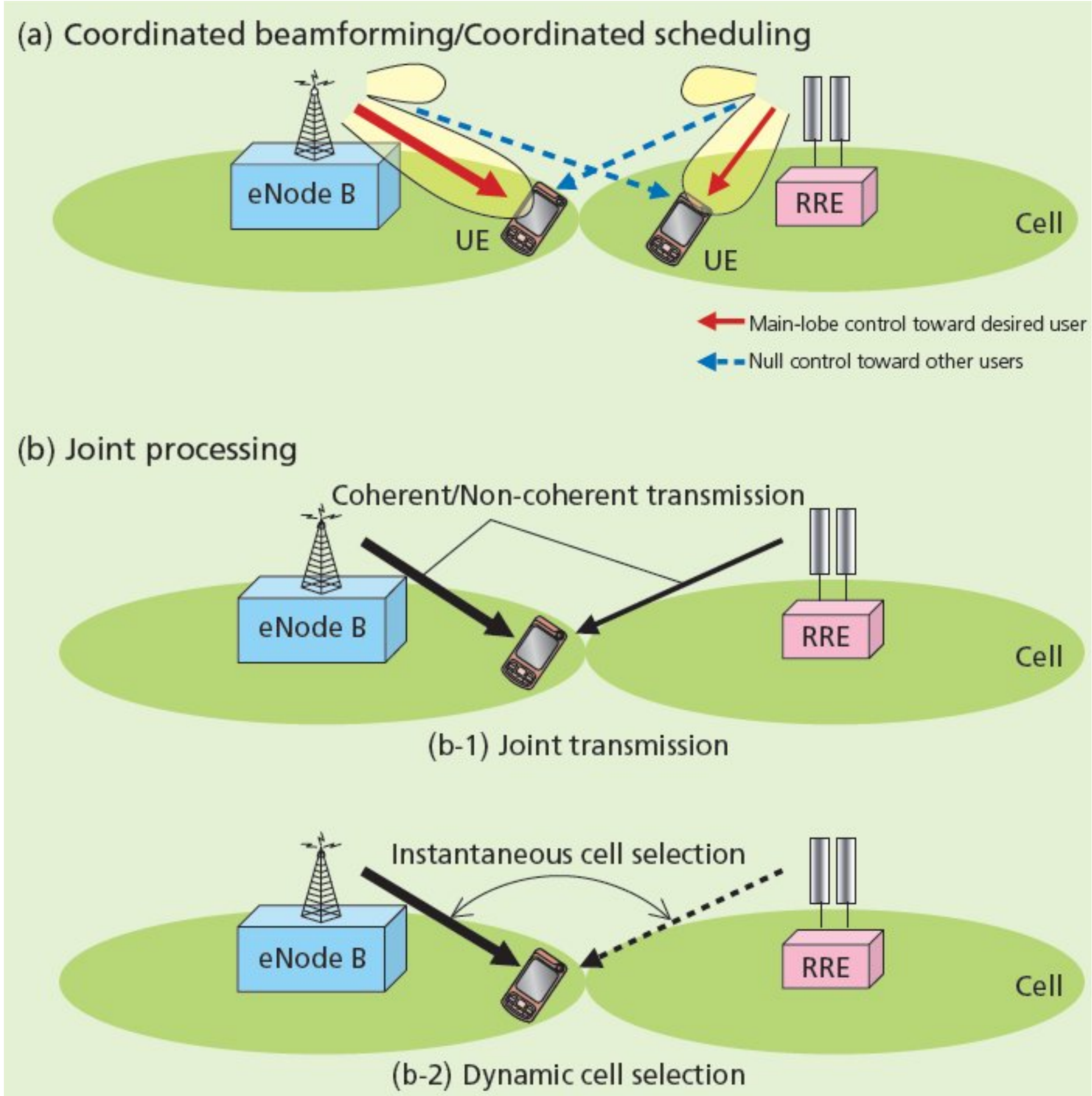


(a) 2D BF with fixed downtilt

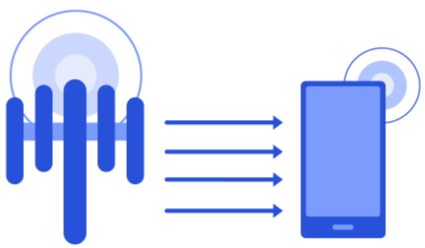
(b) 3D BF with dynamic downtilt



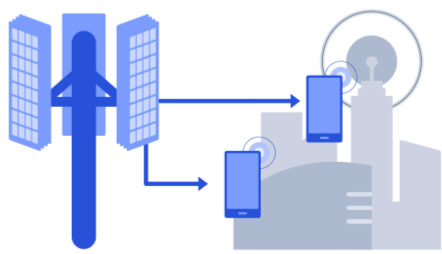
- **Implementation methods**:
  - Coordinated beamforming
  - Joint transmission
  - Dynamic cell selection
- **Support SU-MIMO and MU-MIMO**: applicable for both <u>single</u> and <u>multi</u>-user MIMO



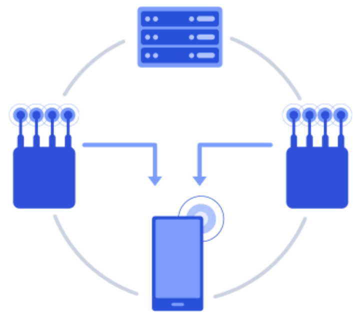
- MIMO
  - LTE MIMO provides basic multi-antenna capabilities
  - 5G Massive MIMO scales up the arrays for higher beamforming gains
  - 5G CoMP enables advanced coordination across cellsites for better coverage and throughput



LTE MIMO

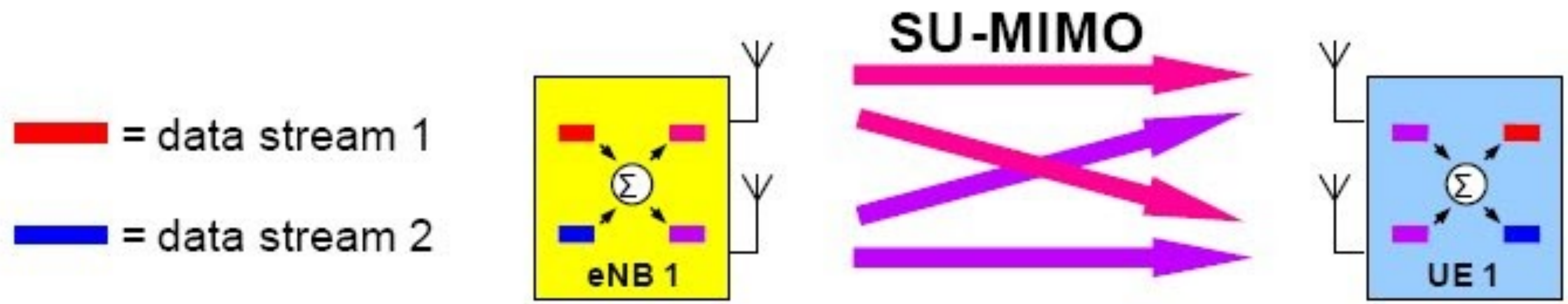


5G Massive MIMO

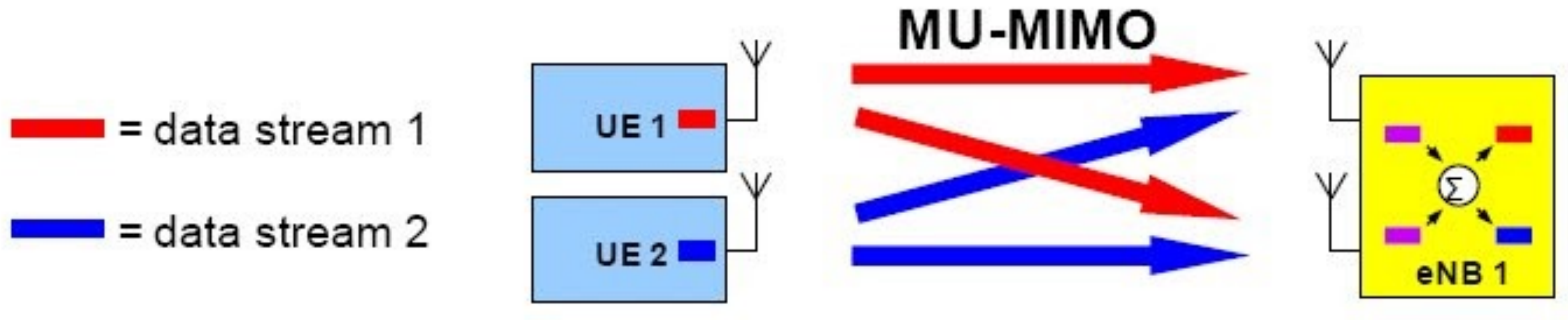


5G CoMP

- **LTE MIMO**
  - Support up to 8 transmit and receive antenna ports
  - Used for SU-MIMO (single user MIMO)
  - Improve peak data rates and spectral efficiency
  - Limited antenna ports restricts beamforming gains
  - 2 Gbps peak-rates with 4x4 MIMO, carrier aggregation and higher order modulation

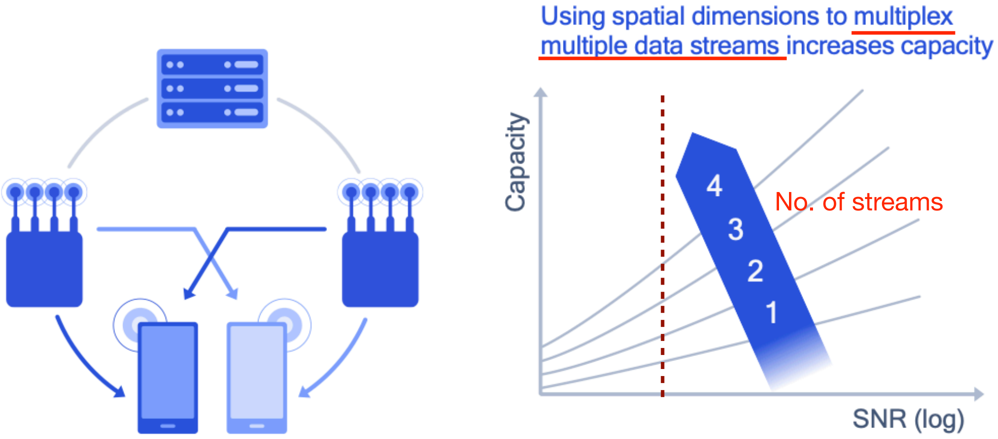


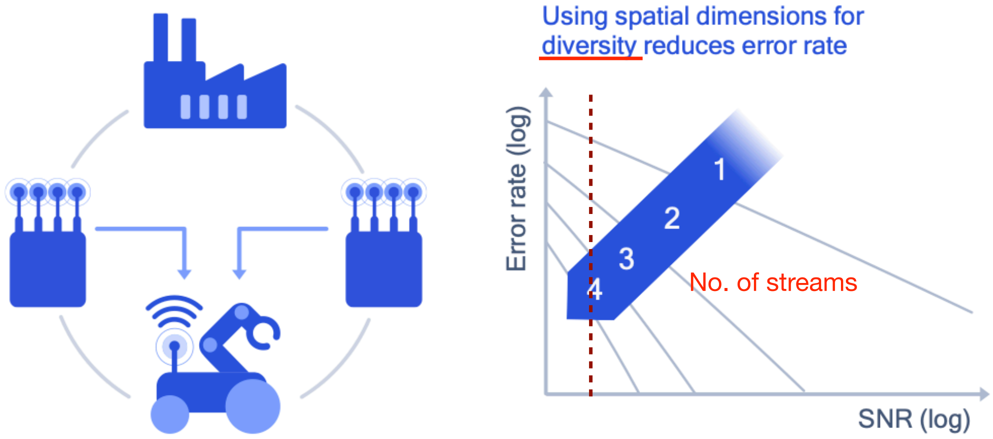
- **5G Massive MIMO**
  - Use hundreds of antenna elements (64-256 typically)
  - Achieve high beamforming gains through large antenna array
  - MU-MIMO (multi-user MIMO) and 3D beamforming for better capacity and cell edge performance
  - Significantly improve spectral efficiency and capacity



- **5G CoMP**
  - Coordination between multiple geographically separated cellsites
  - Joint transmission from multiple cells to improve signal quality
  - Interference management through coordinated scheduling and beamforming
  - Improves coverage, throughput, mobility compared to uncoordinated cells
  - Leverage CoMP diversity and multiplexing to extend 5G to new use cases and verticals
  - Example: Multiple small-cells with 4 antennas

CoMP Expands 5G: Capacity or Ultra-reliability Tradeoff





Capacity from spatial multiplexing

Allows multiple transmissions at the same time to multiple location without interfering

Can also be used to by multiple operators to share spectrum more efficiently

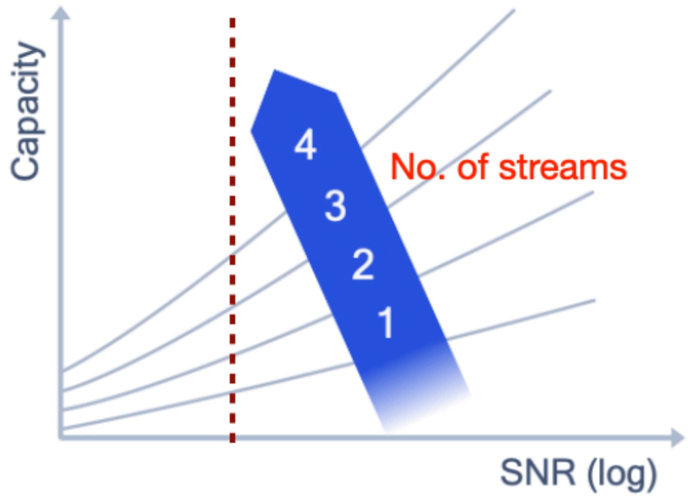
Reliability from spatial diversity

Spatial diversity can overcome radio shadowing in challenging radio environments

Key for URLLC to meet 99.9999% reliability and challenging industrial IoT applications

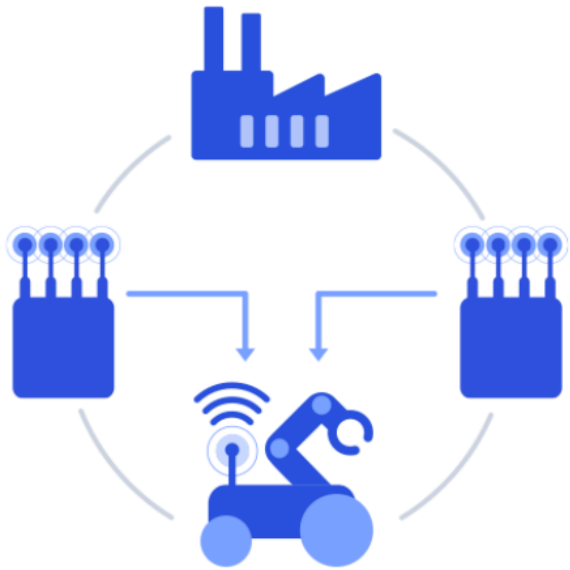
- **Capacity from spatial multiplexing** (increase capacity)
  - Allows multiple transmissions at the same time to multiple location without interfering
  - Can also be used by multiple operators to share spectrum more efficiently

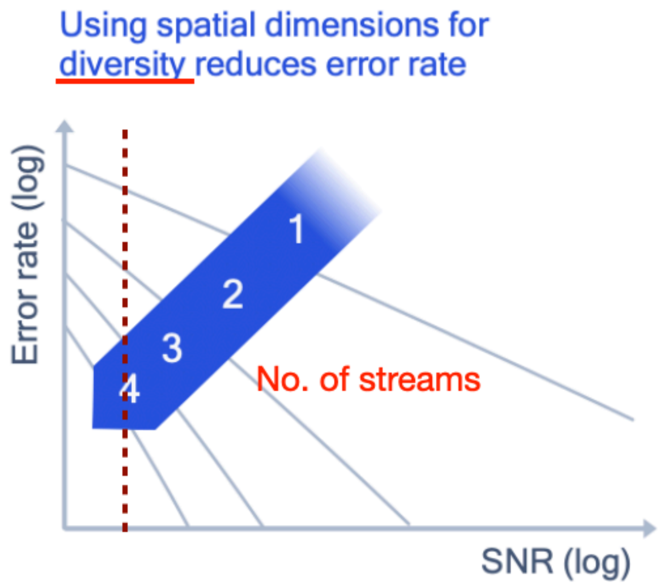
Using spatial dimensions to multiplex multiple data streams increases capacity



Given the fixed SNR, the more no. of streams, the higher the capacity

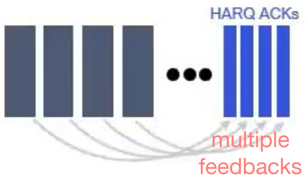
- **Reliability from spatial diversity** (reduce error rate)
  - Spatial diversity can overcome <u>radio shadowing</u> in challenging radio environments
  - Key for URLLC to meet 99.9999% <u>reliability</u> and challenging industrial IoT applications





Given the fixed SNR, the more no. of streams, the lower the error rate

eURLLC



Improved HARQ

Multiple HARQ-ACK feedbacks per slot for latency reduction

Inter-device service multiplexing

Uplink cancellation indicator and power boosting

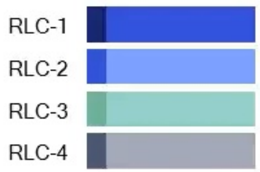
Non-coherent joint transmission

Coordinated multi-point (CoMP)

Multi-TRP[1] for redundant communication paths with spatial diversity

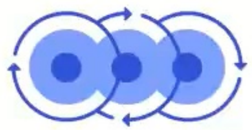
Intra-device channel prioritization

Concurrently supporting differentiated levels of service (e.g., eMBB & mission-critical)



Increased redundancy

Number of PDCP[2] packet duplicates increasing to 4 from 2



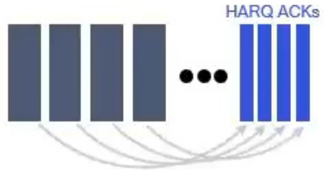
More flexible scheduling

Multiple active SPS[3] configurations & reduced periodicity, more efficient DL control monitoring, UL repetition with cross-slot boundaries

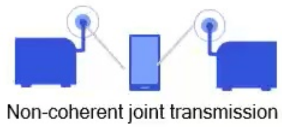
HARQ：Hybrid Automatic Repeat Request
Muli-TRP：Multiple Transmission and Reception Point
PDCP：Packet Data Convergence Protocol
RLC：Radio Link Control
SPS：Semi-Persistent Scheduling

- eURLLC (Enhanced Ultra-Reliable Low Latency Communications)
    - **Ultra low latency**: can achieve one-way radio latency down to 0.5ms for a single transmission
    - **High reliability**: demand packet error rates up to 10^{-5} to 10^{-6}, suitable for mission-critical applications
    - **Determinism**: require deterministic latency with minimal variation, crucial for time-sensitive applications

- eURLLC employed technics and features
    - **Improved HARQ**: allow <u>multiple HARQ</u> <u>feedbacks</u> within a single slot to reduce <u>retransmission latency</u>
    - **CoMP**: leverage multi-point coordination for <u>spatial diversity</u> and <u>redundant communication paths</u> across cells/TRPs, which improves <u>reliability</u>



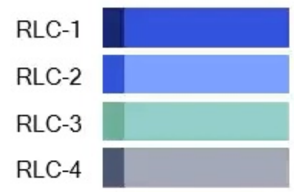
Improved HARQ
Multiple HARQ-ACK feedbacks per slot for latency reduction



Coordinated multi-point (CoMP)
Multi-TRP[1] for redundant communication paths with spatial diversity

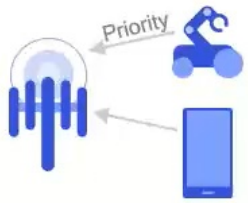
HARQ：Hybrid Automatic Repeat Request
Muli-TRP：Multiple Transmission and Reception Point
PDCP：Packet Data Convergence Protocol
RLC：Radio Link Control
SPS：Semi-Persistent Scheduling

- **Increased redundancy**: increase no. of PDCP packet duplicates from 2 to 4 for higher redundancy and packet delivery reliability



Increased redundancy
Number of PDCP[2] packet duplicates increasing to 4 from 2

- **Inter-device multiplexing**: enable uplink resource sharing between devices through coordination mechanisms like uplink cancellation and power boosting



Inter-device service multiplexing
Uplink cancellation indicator and power boosting

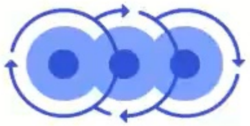
HARQ：Hybrid Automatic Repeat Request
Muli-TRP：Multiple Transmission and Reception Point
PDCP：Packet Data Convergence Protocol
RLC：Radio Link Control
SPS：Semi-Persistent Scheduling

- **Intra-device prioritization**: provide capability to concurrently support different service types like eMBB and mission-critical within a device through internal prioritization

- **Flexible scheduling**: use of techniques like multiple SPS (Semi-Persistent Scheduling) configurations, reduced SPS periodicity, cross-slot repetition etc. to enable more dynamic scheduling required for URLLC applications

Intra-device channel prioritization

Concurrently supporting differentiated levels of service (e.g., eMBB & mission-critical)



More flexible scheduling

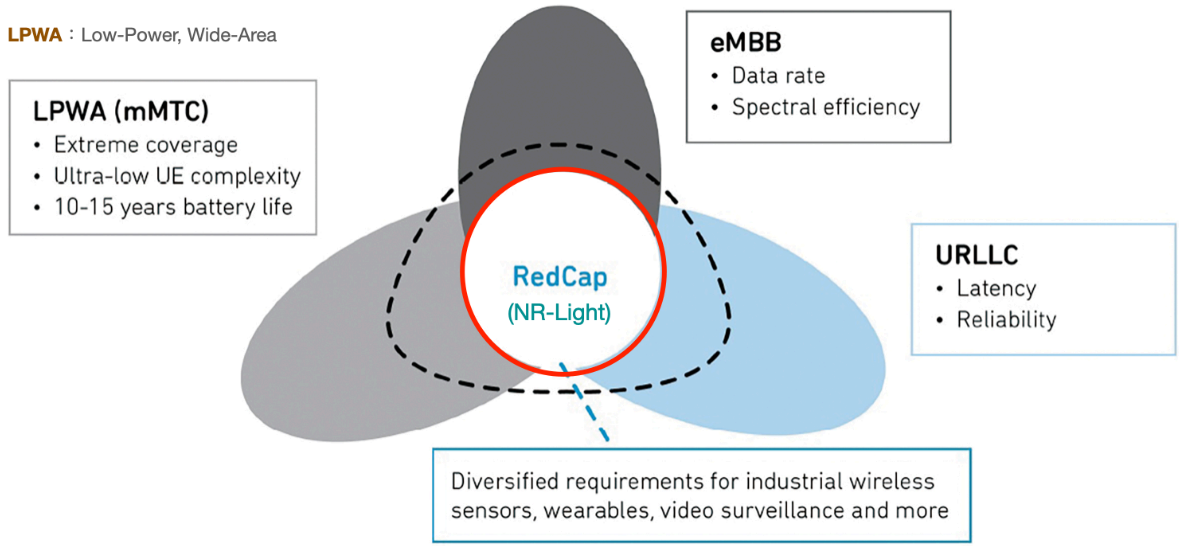
Multiple active SPS[3] configurations & reduced periodicity, more efficient DL control monitoring, UL repetition with cross-slot boundaries

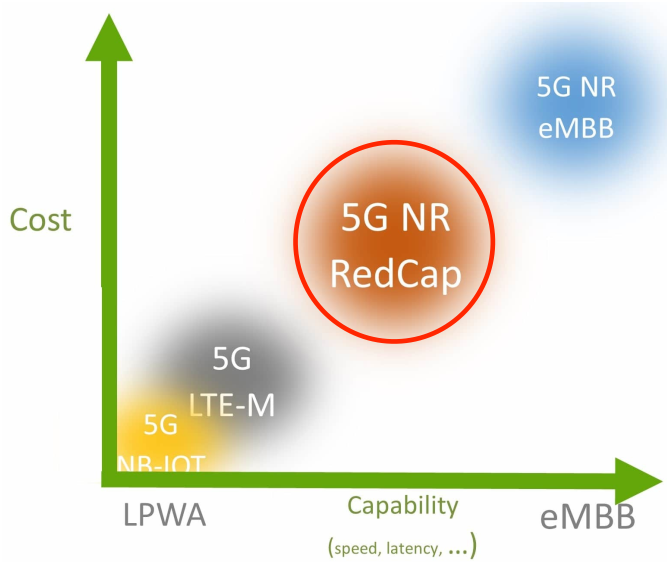
HARQ：Hybrid Automatic Repeat Request
Muli-TRP：Multiple Transmission and Reception Point
PDCP：Packet Data Convergence Protocol
RLC：Radio Link Control
SPS：Semi-Persistent Scheduling

RedCap (Redundant Capacity or Reduced Capability)

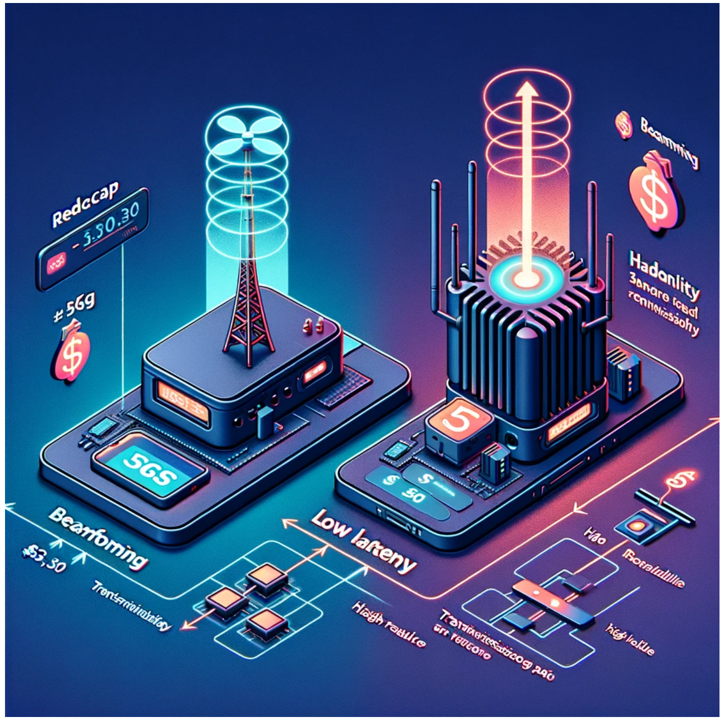
- A standard within 5G framework, primarily aimed at catering to IoT applications and devices that don't require high speeds of typical 5G connections, but still need the low latency and high reliability that 5G offers

- Offer redundant transmission capacity to meet stringent service availability requirements through failover between redundant paths



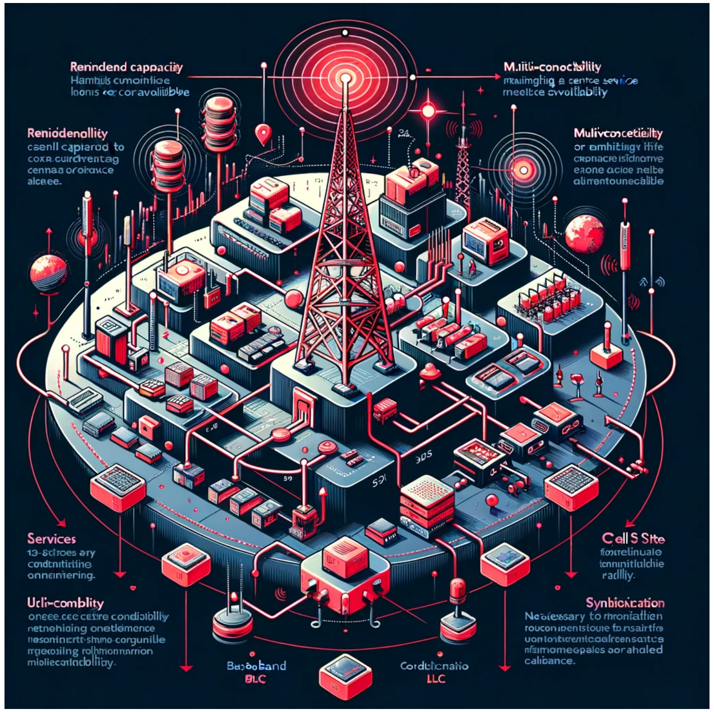


- Benefits of RedCap
  - **Reduced cost**: RedCap devices are simpler and less expensive to manufacture than traditional 5G devices
  - **Low latency**: RedCap devices can achieve low latency by using techniques such as beamforming and HARQ
  - **High reliability**: RedCap devices can achieve high reliability by using redundant transmission capacity and failover between redundant paths



- Applications of RedCap
  - **IoT**: RedCap is a good choice for IoT applications that require low latency and high reliability, such as smart grids, industrial automation systems, and medical devices
  - **Mobile broadband**: RedCap can also be used for mobile broadband applications in areas where high data rates are not required, such as rural areas and indoor environments

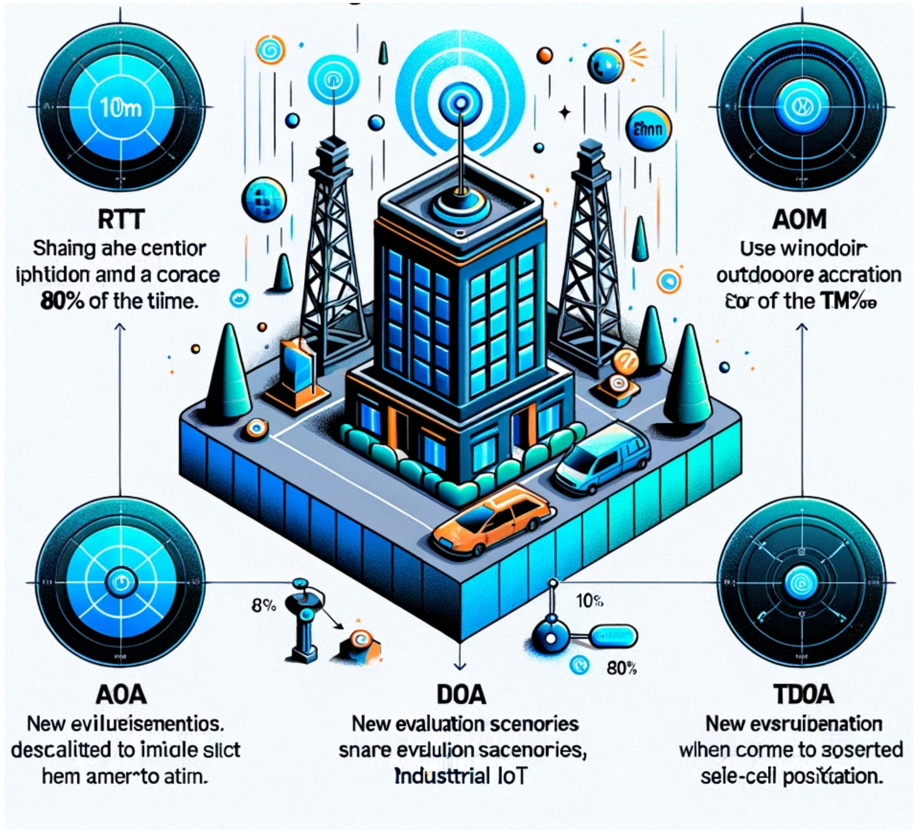
- Key aspects
  - Provides redundant capacity to replicate critical user plane traffic over spatially separated communication paths to maximize service availability
  - Implemented through multi-connectivity across different cell sites or baseband units
  - Used for services like URLLC that demand extreme reliability like 99.999% availability
  - Requires tight coordination and synchronization between redundant paths for seamless switchover



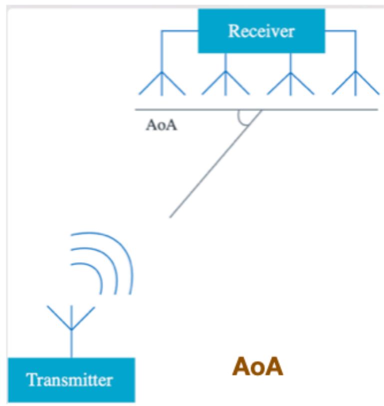
5G Positioning Evolution

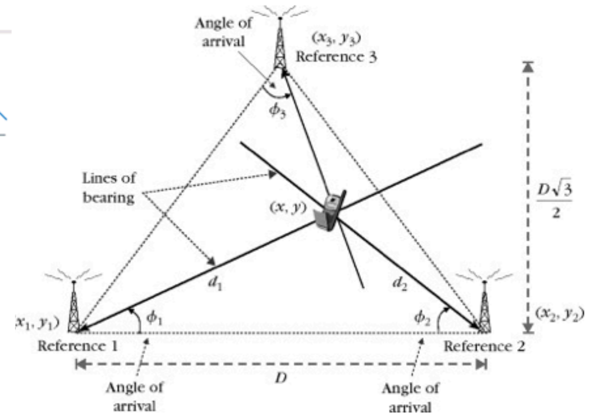
AoA : Angle-of-Arrival
AoD : Angle-of-Departure
TDoA : Time Difference of Arrival
RTT : Round Trip Time

- **Release 16 - establishing foundation**
  - Achieving <u>accuracy</u> of 3m/10m (indoor/outdoor) for 80% of time
  - Supporting RTT, AoA/AoD, TDOA, single-cell positioning
  - Including new evaluation scenarios, i.e., industrial IoT

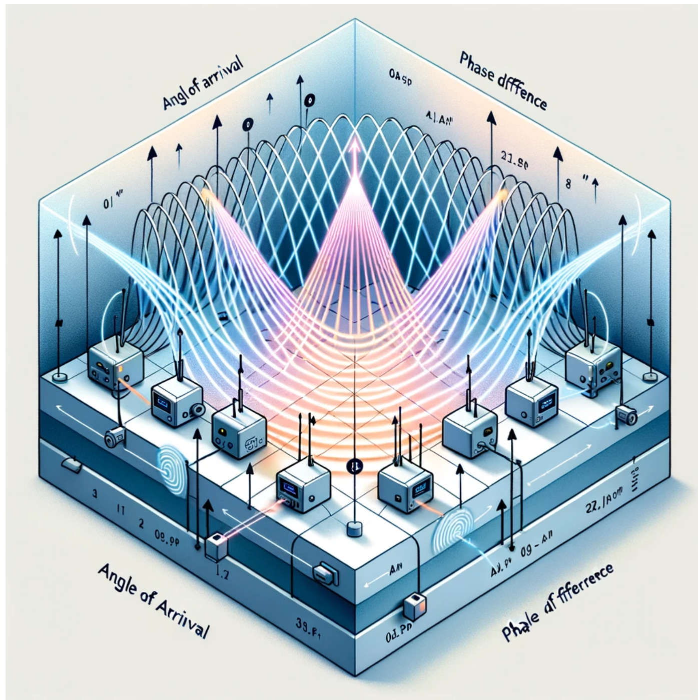


- **Angle of Arrival (AoA)**
  - Measure the angle at which a signal arrives at a receiver
  - Use multiple receivers and measure the phase difference between the signal received at each receiver
  - AoA is a relatively accurate technique, but it can be difficult to implement in practice, especially in multipath environments

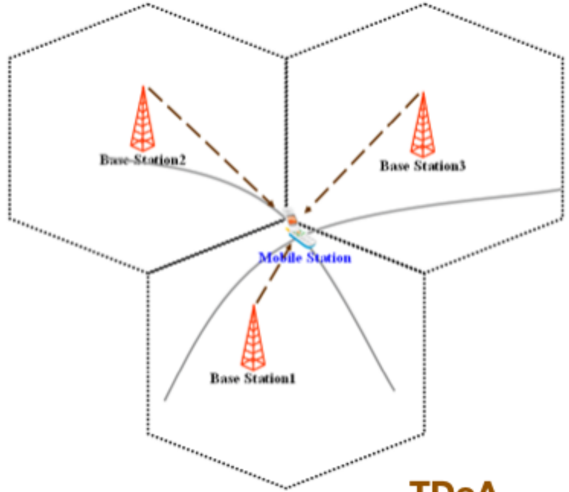




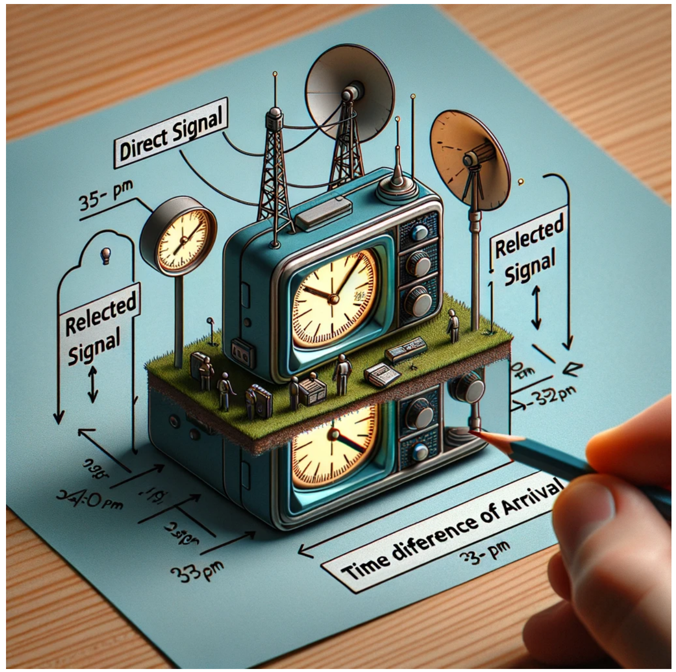
AoA



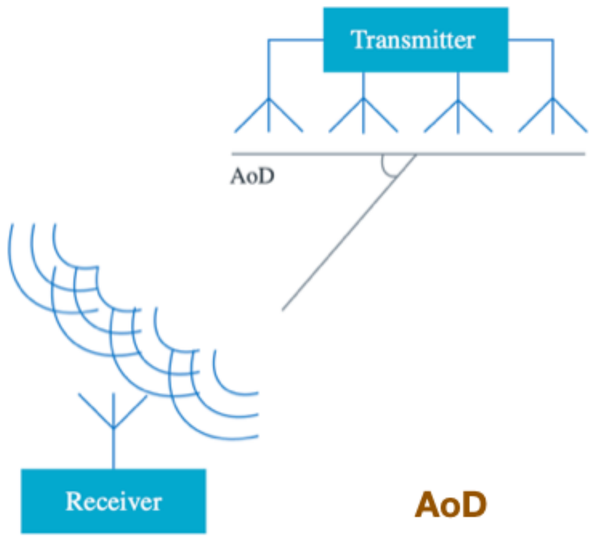
- **Time Difference of Arrival (TDoA)**
  - Measure the time difference between the arrival of a signal at two or more receivers
  - Use a single receiver and measure the difference in time between the arrival of the direct signal and the arrival of a reflected signal
  - TDoA is a relatively simple technique to implement, but it is less accurate than AoA, especially in multipath environments



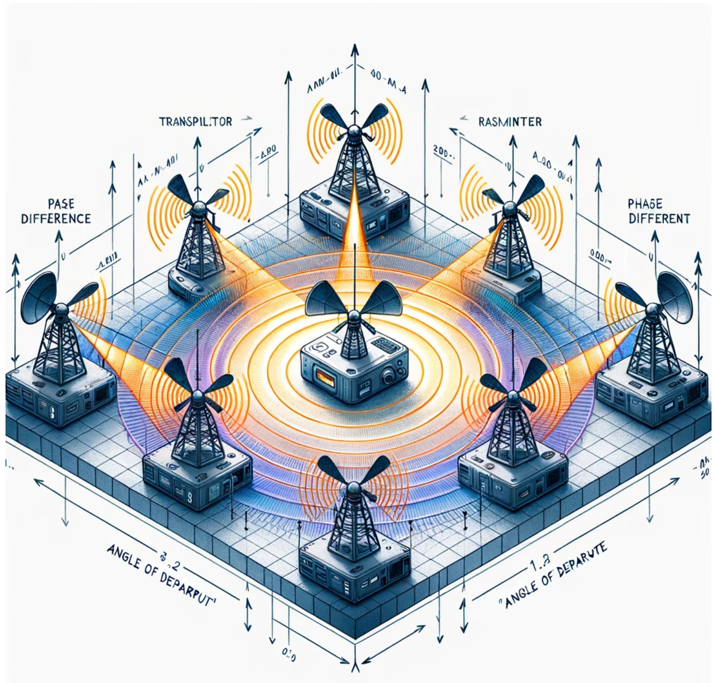
TDoA



- **Angle of Departure (AoD)**
  - Measure the angle at which a signal <u>leaves</u> a transmitter
  - Use <u>multiple transmitters</u> and measure the <u>phase difference</u> between the signal transmitted at each transmitter
  - AoD is a relatively <u>accurate</u> technique, but it can be <u>difficult to implement</u> in practice, especially in <u>multipath</u> environments



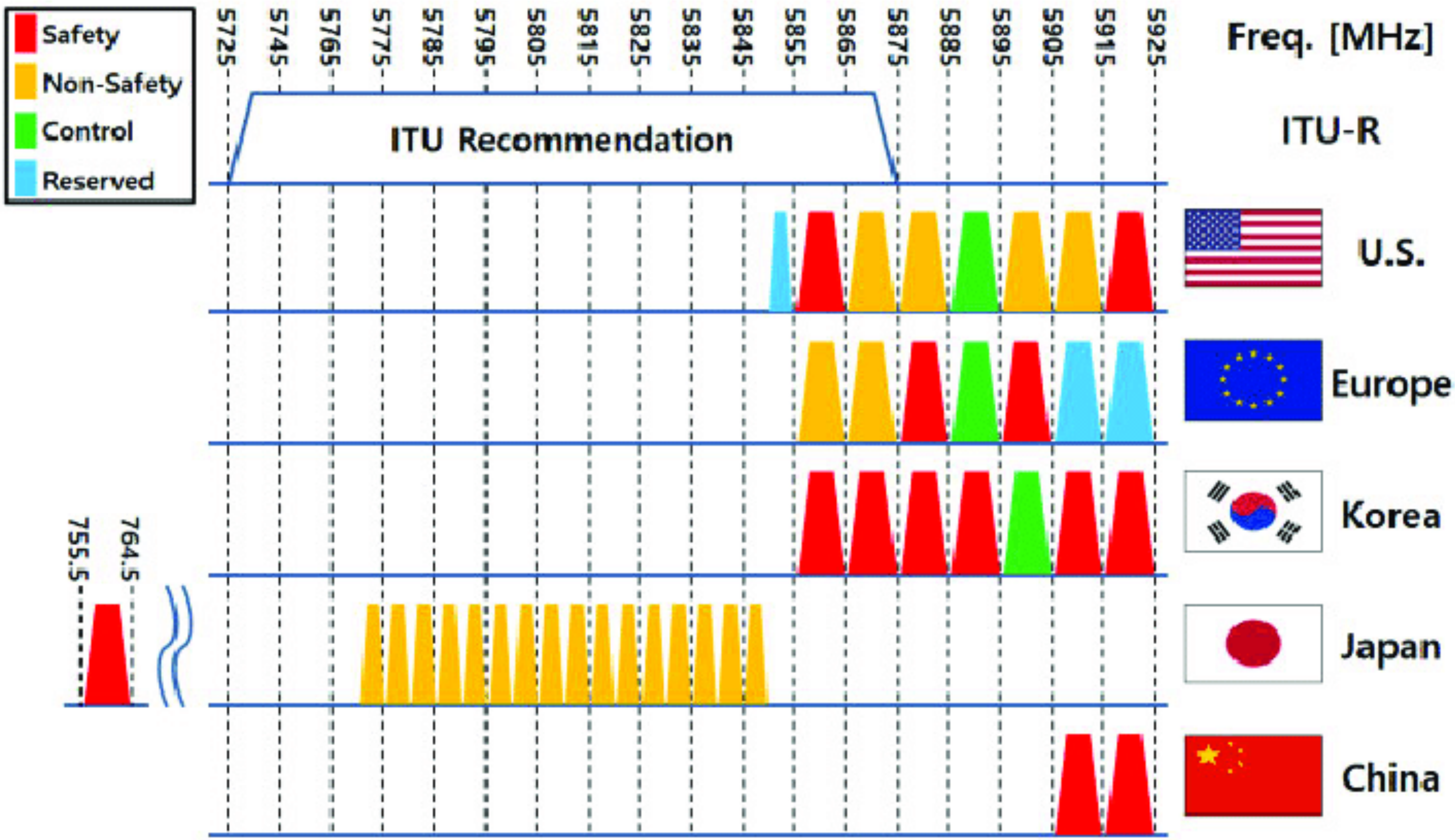
AoD



Characteristic	AoA	TDoA	AoD
Accuracy	High	Medium	High
Implementation complexity	High	Medium	High
Sensitivity to multipath	Low	High	Low

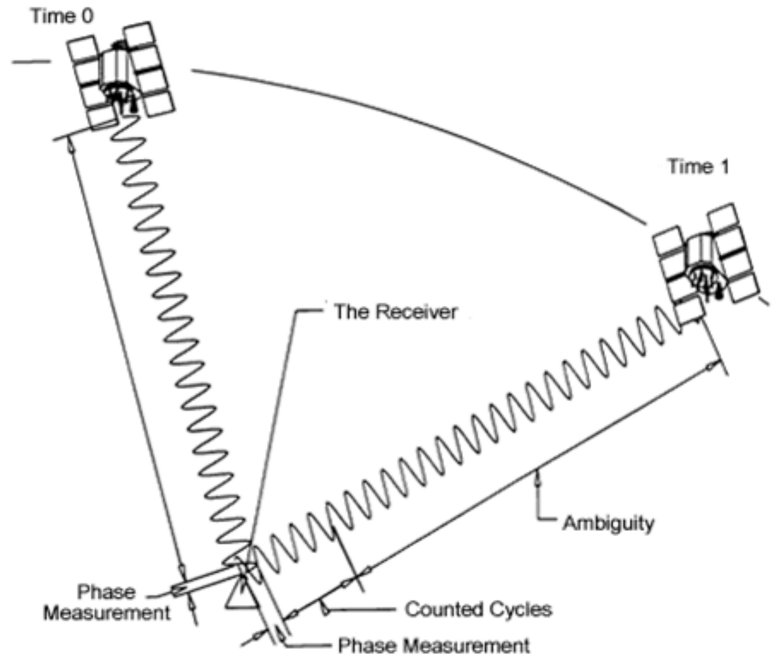
- **Release 17 - enhancing performance**
  - Meeting <u>centimeter-level</u> absolute accuracy requirement of down to 0.3m
  - Reducing positioning <u>latency</u> to as low as 10 ms
  - Scaling to <u>higher capacity</u> for millions of simultaneous devices (e.g., IoT, automotive)

- **5G Advanced in Release 18** - improving performance, expanding to <u>new devices</u> and <u>deployments</u>
  - **Sidelink <u>positioning</u> and <u>ranging</u>**
    - Defining methodologies, reference signals, measurements, procedures for <u>absolute</u> and <u>relative</u> (e.g., ranging) sidelink positioning in <u>licensed</u> and <u>ITS</u> (Intelligent Transport Systems) spectrum



ITS spectrum usages for U.S., Europe, Korea, Japan, and China

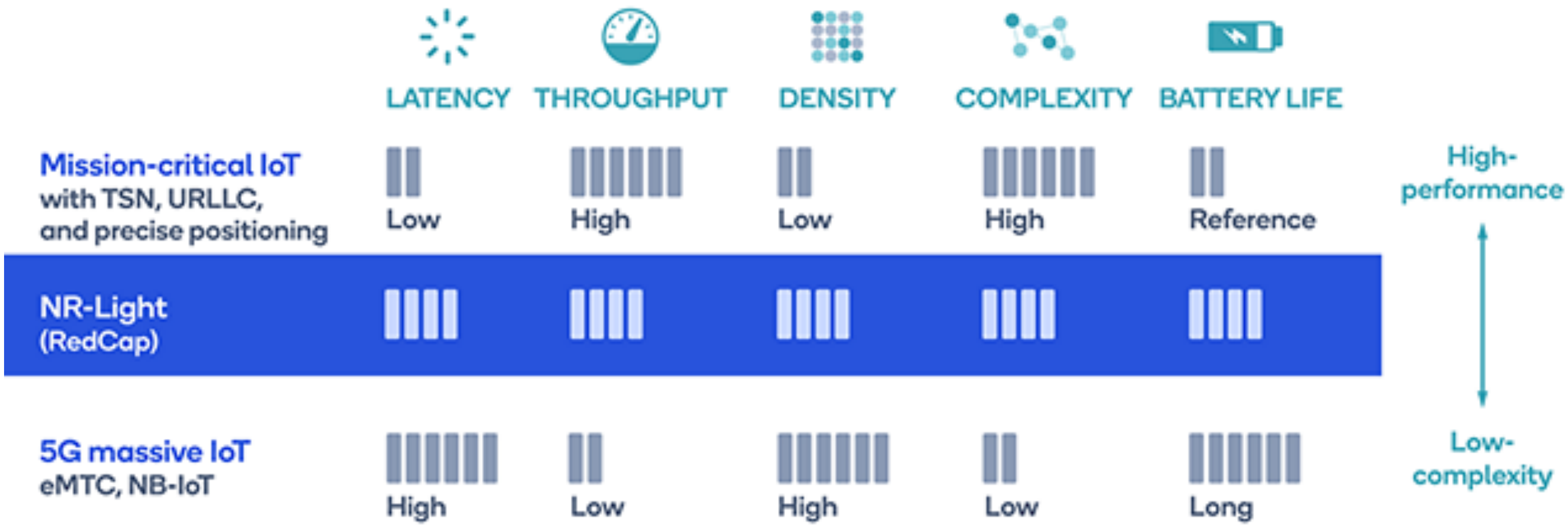
- **Improved positioning <u>performance</u>**
  - Specifying <u>higher layer solutions</u> for
    - <u>RAT dependent</u> positioning techniques
    - <u>Accuracy</u> improvement based on PRS/SRS bandwidth aggregation
    - <u>Carrier phase</u> measurements



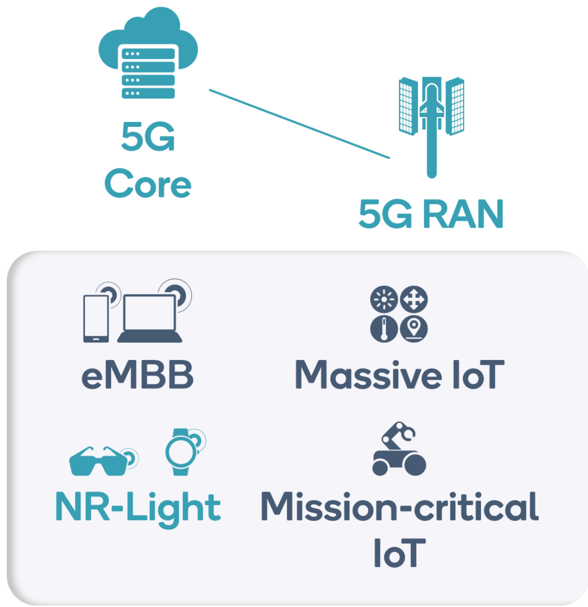
Carrier phase measurement

RAT : Radio Access Technology
PRS : Positioning Reference Signal
SRS : Sounding Reference Signal

- **NR-Light (RedCap) positioning**
  - Setting performance requirements, evaluating performance for R17 positioning procedures, and identifying potential enhancements



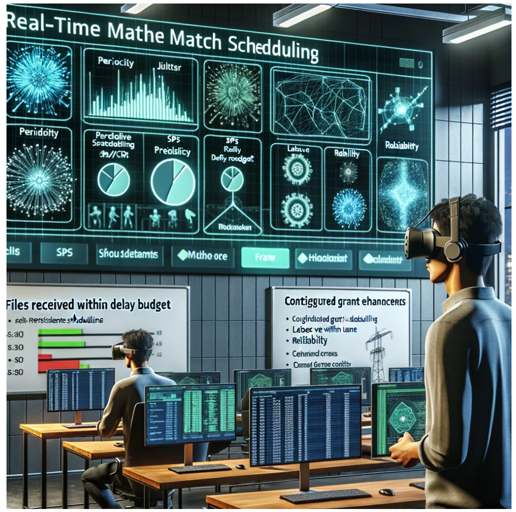
	LTE Cat-1bis	LTE Cat-4	5G NR-Light (Rel-17)
Bandwidth	20 MHz	20 MHz	20 MHz (sub-7 GHz)
Peak data rate DL/UL	10/5 Mbps	150/50 Mbps	150/50 Mbps or higher
Duplexing	FD-FDD, TDD	FD-FDD, TDD	HD-FDD, FD-FDD, TDD
Tx/Rx chain	1 Tx, 1 Rx	1 Tx, 2 Rx	1 or 2 Tx, 1 or 2 Rx
MIMO layers DL/UL	1/1	2/1	1 or 2/1
Maximum coupling loss	140 dB	144 dB	140 dB



Unified 5G platform for all use cases can simplify system management and security

XR (Extended Reality) - Boosting AR, VR and Cloud Gaming Experience

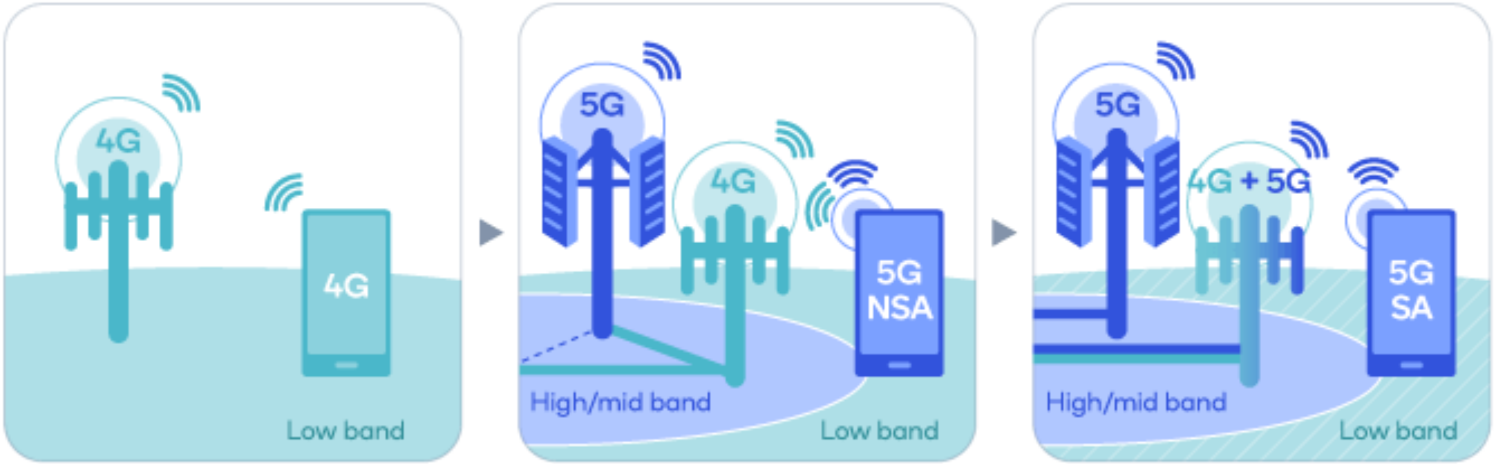
- XR services require high capacity and low latency to deliver a smooth and immersive experience
- Scheduling XR services is challenging due to their unique requirements, such as periodicity, multiple flows, jitter, latency, and reliability



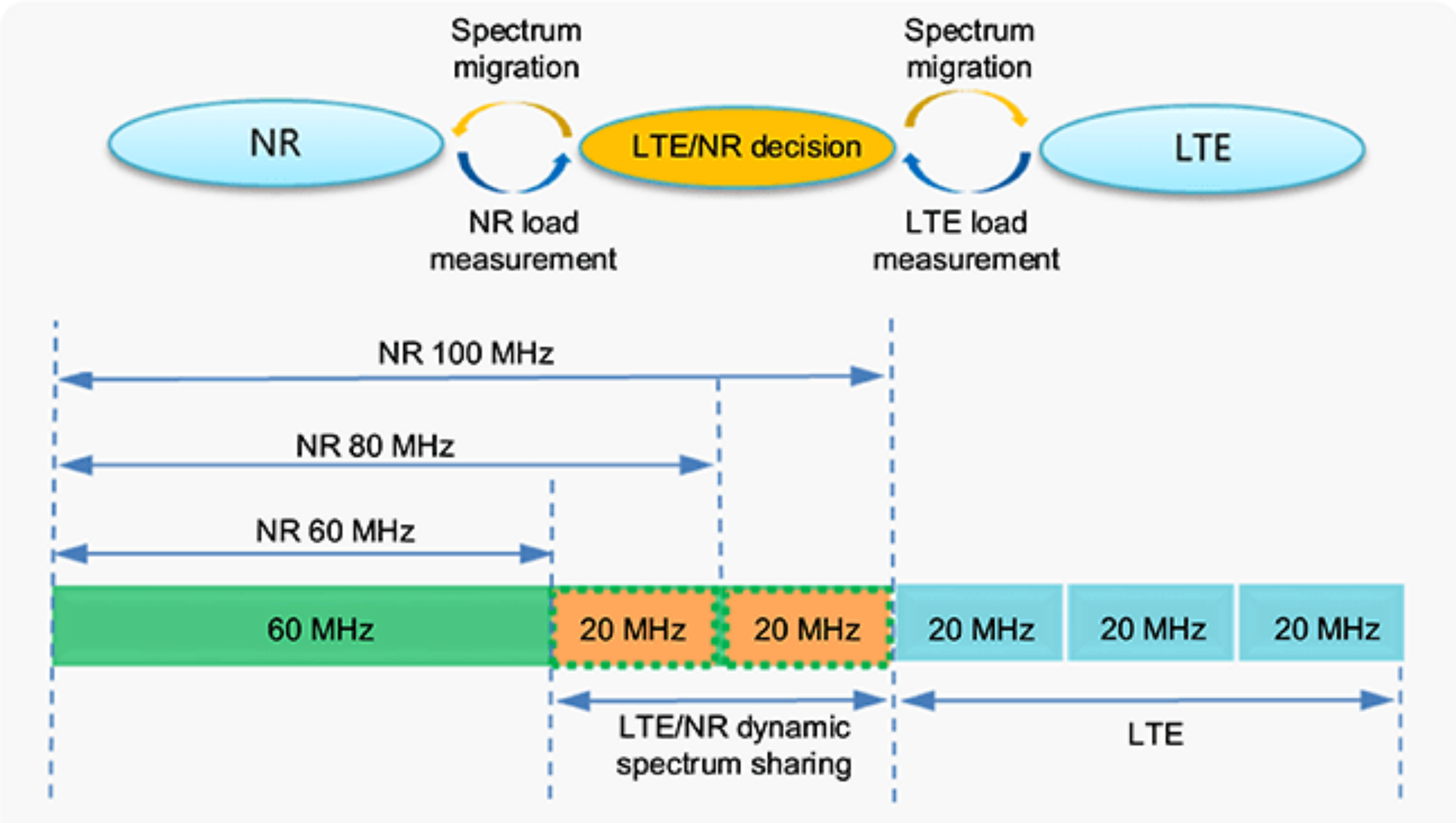
- Enhancements
  - **Semi-Persistent Scheduling (SPS)**: allocate resources to XR services for a longer period of time, reducing scheduling overhead and improving latency
  - **Configured grant enhancements**: allow operators to configure the 5G network to give priority to XR services
  - **Dynamic scheduling/grant enhancements**: allow 5G network to dynamically adjust scheduling and grant allocation based on the real-time needs of XR services

Dynamic Spectrum Sharing (DSS)

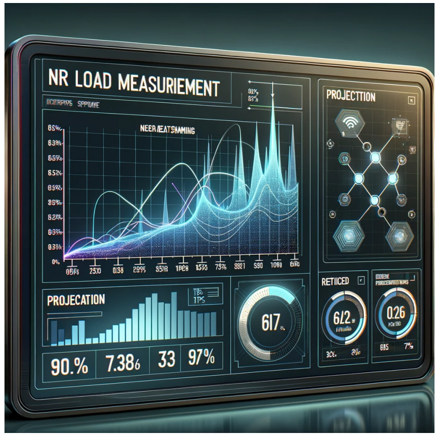
- Allow both 4G LTE and 5G NR to share the same spectrum and make the 5G deployment faster

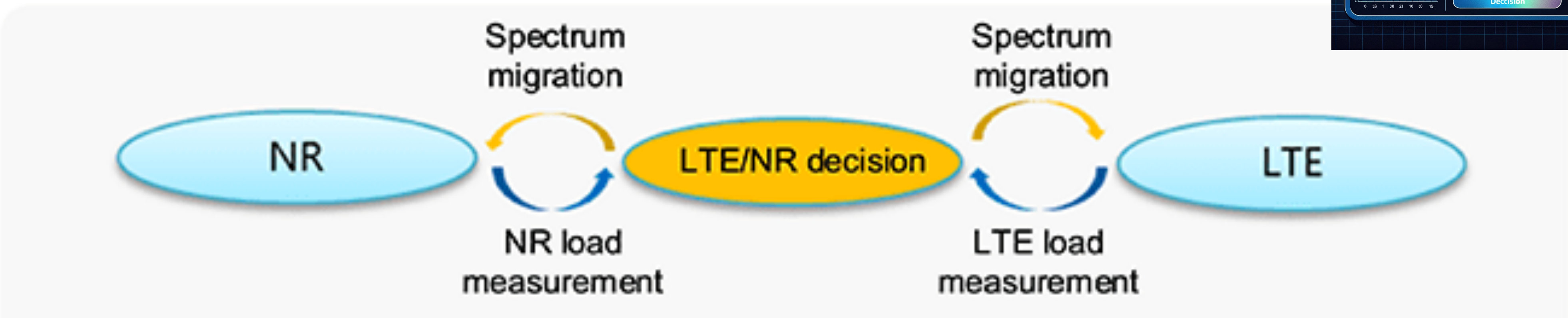


1. 4G
2. 4G/5G NSA with Dual Connectivity
3. 4G/5G SA with Dynamic Spectrum Sharing

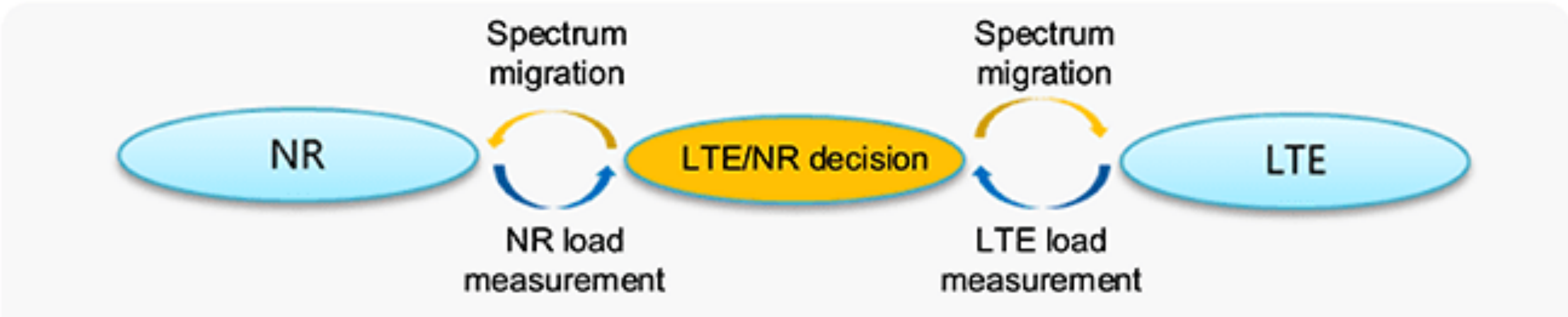

Spectrum
migration
Spectrum
migration
NR
LTE/NR decision
LTE
NR load
measurement
LTE load
measurement
NR 100 MHz
NR 80 MHz
NR 60 MHz
60 MHz
20 MHz
20 MHz
20 MHz
20 MHz
20 MHz
LTE/NR dynamic
spectrum sharing
LTE

- **NR load measurement**: determine how much spectrum is needed for NR by measuring the amount of NR traffic in the network and by predicting future NR traffic growth
- **LTE/NR decision**: once the NR load has been determined, a decision is made about how much spectrum to migrate from LTE to NR considering
  - No. of LTE and NR users in the network
  - QoS requirements for each service
  - Availability of spectrum in other bands





- **LTE load measurement**: determine the impact of the spectrum migration on LTE users by measuring the amount of LTE traffic in the network and by predicting future LTE traffic growth
- **NR migration**: move NR users from LTE spectrum band to NR spectrum band using handover and cell reselection, etc.
- **LTE/NR dynamic spectrum sharing**: after the spectrum migration is complete, LTE and NR can share the spectrum band using DSS by dynamically allocating spectrum to LTE and NR based on the needs of each service



6G

Key Features of 6G

6G

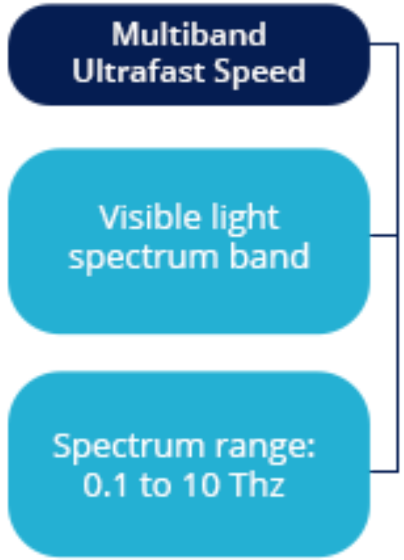
Multiband Ultrafast Speed
- Visible light spectrum band
- Spectrum range: 0.1 to 10 Thz

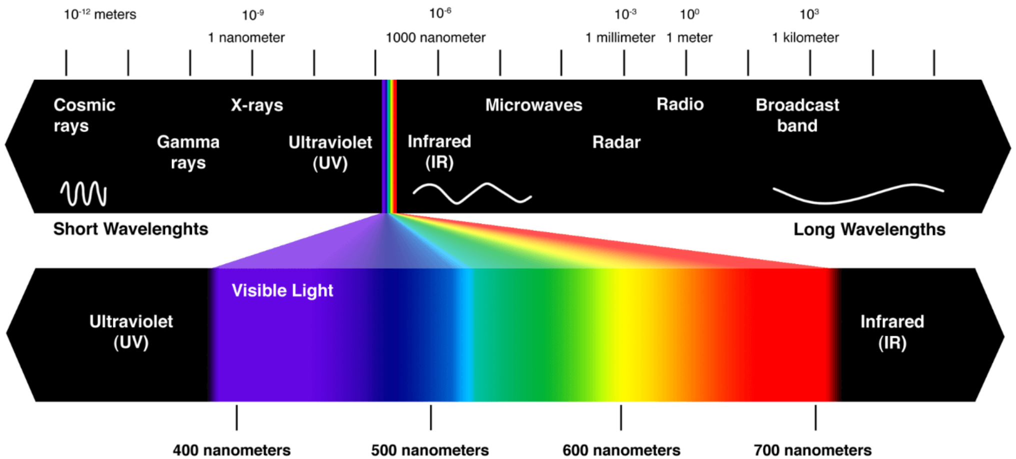
Energy Efficient Comunication
- Wireless charging by inductive coupling, magnetic coupling etc.
- Energy to be harvested from sunlight
- Energy to be harvested from ambient radio frequencies

Artificial Intelligence
- Service Intelligence
- Environmental Intelligence
- Operational Intelligence

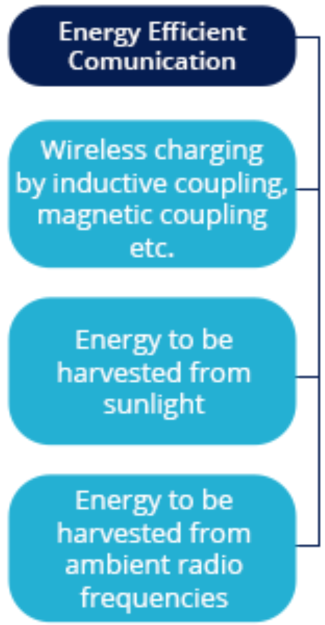
High Security, Secrecy and Privacy
- Distributed management mechanism for multi level security
- Block Chain Technology
- Quantum key distribution

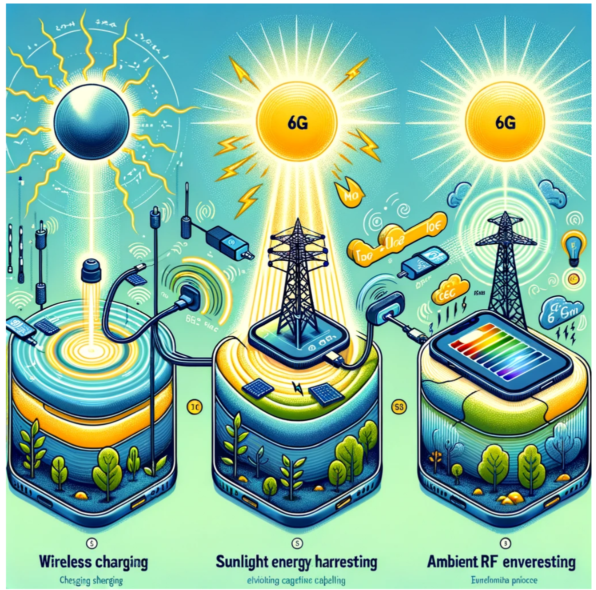
- **Multiband Ultrafast Speed**
  - **Visible light spectrum band**: much <u>higher frequency</u> than radio waves, which allows for much <u>higher data rates</u>
  - **Spectrum range: 0.1 to 10 Thz**: a wider range of spectrum from 0.1 to 10 Thz, which allows for even <u>higher data rates</u> and <u>more capacity</u>



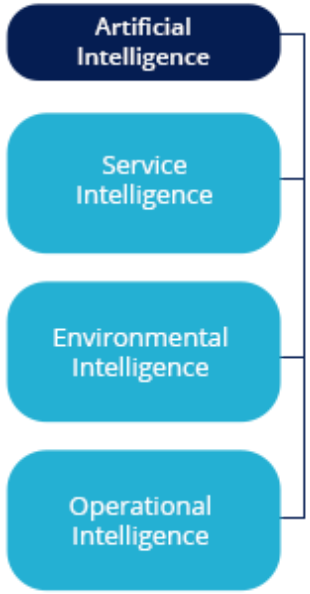


- **Energy Efficient Communication**
  - **Wireless charging by inductive coupling, magnetic coupling etc.**: eliminate the need for charging cables and make it easier to keep devices charged
  - **Energy to be harvested from sunlight**: harvest energy from sunlight to power themselves, thus extend the battery life of devices and reduce the need for external power sources
  - **Energy to be harvested from ambient radio frequencies**: harvest energy from ambient radio frequencies, thus further extend the battery life of devices and make them more energy efficient

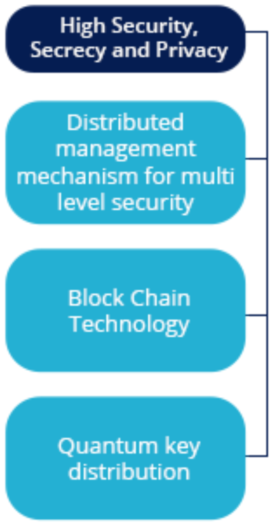


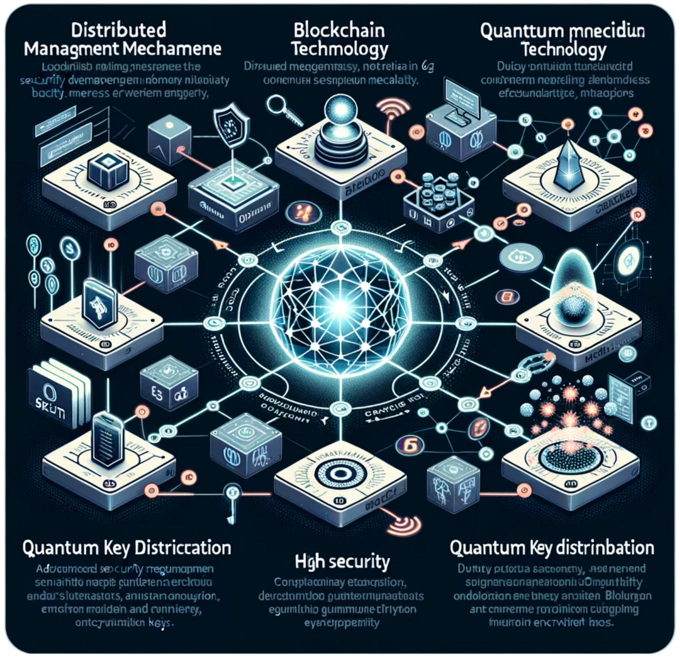


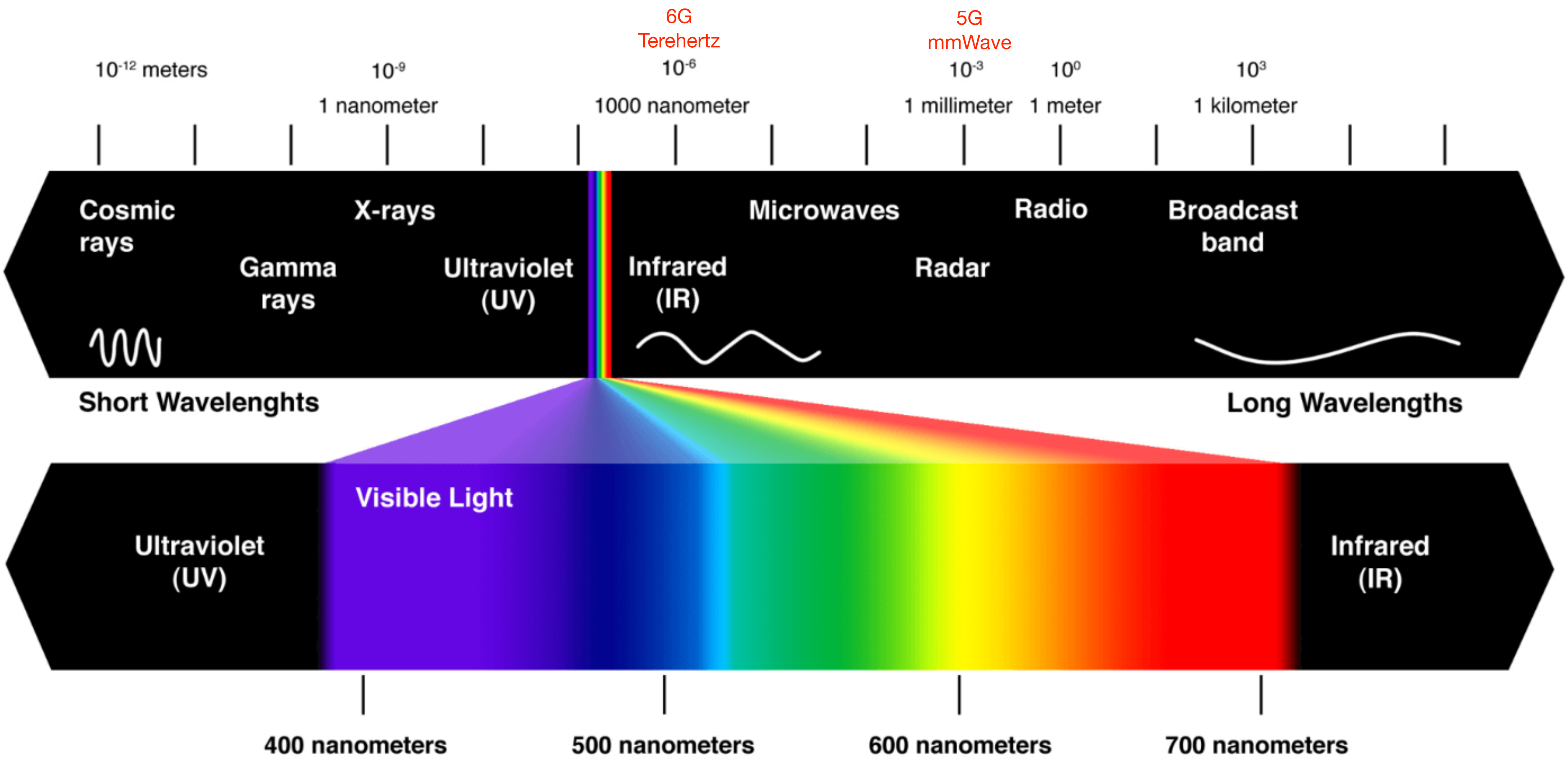
- **Artificial Intelligence**
  - **Service Intelligence**: use AI to improve the performance of various services, e.g., video streaming, gaming, and augmented reality
  - **Environmental Intelligence**: use AI to understand the environment in which it is operating and to adapt its performance, e.g., use of spectrum and to reduce interference
  - **Operational Intelligence**: use AI to automate the operation and maintenance of the network, thus reduce costs and improve the efficiency of the network



- **High Security, Secrecy and Privacy**
    - **Distributed management mechanism for multi level security**: use a distributed management mechanism to improve security and privacy
    - **Blockchain technology:** use blockchain technology to improve the security and transparency of the network due to the distributed ledger technology of blockchain, which is very secure and tamper-proof
    - **Quantum key distribution**: use quantum key distribution (QKD) to provide the highest level of security for sensitive communications by generating secure encryption keys

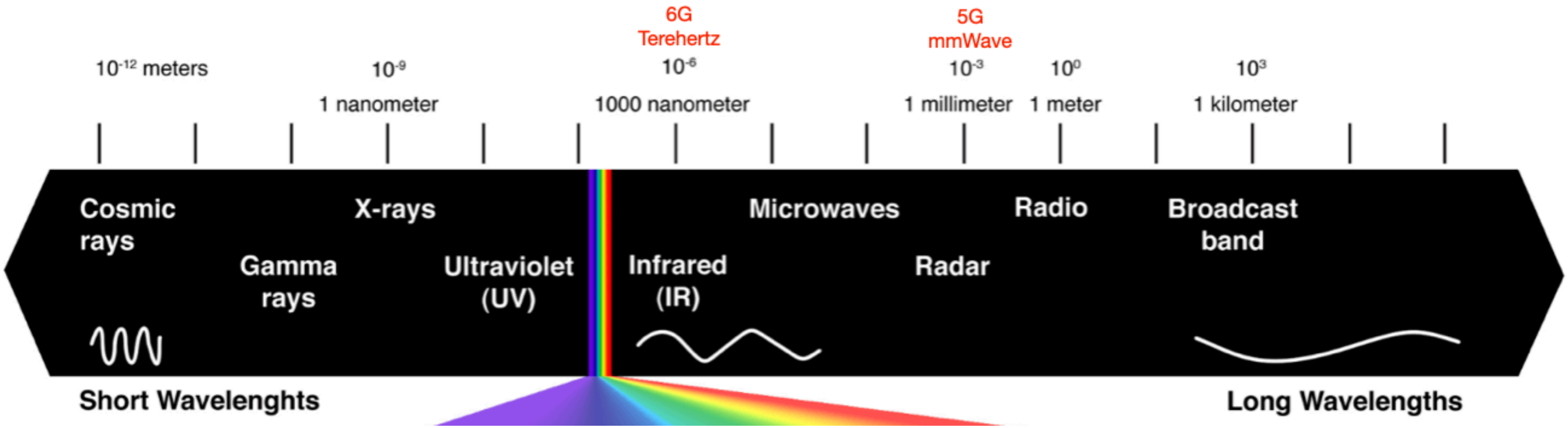




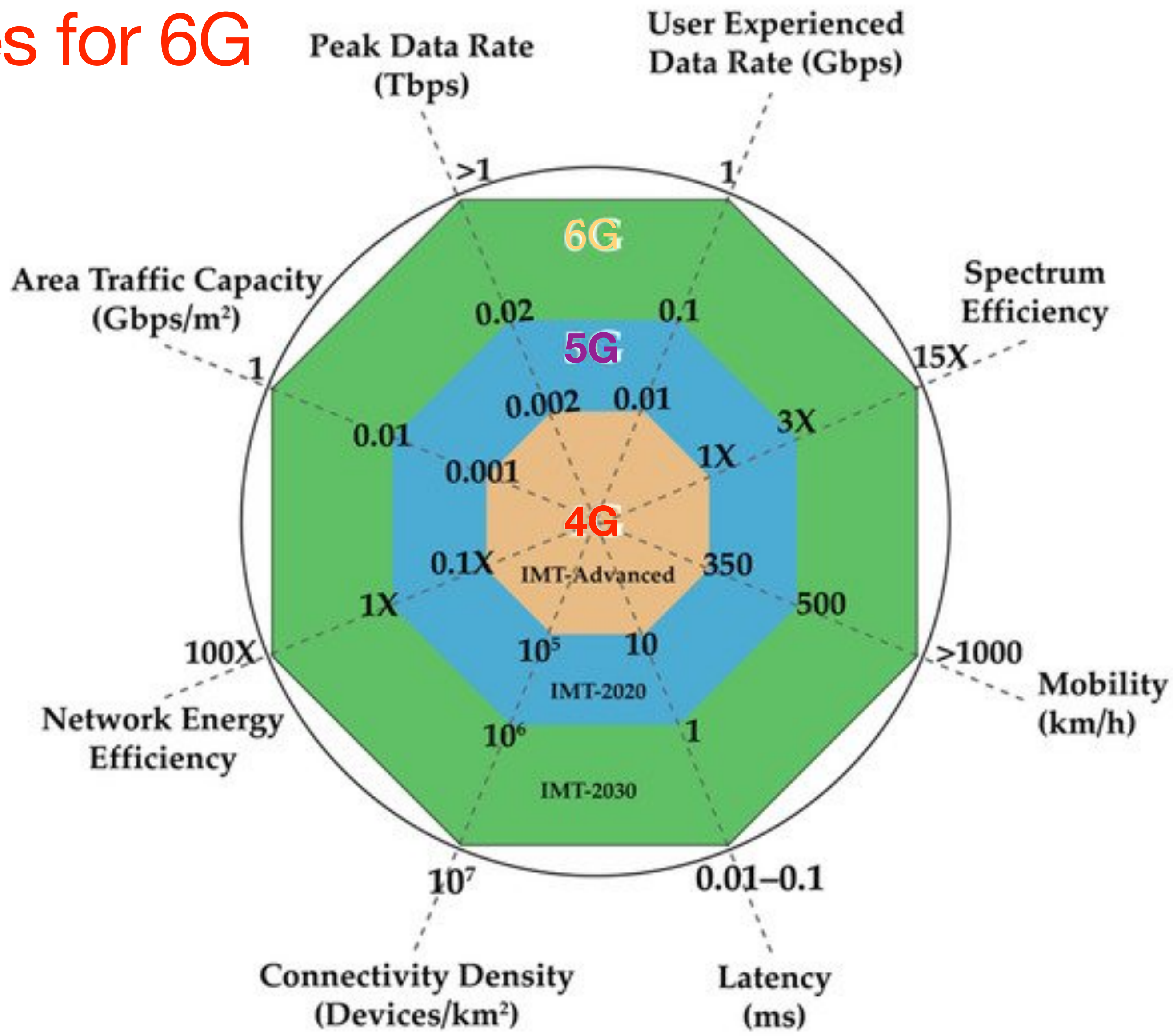


6G
Terehertz
5G
mmWave
10^{-12} meters
10^{-9}
1 nanometer
10^{-6}
1000 nanometer
10^{-3}
1 millimeter
10^{0}
1 meter
10^{3}
1 kilometer
Cosmic rays
Gamma rays
X-rays
Ultraviolet (UV)
Infrared (IR)
Microwaves
Radar
Radio
Broadcast band
Short Wavelenghts
Long Wavelengths
Visible Light
Ultraviolet (UV)
Infrared (IR)
400 nanometers
500 nanometers
600 nanometers
700 nanometers

- The wavelength ranges of different types of electromagnetic radiation, such as 5G <u>mmWave</u> and 6G <u>Terahertz</u>
- These types of radiation have <u>shorter wavelengths</u> than visible light, which makes them useful for <u>high-speed</u> wireless communication

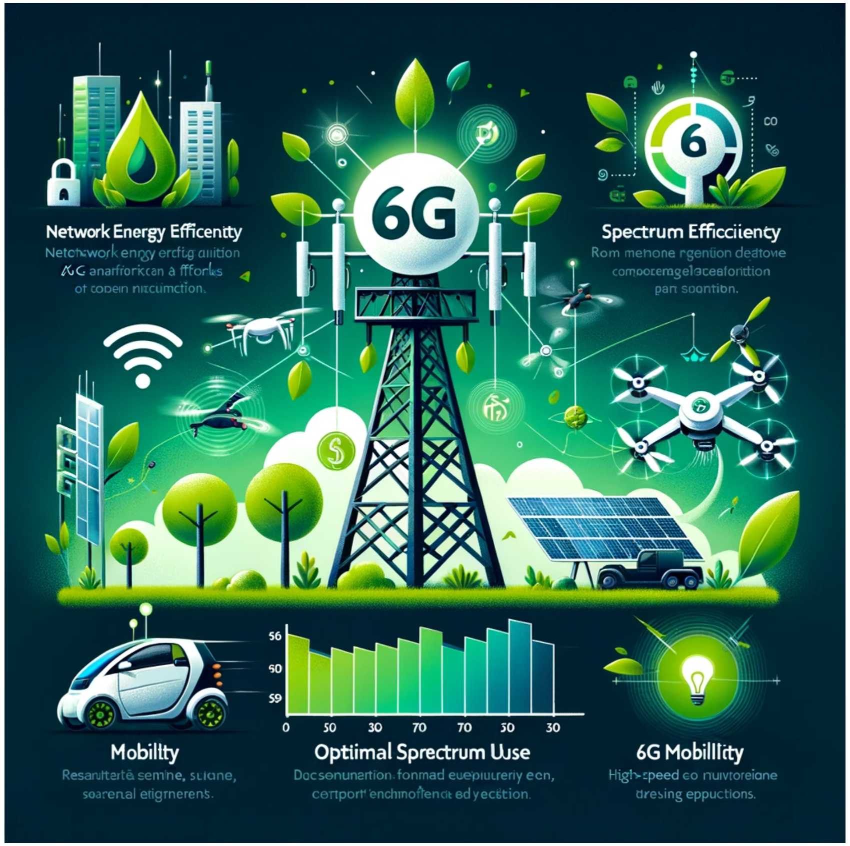


Key Capabilities for 6G



- **Peak data rate**: enable new applications such as real-time streaming of ultra-high-definition video, augmented reality, and virtual reality
- **User experienced data rate**: provide users with a more consistent and reliable data experience, even in crowded areas
- **Area traffic capacity**: support a much higher density of connected devices, making it ideal for applications such as the IoT and smart cities

- **Network energy efficiency**: reduce the energy consumption of mobile networks, making them more sustainable
- **Spectrum efficiency**: more efficient use of radio spectrum, which is a limited resource
- **Mobility**: support high-speed mobility for applications such as autonomous vehicles and drones



- **Connectivity density**: connect a massive number of devices in a small area, making it ideal for applications such as industrial automation and smart buildings

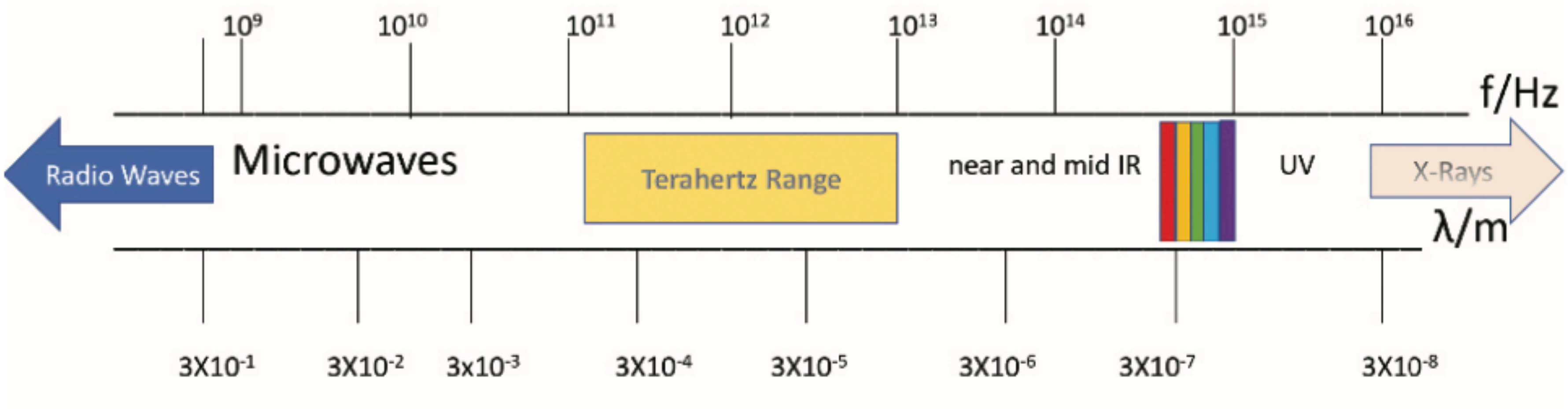
- **Latency**: reduce latency to near-zero levels, making it possible for applications such as real-time control and monitoring

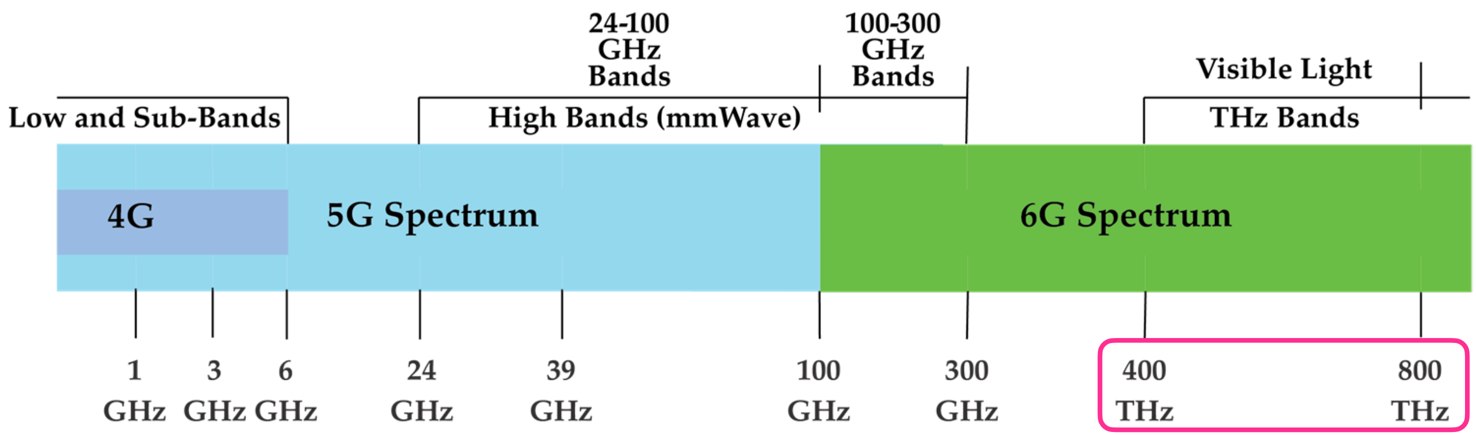
Capability	6G	5G	IMT-Advanced
Peak data rate	10 Tbps	10 Gbps	1 Gbps
User experienced data rate	10 Gbps	1 Gbps	100 Mbps
Area traffic capacity	10 Gbps/m^2	1 Gbps/m^2	100 Mbps/m^2
Network energy efficiency	10%	1%	0.1%
Spectrum efficiency	100X	10X	1X
Mobility	>1000 km/h	500 km/h	350 km/h
Connectivity density	10^7 devices/km^2	10^6 devices/km^2	10^5 devices/km^2
Latency	0.1-0.01 ms	1-10 ms	10-100 ms

5G vs. 6G KPIs

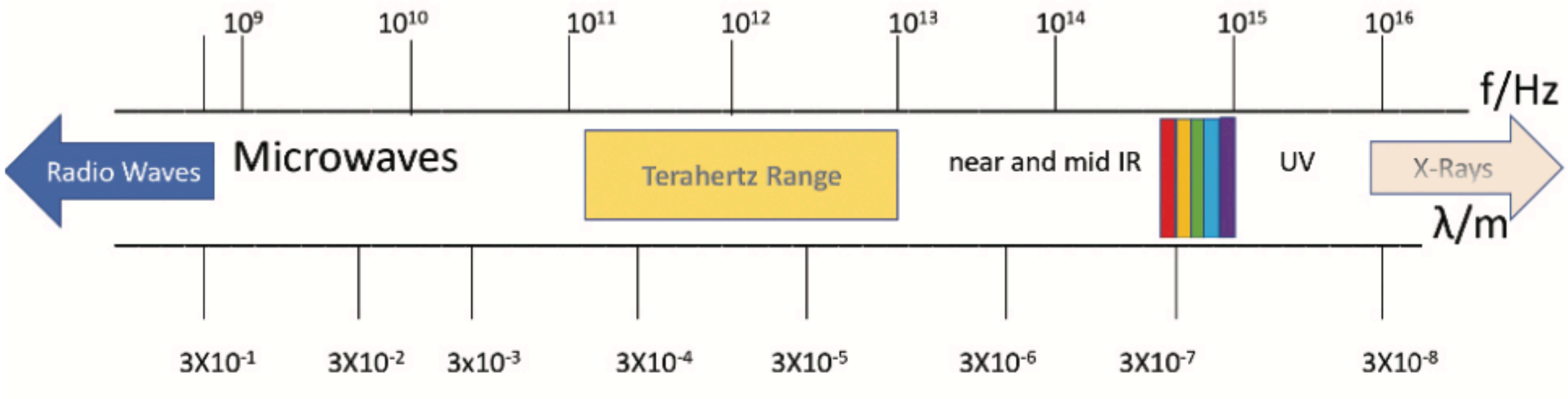
KPIs	5G	6G
Maximum Bandwidth	1 GHz	100 GHz
Peak Data Rate	20 Gb/s	>= 1 Tb/s
Experienced Data Rate	0.1 Gb/s	1 Gb/s
Spectrum Efficiency	Peak: 30 b/s/Hz Experienced: 0.3 b/s/Hz (3 times that of 4G)	Peak: 60 b/s/Hz Experienced: 3 b/s/Hz (5 to 10 times that of 5G)
Network Energy Efficiency	Not Specified	1 pJ/b
Area Traffic Capacity	10 Mb/s/m^2	1 Gb/s/m^2
Connection Density	10^6 devices/Km^2	10^7 devices/Km^2
Latency	1 ms	10 to 100 µs
Jitter	Not specified	1 µs
Reliability or FER	1×10^{-5}	1×10^{-9}
Mobility	500 Km/h	>= 1000 Km/h
Uniform User Experience	50 Mb/s, 2D everywhere	10 Gb/s, 3D everywhere
Localization Accuracy	10 cm in 2D	1 cm in 3D

Terahertz Spectrum

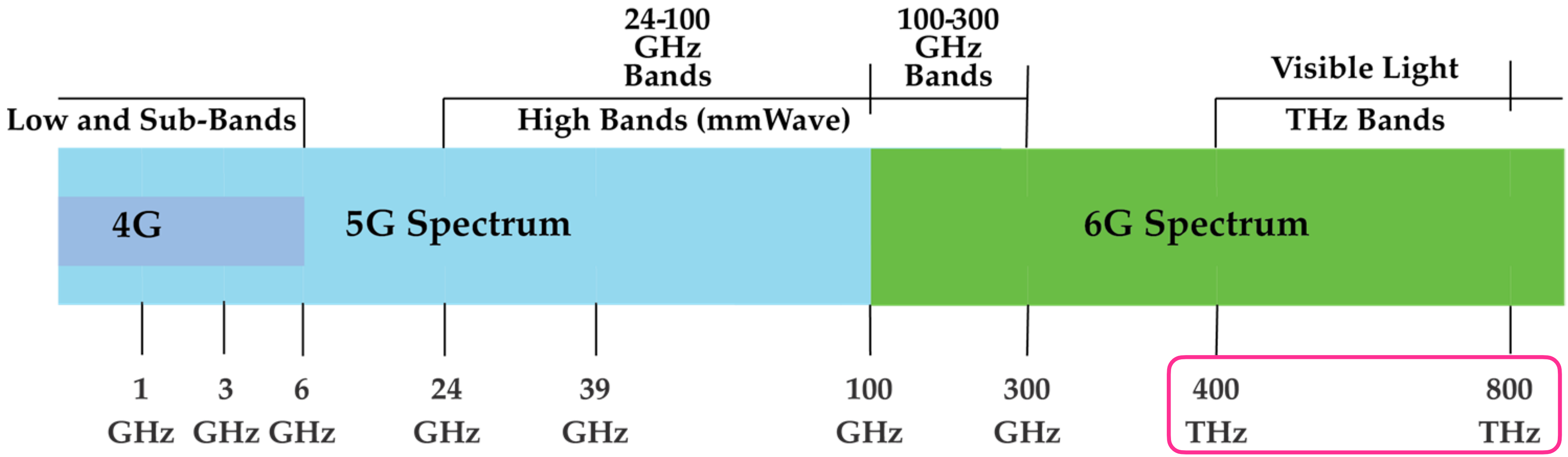




- Bands of Terahertz
  - **Low Terahertz (0.3-1 THz)**: This band is well-suited for imaging and sensing applications
  - **Mid Terahertz (1-10 THz)**: This band is well-suited for spectroscopy and communications applications
  - **High Terahertz (10-30 THz)**: This band is well-suited for high-speed communications and security applications



- 4G: Low and Sub-Bands
- 5G Spectrum: Low and Sub-Bands, High Bands (mmWave)
- 6G Spectrum: High Bands (mmWave), THz Bands



Enabling Technologies for B5G/6G

B5G / 6G Technologies	
Edge/Fog Computing	Distributed AI & Big Data
Ultra-dense Small Cell Network	Quantum Communications
Virtualized Network	Visible Light Communications
Energy Harvesting	Optical-Wireless Convergence
Energy Efficiency	3D Network
THz Communications	Full Duplex Communications