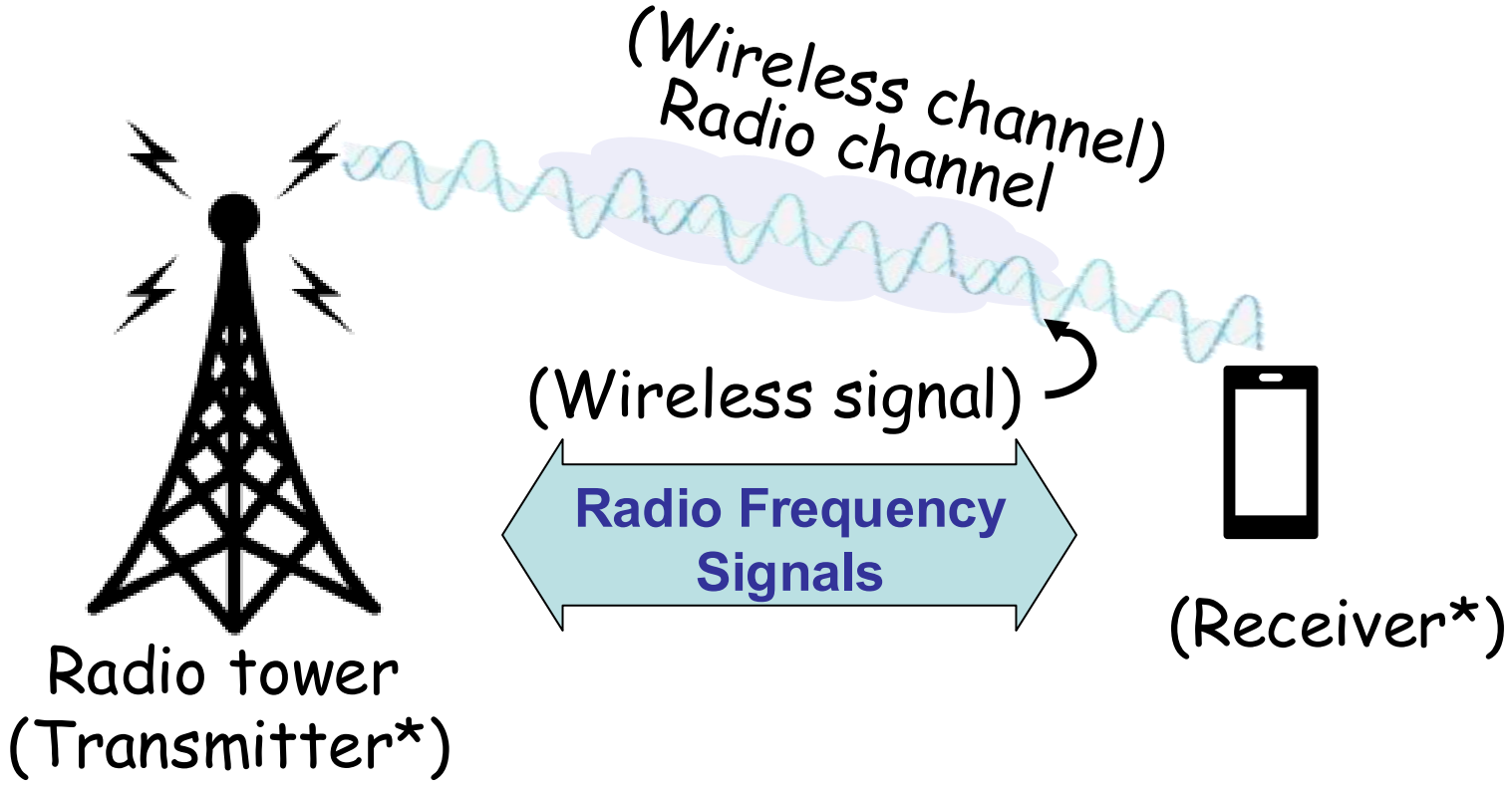
Mạng thế hệ sau
(Next Generation Networks)

Đinh Thị Hà Ly

lydth@soict.hust.edu.vn

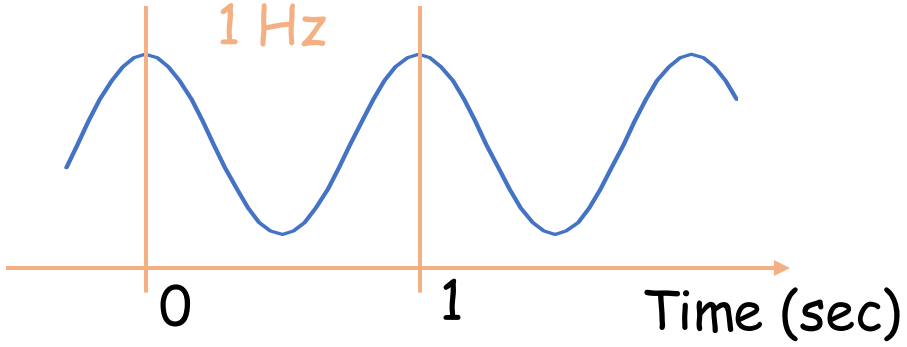
Wireless communications

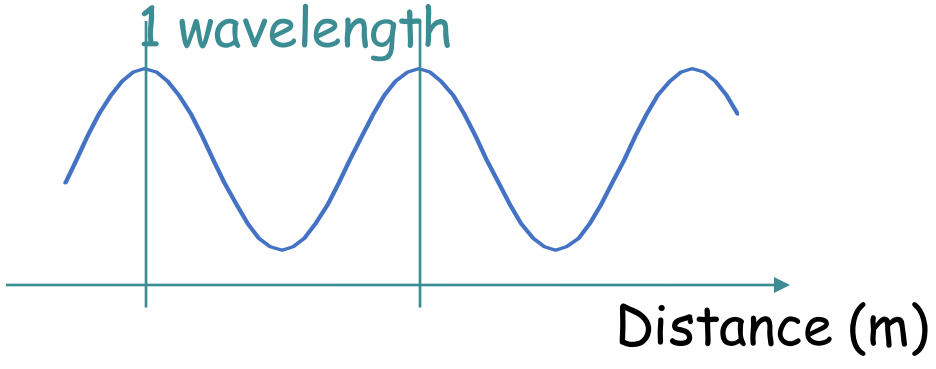
- **Transfer information** between a transmitter and a receiver **without a physical medium**
  - Transfer information by **radio frequency signals**
- Composed of **four fundamental components**



Radio signal properties

- All radio signals travels at the light speed $\sim 3 \times 10^8\ m/s$
- Characterized by their $frequency\ (\mathrm{Hz}) = \frac{Light\ speed\ (\mathrm{m/s})}{wavelength\ (\mathrm{m})}$





Frequency: #repetitions of radio signal in one second

Wavelength: distance a radio signal travels during one complete cycle

- Radio frequencies range 3 kHz ~ 300 GHz
- Wavelengths range 100 km ~ 1 mm

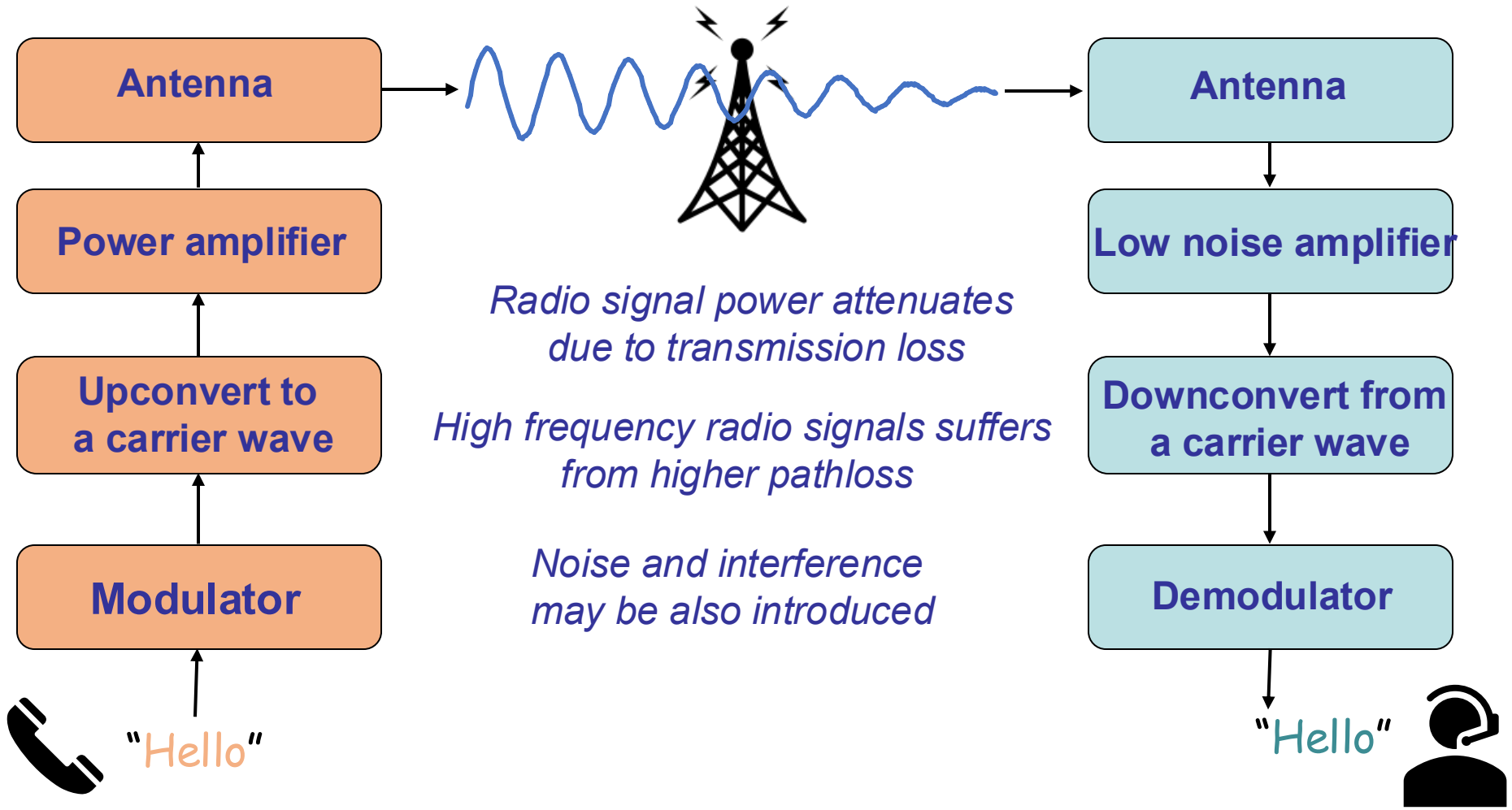
Carrier waves and Modulation

- Information is “carried” by radio frequency (RF) signals
  - Analog information, e.g., voice
  - Digital information, e.g., email, web pages, pictures, videos...
- **RF signals** are used as **a vehicle to transfer information**

→ Referred to as **Carrier waves**

- **Modulation** is a process by which we “put” information onto the carrier wave for transmission
  - Specific attributes of radio signals are changed, e.g., frequency, wavelength
  - Analog or digital modulation is performed depending on the nature of data
- **Demodulation** is a process to recover the information

Phone conversation



Transmitter (Tx) sends information

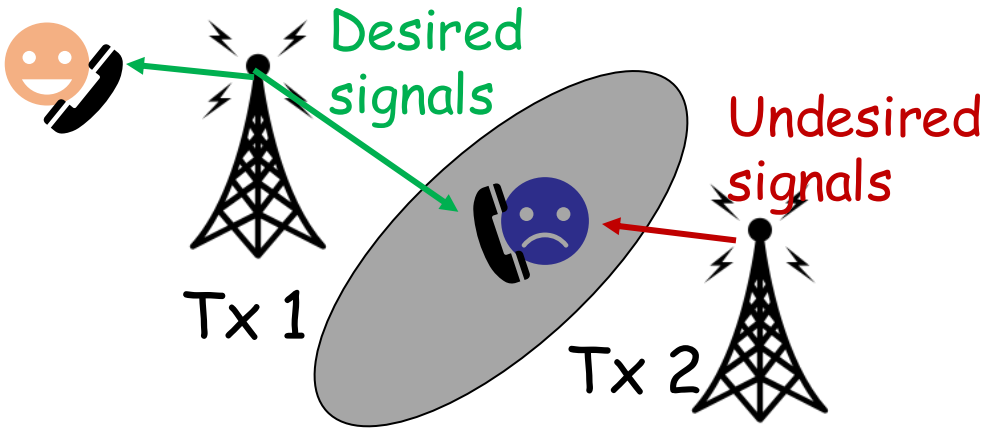
More power = better coverage

Receiver (Rx) reacquires information

More sensitivity = better reception

Noise and interference

- **Noise** is **unwanted** energy or signals
  - Presents in any device or communication link
  - Some noise is generated within the communication device
- **Interference** is created by **nearby transmitters** using the **same radio frequency** at the **same time**



*Noise and interference **reduce the quality** of the signal received by the user*

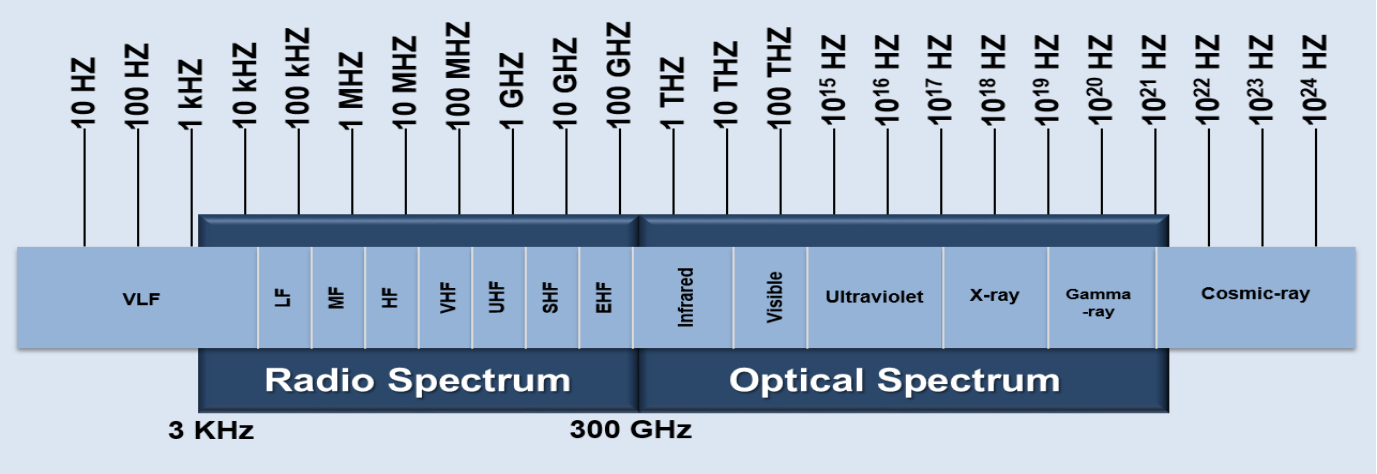
- **Signal quality** is quantified by the **ratio of desired signal to noise and/or interference**

$$\text{SNR} = \frac{Signal}{Noise}$$

$$\text{SINR} = \frac{Signal}{Noise + Interference}$$

Radio spectrum

- **The range of radio frequencies** over which wireless communication takes place for a specific purpose



- Mobile phones are allocated frequencies: 450 MHz ~ 39 GHz

- Who decides what the radio frequencies are used for?

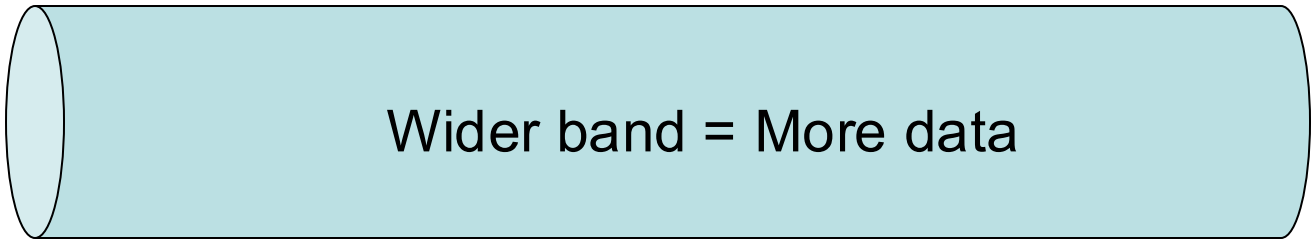
→ Each country has its own regulatory entity to carefully assign dedicated slices of radio spectrum to different services

Radio channel and Bandwidth

- To carry information, radio signal uses a **range of frequencies** over which the communication link is established
- That **range of frequencies** is called a **channel**
- Its **width** is called **bandwidth**

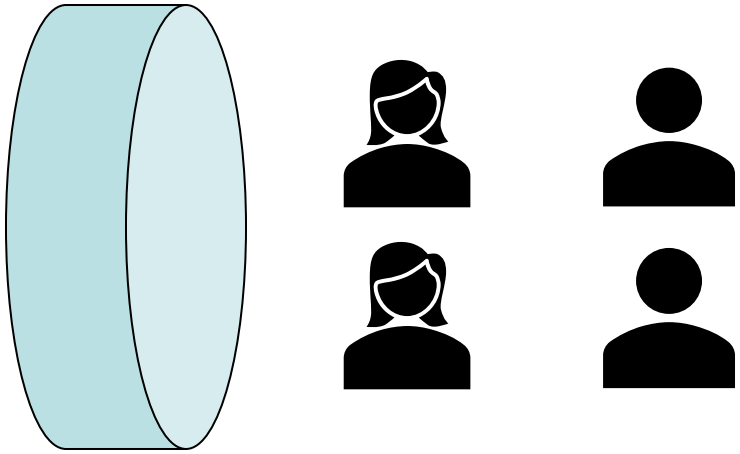
- Radio channel can be loosely classified as
  - Narrow band: A small amount of radio spectrum (~kHz)

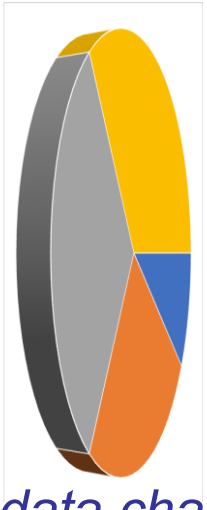
  - Wide band: A larger amount of radio spectrum (~ MHz)



Sharing radio channel

- Sharing the radio channel allows **multiple access**





Shared data channel is like a shared pipe

- As the users are **sharing the same wireless channel**, they will be allocated **fewer resources**

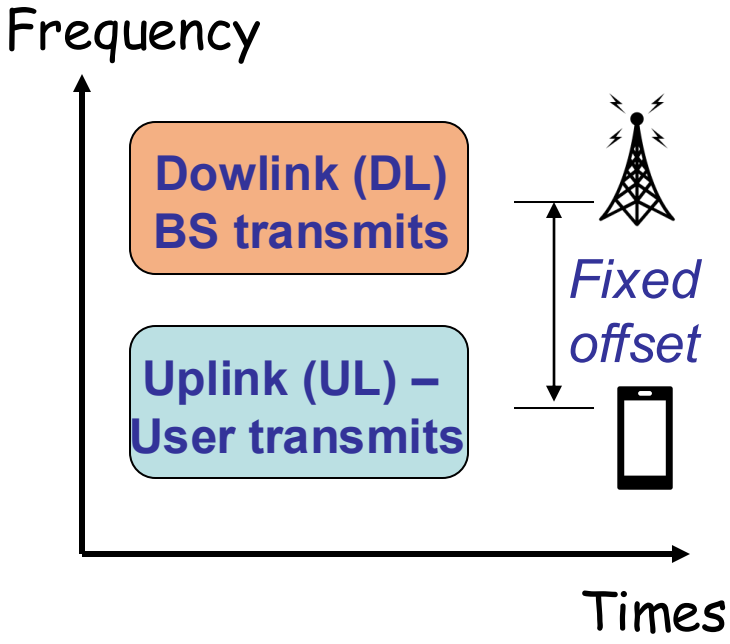
- Multiple access **smartly utilizes the attributes of the wireless channels**

Sharing radio channel

- Two ways to share the spectrum (limited and expensive)

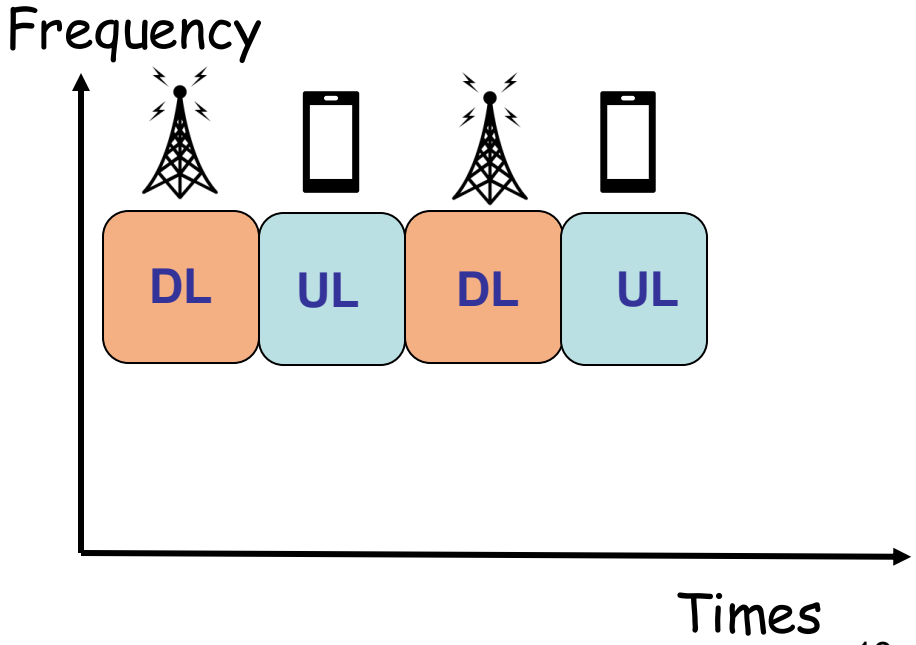
FDD
(Frequency Division Duplexing)

- A pair of channels for **simultaneous two-way communication**
- Both sides can transmit information at the same time on **independent links**



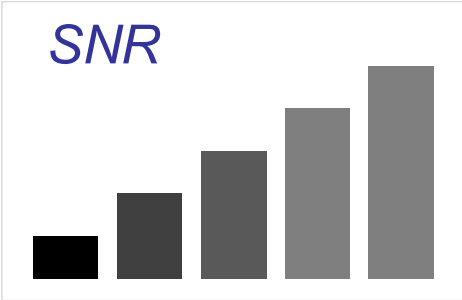
TDD
(Time Division Duplexing)

- A **single** radio channel but used in different direction in different time
- Cheaper and more flexible than FDD, but lower data speeds



Factors affecting data rate

- How fast is my connection?
  - *How many bar does my phone have?*



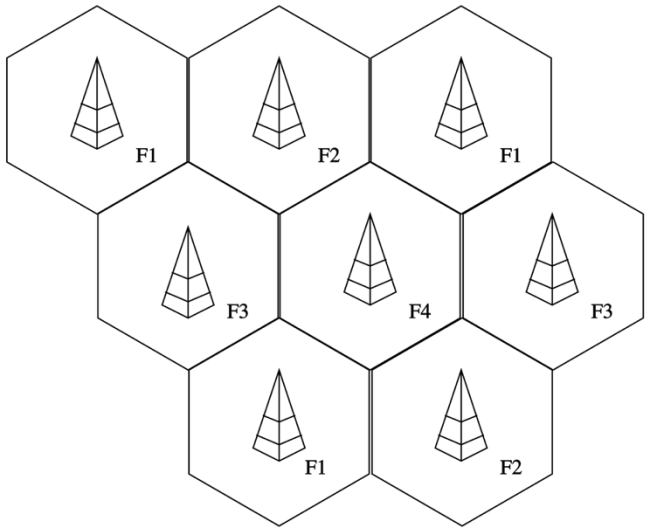
  - *How wide is my channel and how crowded is it?*

Channel capacity & Network load

  - *How frequently, and efficiently, can my phone use the available channel?*

Cellular concept

- An FM radio station and mobile network cover the city differently
- A mobile network's coverage area is divided into "**cells**"
  - Each cell is served by a base station (a "tower")
  - Cells are designed to have **"tessellating" coverage**
  - As driving, you are **handed off** from one BS to the next by the network

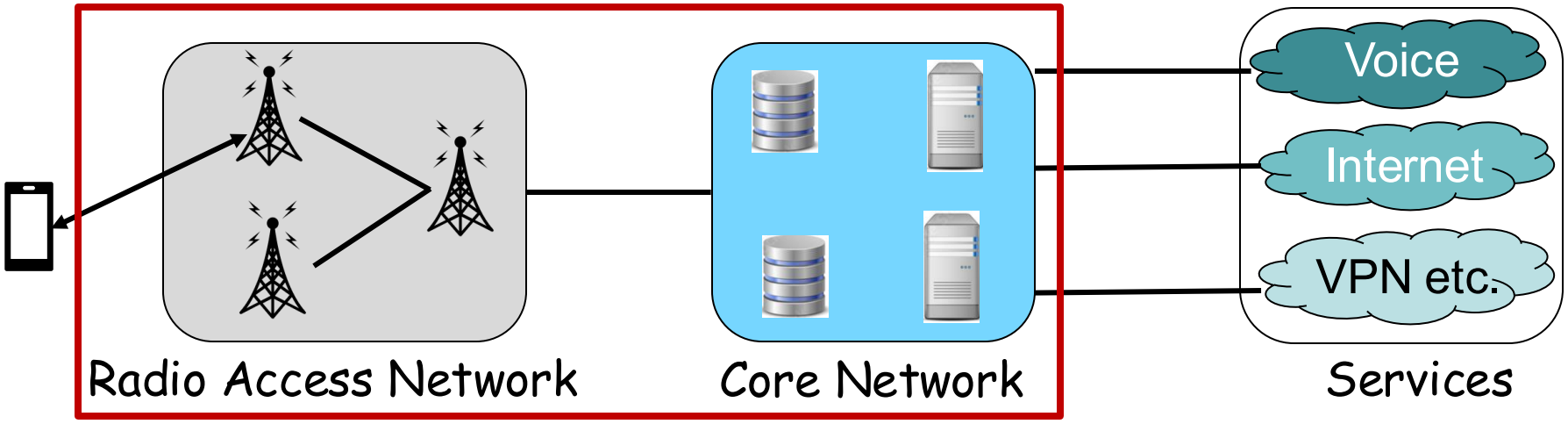


Areas lacking coverage within a cell or at the cell boundary can result in dropped calls!

Mobile network planning involves:
*- **Minimizing dropped calls***
*- **Maximizing data rate** and **coverage area** with limited number of towers*

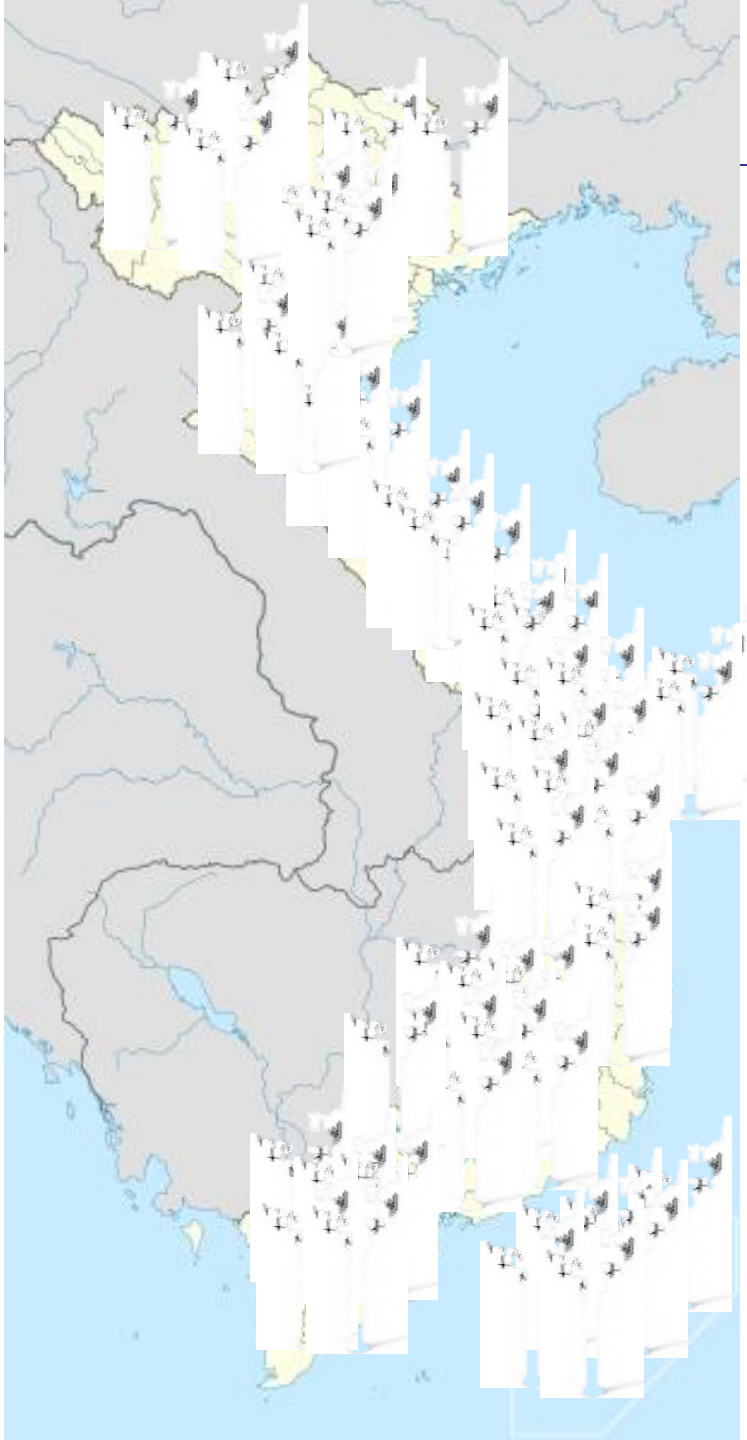
In reality, cells will not have a perfect hexagonal shape as depicted

What is a cellular network?

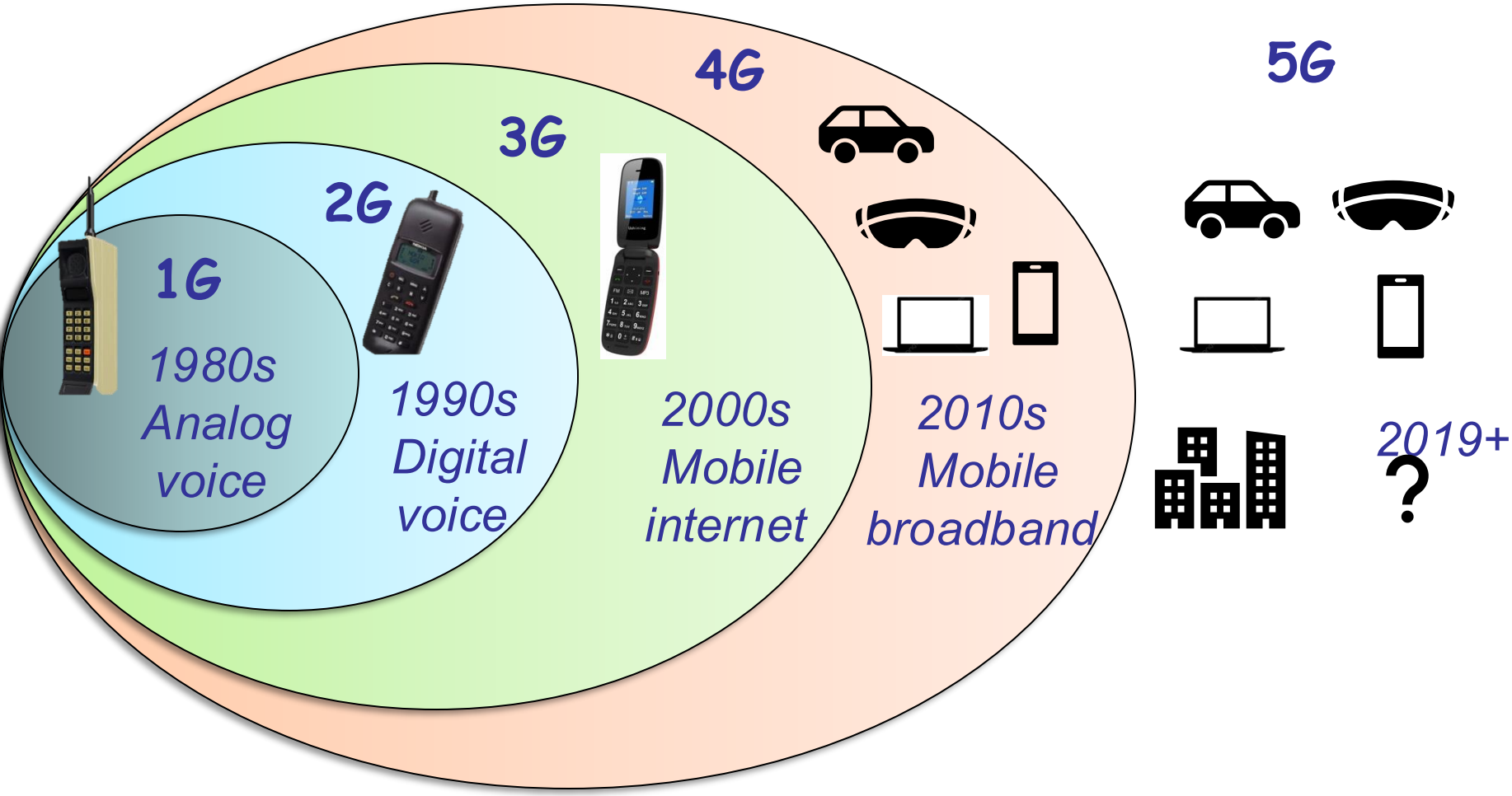


- RAN provides wireless connections to users
  - BS are interconnected → Ubiquitous mobile coverage
  - User communicates with one BS at any time
- Core network connects RAN to service networks
  - Authentication & network access
  - Switching, routing & seamless connectivity to services

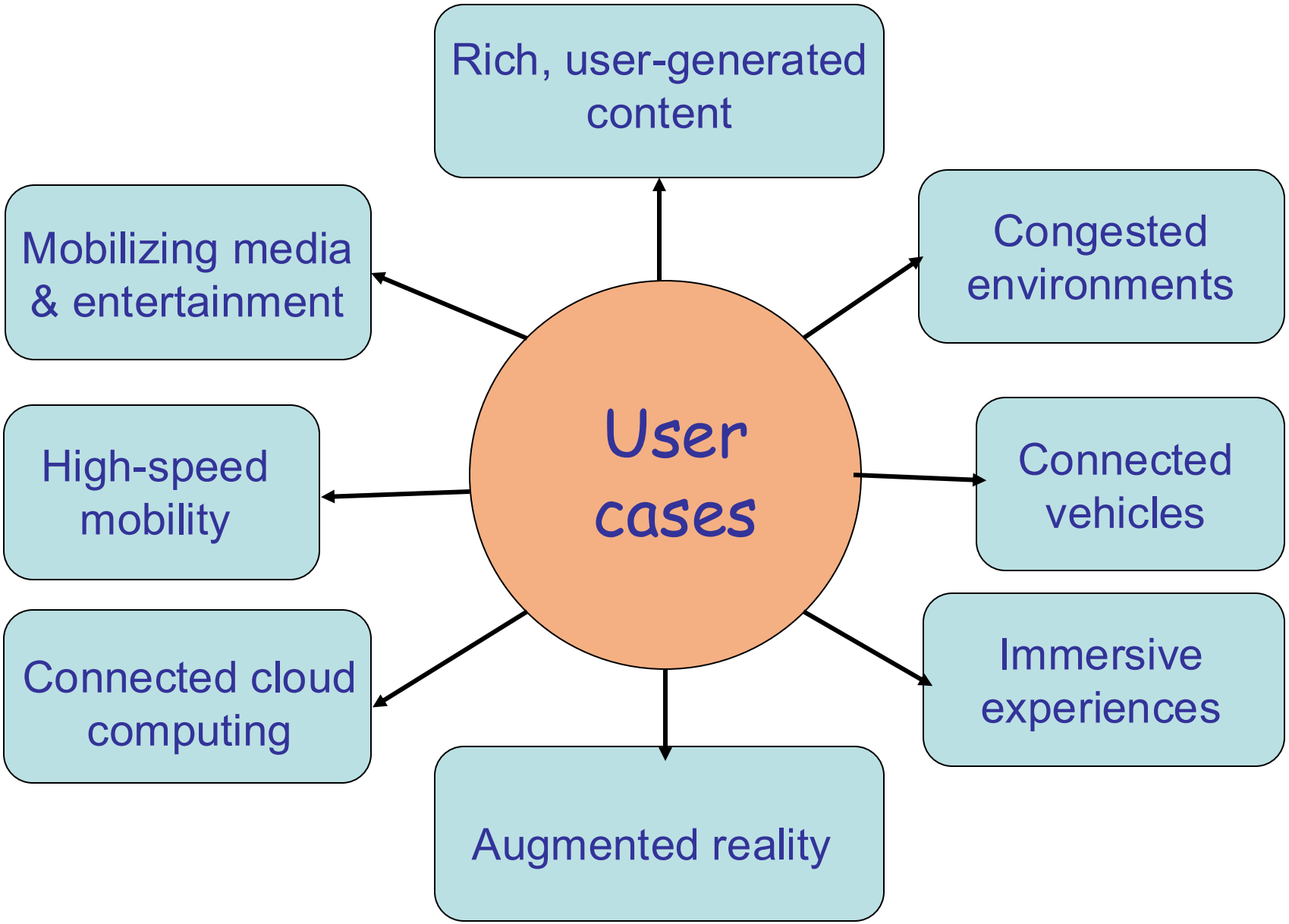
What is a cellular network?



Evolution of wireless technologies



Why do we need something beyond 4G?



5G NR: New levels of capability and efficiency

- Not just linear enhancements, but on the orders of magnitude

Multi-Gpbs peak rates for both DL, UL

Lower latency ~ 1ms

Uniform experience ~ 100 Mbps wherever

Lower cost-per-bit

10x experienced throughput

10x decrease in end-to-end latency

10x connection density

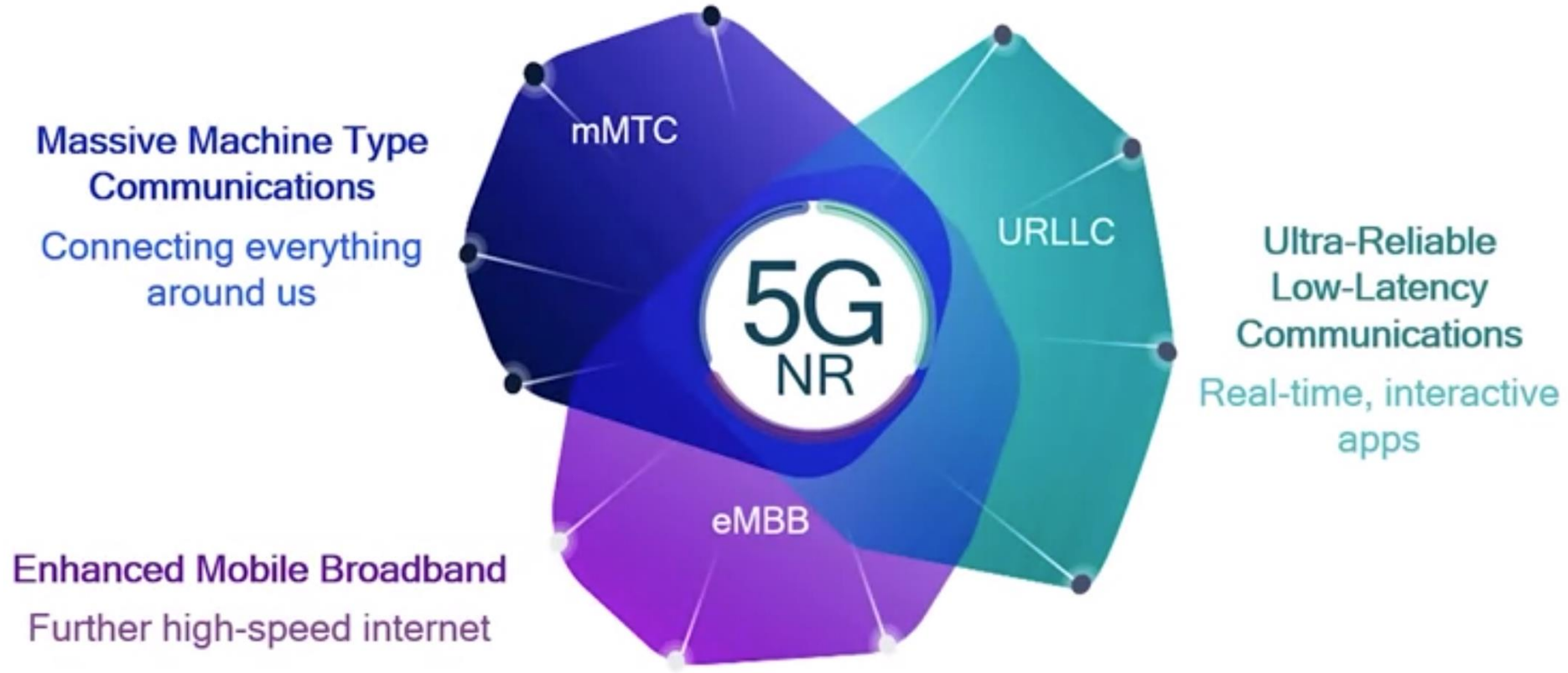
3x spectral efficiency

100x traffic capacity

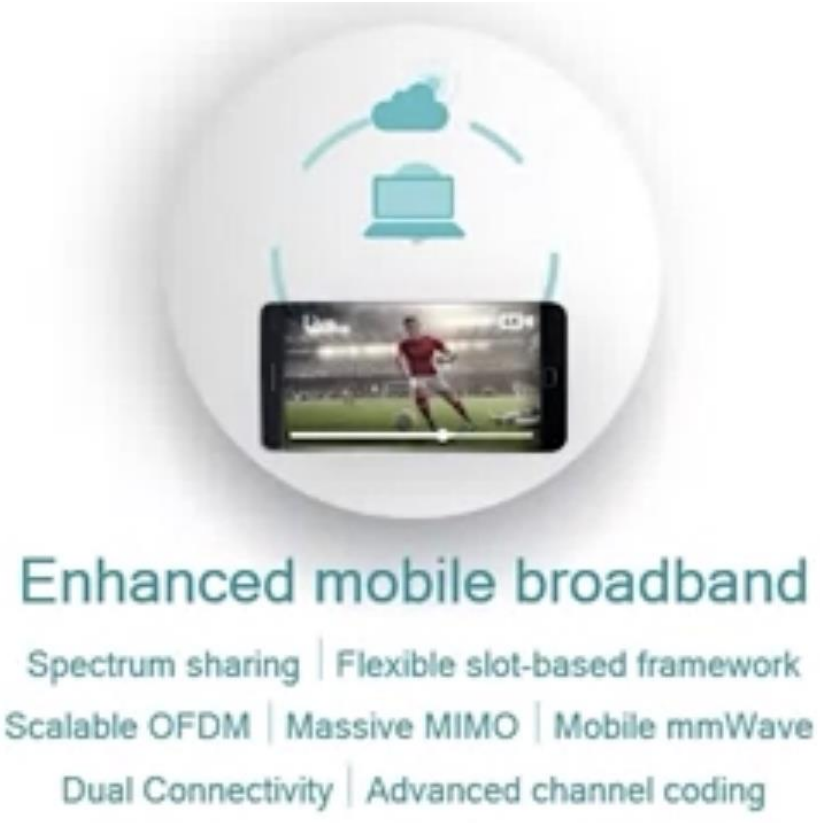
100x network efficiency

Overview of 5G NR service classes

- The same 5G framework can facilitate a diverse set of services



Enhanced mobile broadband (eMBB)



- Emphasis on higher speeds and spectral efficiency
  - Bandwidth and power usage is secondary
- Peak user data rate > 10 Gbps
- Network throughput > 1 Tbps
- Operate in macro and small cells
- Support for high-speed mobility up to 500 Kmph

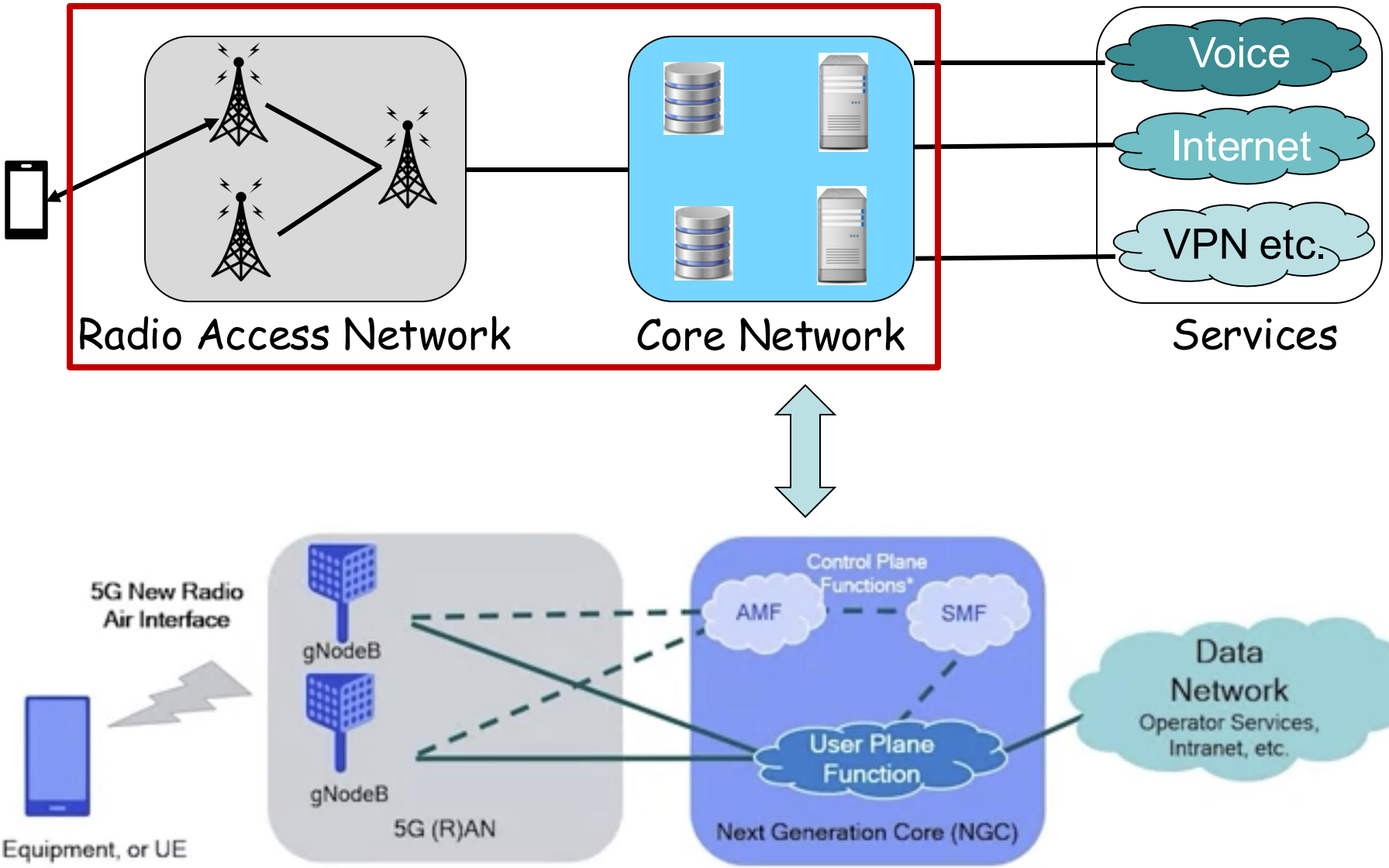
Massive machine type (mMTC)

- Connect not just people, but the worlds
- Support for high device density
  - Up to 1 million devices/km^2
- Operate over long range and in challenging coverage condition
- Simple, low-cost devices
- Expectation of very long battery life
- Emphasis on power conservation & simplicity of protocols, instead of speed & efficiency

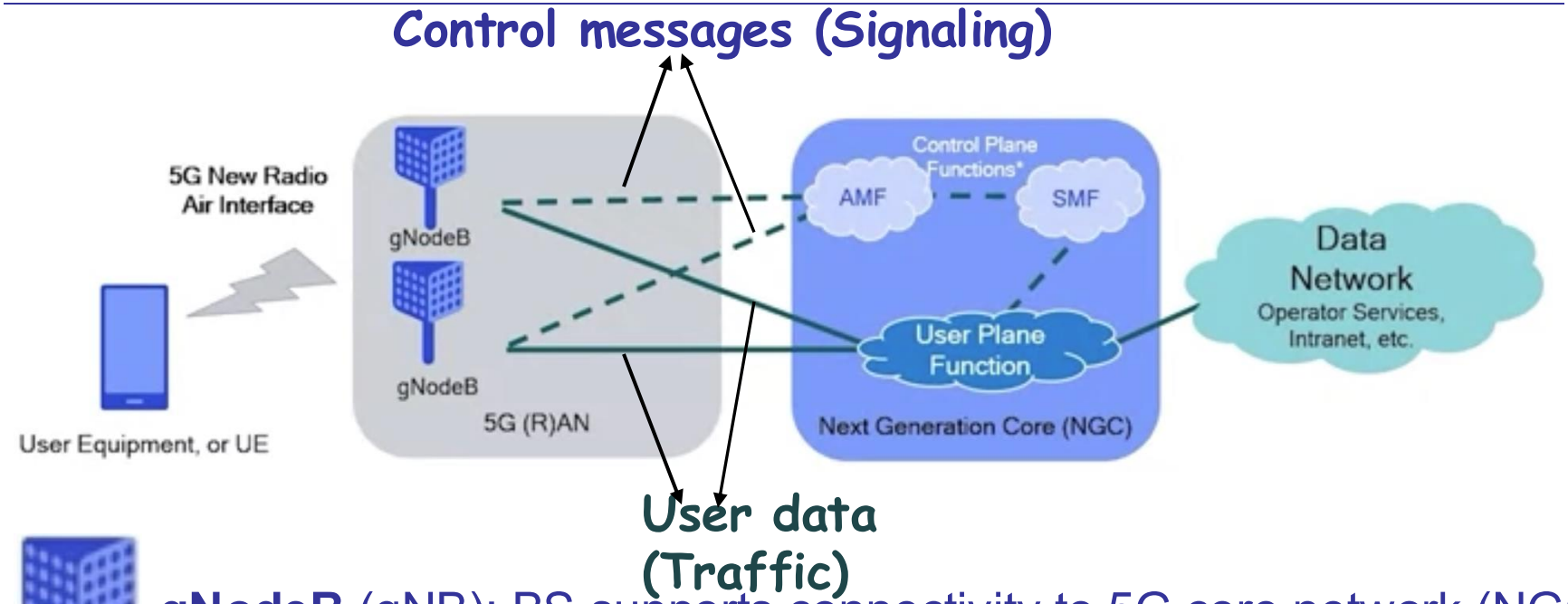
5G URLLC

- Ultra-responsive, instant connections necessary for mission-critical services
- Emphasis on E2E latency, instead of speed
- Ultra-high reliability & availability
- Support for high-speed mobility
- Fundamental redesign of protocols

5G Network terminology & concept



5G Network terminology & concept



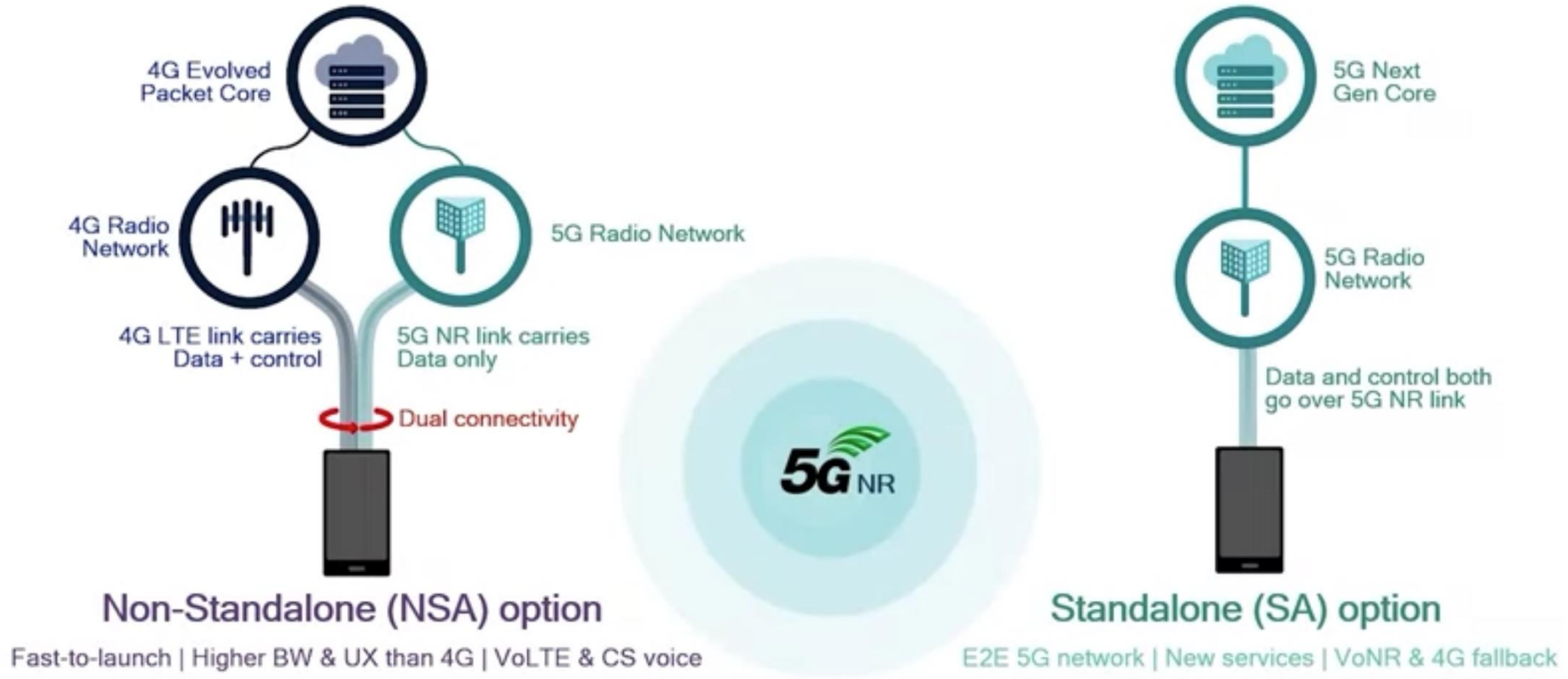
gNodeB (gNB): BS supports connectivity to 5G core network (NGC)

Access & Mobility Management Function (AMF): supports UEs' network access and manage its mobility

Session Management Function (SMF): supports signaling for IP address allocation and connectivity

User Plane Function (UPF): handles all the content generated/consumed by apps (web pages, photos, videos,…)

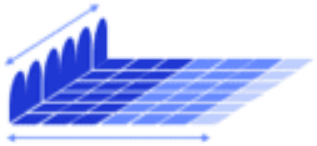
Network architecture options for 5G NR



- **Radio network**: **macro** or **small** cells, or **mix**
- **5G radio** can be **sub-6GHz**, or **mmWave**, or **mix**
- Operators **can** choose to **deploy both sub-6** and **mmWave 5G** networks in a given region where their **carrier aggregation is possible**

Overview of 5G techniques

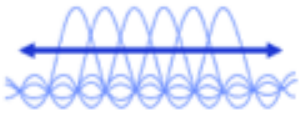
Flexible slot-based framework



Self-contained slot structure

Low latency, forward compatibility

Scalable OFDM-based air interface



Scalable OFDM numerology

Address diverse services, spectrum, deployments

Advanced channel coding

Multi-Edge LDPC and CRC-Aided Polar

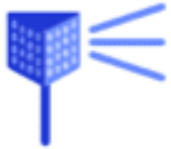
More efficient delivery of multi-Gbps throughput

Massive MIMO

Reciprocity-based MU-MIMO

Increased network coverage and capacity

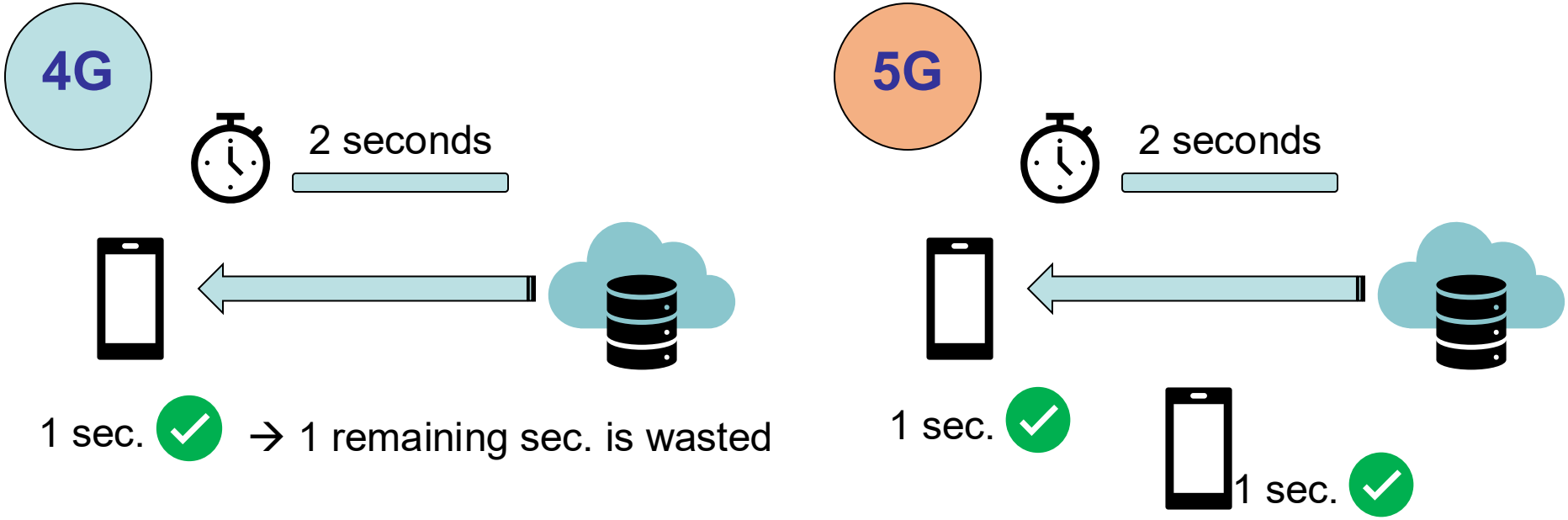
Mobile mmWave



Beamforming and beam-tracking

Extreme capacity and throughput

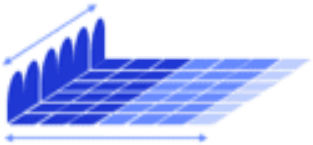
Flexible slot-based framework



Flexible slot-based framework is **carefully utilizing** the resource and **making certain changes at runtime** to significantly **improve** the **operational efficiency**

Flexible slot-based framework

Flexible slot-based framework

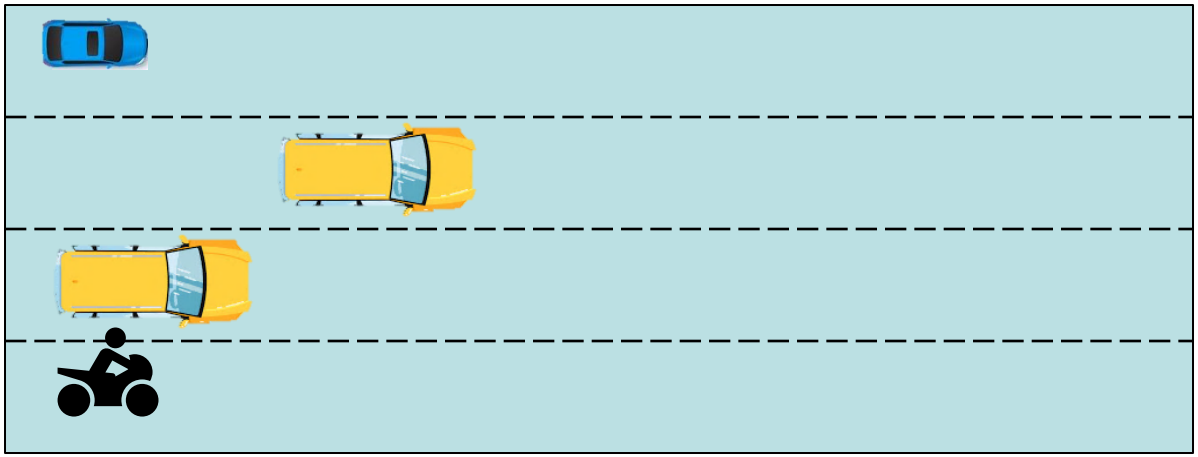


Low latency, forward compatibility

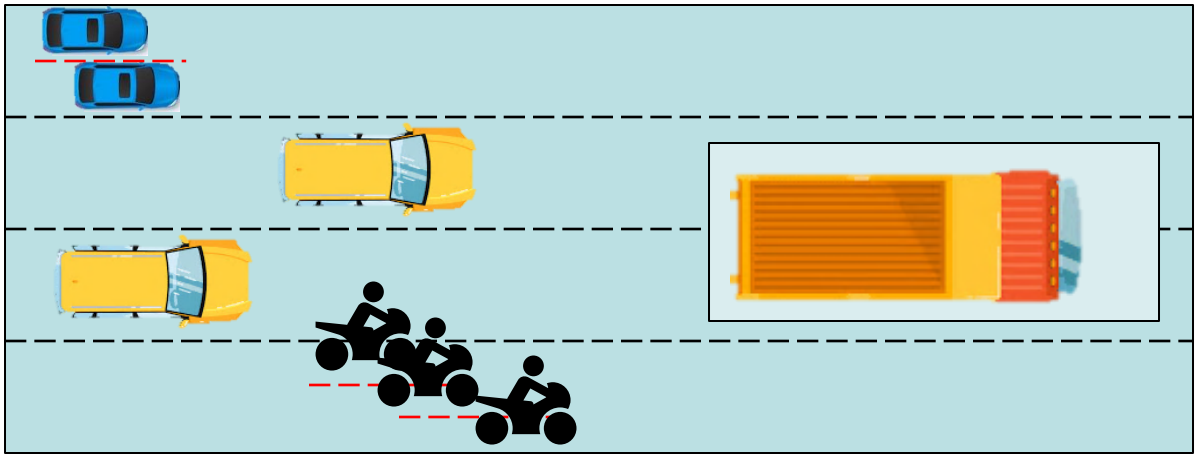
≈

Flexible road framework

Dynamically and efficiently adapt to all traffic types and situations

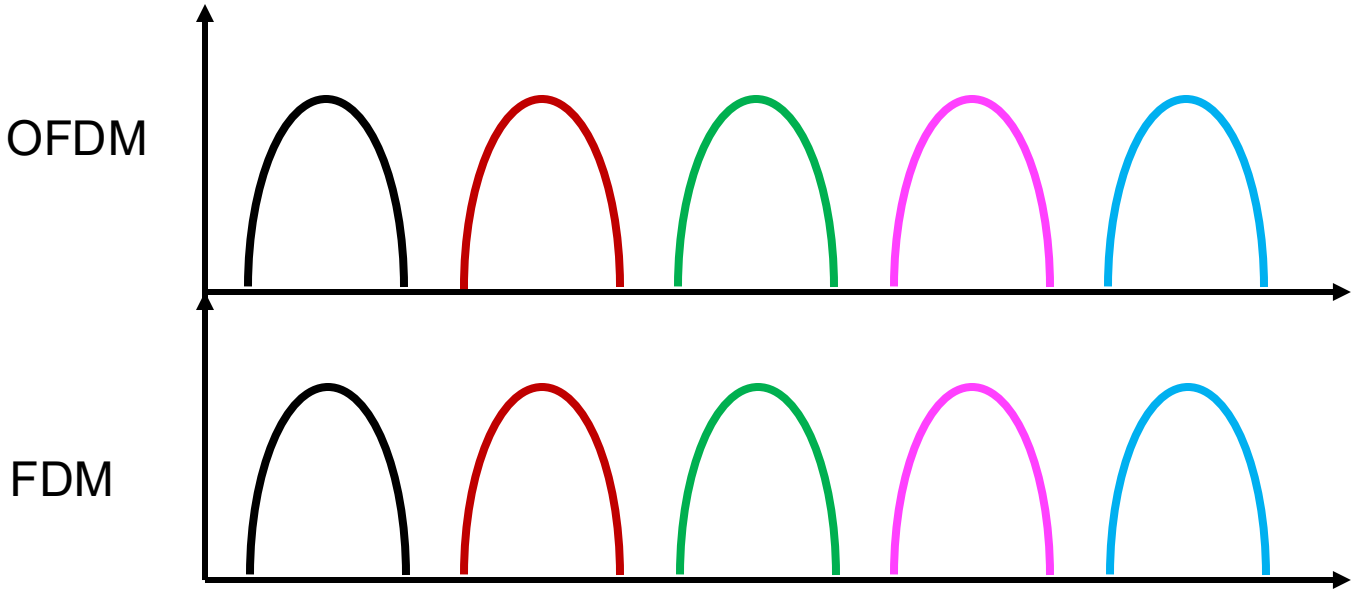


Fix-sized vehicle, but dynamic lane



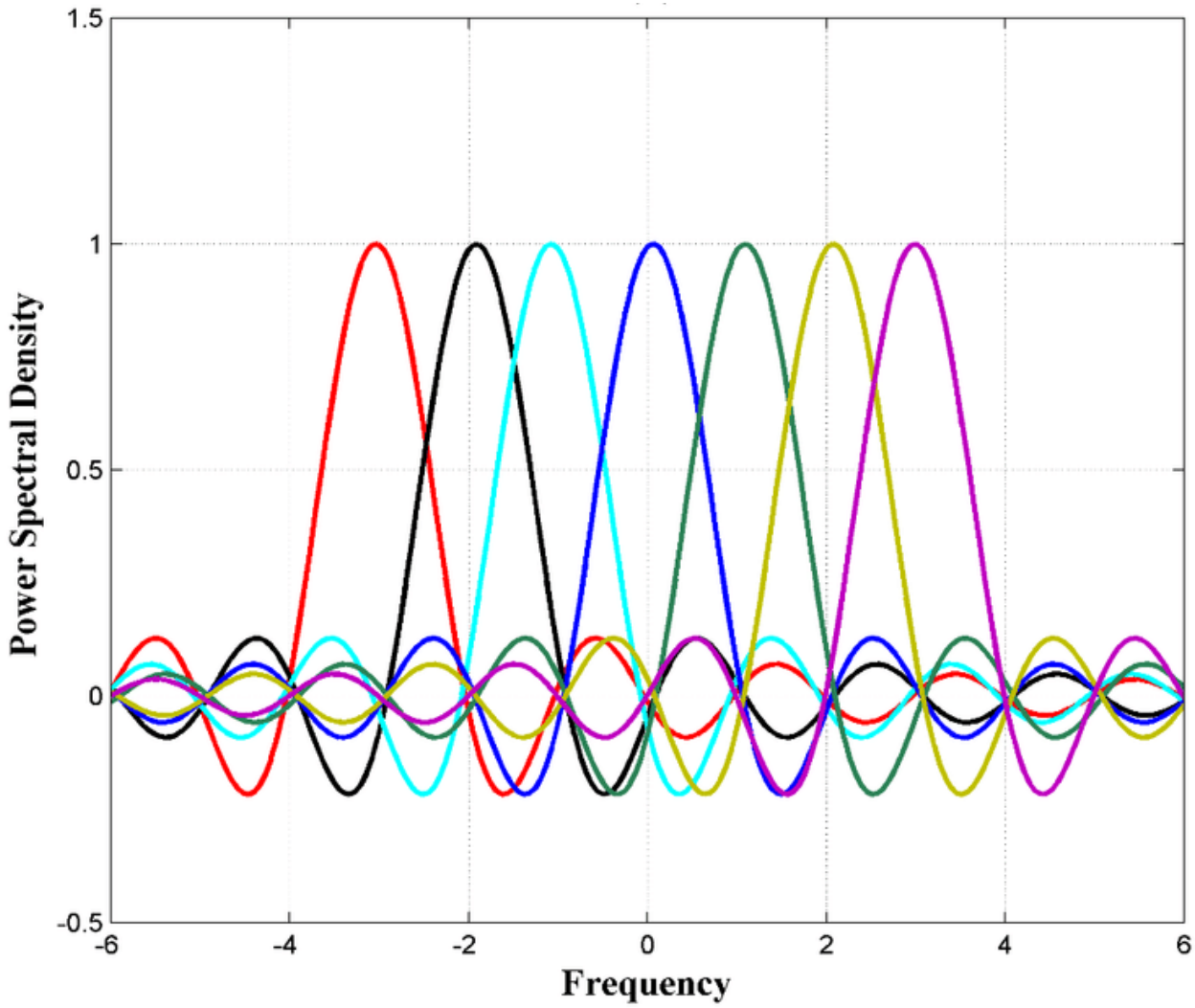
Scalable OFDM-based air interface

- OFDM: orthogonal frequency division multiplexing



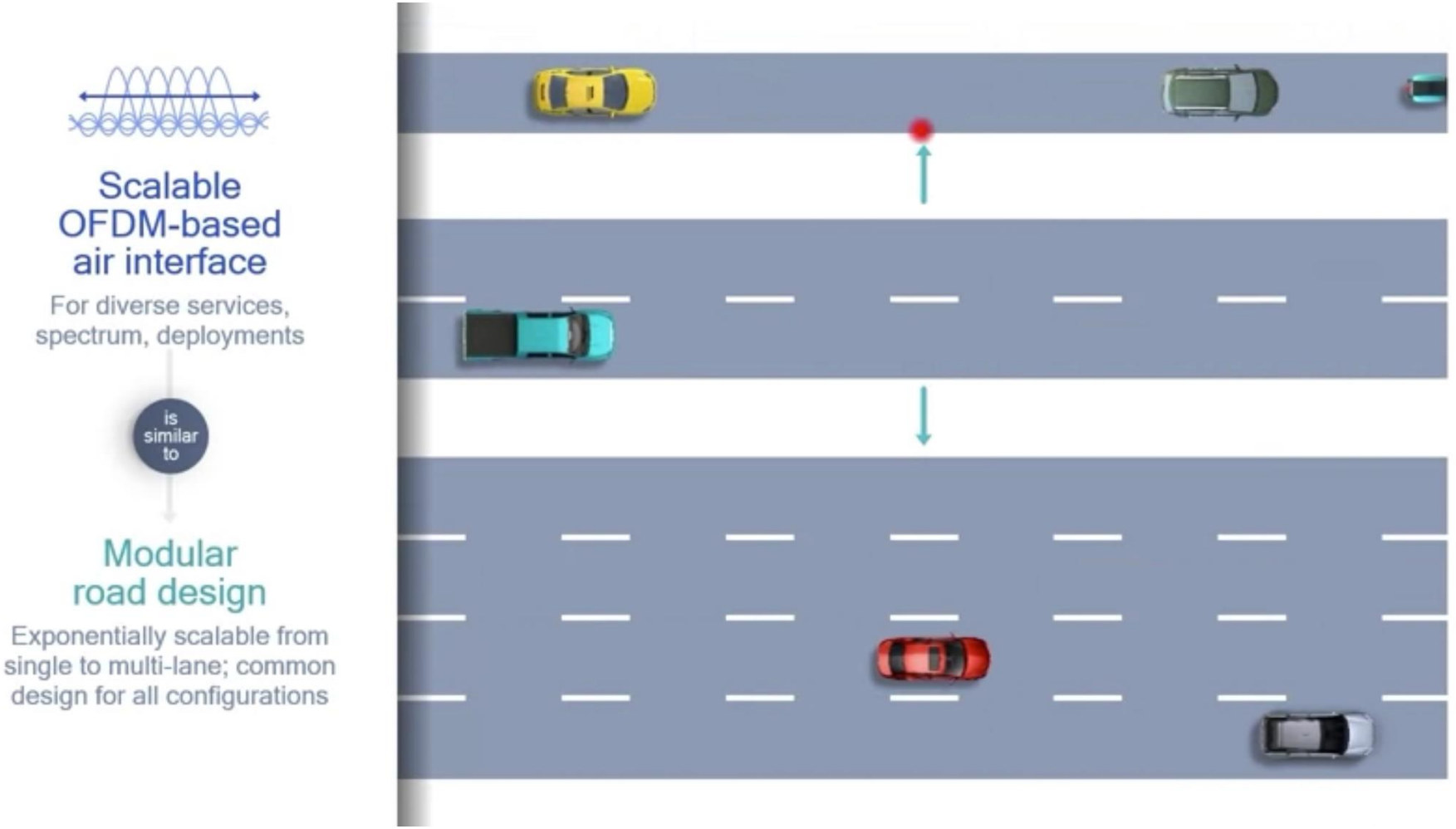
Scalable OFDM-based air interface

- OFDM: orthogonal frequency division multiplexing



Scalable OFDM-based air interface

- Scale OFDM?



Advanced channel coding

- Wireless signal **faces** several **impediments**
  - Pathloss, interference, noise,…

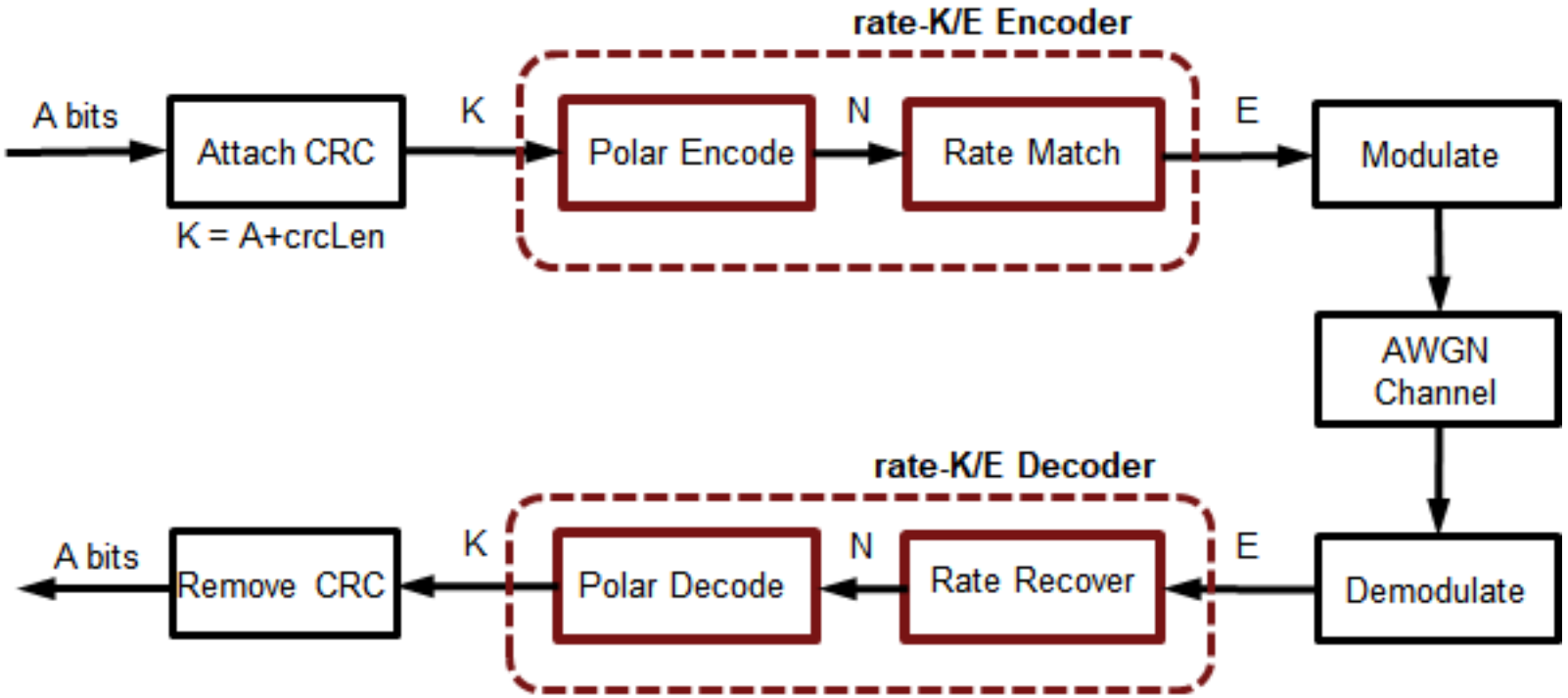
→ Receiver is **difficult to decode** & **demodulate** or **extract** the intended data from the carrier wave

- **Channel coding**: protection mechanism to **limit** the **effect** of such **impediments** on the outgoing wireless signal
  - Error control coding, Forward error correction code
  - **Wrap additional metadata** to the intended data
  - The receiver **could decode** and **demodulate** the data **even** in presence of **noise** and **interference**.

→ Channel coding **improves efficiency** of communication overall

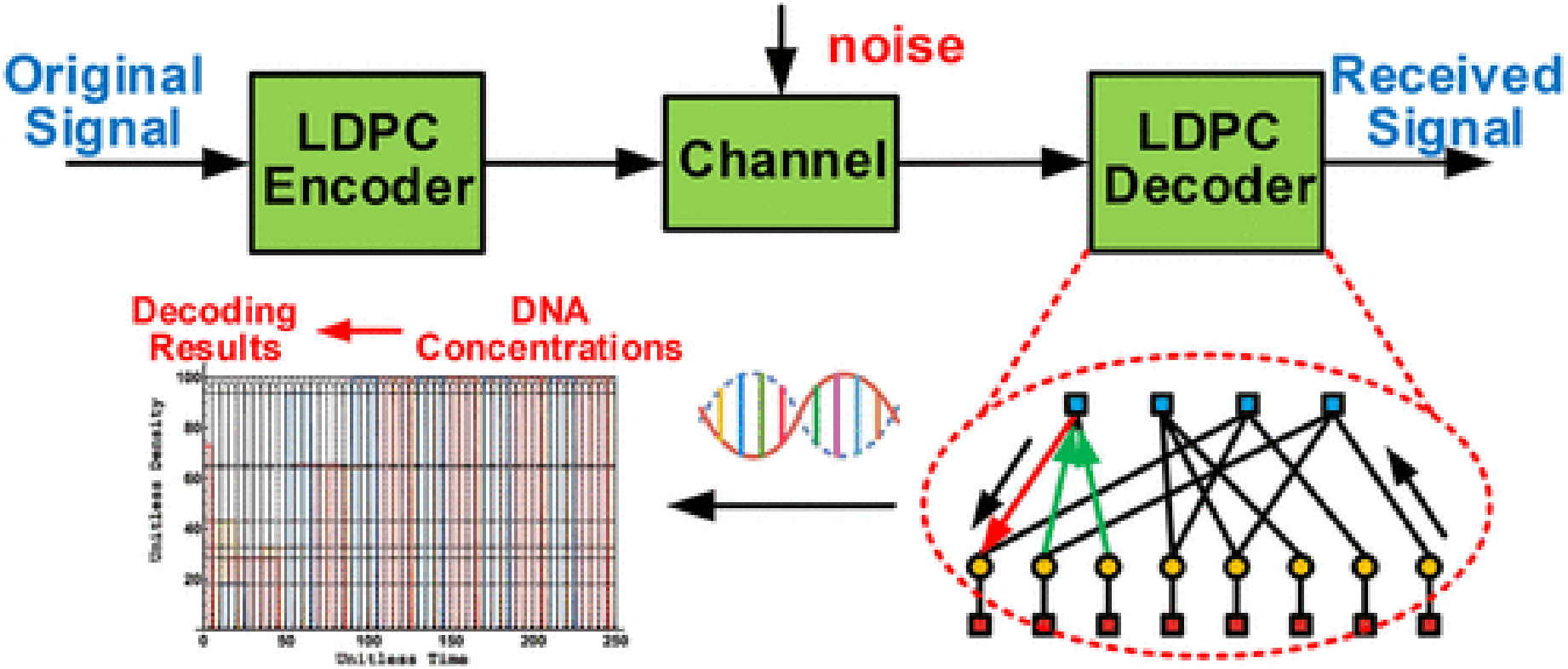
Advanced channel coding

- Polar codes
  - A type of linear block code
  - First introduced by Arikan in 2009



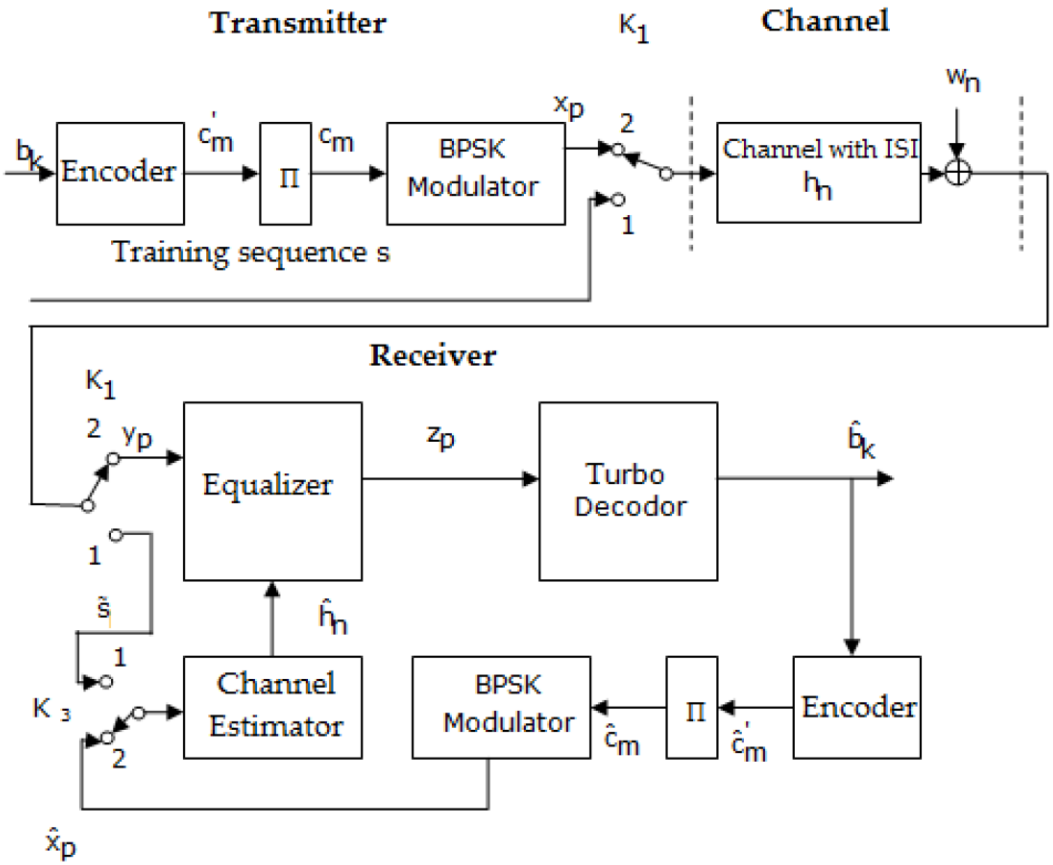
Advanced channel coding

- Low-density parity-check (LDPC) codes
  - a linear error correcting code
  - Constructed using a sparse Tanner graph



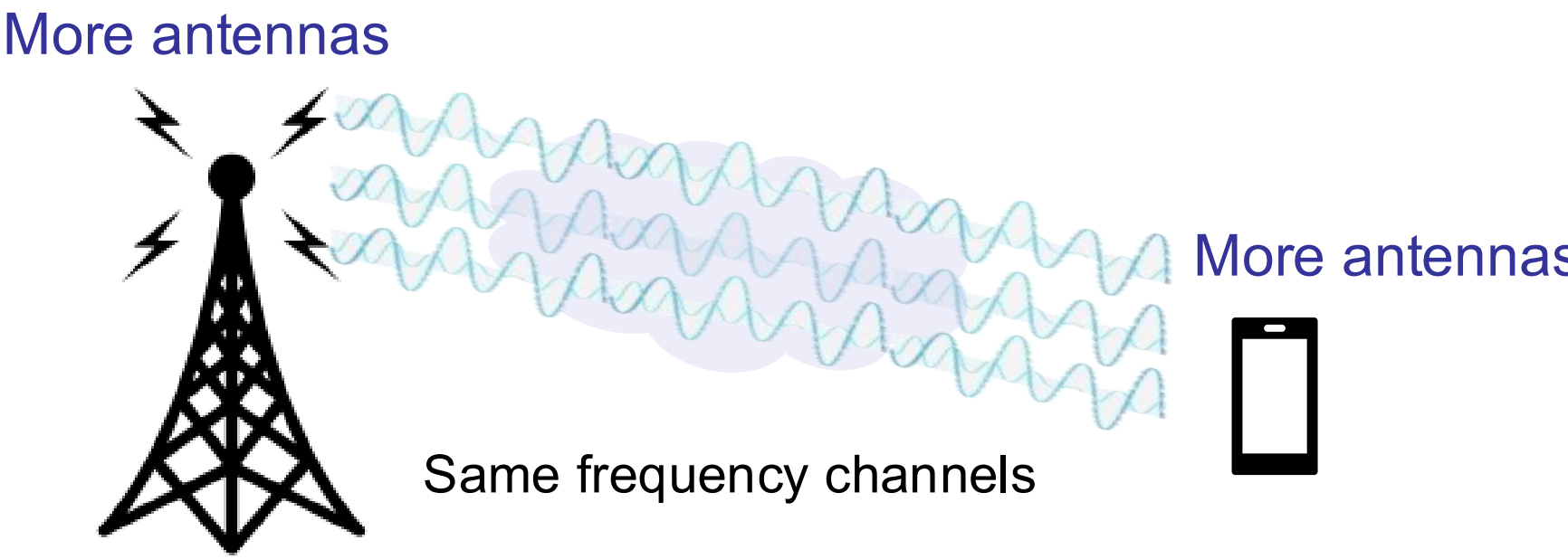
Advanced channel coding

- Turbo codes:
  - Forward error correction



Massive MIMO

- MIMO: Multiple Input, Multiple Output



Massive MIMO

Massive MIMO

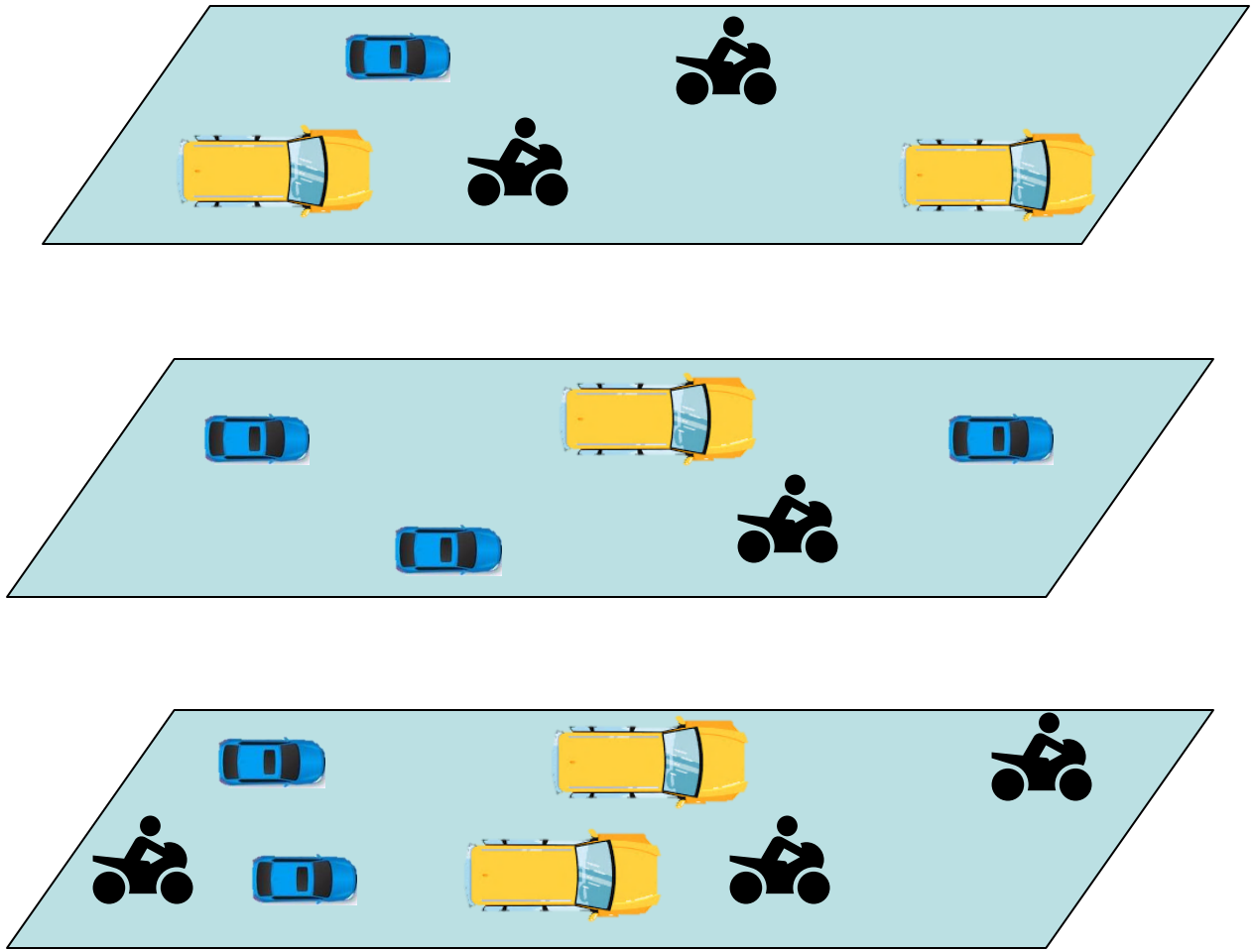
Reciprocity-based MU-MIMO

Increased network coverage and capacity

≈

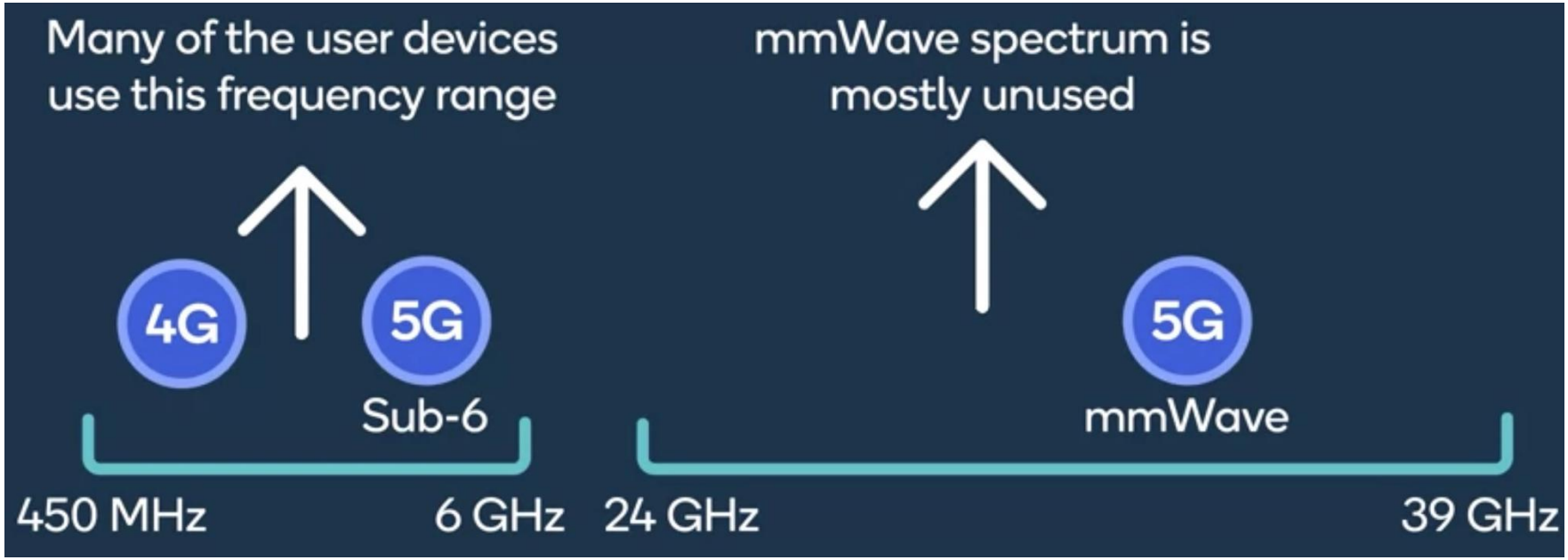
Multi-deck road

Stacking roads to allow more cars to travel faster



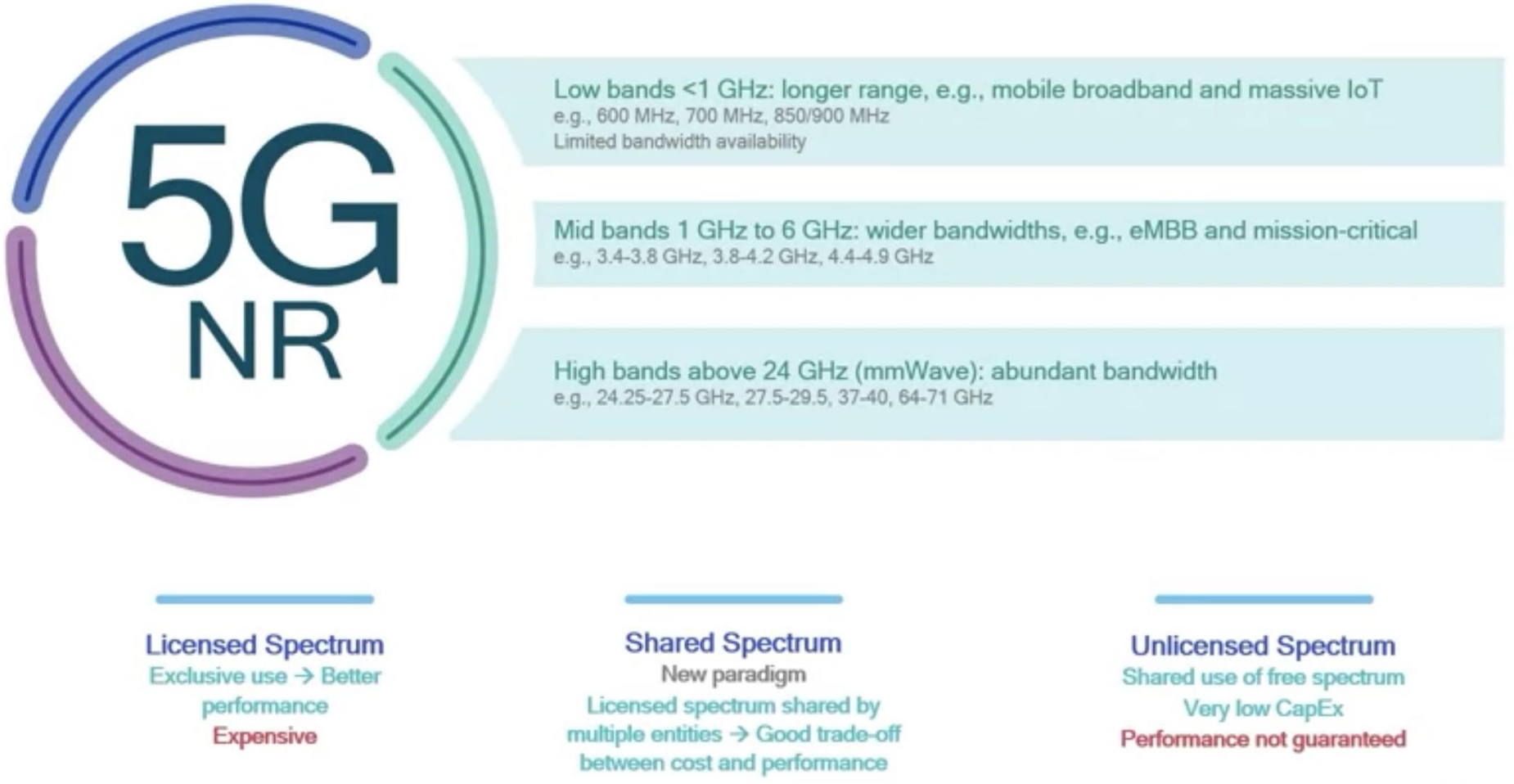
Mobile mmWave

- mmWave: a certain range of frequencies where your signal wavelength is on the order of a few millimeters.

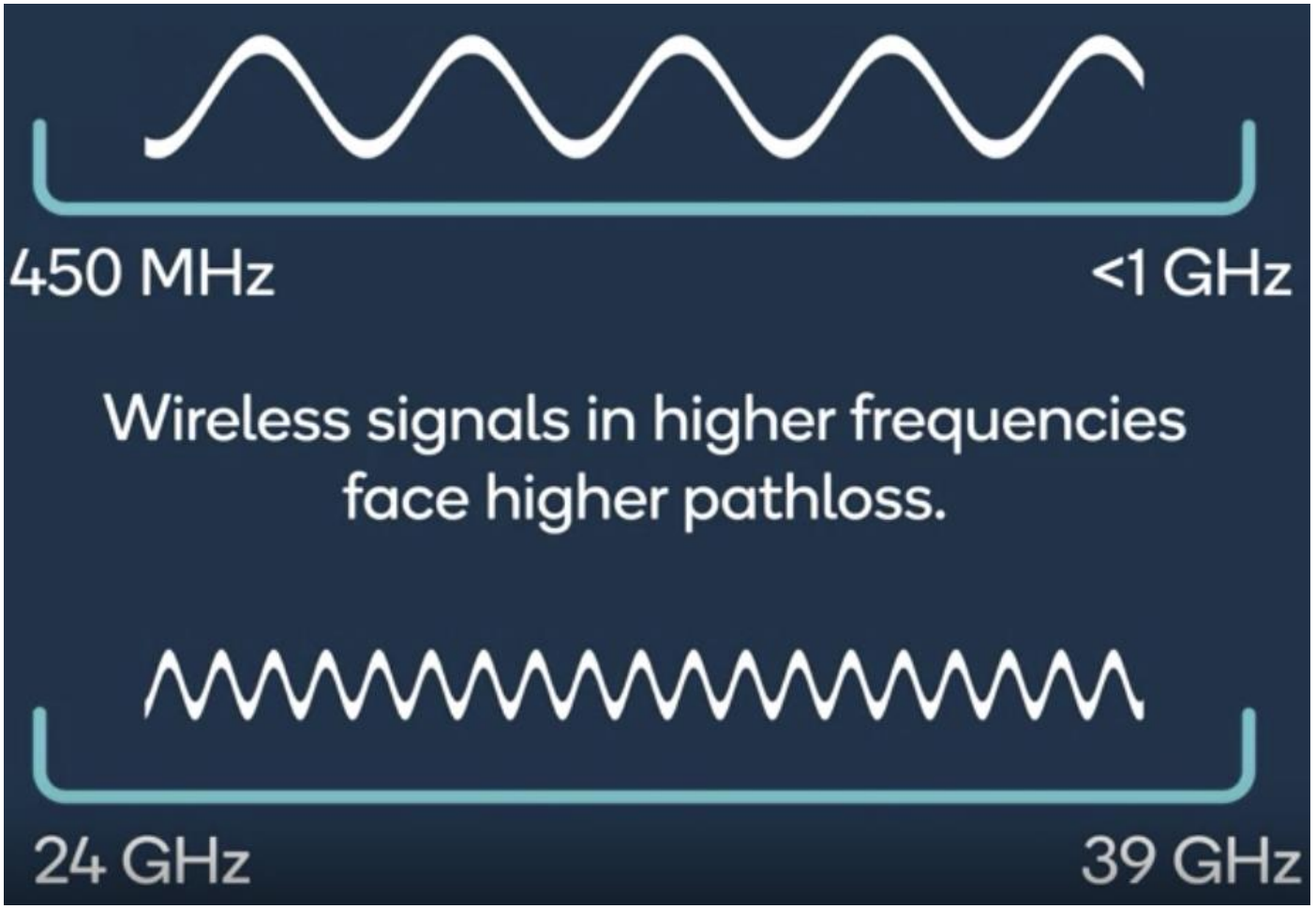


Mobile mmWave

- mmWave: a certain range of frequencies where your signal wavelength is on the order of a few millimeters.

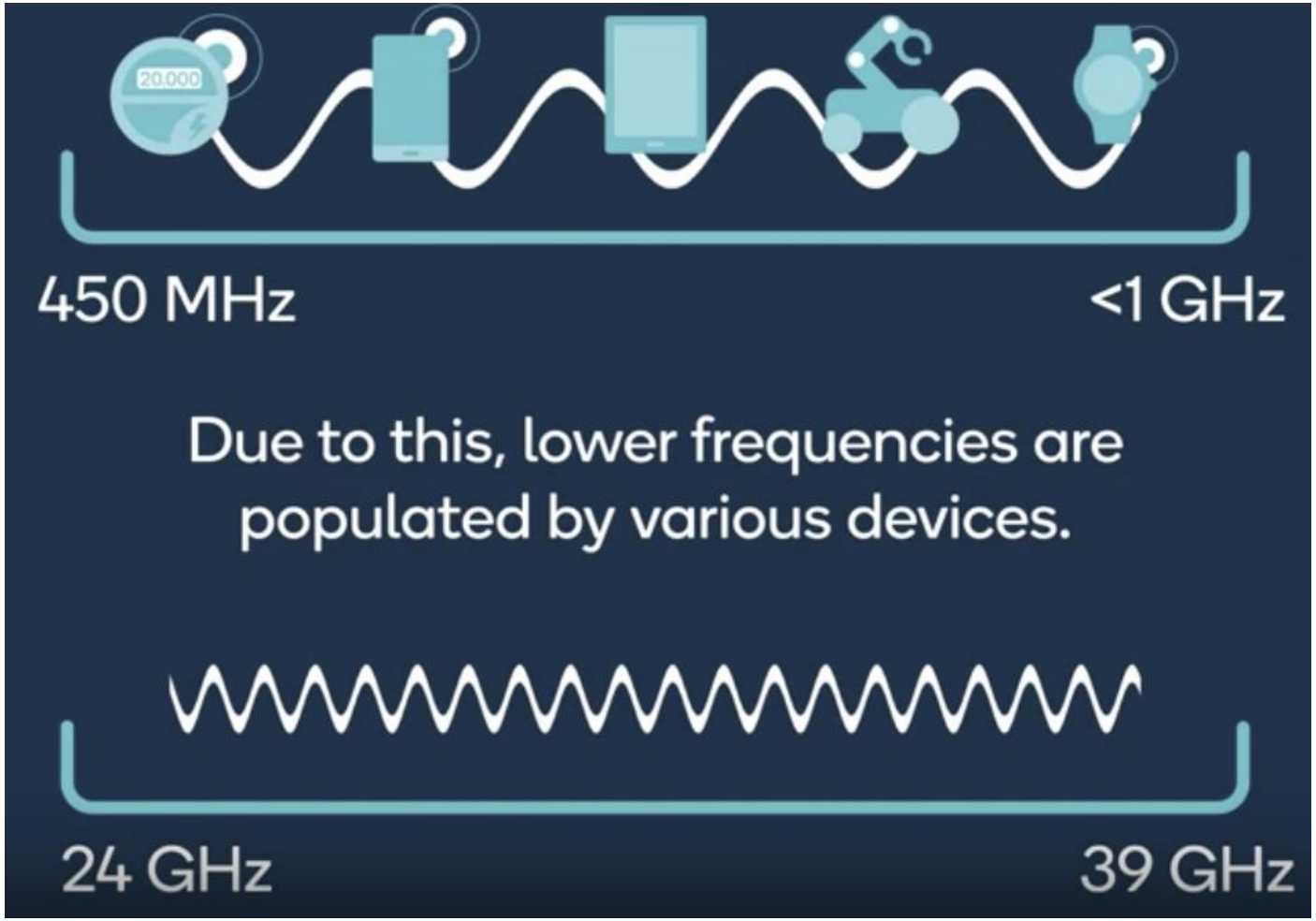


Mobile mmWave



- mmWave: a certain range of frequencies where your signal wavelength is on the order of a few millimeters.

Mobile mmWave

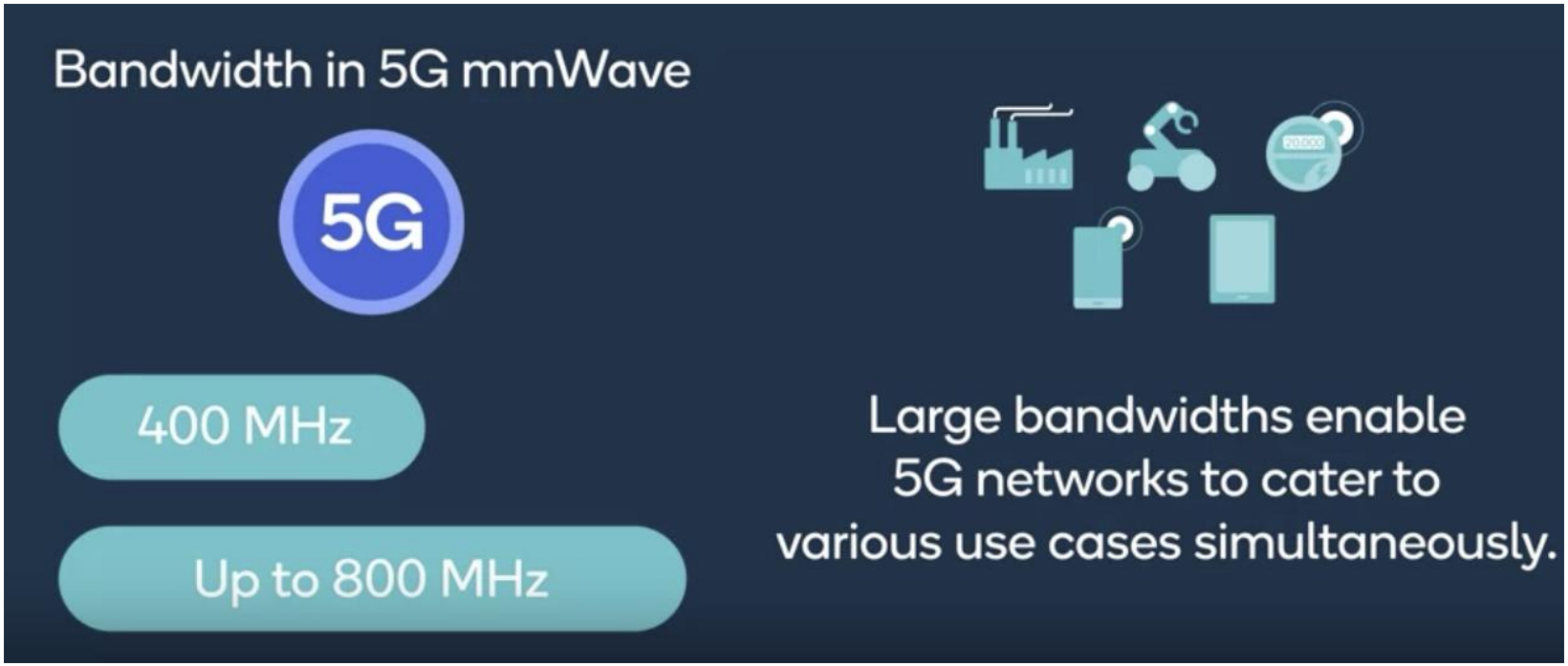


- mmWave: a certain range of frequencies where your signal wavelength is on the order of a few millimeters.

Motivation behind mmWave deployments

- Why mmWave?
  - Currently, mmWave is largely unused → ample spectrum available
  - Enormous bandwidth

  → can fulfill the demand of data-hungry 5G use cases



Challenges behind mmWave deployments

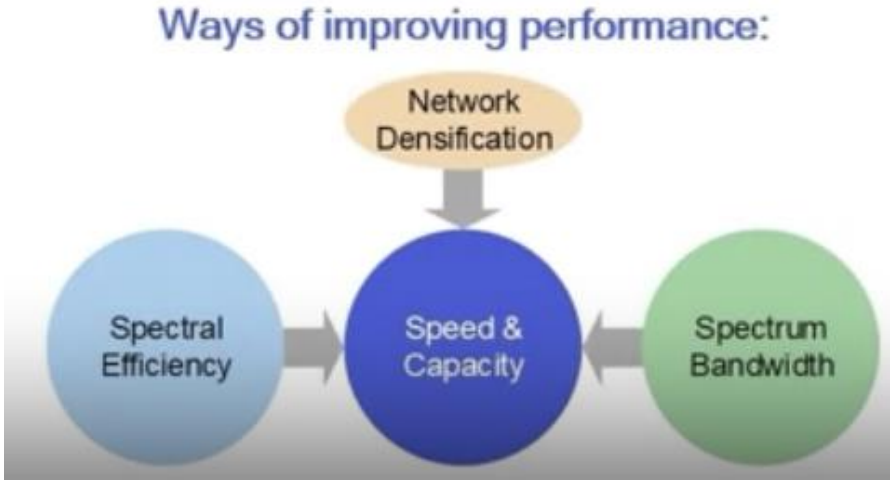
- Challenges?
  - Inferior propagation: higher frequency → significantly higher PL
  - Building penetration loss: Deep indoor coverage is challenging
  - Severe attenuation due to rain and foliage

- Advantages of high-frequency
  - Large bandwidth → Less crowding
  - More antennas → Higher gain
  - High directivity → Better focus

  → Higher spectral efficiency

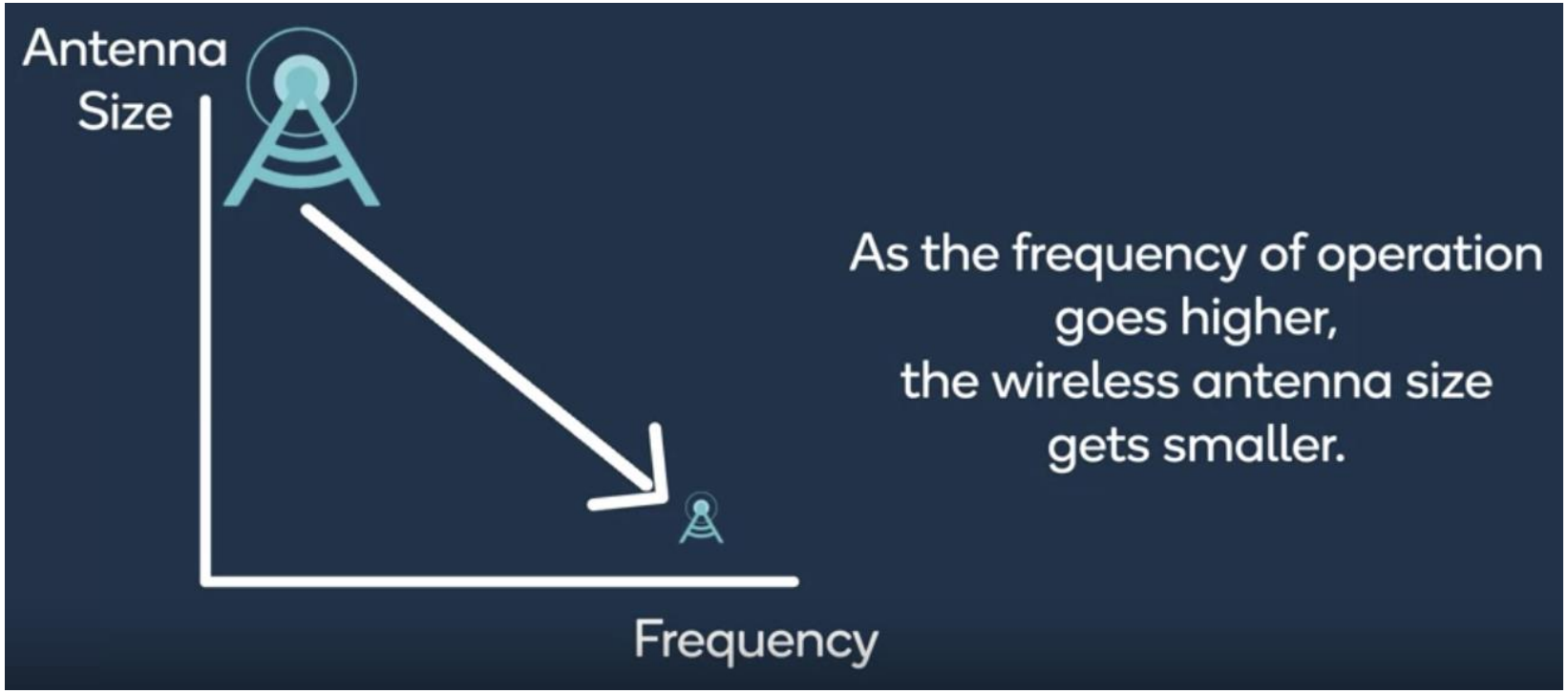
  - Higher Pathloss and directivity

  → Better spatial reuse



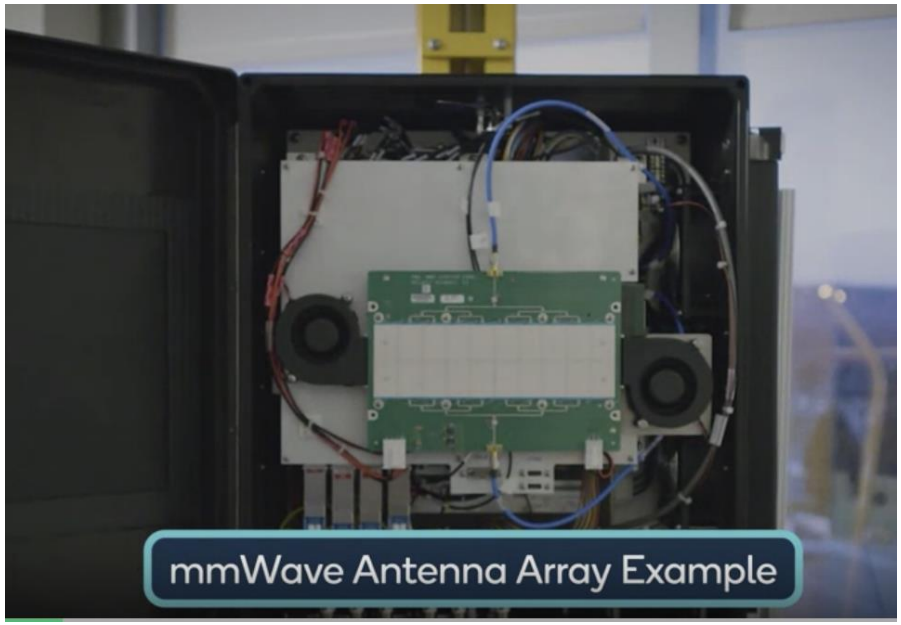
Advantage of mmWave

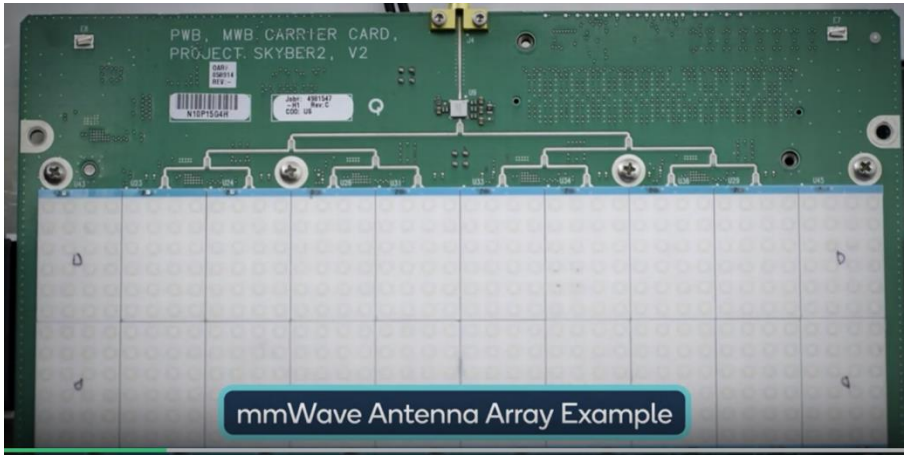
- More antennas → Higher gain

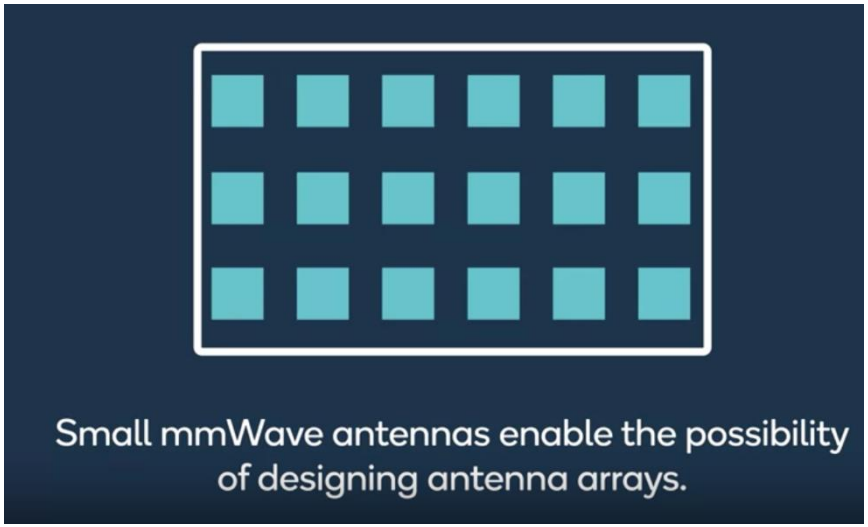


Advantage of mmWave

- More antennas → Higher gain

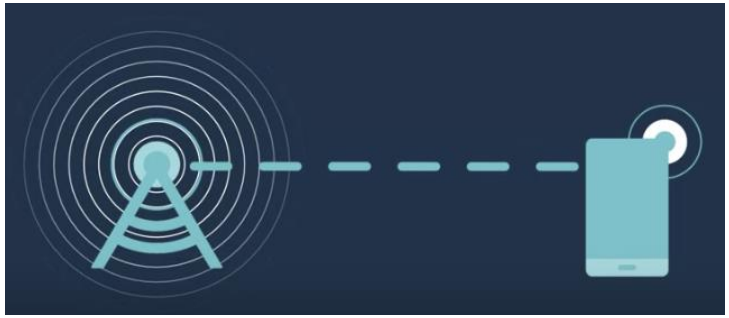


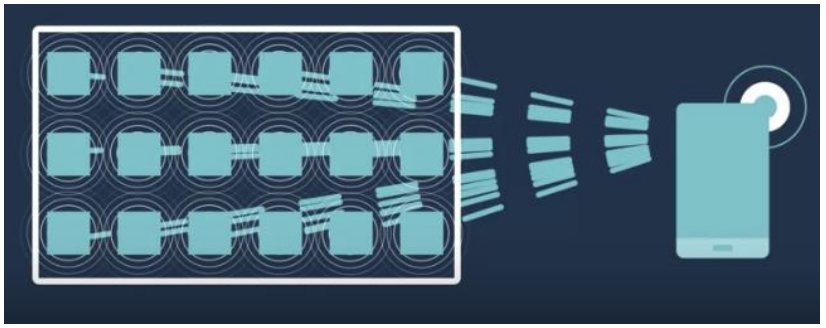


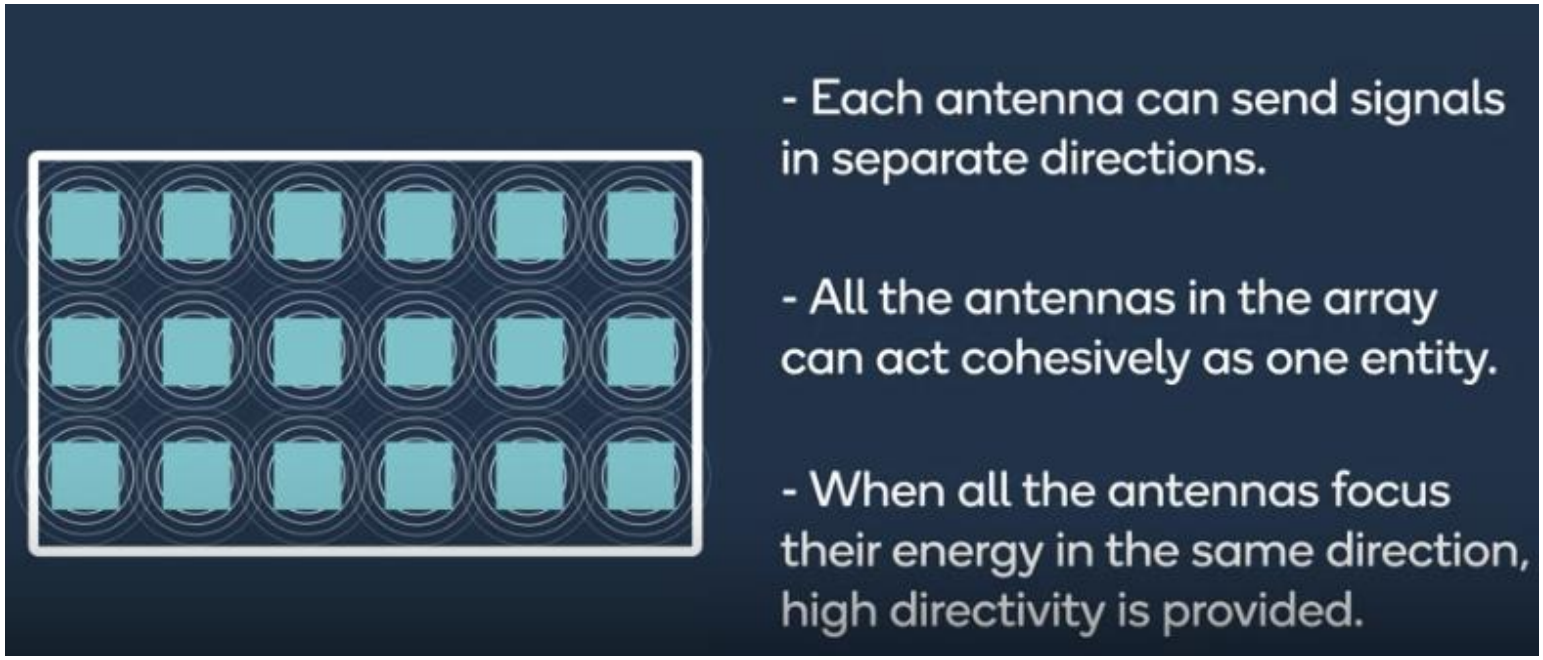


Advantage of mmWave

- High directivity → Better focus → Higher spectral efficiency

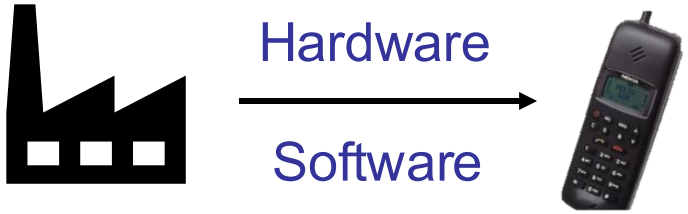


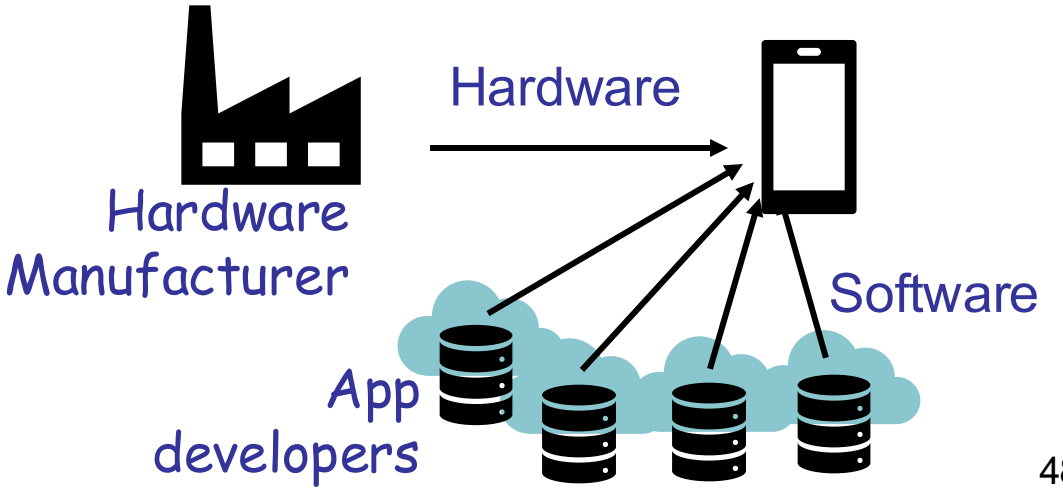




5G network principles

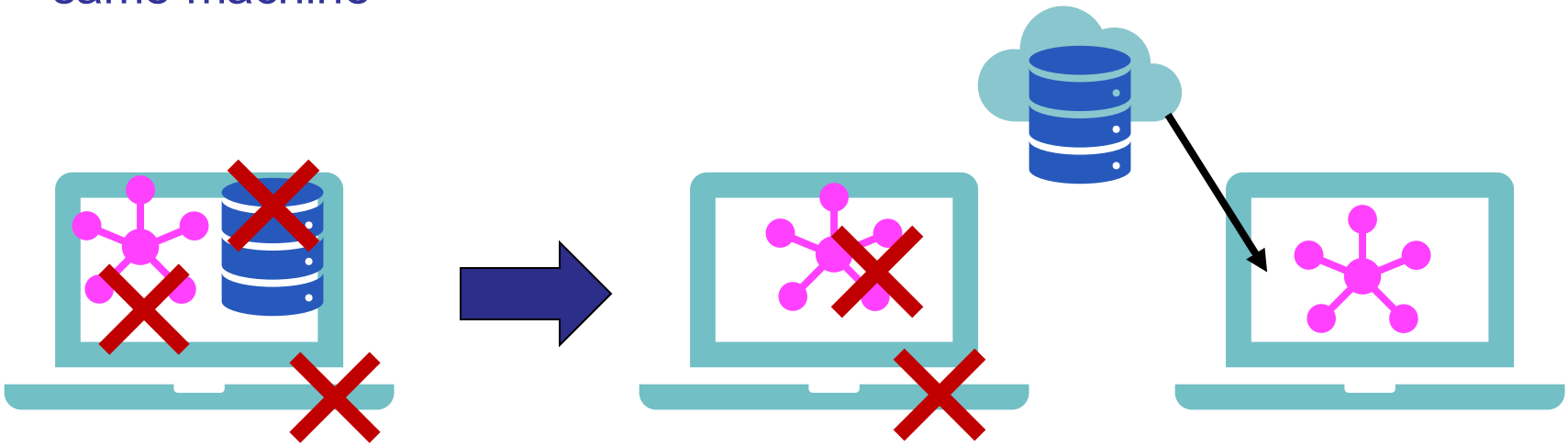
1. Independence of software from hardware
   - Legacy technologies (e.g., 4G, Wi-Fi): most network components are **an integrated box**, performing a specific functionality with its **own hardware and software**





5G network principles

1. Independence of software from hardware
2. Decoupling of compute and storage resources
   - **Compute resource**: network servers for **performing high-power computations**
   - **Storage resource:** anything **stores data** for the **long-term**
   - Previous technologies: compute and storage resources on the same machine



5G network principles

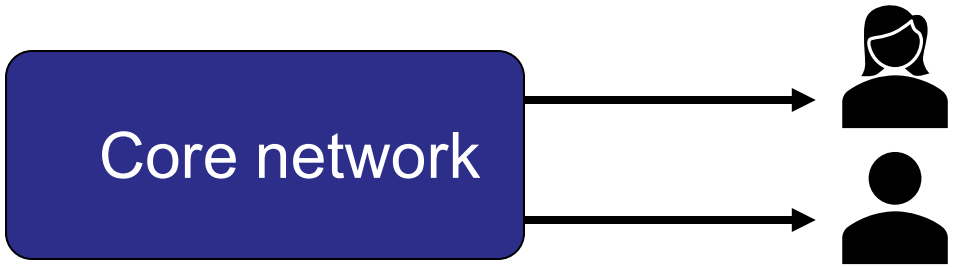
1. Independence of software from hardware
2. Decoupling of compute and storage resources
3. Separation of user plane from control plane (signaling)
4. Cloud-compatible design: flexible and easily scalable

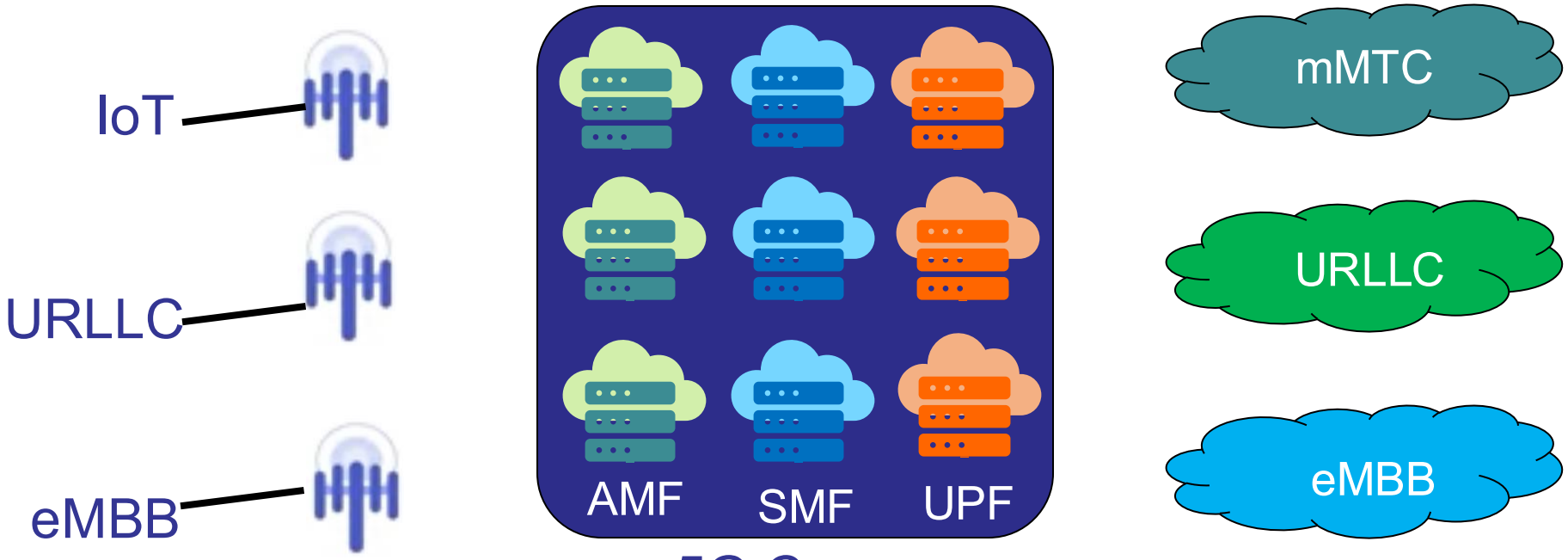
- To implement these principles in reality, 5G leverages the following features

Network Slicing	SDN Software-Defined Network	NFV Network Function Virtualization	MEC Mobile Edge Computing

Network slicing

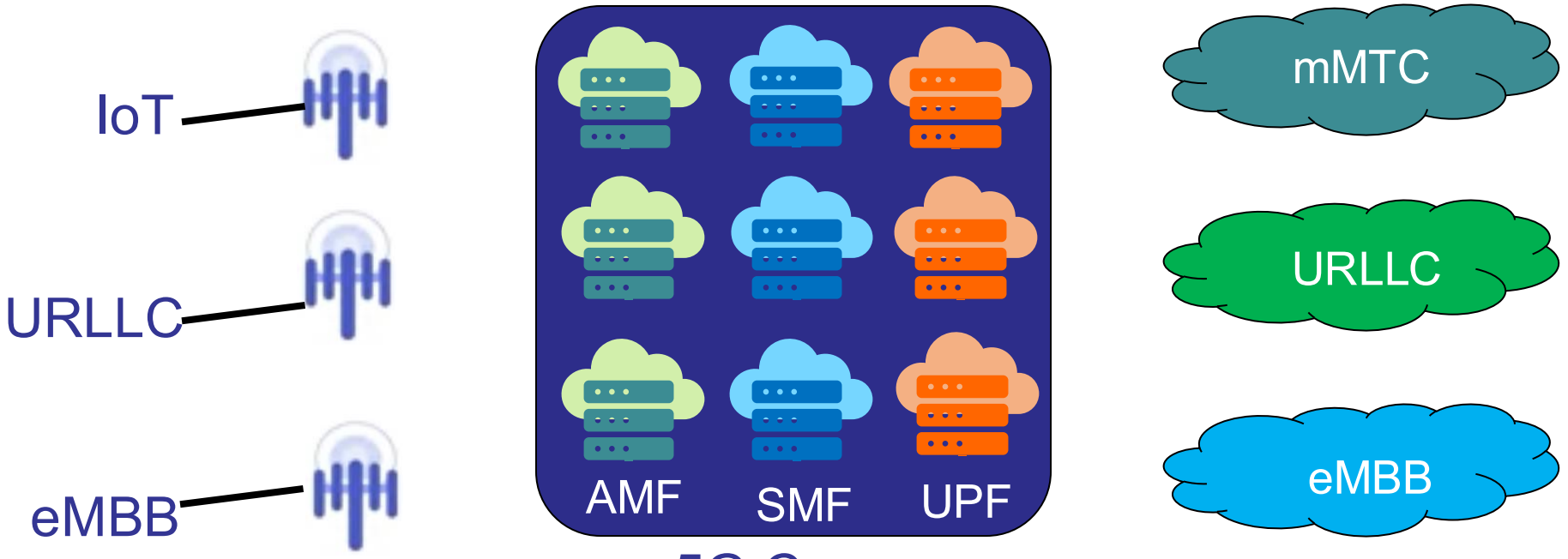
- How were the traditional cellular networks (core network) deployed?





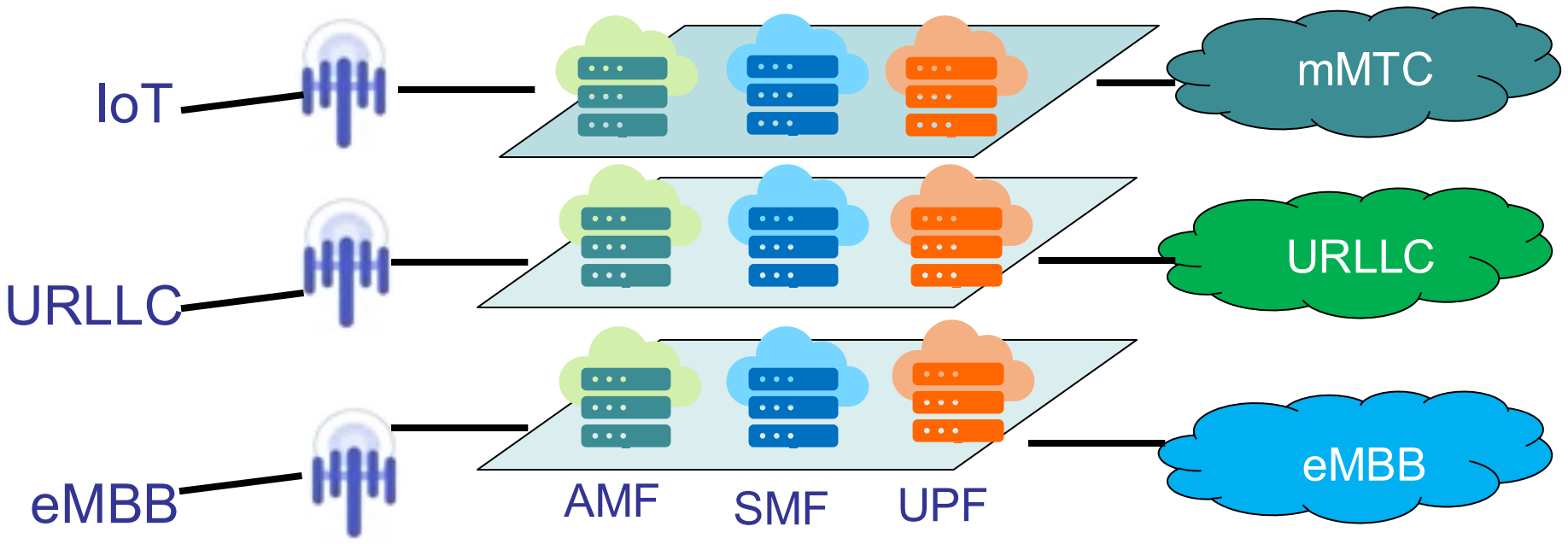
Network slicing

- A slice is a subset of the available network components providing an E2E services
- A slice can be designed & licensed upon the needs of services
- Diverse requirements of different services can be met by serving them with different slices of the same network



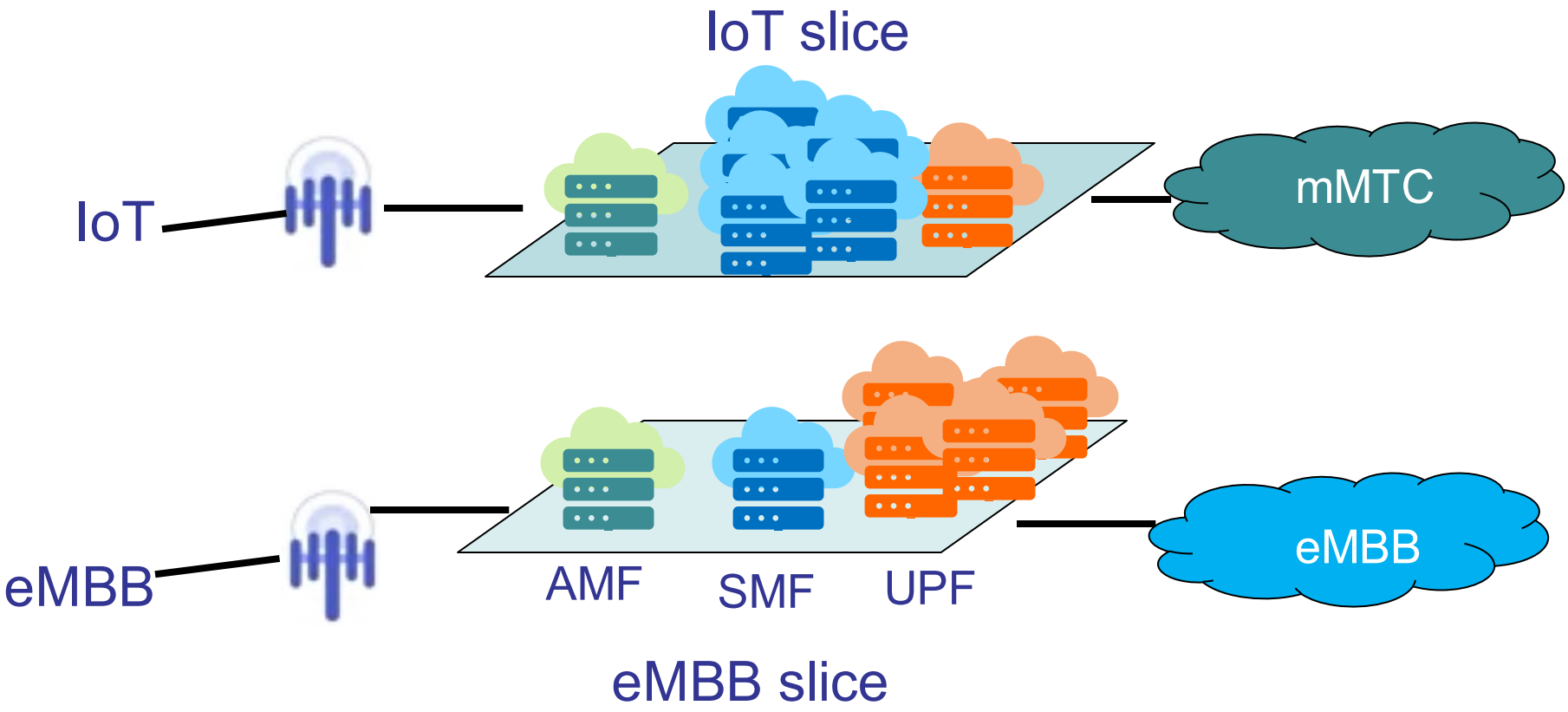
Network slicing

- A slice is a subset of the available network components providing an E2E services
- A slice can be designed & licensed upon the needs of services
- Diverse requirements of different services can be met by serving them with different slices of the same network



Network slicing

- A slice is a subset of the available network components providing an E2E services
- A slice can be designed & licensed upon the needs of services
- Diverse requirements of different services can be met by serving them with different slices of the same network

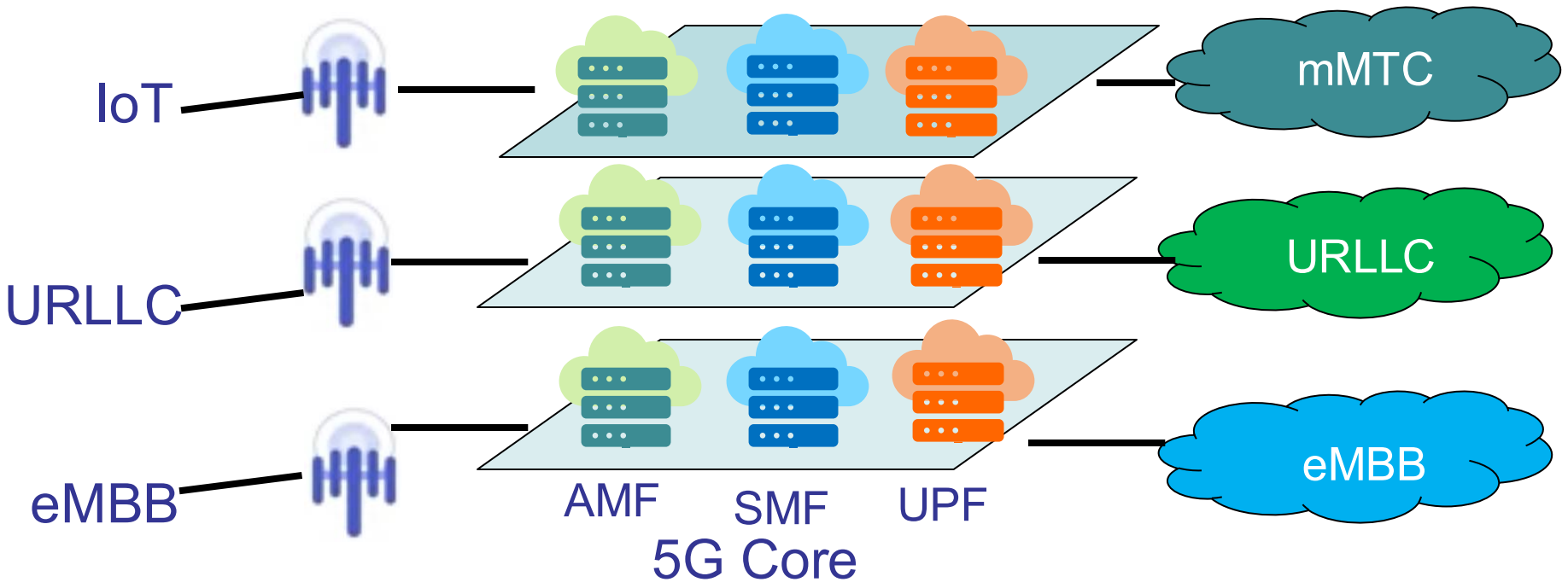


Network slicing

- A slice is a subset of the available network components providing an E2E services
- A slice can be designed & licensed upon the needs of services
- Diverse requirements of different services can be met by serving them with different slices of the same network

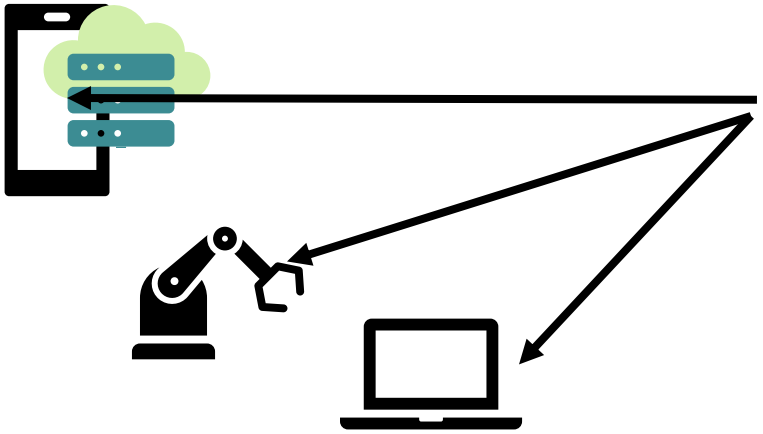
→ *Dynamic, efficient resource allocation & utilization; isolation among services*

→ *Flexible subscription models*



SDN and NFV

- SDN (Software-Defined Network): An emerging network architecture
  - Making the network more software-oriented than they were before
  - Implementing many functionalities in a generic software
  - → Be compatible between different vendors

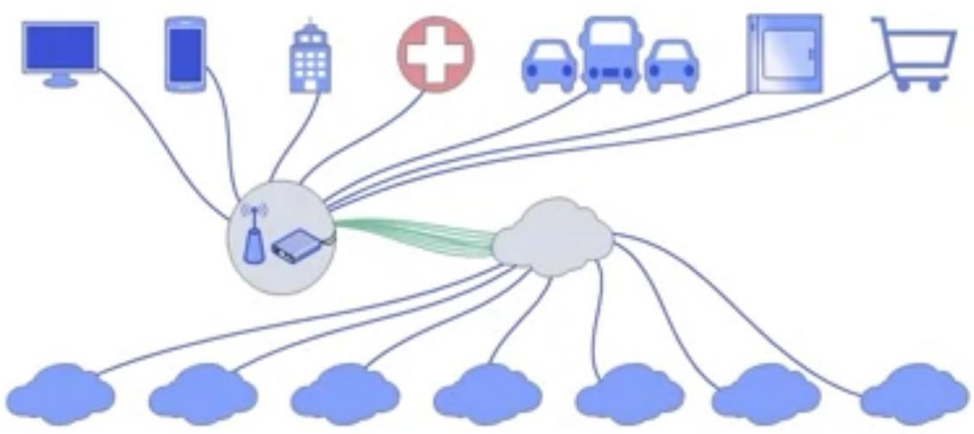


- Benefits:
  - Centralized management and control of network devices
  - Rapid innovation on new network capabilities and service
  - Network function virtualization (NFV)

SDN and NFV

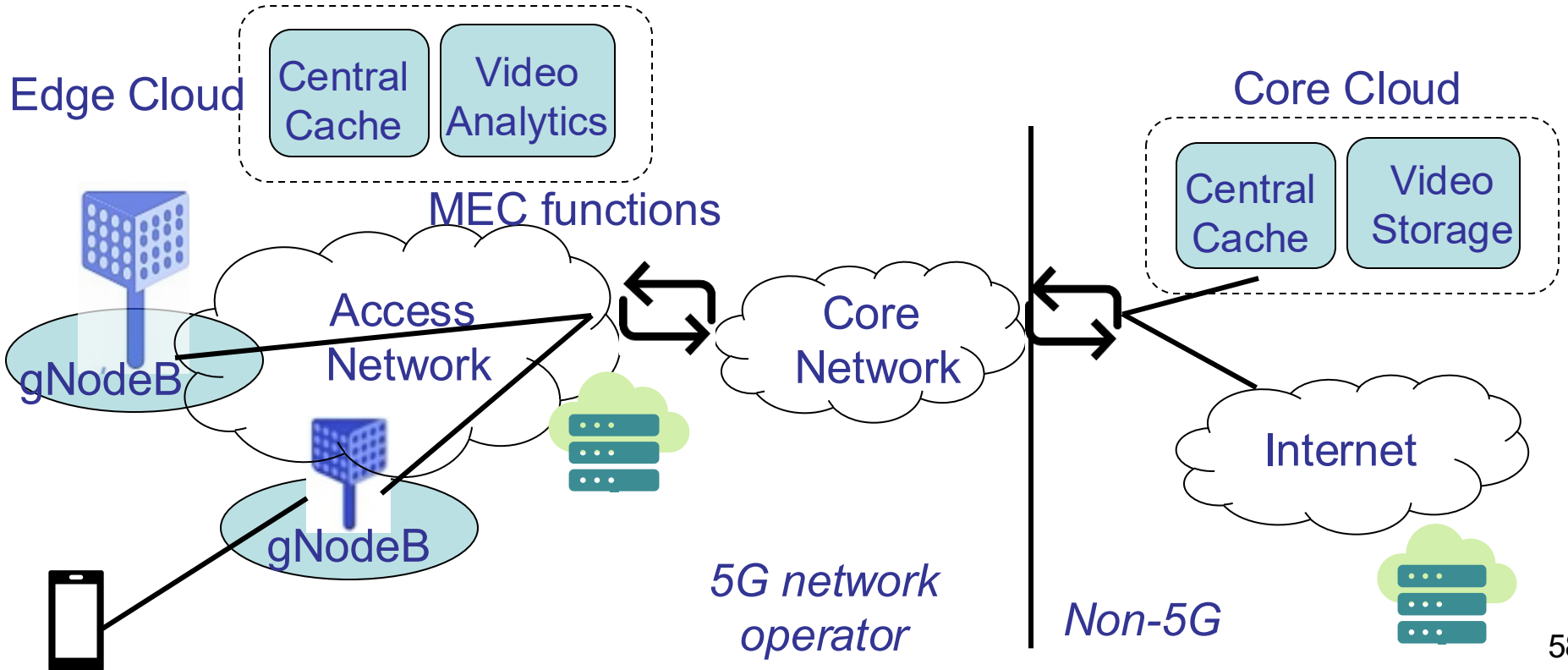
- NFV (Network Function Virtualization): An emerging network architecture
  - Up to 4G, network required specialized software running on specialized hardware
  - NFV aims to transform network architecture
    - Involves implementation of network function (NF) in software
    - NFs can run on a range of industry-standard server hardware
    - NFs can reside in a cloud instead of on the operator places

- Benefits:
  - Decoupling software& hardware
  - Flexible, scalable, dynamic network deployments
  - Cost-effective operation



Mobile Edge Computing (MEC)

- Edge computing brings compute, storage & network resources closer to applications, devices, users
- Edge computing is a broader concept, not tied to or dependent on, a specific generation of cellular communications



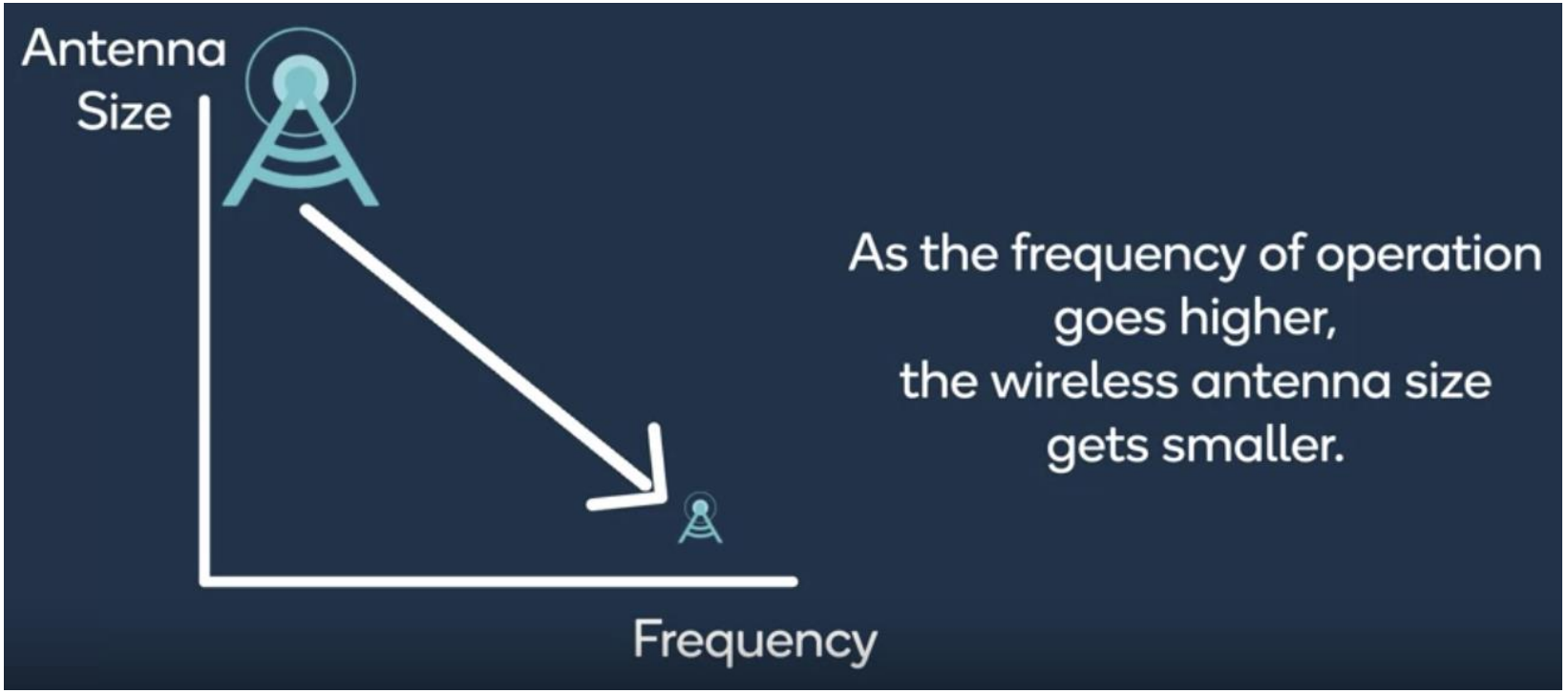
Massive MIMO

- Antenna array:
  - A panel with many antennas, each of which is very small
  - High frequency of 5G operation makes small antennas possible

- Beamforming: Enabled by Massive MIMO
  - Focus transmitted signal only in the desired direction --> Narrow beam
  - Multiple narrow beam can be generated
  - Individual beam can serve different users
  - Horizontal and vertical beamforming → 3D coverage

Antenna array

- The transmission& reception conversion efficiency of antenna is optimized **as length of antenna is ¼ of the wavelength**.

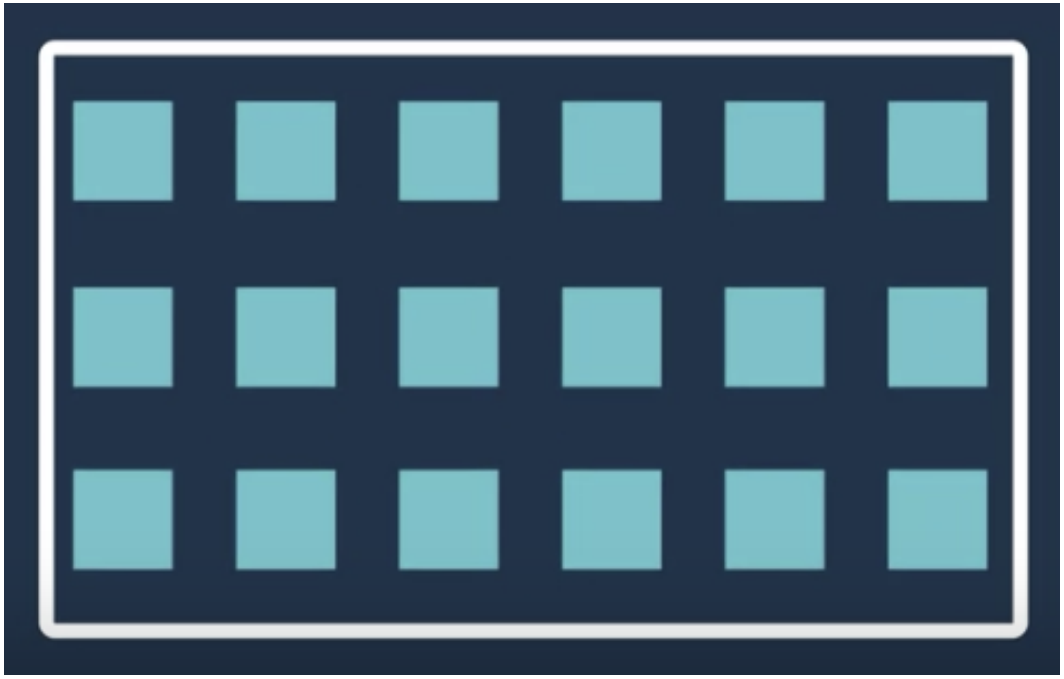


→ mmWave antennas are significantly smaller than sub-6GHz

Antenna array

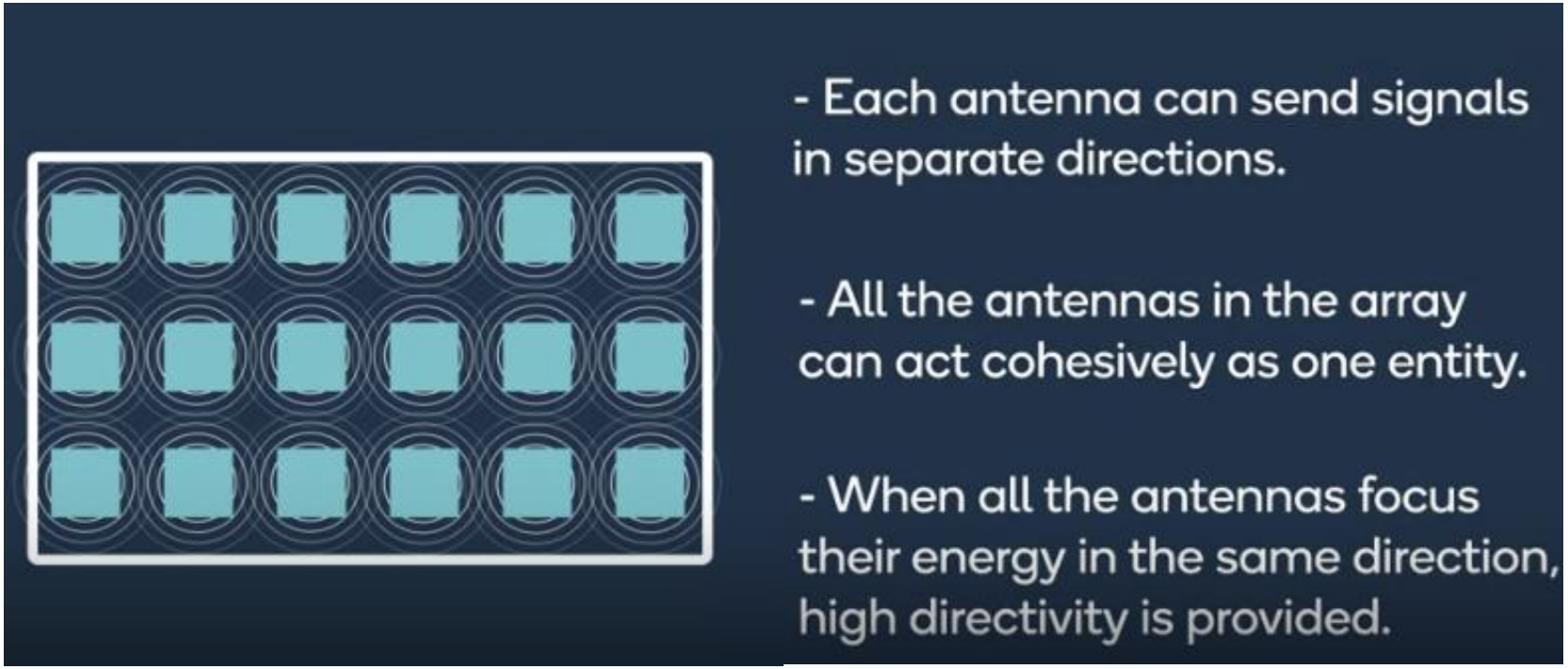
- The transmission& reception conversion efficiency of antenna is optimized **as length of antenna is ¼ of the wavelength**.

→ mmWave antennas are significantly smaller than sub-6GHz



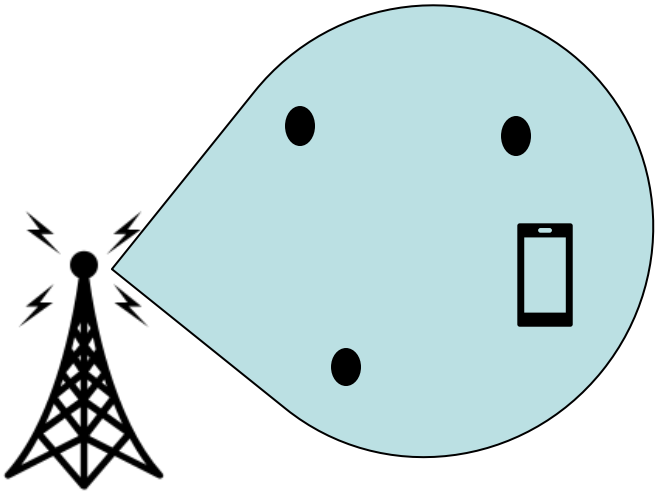
Antenna array

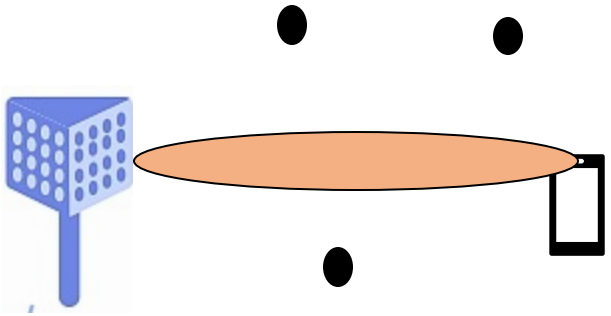
Beamforming



Beamforming – Narrow beam

$$\mathrm{SNR} = \frac{Signal}{Noise}$$



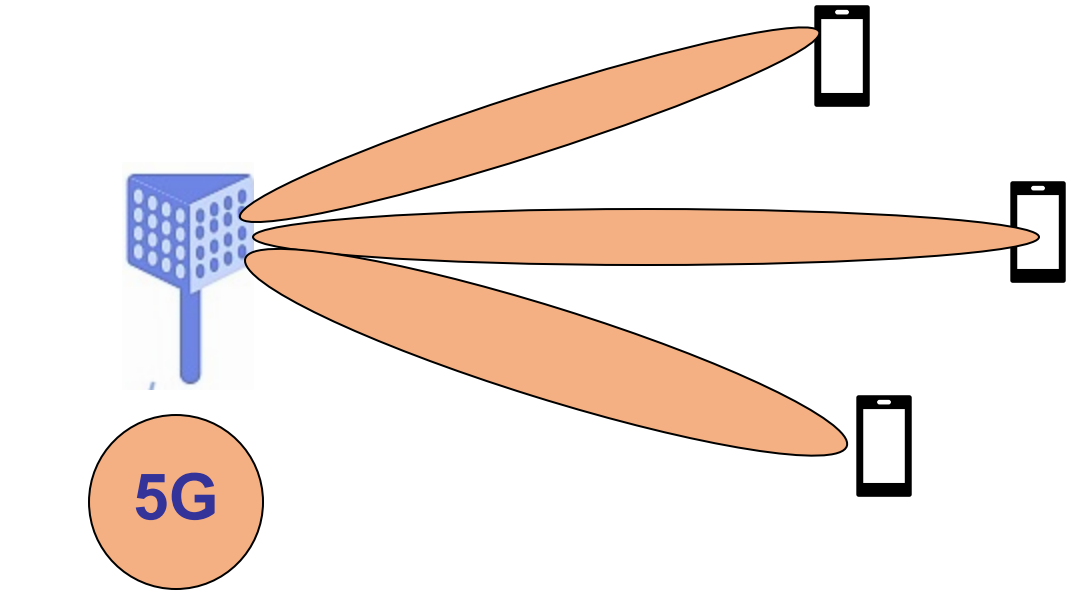


4G

5G

Massive MIMO

Beamforming – Multiple narrow beam

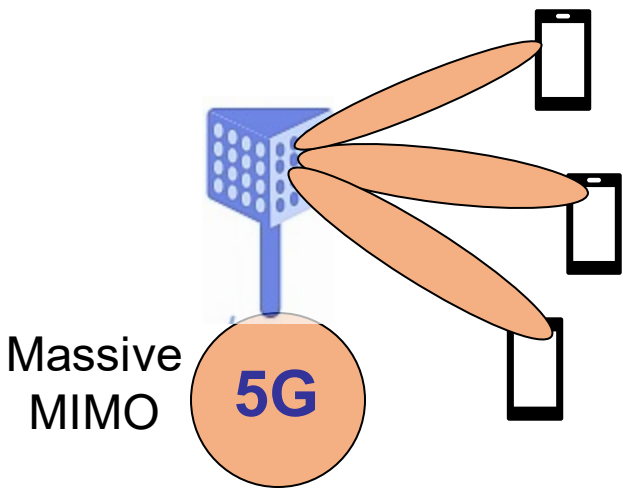


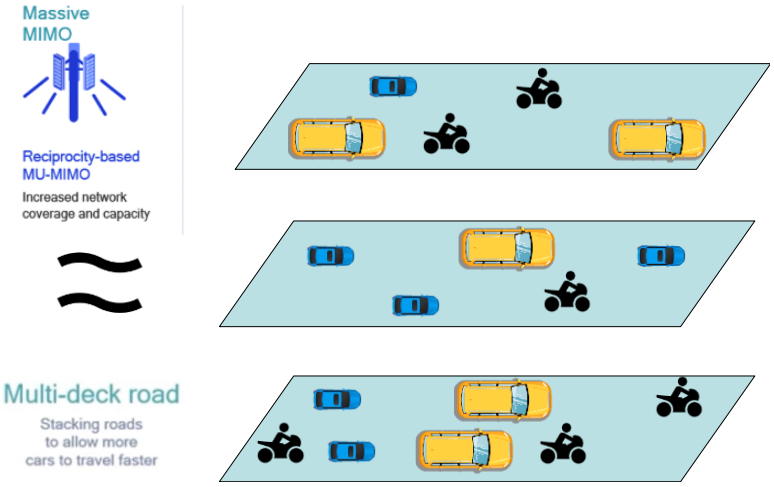
Massive MIMO

? Can 5G gNodeB send different beams to different users simultaneously?

✓ Yes, it can, but depends on implementation (software, hardware)

Beamforming – Individual beam for individual user





? Do those beams use the same frequency channel?

✓ Yes, they are sent by the same antenna array → same frequency channel.

? If so, how come there is no interference?

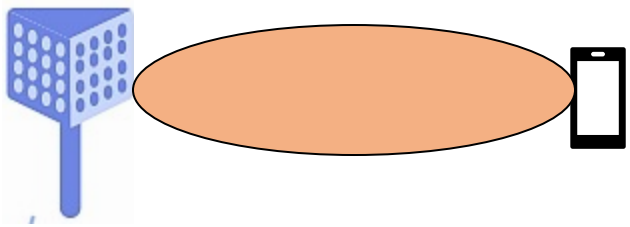
Beamforming

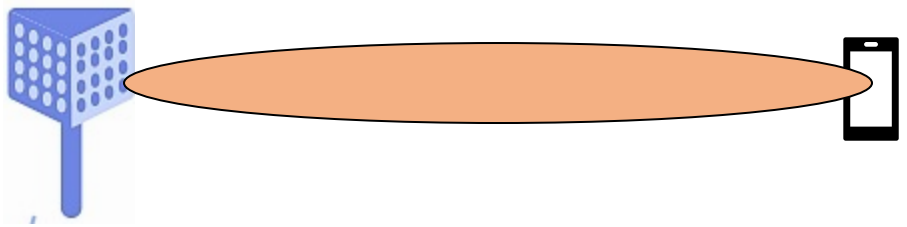
- Antenna array:
  - A panel with many antennas, each of which is very small
  - High frequency of 5G operation makes small antennas possible

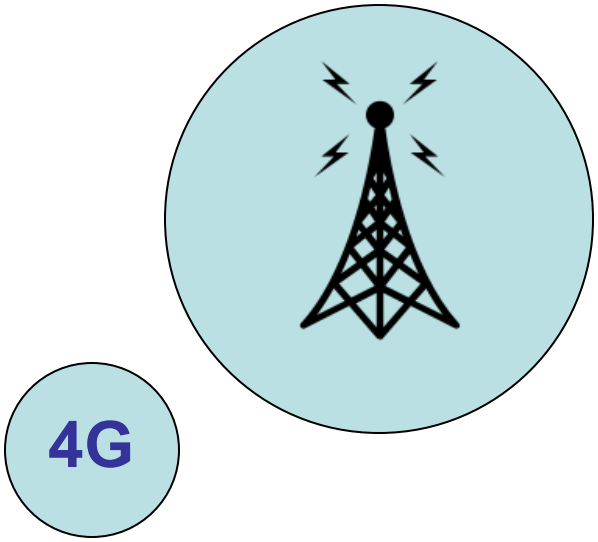
- Beamforming: Enabled by Massive MIMO
  - Focus transmitted signal only in the desired direction --> Narrow beam
  - Multiple narrow beam can be generated
  - Individual beam can serve different users
  - Horizontal and vertical beamforming → 3D coverage

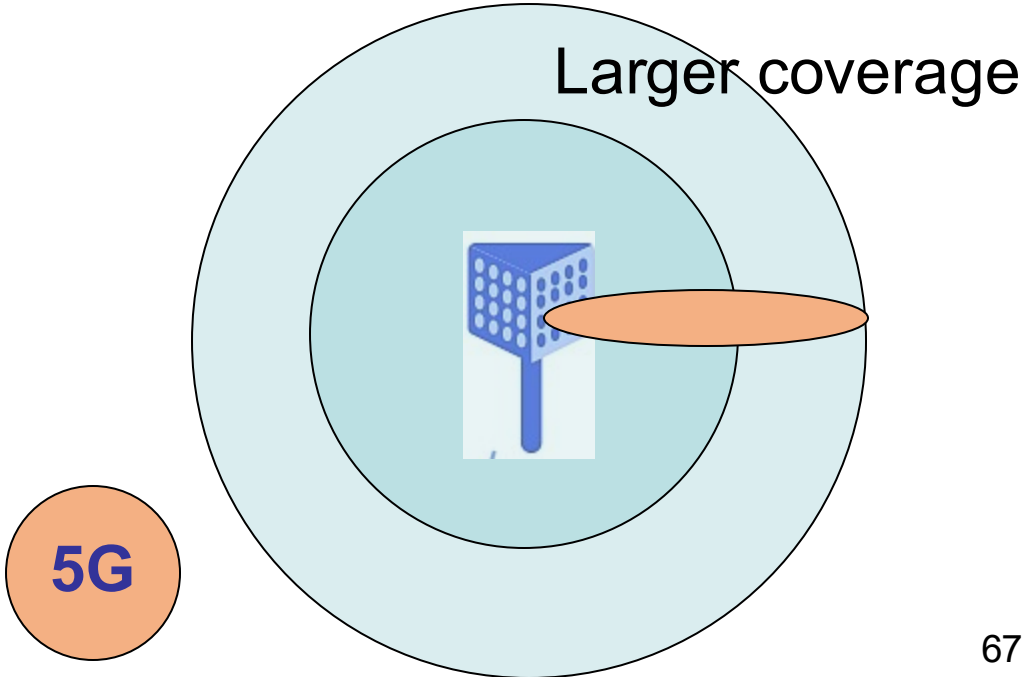
Beamsweeping for coverage

- 5G gNodeB employs massive MIMO-based beamforming to create narrow beams
- Narrow beams travel farther and provide better signal quality



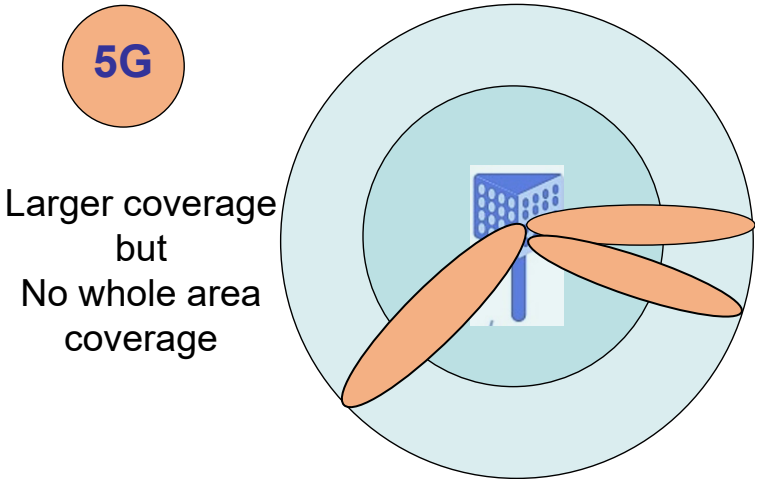


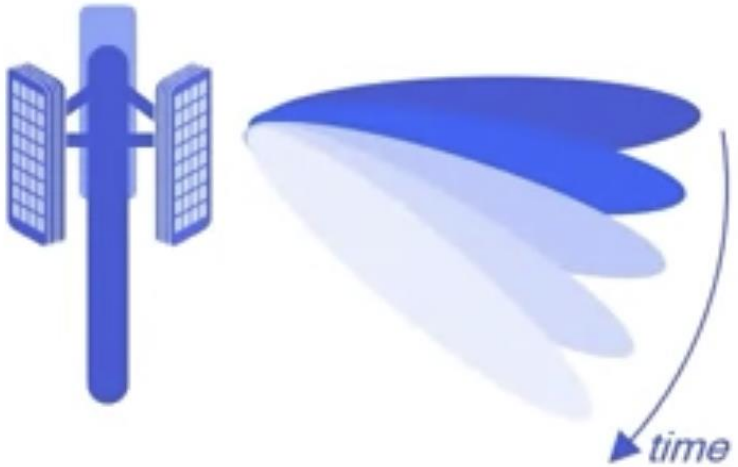




Beamsweeping for coverage

- However, no narrow beam can cover a whole area





Beamsweeping

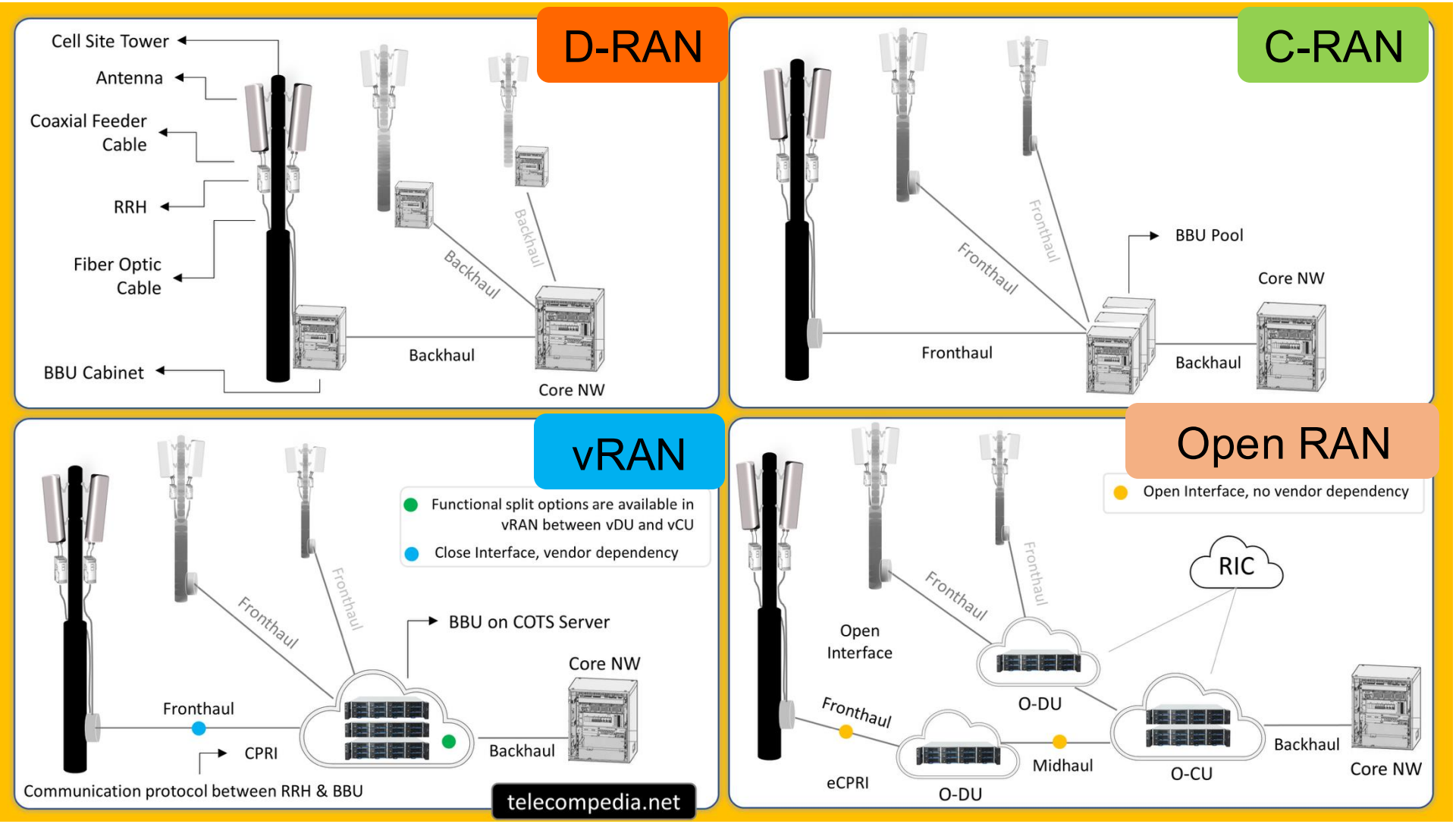
- Beamsweeping allow gNode B periodically steer one narrow beam in different directions to cover a wide area
- *To transmit generic information that is useful and applicable to all the users no matter where they are located in the cell.*

Radio Access Network (RAN)

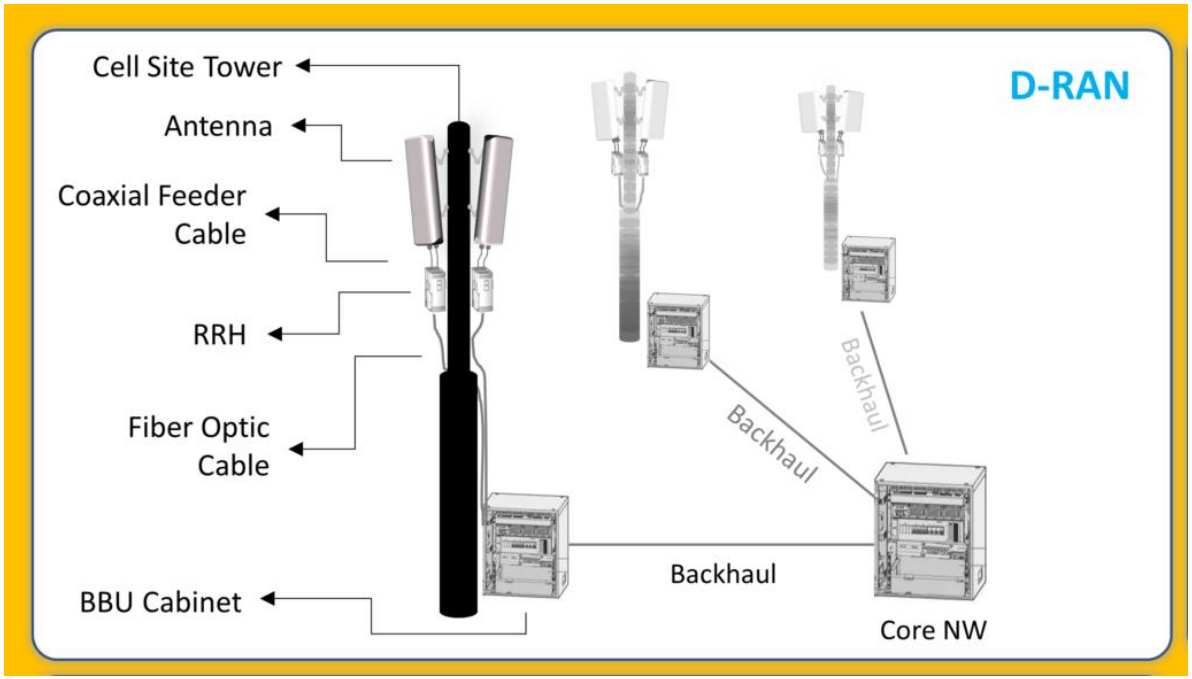
- An expensive part of any cellular network (60%)
- No matter the generation, RAN basically has two components:
  - BBU or the baseband unit,
  - RRH, or remote radio head, or simply RU

- Baseband:
  - What you see on the mobile devices,
  - Converted into bits before transmitting as a radio frequency
- RRH:
  - Once your baseband signal is converted into higher radio frequencies → the realm of RRH.
  - Radio frequency processing

Evolution of RAN

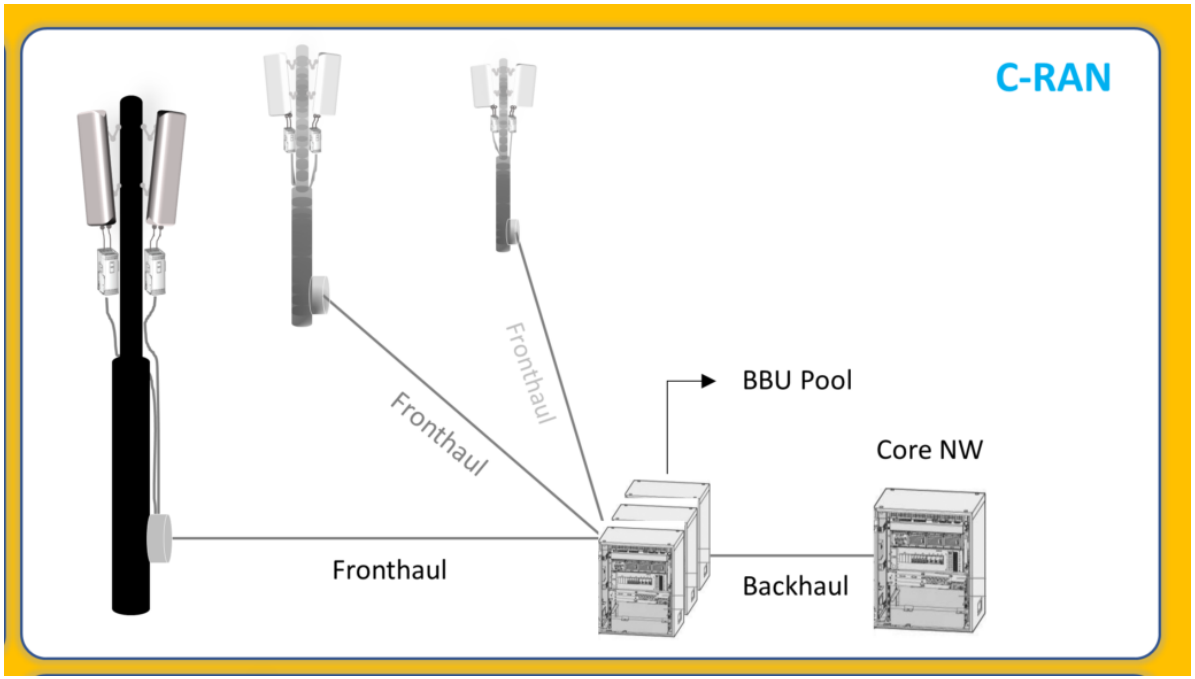


Evolution of RAN



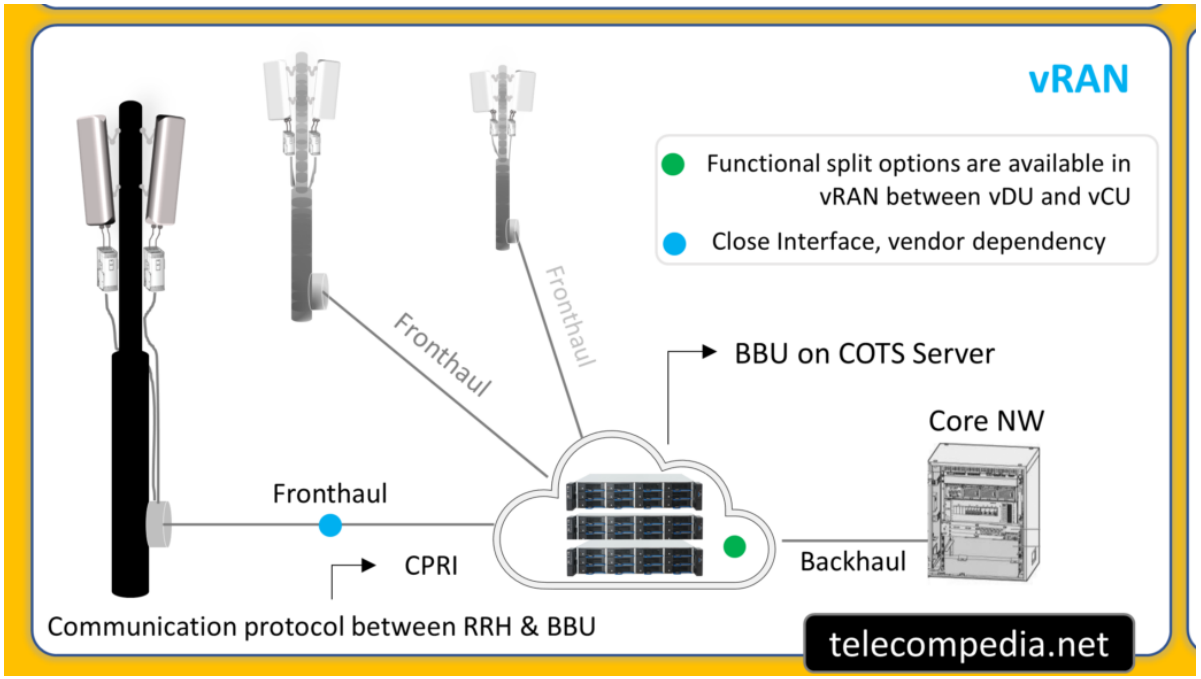
- D-RAN (Distributed-RAN):
  - Each BS has its own BBU and RRH
  - Co-located in the physical location for each cell
  - RAN is distributed all over the geographical area

Evolution of RAN



- C-RAN (Centralized-RAN, Cloud-RAN):
  - Combine several BBUs → one single BBU pool
  - BBU pool handles multiple RUs
  - One common BBUs across multiple base stations

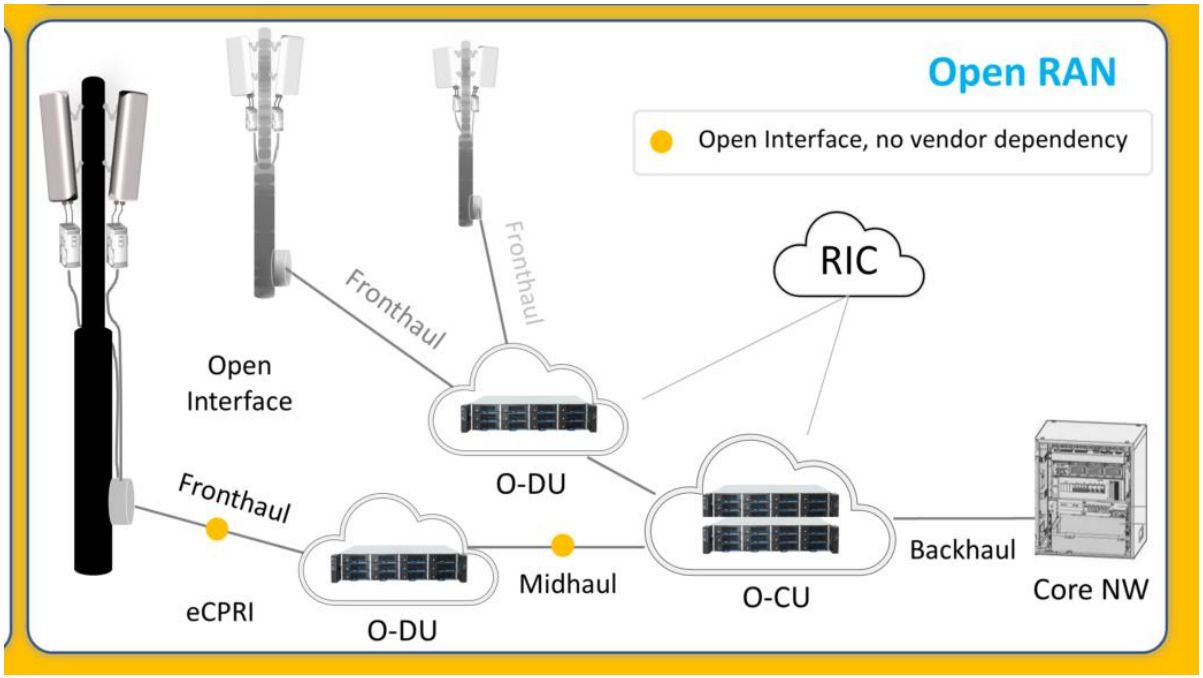
Evolution of RAN



- vRAN (Virtualized-RAN):
  - BBU pool is offloaded into a cloud
  - no hardware dependency on some major entities of the RAN architecture

→ vRAN is a key enabler for creating dynamic multi-vendor ecosystem to enable device 5G services

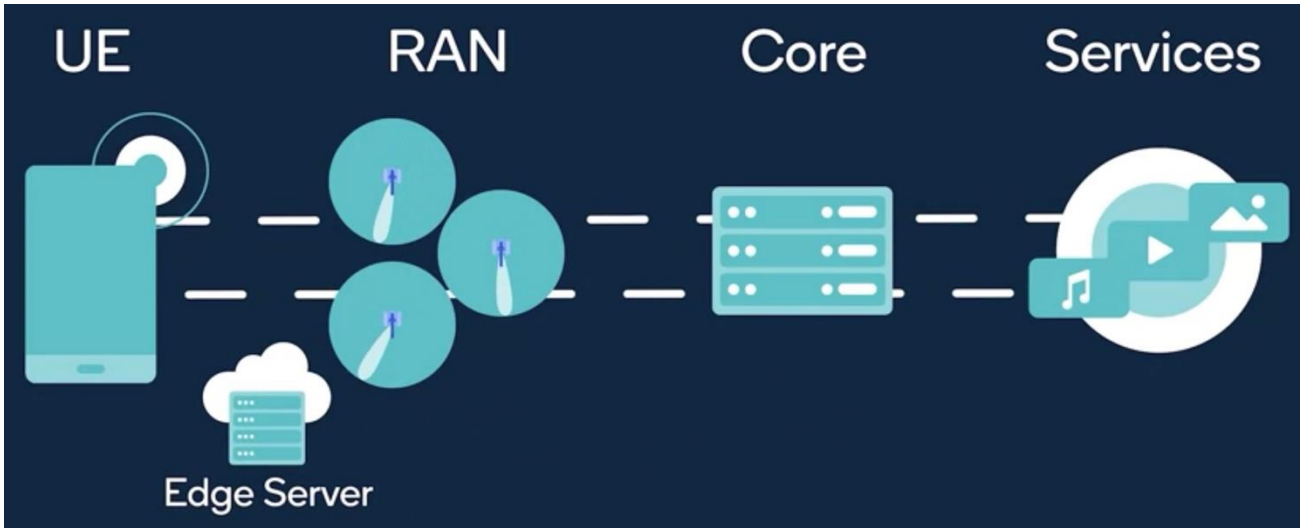
Evolution of RAN



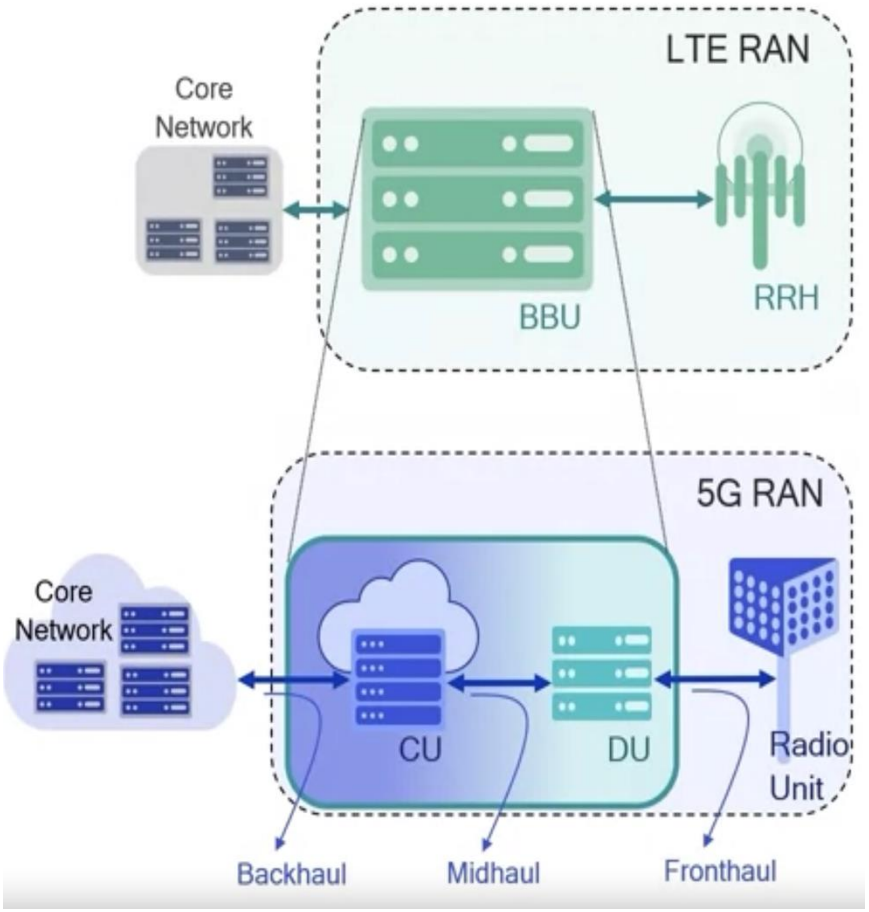
- Open RAN:
  - latest enhanced version of RAN solution
  - Open interface between RRH vs BBU

Motivation for RAN virtualization

- Save capital and operating expensive
  - Operators don't have to host the BBU by themselves
- Cell densification
  - In previous architecture (D-RAN), need to buy both BBU and RRH
  - In vRAN: only RRH
- New services



RAN functional split



- LTE RAN:
  - BBU: baseband processing
  - RRH composed of antennas: RF processing
- 5G RAN: Enables functional split of BBU
  - Centralized unit (CU): handles multiple DU, upper layers processing
  - Distributed unit (DU): Lower layers processing, connected to one CU

Private network

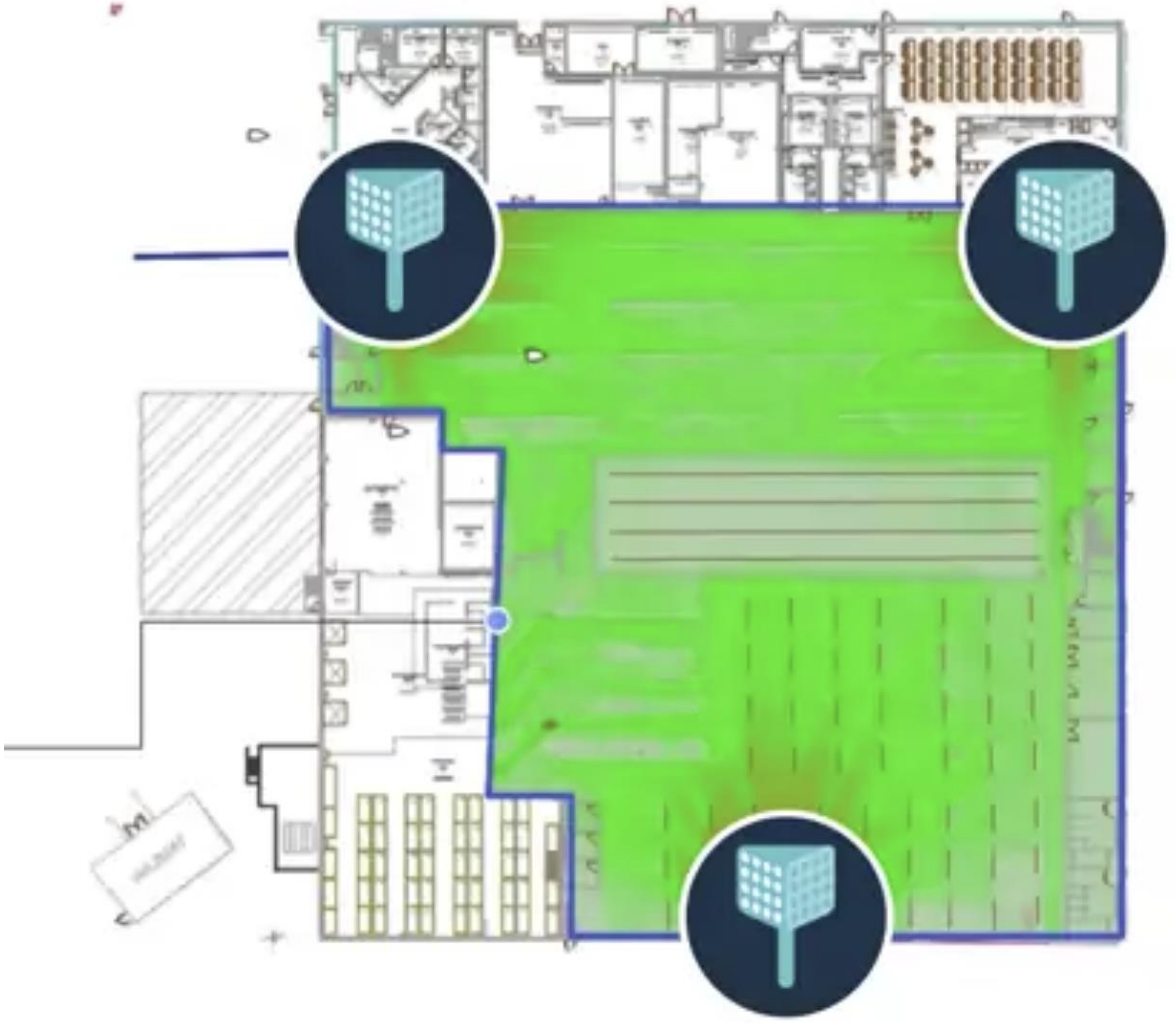
- **Dedicated** networks designed and deployed for the **use of single enterprise**, for the **specific operational requirements**
- **Salient difference between public and private networks**

- Provide **a broad array of services** to all subscribers
- Requires **a dozens of BS**
- Influenced by extraneous factors: building, roads,…
- Mostly **licensed**
- Public subscribers cannot avail service from a private networks
- Urban cellular networks

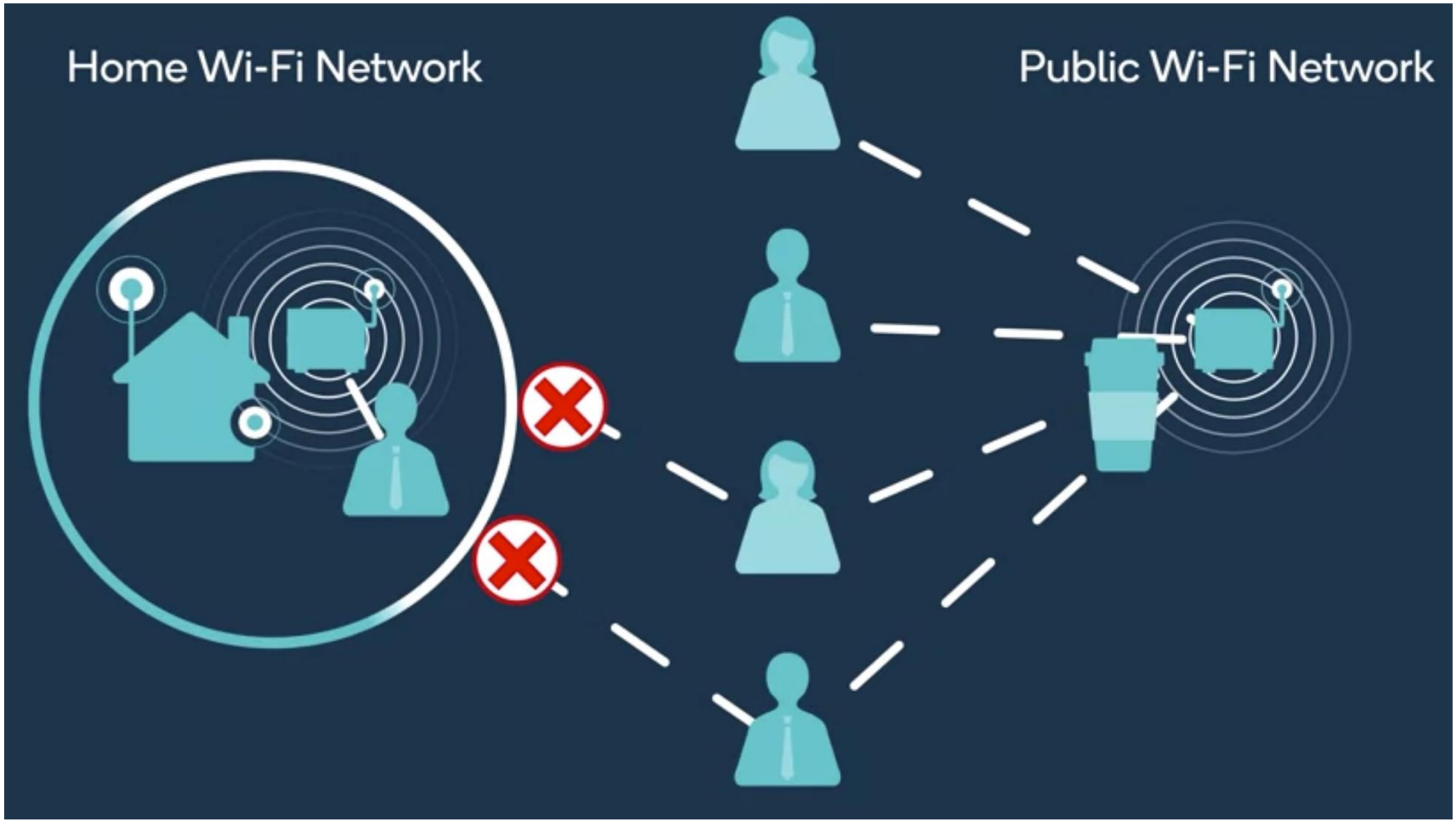
- Prioritize **specific services** to specific customers
- Requires **very few BS**
- Tailored specifically for the area of interest
- Can be (un)licensed, shared
- Private subscribers can avail service from public networks
- Industries, warehouses,…

Private network

- **A factory (35000m2) can be covered by only three mmWave BS**



Private network



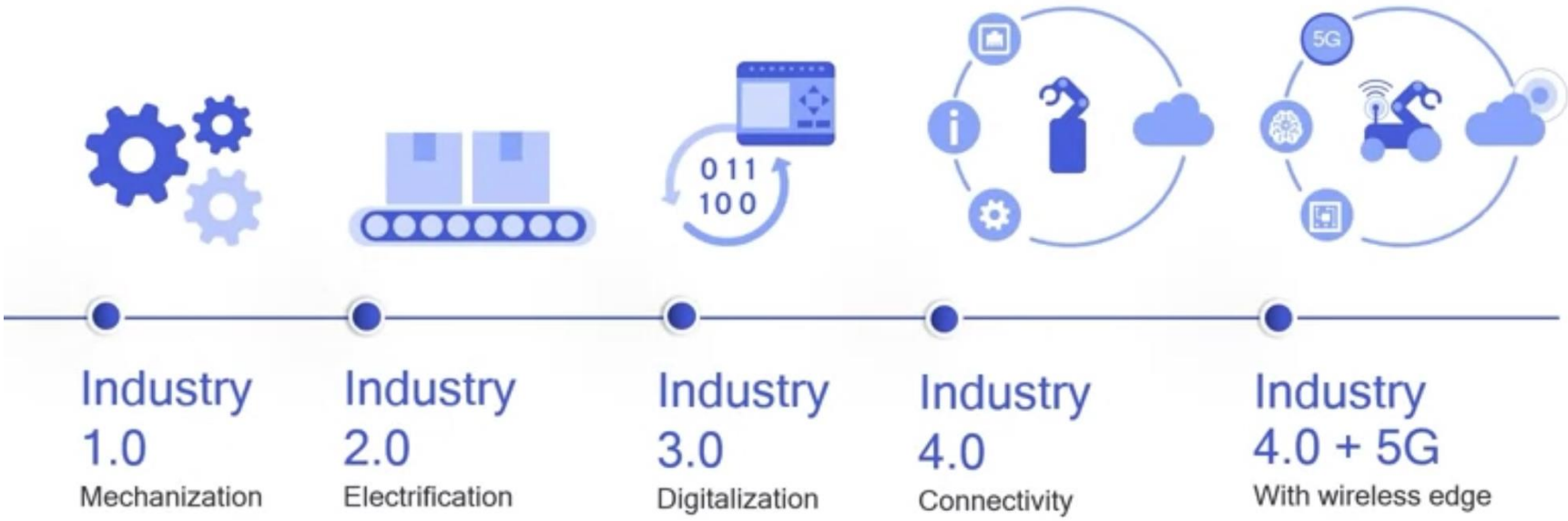
Benefits of private network

- **Control over network design and deployment:**
  - ✓ Optimized wireless coverage
  - ✓ Guaranteed QoS, throughput and latency
- **High degree of service reliability and availability**
- **On-premise deployment**
  - ✓ Great operational control and service flexibility
  - ✓ Proprietary data can stay on site → Great data security
  - ✓ Option to deploy multiple customized features such as MEC and network slicing
- **Facilitate multiple use cases:**
  - ✓ Time-sensitive networking for latency-sensitive services
  - ✓ eMBB for high-throughput applications, e.g. security cameras
  - ✓ Indoor positioning for robotic vehicles

This leads to the paradigm of Industrial IoT

Industrial IoT and 5G

- **Industrial IoT: next step in the industrial revolution**



With high-speed, low-latency, reliable and secure communication, 5G can take industry 4.0 to the next level

Industrial IoT and 5G

5G has a broad appeal to a wide array of industries

Industrial IoT and 5G

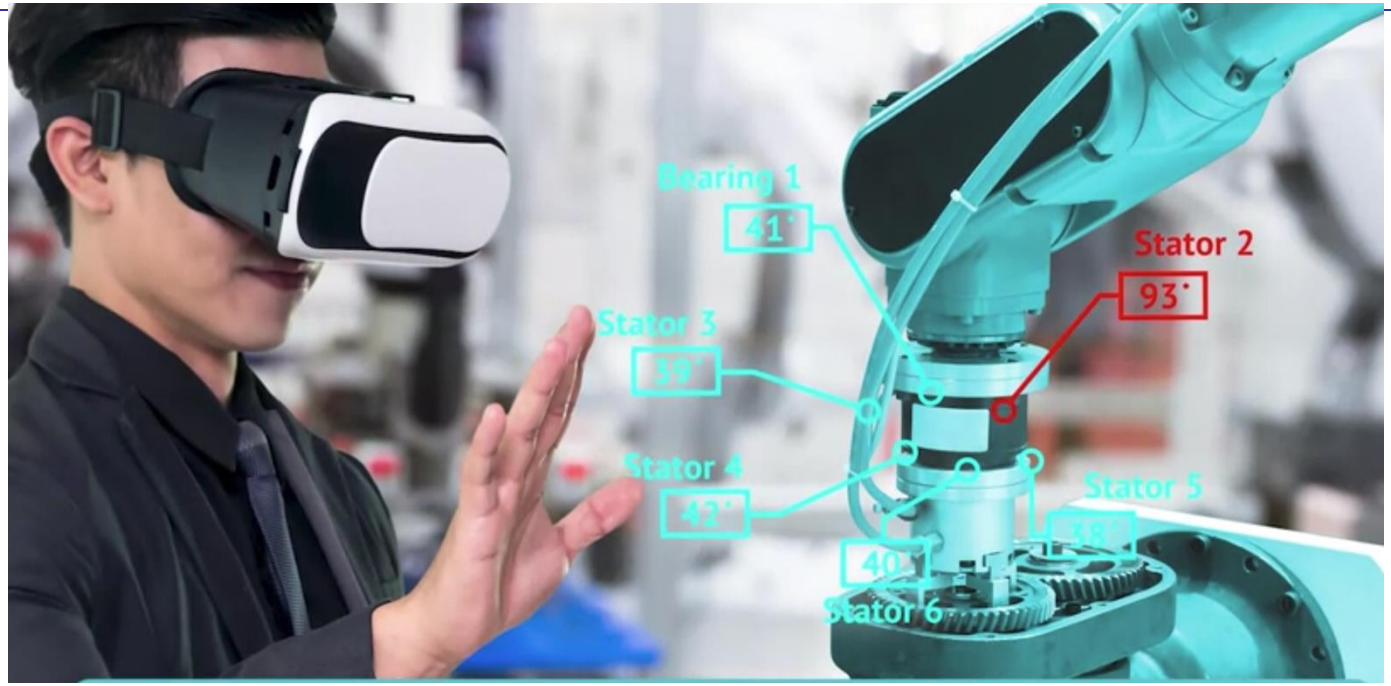
5G has a broad appeal to a wide array of industries

Industrial IoT and 5G

- Ports are populated with metal containers which reflect wireless signal
- Hardly anything at a container ports is sitting study

5G private networks can overcome the challenges of wirelessly operating in such environment with constant movement

Industrial IoT and 5G



- Robotic arms that require instructions at a millisecond level

5G private networks can satisfy stringent requirement of many such use cases

Industrial IoT and 5G

5G URLLC can provide the much-needed safety in mines and construction sites with miliseconds latency performance

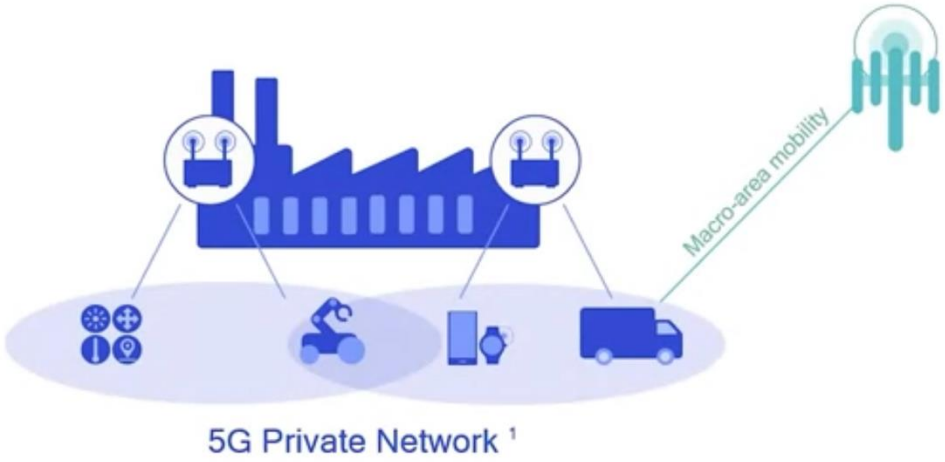
Industrial IoT and 5G

Precise indoor positioning in warehouse can be executed wirelessly with the help of 5G private networks

Industrial IoT and 5G

Wind farms can be prime candidates for 5G mmWave and their specific operational needs can be satisfied by 5G private networks

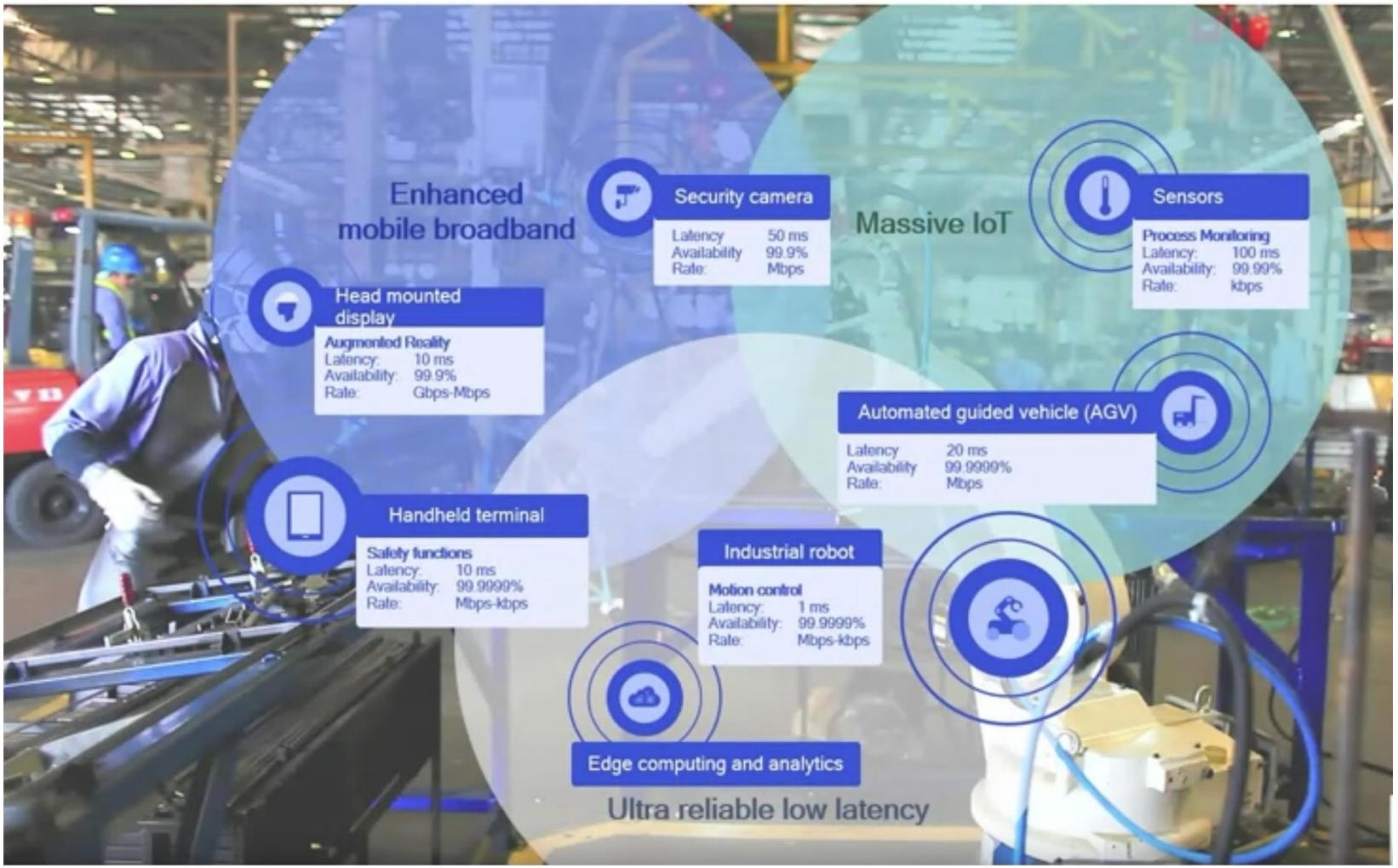
5G Private networks for I-IoT



- **Optimized:**
  Tailored for industrial apps, e.g., QoS, latency
- **Dedicated:**
  Local network, easy to deploy, independently managed
- **Secure:**
  Cellular-grade security & keeping sensitive data local
- **Best of both worlds:**
  Wire-like performance with flexibility of wireless

Optimizeing for IIoT → **New chances & scalability with 5G NR capacities** → **Standardized roadmap with periodic new features**

I-IoT and Massive IoT



5G IIoT is more than just massive IoT

Private network deployment

- **Region-specific implications**

Spectrum

Handful of countries with spectrum earmarked for private networks

Network Architecture

SA or NSA, cloud vs local core, etc.

Infrastructure equipment

Traditional infra vendors vs new entrants, vRAN, etc.

Spectrum options for Private network

Licensed spectrum owned by mobile network operators

Operators can allocate or lease spectrum

Dedicated spectrum

In some region's spectrum is dedicated for industrial IoT use (e.g., 3.7 GHz Germany)

Unlicensed spectrum

NR-U can be used for private 5G networks that do not require URLLC

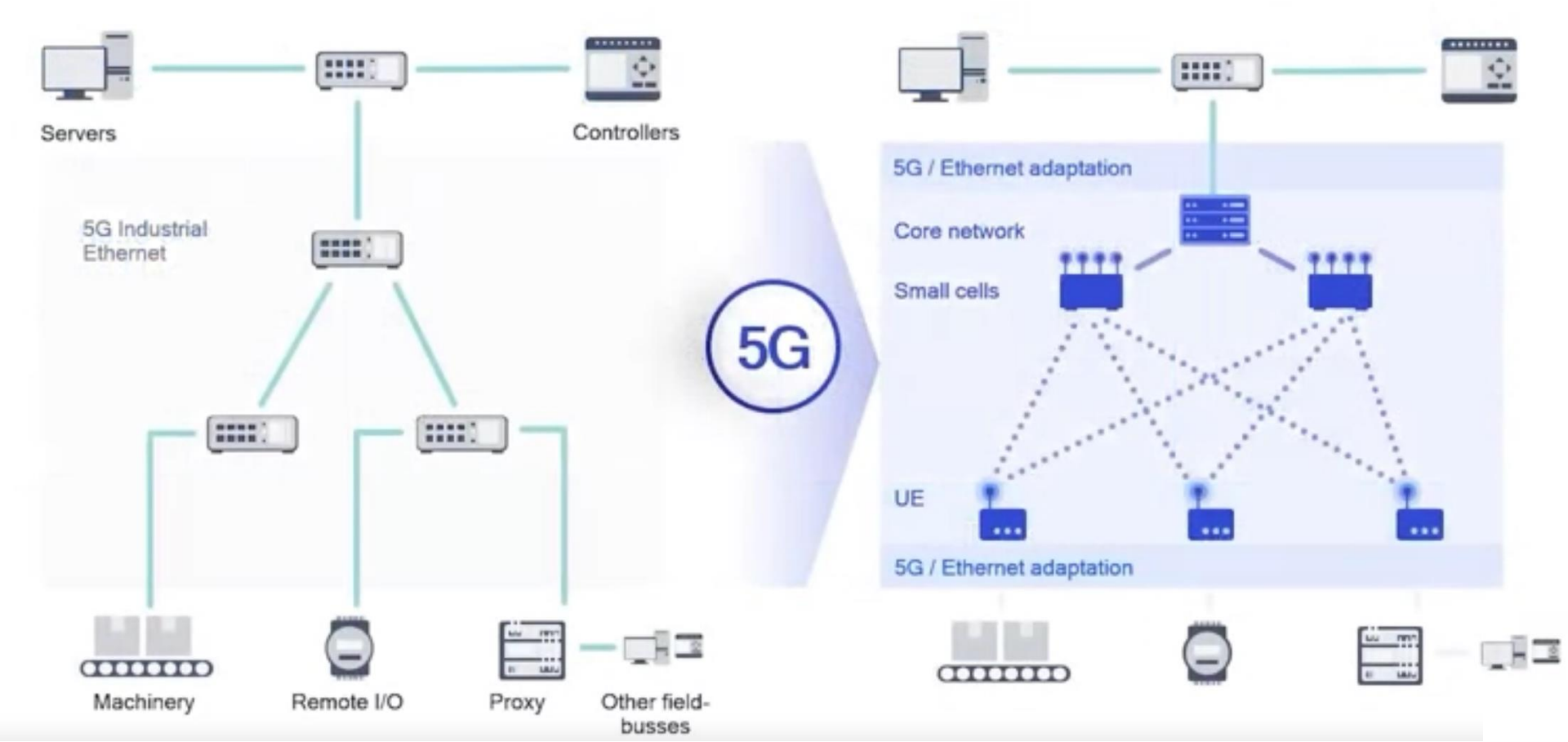
Unlicensed spectrum with synchronized sharing

Synchronized sharing can provide significant capacity gains and URLLC

Today

Tomorrow and beyond

Example of IIoT with 5G Private network

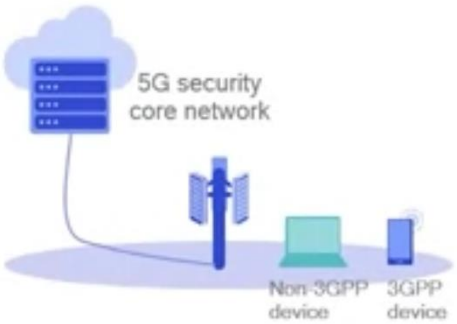


Overview of Security in 5G

- **Building on proven, solid security foundation of 4G**

Flexible framework

To support new devices, use cases, and deployments



Unified authentication for 3GPP and non-3GPP access (e.g., Wi-Fi), security anchor function, and network slicing

Tighter security

To expand protection and increase flexibility

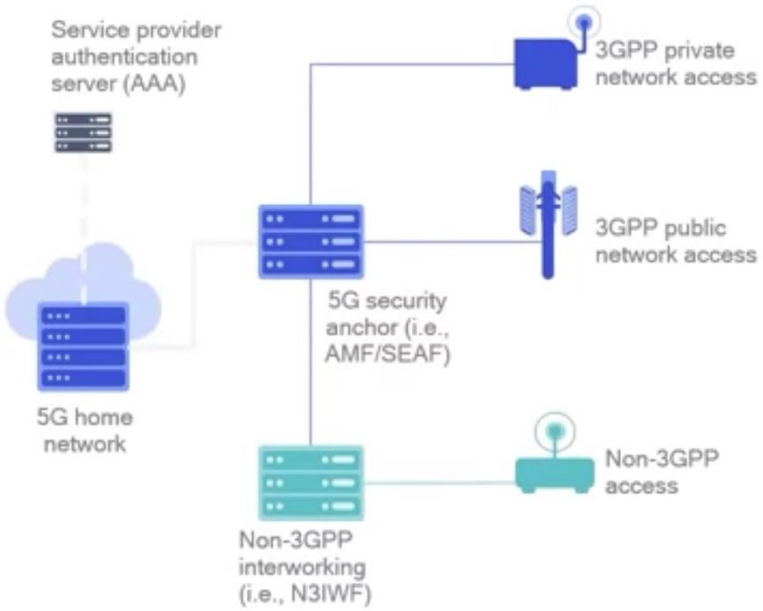
Added user plane integrity protection; lower trust in serving networks to allow for flexible deployment; subscription credentials can be stored in secure hardware element

Enhanced privacy

To eliminate communication of unprotected device-specific information

User permanent identity (e.g., IMSI) and device-specific information are ciphered before being exchanged over the air

Overview of Security in 5G



- **Unified Authentication Framework**
  - Same authentication for both 3 GPP and non-3GPP access
  - Security level can be tailored/scaled for a wide range of use cases and deployments
  - Non-SIM credentials can be used for security, suitable, e.g., private networks

- **Security Anchor Function (SEAF)**
  - Mobility/session management can move to the edge without compromising security, whic stays deeper in the network where physical security is highest