Multiple Access in Cognitive Radio Networks: From Orthogonal and Non-Orthogonal to Rate-Splitting

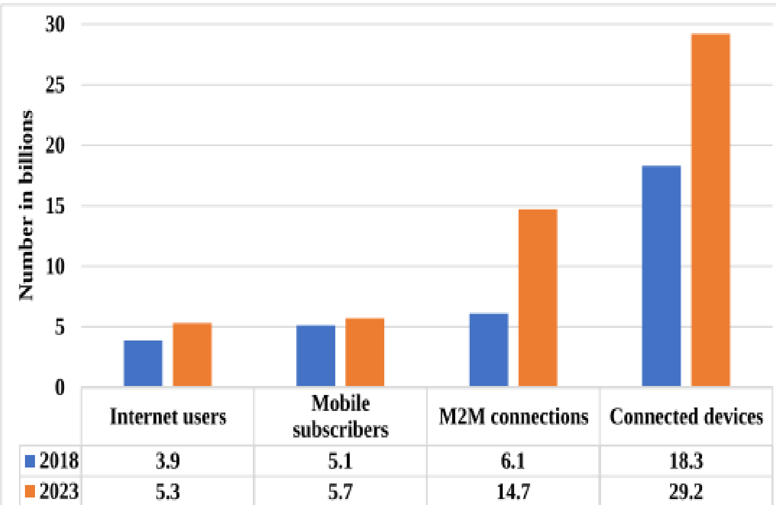
Objective

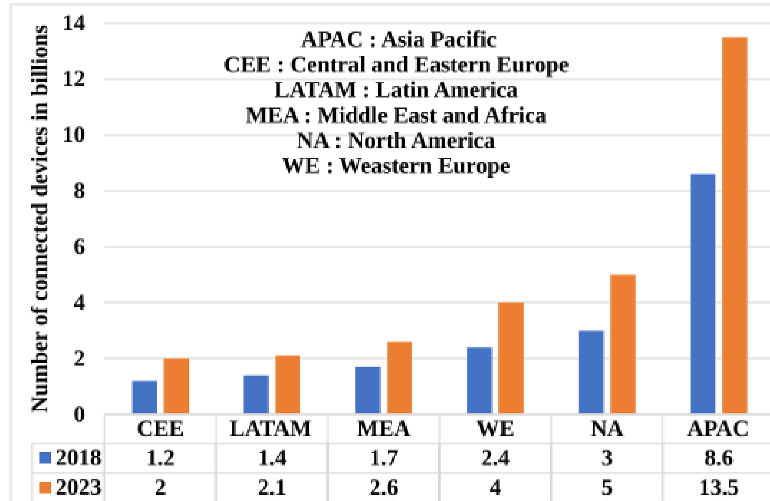
- A comprehensive study regarding the key multiple access schemes presented for CRN(Cognitive Radio Network)s

- Enhance the use of spectral resources

- Highlights the key implementation challenges

Recent Trend

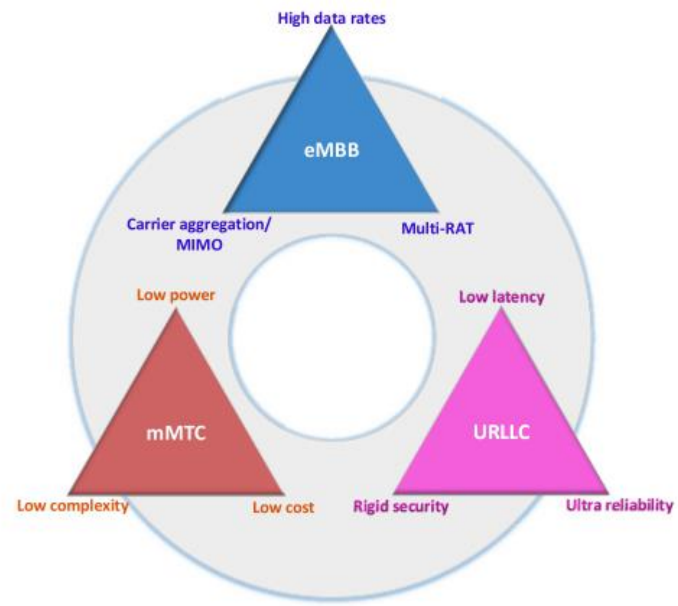




- The number of Internet users is expected to be 5.3 billion and the number of M2M and connected devices is expected to be doubled by 2023

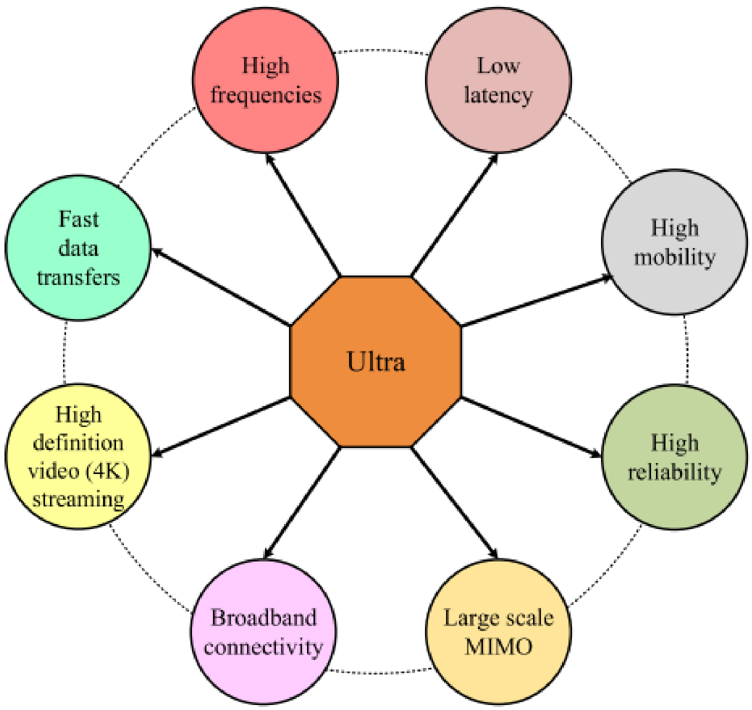
- Total number of connected devices for six different regions between 2018 and 2023

5G Requirements



- enhanced Mobile BroadBand service (eMBB)
- massive Machine Type Communications (mMTC)
- Ultra-Reliable and Low Latency Communications (URLLC)
- High throughput, end-to-end low latency, low energy consumption, high scalability

6G Vision

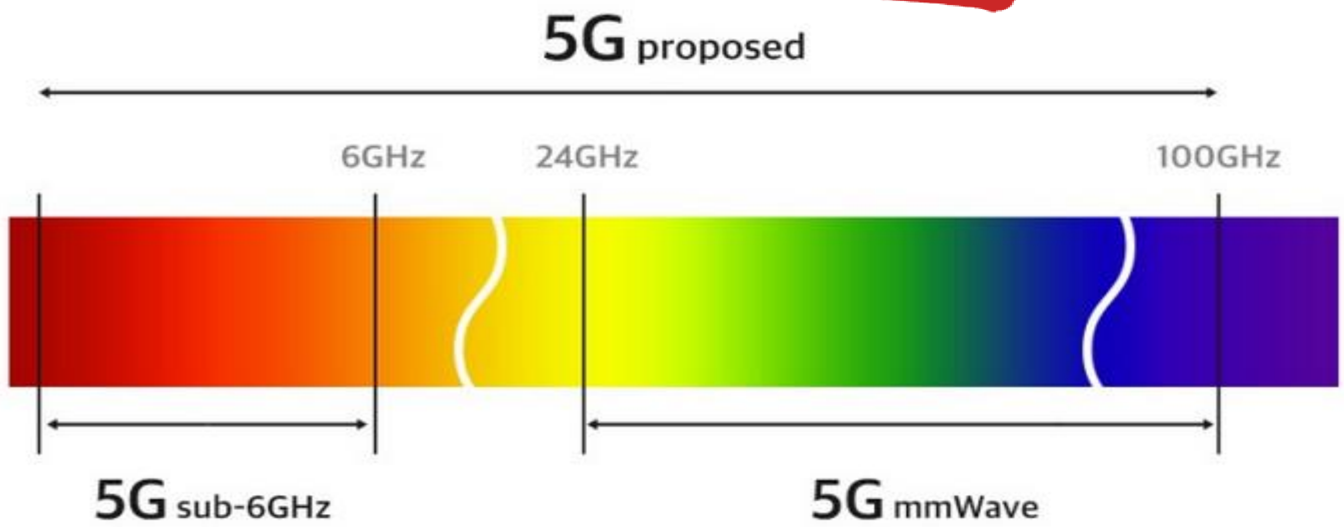


- High data rate / spectral efficiency
- Energy efficiency of 10x higher than 5G networks
- Increasing the connectivity and providing full coverage
- Security, secrecy and privacy
- Ultra-high-reliable and low-latency
- High Mobility

6G Wireless Communication

- The integration between different networks (ex. terrestrial and non terrestrial networks)
- network slicing and multi-access edge computing
- utilize ultra-high frequencies (mmWave, THz)
- support the Tactile Internet communication

Millimeter Wave (mmWave)

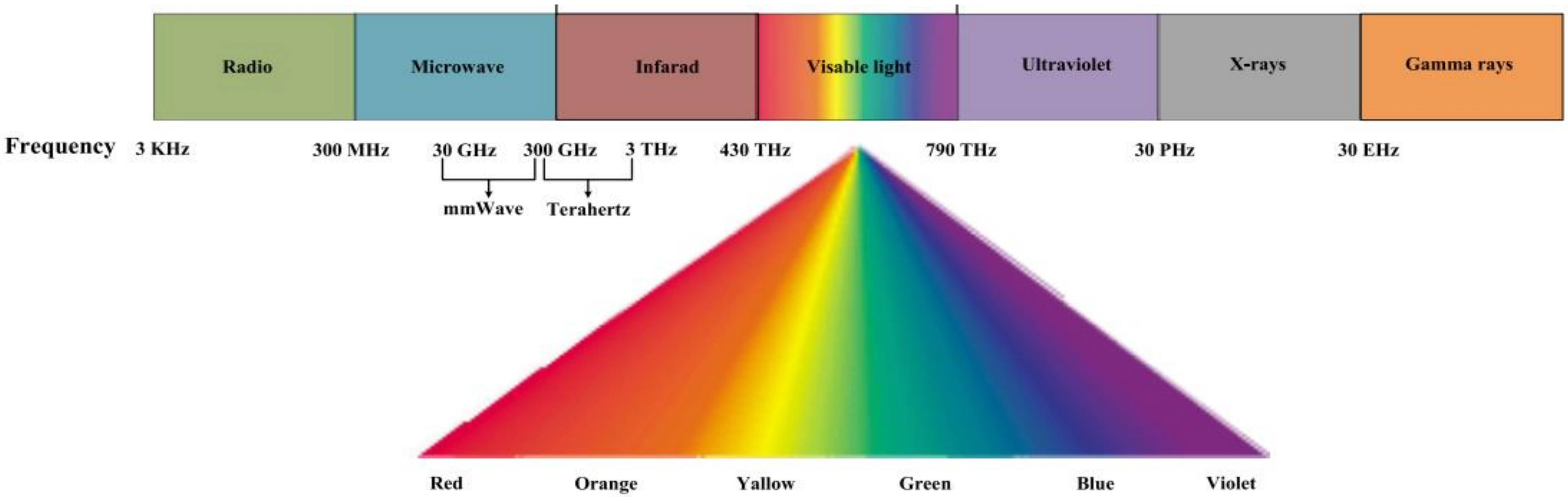


- Spectrum range : 30~300GHz
- wavelength : $\lambda = \frac{c}{f}$, $\begin{pmatrix} f: \text{frequency} \\ c: \text{speed of light} \end{pmatrix}$

$$\frac{3\times10^8\text{m/s}}{30\times10^9\text{Hz}} = 10\text{mm} \sim \frac{3\times10^8\text{m/s}}{300\times10^9\text{Hz}} = 1\text{mm}$$

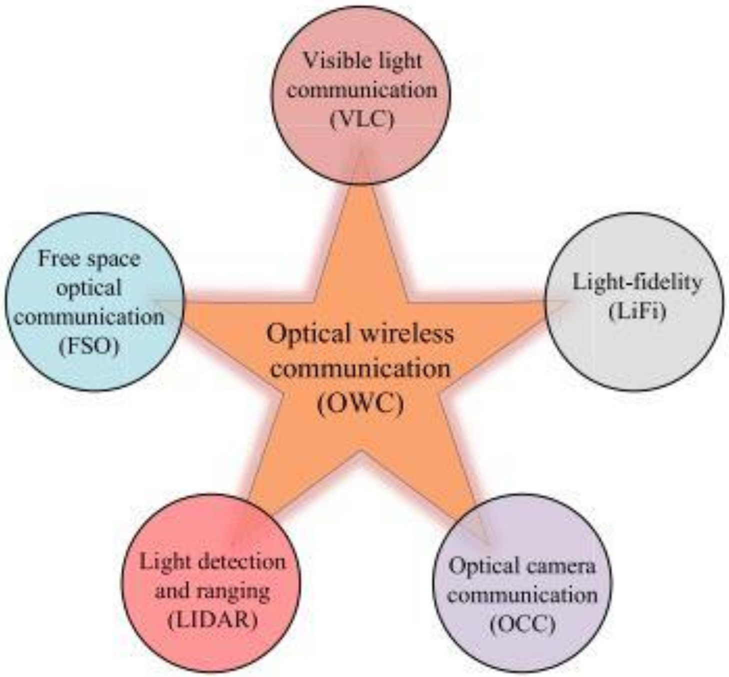
- High data rate and low latency (used to Automated vehicular communication, AR&VR, etc..)
- Specific propagation behaviors(high signal attenuation and absorption, high penetration loss), significant increase in path loss

TeraHertz (THz)



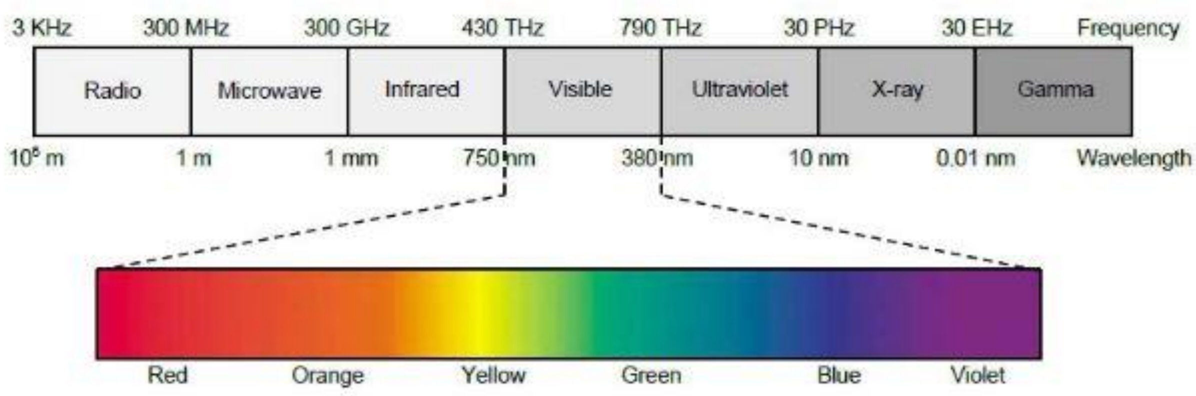
- Spectrum range : 0.1~10THz
- wavelength : $\frac{3\times10^{8}\text{m/s}}{0.1\times10^{12}\text{Hz}} = 3\text{mm} \sim \frac{3\times10^{8}\text{m/s}}{10\times10^{12}\text{Hz}} = 0.03\text{mm}$
- offer more bandwidth than mmWave frequency and provide an enhanced propagation condition in comparison to the IR band
- Internet of NanoThings(IoNT), Internet of BioNanoThings(IoBT)

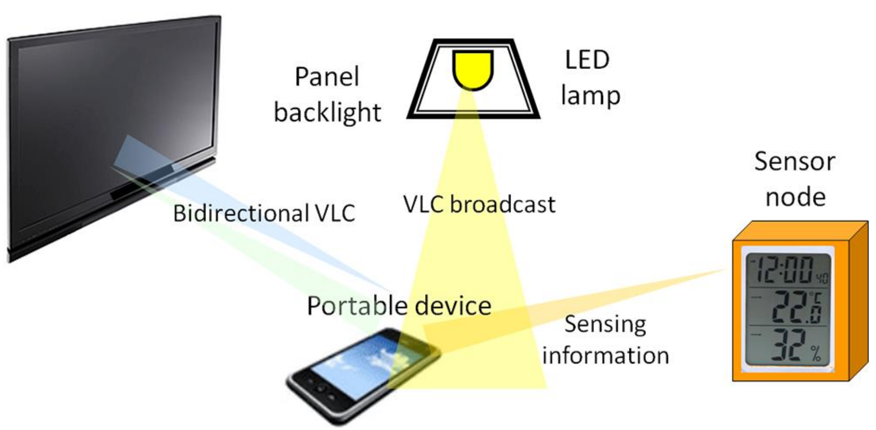
Optical Wireless Communication



- IR + Visible + Ultraviolet frequency bands
- Support a wide range of IoT connectivity and applications
- Hospitals, large shopping malls, stadiums, homes, offices, public transportation stations
- Visible light communication(VLC),
- Light fidelity(LiFi),
- Free space communication(FSO),
- Optical camera communication(OCC),
- Light detection and ranging(LiDAR)

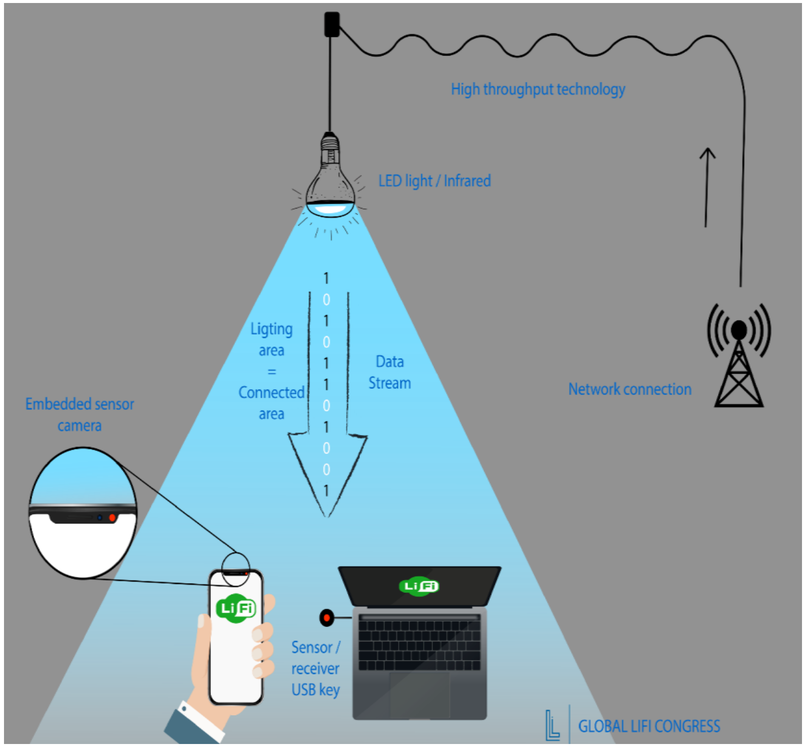
Visible Light Communication(VLC)





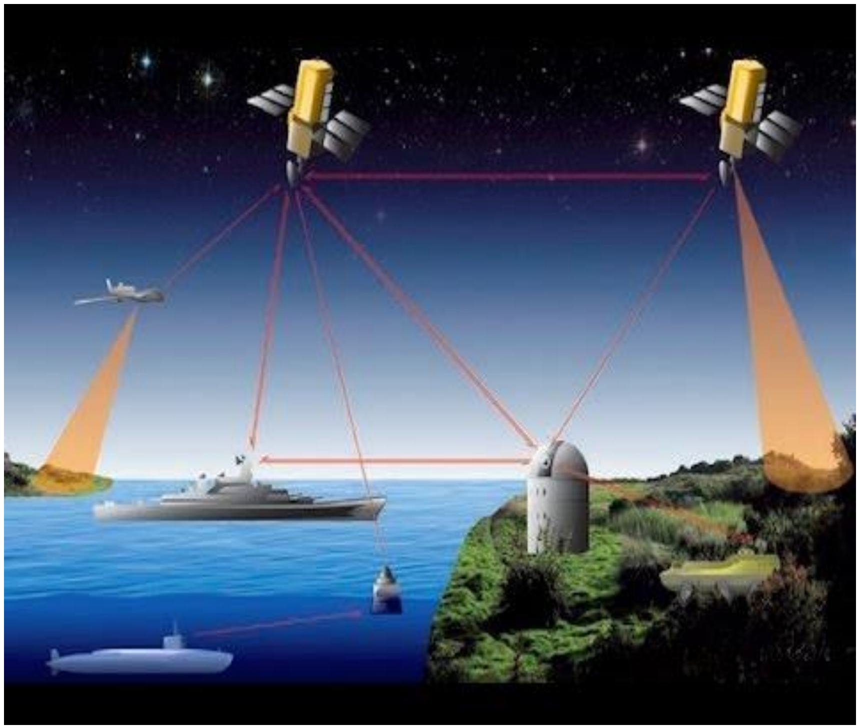
- A special from of OWC that uses the visible part of the spectrum for wireless transmission of information
- Combining lighting and high-speed wireless communication
- LEDs are used at the transmitter to transfer high-speed data rates
- Low-complexity and cost-efficiency, secure

Light-Fidelity(LiFi)



- Technology to complement wireless fidelity(WiFi) network
- Infrared and visible light spectrum
- LED transmit data symbols and photodetectors at receiver receive these data symbols
- Secure, bi-directional, high data rate, fully connected wireless network
- Support user mobility and handover

Free-Space Optical Communication (FSO)



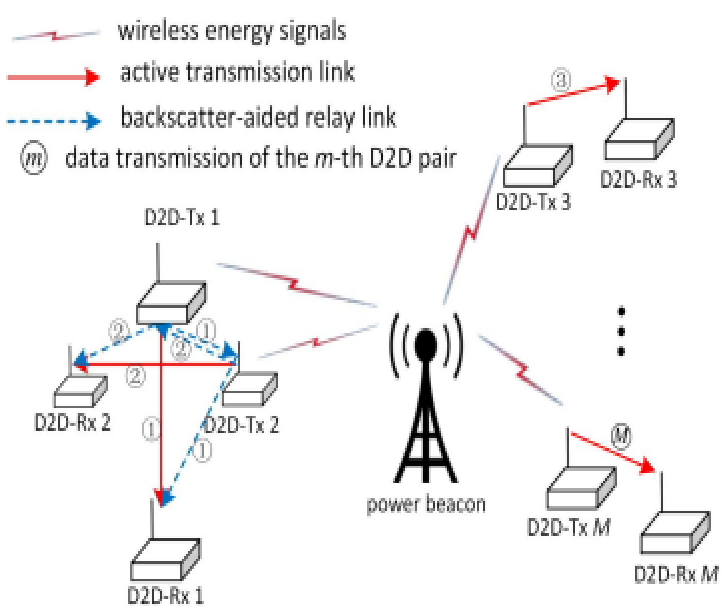
- Take place in the near-infrared frequency range
- Provide wireless backhaul broadband connectivity to enable long-range communication
- Laser diodes at the transmitter side and photodiode at the receiver side
- High-frequency reuse, secure communication, immunity against electromagnetic interference, reducing the power consumption

Enhancing Energy Efficiency for Green Communications

- Finding feasible energy-efficient design for future 6G networks with an aim to reduce the undesirable CO2 emission becomes essential

- Green radio access network concept has been introduced to optimize the spectrum resources and minimize energy consumption

Backscatter Communication



- In 6G network, there are a massive number of IoT devices, which are powered by batteries that have limited capabilities

- 1. Energy harvest
- 2. transmit data by active transmission
- 3. transmit backscatter signals to help other transmitter to forward data

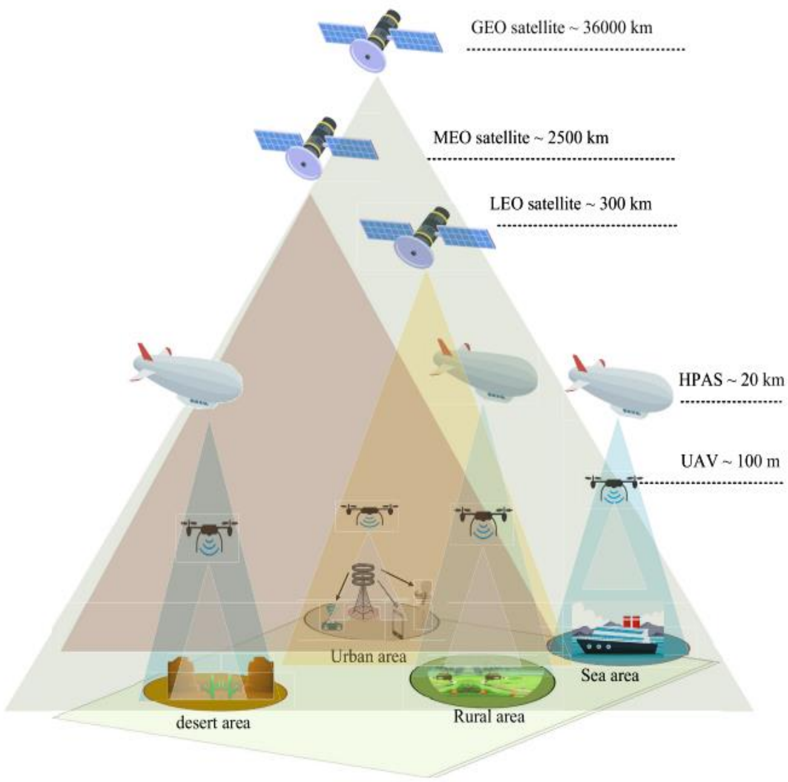
- Technical challenges : low data rate, uni-directional data transmission, short communication range, weakness of security and jamming signal attacks, self-interference

Increasing Connectivity and Full Coverage

- 6G communications systems aim to support the emerging data-hungry applications by increasing connectivity and extending network capabilities

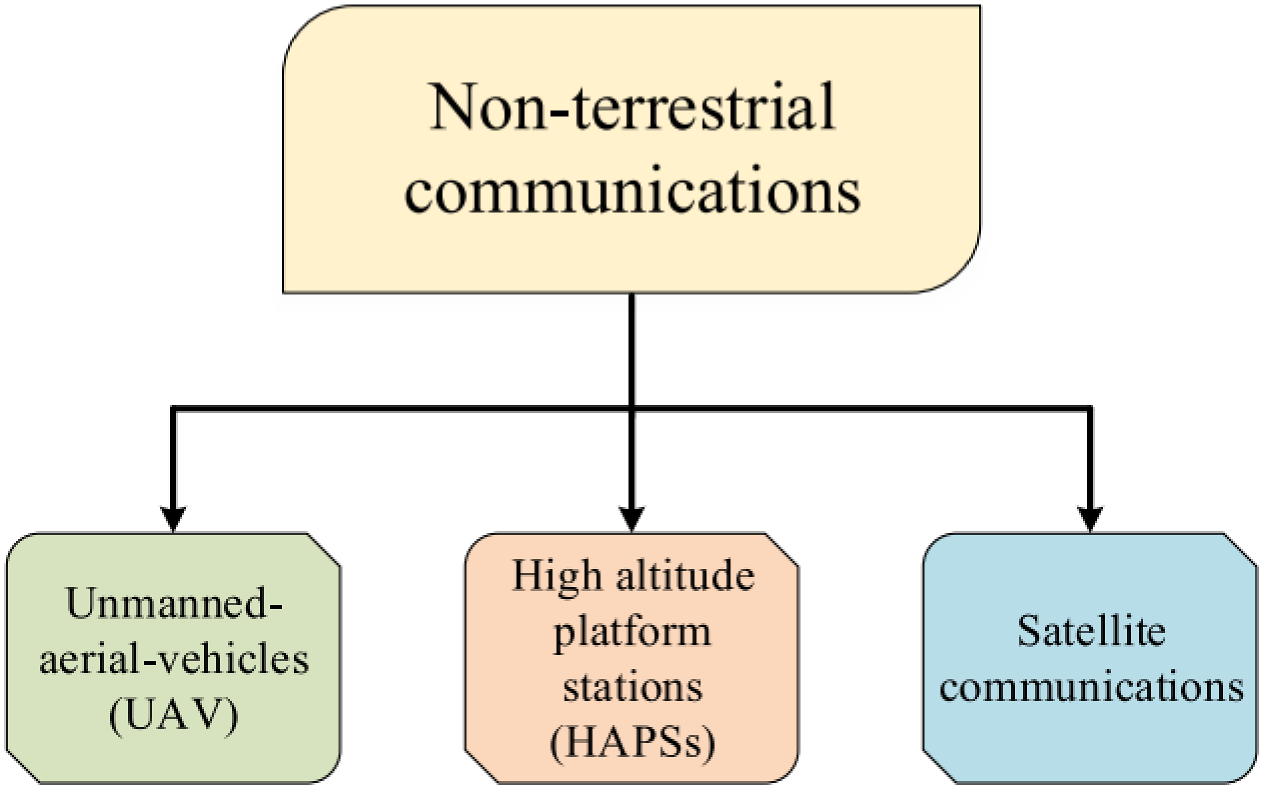
- To achieve connectivity demands and full-coverage requirements, 6G networks are intended to be decentralized and designed based on integrating different networks

Integration of Terrestrial and Non-Terrestrial Communication Networks

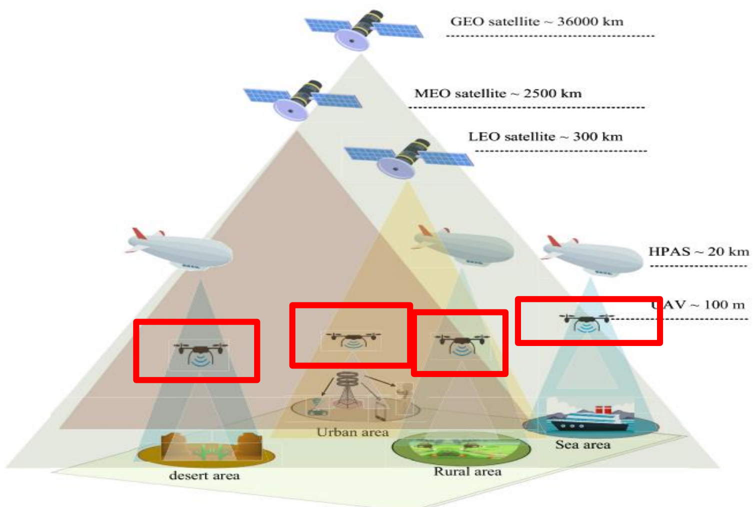


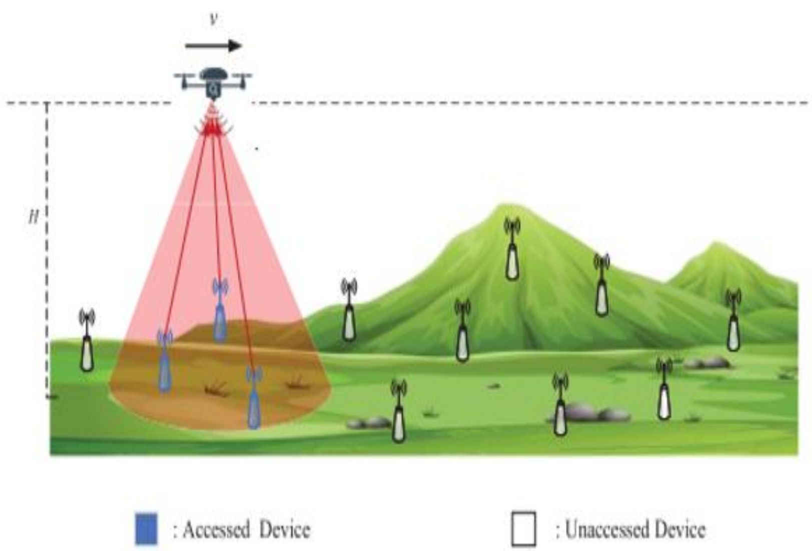
- terrestrial platforms(conventional base station) + non-terrestrial(airborne) platforms(UAVs, HAPSs, satellites communications)
- cost-efficient, high-speed data rate, ubiquitous broadband connectivity and full coverage
- Increase the wireless coverage to reach unserved areas or poorly-served areas
- Support network flexibility, scalability and adaptability

The classification of non-terrestrial networks



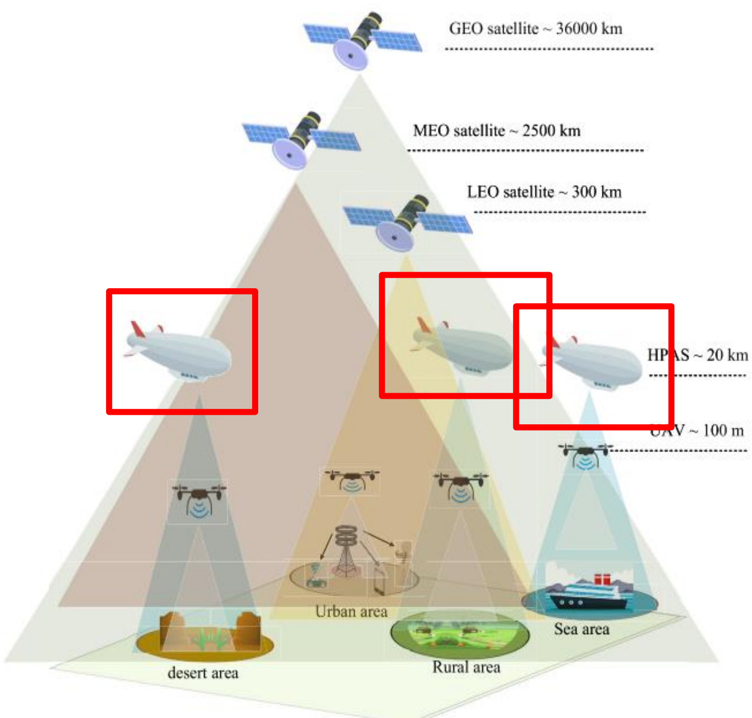
UAVs Communications





- Cell-free communications
- Low Altitude Platforms(LAPs) (0~4km)
- Due to the time flight restriction and movement constraint, UAVs would need the shortest paths to perform their given missions
- Flying base stations, access points, relays with cost and energy efficiency to provide radio coverage for users in various geographical areas

High Altitude Platform Station (HAPS)



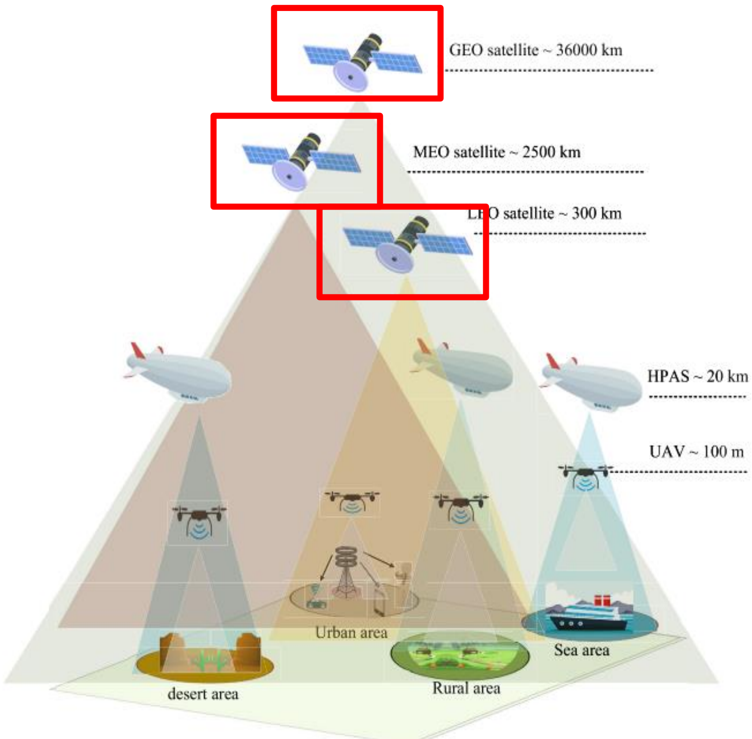
- Quasi-stationary networked aerial platforms located in the stratosphere region of the atmosphere

- Middle Altitude Platforms(LAPs) (15~25km)

- Repeater flying to provide broadcast/multicast wireless broadband services and extend wireless connectivity and coverage

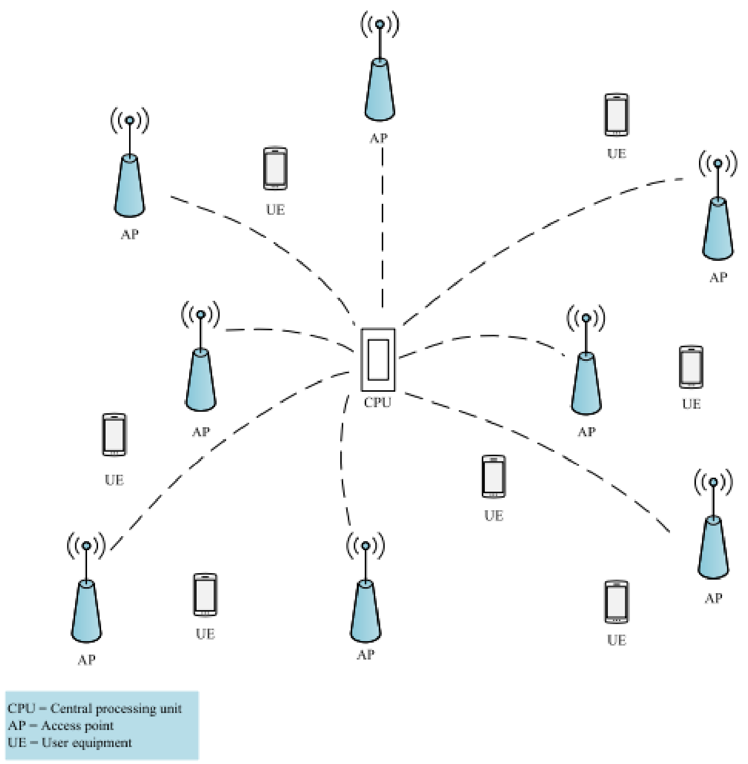
- Operational simplicity, implementation simplicity, low-cost deployment and launch, efficiently utilize the available spectrum, supporting long geographical coverage

Satellite Communication



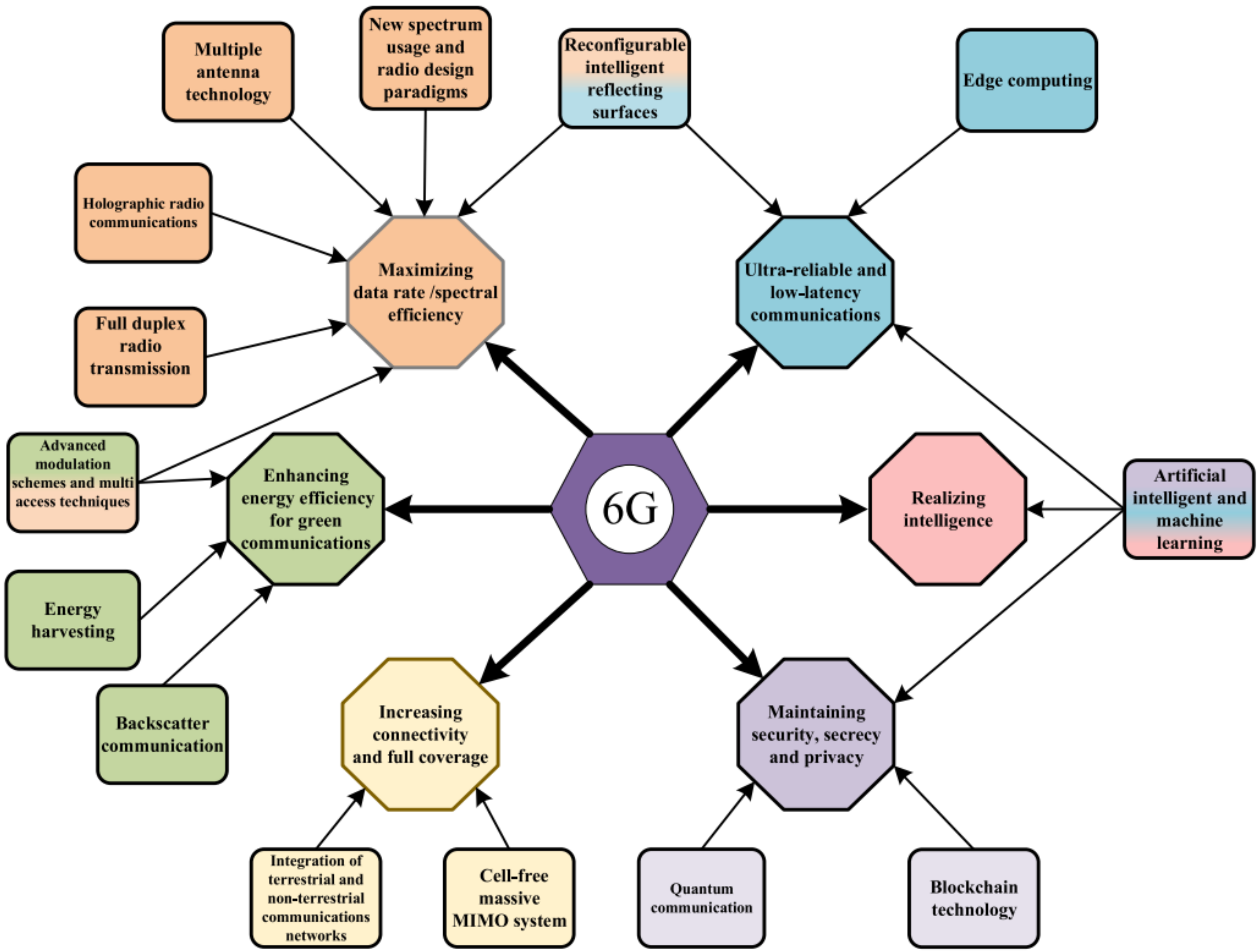
- Broadband connectivity, high-capacity airborne platforms, accurate global coverage, high-speed data rate backbone links
- Provide backhaul support and additional wide area coverage
- Used in navigation, emergency rescue, positioning, tracking, detection
- Geostationary Earth Orbit(GEO) : 35,800km
- Medium Earth Orbit(MEO): 2,000~35,800km
- Low Earth Orbit(LEO): 200~2,000km

Cell-Free Massive MIMO System

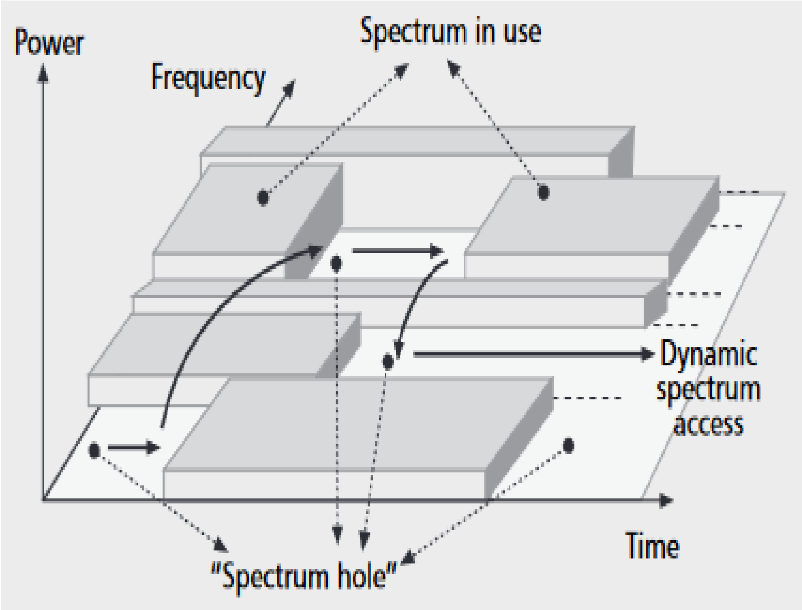


- Cell-Free communication + Massive MIMO
- Inter-cell interference caused by mobile users located at cell boundaries can effectively be mitigated or even eliminated
- Main objective : To achieve coherent processing over large geographically distributed BS antennas
- Enhanced quality of service, nearly uniform achievable rates across the coverage area, seamless handover across all mobile users regardless of their position in the networks

6G Key Performance Indicators and Technologies



Cognitive Radio Network



CRN:

- Use the best wireless channel in its vicinity("Spectrum hole")
- To avoid user interference and congestion
- Automatically detects available channels in wireless spectrum

Characteristics of MA Techniques with CRN

Avoiding the interference amongst SUs

- Since different SUs can coexist and share the resources, interference can originate if they simultaneously decide to use the same spectrum band, based on their spectrum sensing results.
- The main reason behind the origination of the interference between SUs is that each SU may only be aware of the existence of PU and selfishly unaware of the existence of other SUs sharing the spectrum.

Interference Control and Avoidance at PUs

- This is the main requirement/condition when deciding to share the spectrum between SUs and PUs.
- The multiple access scheme should take into consideration the mode of sharing the spectrum, either spectrum overlay or spectrum underlay.

Cognitive Radio Preliminaries

Cognitive capability

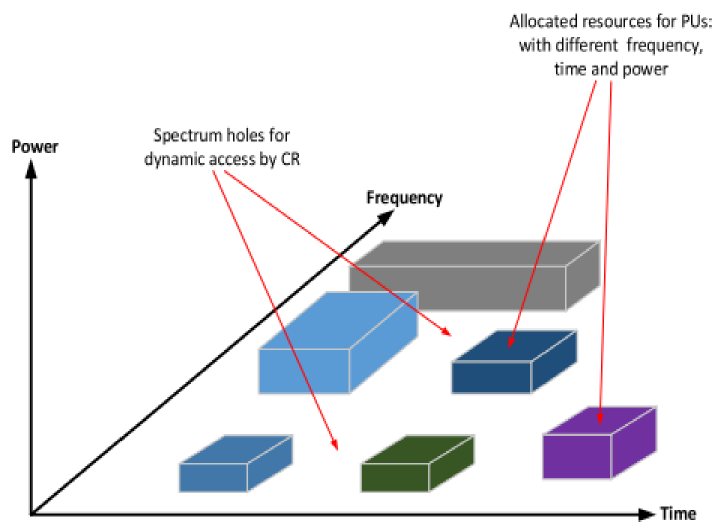


FIGURE 4. Spectrum holes and spectrum cognition.

- Portions of the spectrum are not efficiently used at a particular time or locations
- Temporally unused spectrum, which is indicated as "spectrum hole" or "white space".
- The best spectrum can be selected, shared with other users, and exploited without interfering the licensed user.

Cognitive Radio Preliminaries

Reconfigurability

- CR can be programmed to transmit and receive on various frequencies while using distinctive access technologies which are supported by its hardware design.
- Through this capability, the most excellent spectrum band and the foremost suitable operating parameters can be chosen and reconfigured.

Spectrum Management Framework

- The main CRNs challenge is abstracted in its coexistence with primary networks, which require considering both interference issue as well as diverse QoS requirements.

- To address these challenges, versatile functionalities are activated for spectrum management which called “cognitive cycle”. Figure 5 shows spectrum handling through four prime steps which constitute the cognitive cycle: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility.

Spectrum Sensing

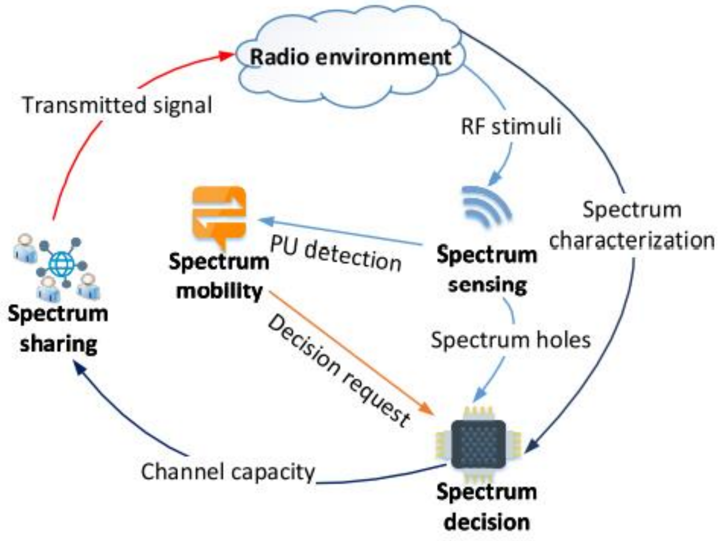


FIGURE 5. Spectrum cognition cycle.

- Spectrum Sensing
- Spectrum mobility
- Spectrum decision
- Spectrum sharing

Multiple Access

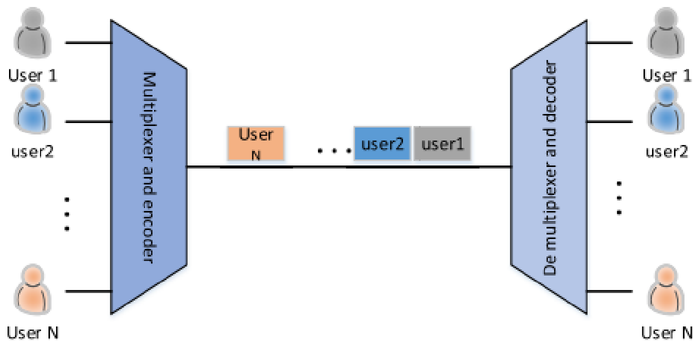
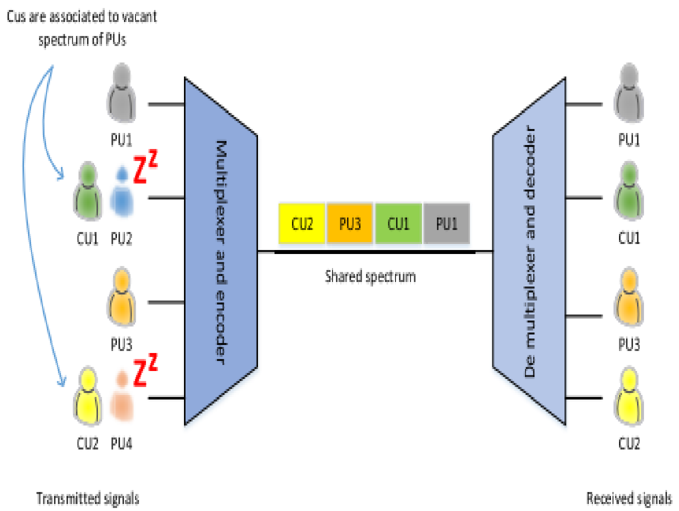


FIGURE 6. Multiple access concept.

- the mechanism of combining multiple users' signals
- capacity enhancement
- overcome the growing request of extra spectrum.

Multiple Access Scheme To CRN



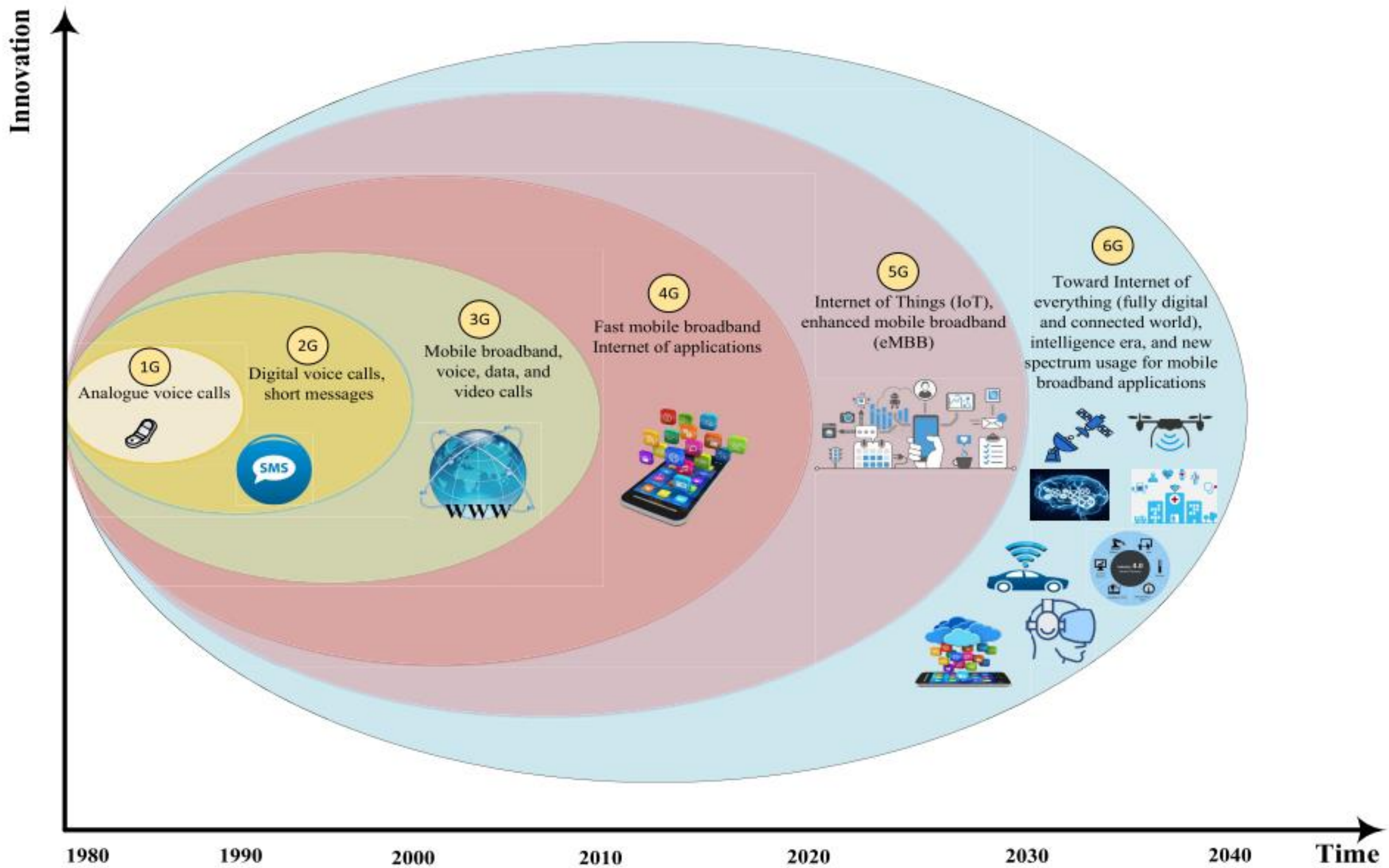
- **Major Component:**
  - Transmitter
  - Available Spectrum/Medium
  - Receiver

- **Users:**
  - 4 Primary Users
  - 2 Cognitive Users

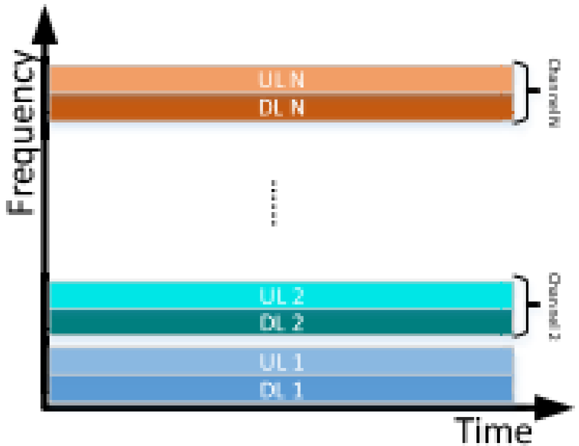
1G to 5G mobile wireless communications

Key indication	**1G**	**2G**	**3G**	**4G**	**5G**
Period	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030
Technology	Analog voice	GSM	CDMA-2000	WiFi, WiMax, LTE	5G NR, IPv6, LAN, WAN, PAN
Multiplexing	FDMA	TDMA, CDMA	CDMA	CDMA, OFDM	OFDM, BDMA
Data Rate	2.4 - 14.4 kb/s	14.4 - 64 kb/s	3.1 - 14.7 Mb/s	100 Mb/s - 1 Gb/s	1 Gb/s and above
Bandwidth	150 kHz	5 - 20 MHz	25 MHz	100 MHz	1 - 2 GHz
Architecture	SISO	SISO	SISO	MIMO	Massive-MIMO
Main Network	PSTN	PSTN	Packet	Internet	Internet
Features	Voice	Voice, SMS	Voice, data	Video	VoIP, ultra HD
Band-type	Narrow	Narrow	Broad	Ultra-broad	Ultra-wide
Highlight	Mobility	Digitization	Internet	Real-time streaming	Extra-high-rate
Switching	Circuit	Circuit, packet	Packet	All packet	All packet
Handoff	Horizontal	Horizontal	Horizontal	Horizontal, vertical	Horizontal, vertical

1G to 5G mobile wireless communications



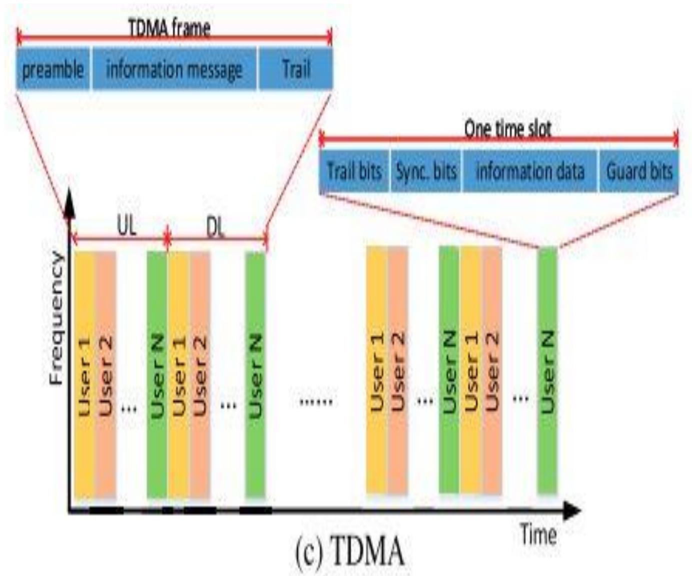
FDMA Scheme



(a) FDMA

- Frequency Division
- Generally utilized in analog system
- User frequency band
  - Sending information
  - Receiving information
- Guard band

TDMA Scheme

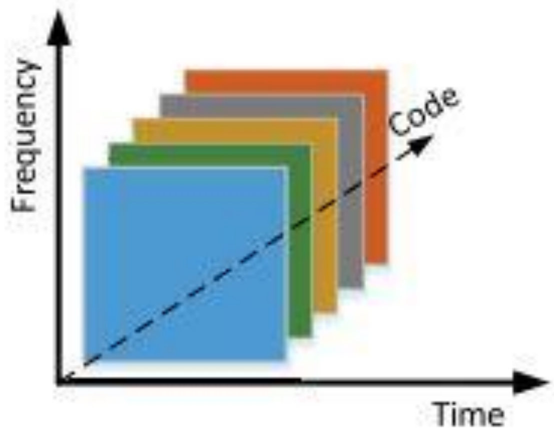


- Time Division

- Each Frame:
  - Preamble
  - Information message
  - Trail bits

- One Time Slot:
  - Trail bits
  - Sync. bits
  - Information data
  - Guard bits

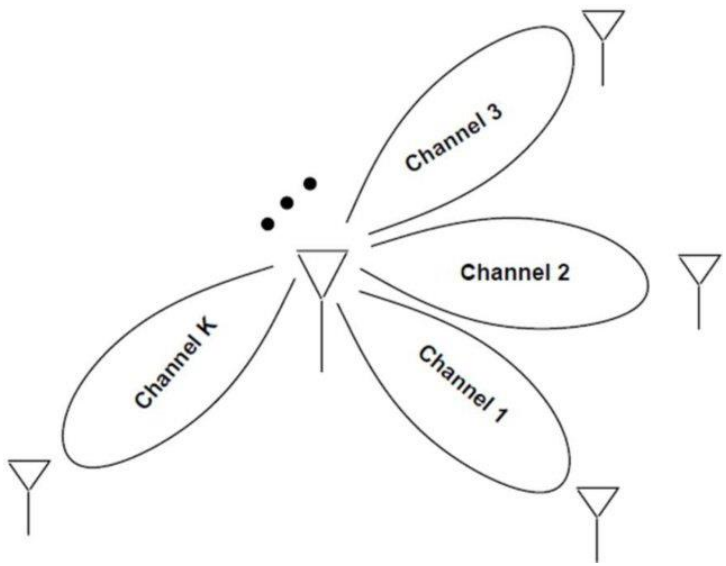
SSMA Scheme



(b) CDMA

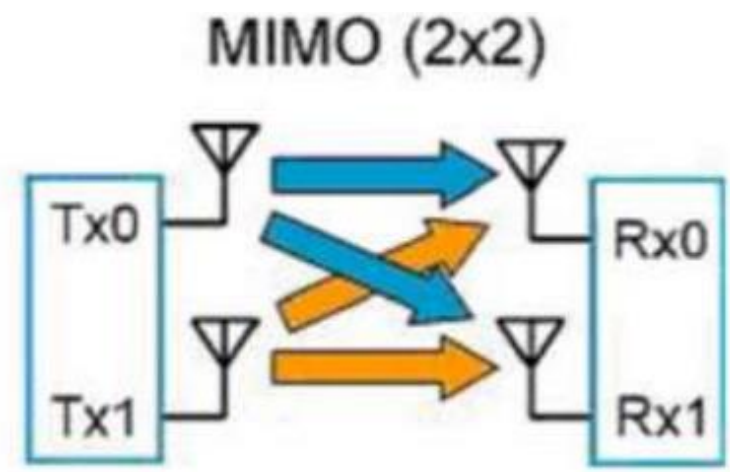
- Spread Spectrum
- MU access scheme in 3G networks
- Special type of code known as Pseudo-Noise sequence
  - Direct-Sequence Code Division Multiple Access(DS-CDMA)
  - Frequency-Hopping Code Division Multiple Access(FH-CDMA)
- DS-CDMA :
  - Same Bandwidth, Different Assigned Codes, Orthogonal to each other
- FH-CDMA :
  - Pseudo-random hopping algorithm

SDMA

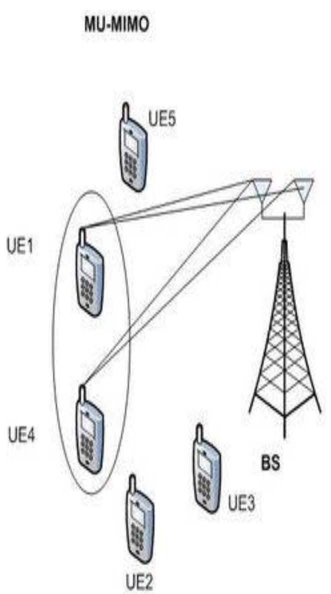


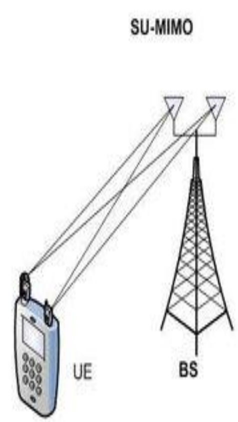
- Spatial (or Space) Division
- Traditional Cellular BS radiate power in all directions
  → power waste, cause interference
- Tracking the spatial location of mobile devices (Smart antenna technology)
- By adjusting the phase of signals from several antennas, BS can effectively steer a beam or a spot of RF power to or from each user (Precoding)
- Expensive, complex to construct and design, high insertion loss

MIMO



- Multiple-input Multiple-Output
- Use of multiple antennas at the transmitter and receiver
- Increasing the capacity of wireless communication

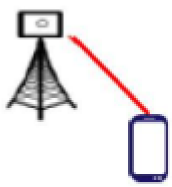


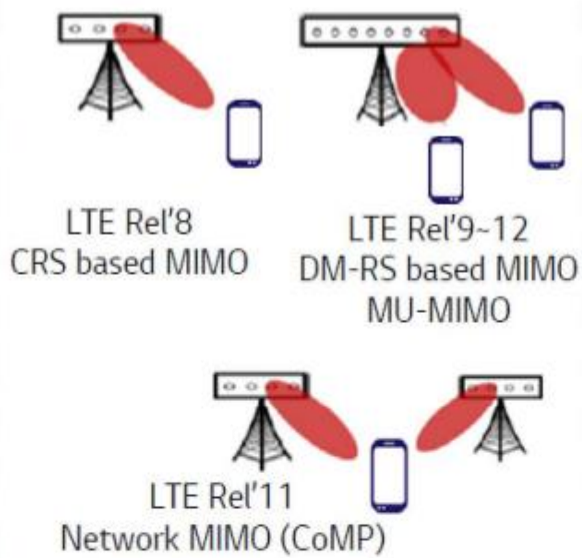


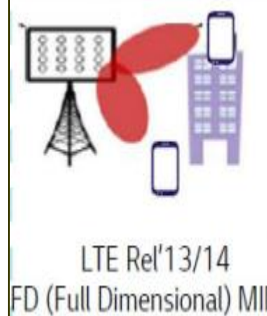
- SU(Single User)-MIMO
- MU(Multi User)-MIMO
- Massive MIMO

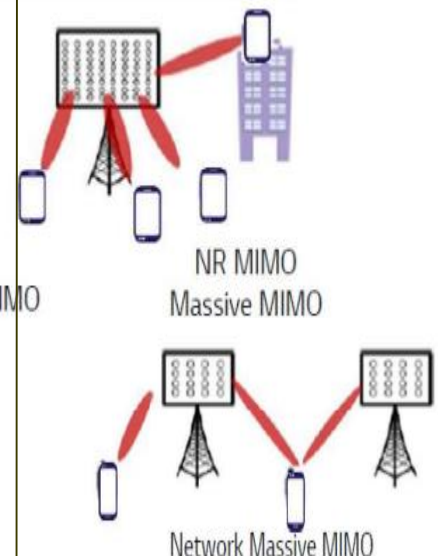
MIMO

3G	4G	5G
	▪ 4Tx MIMO in Release-8 ▪ MIMO enhancements in Release-9~12 ▪ FD(Full Dimensional MIMO) in Release-13~14	▪ Massive MIMO ▪ Network Massive MIMO



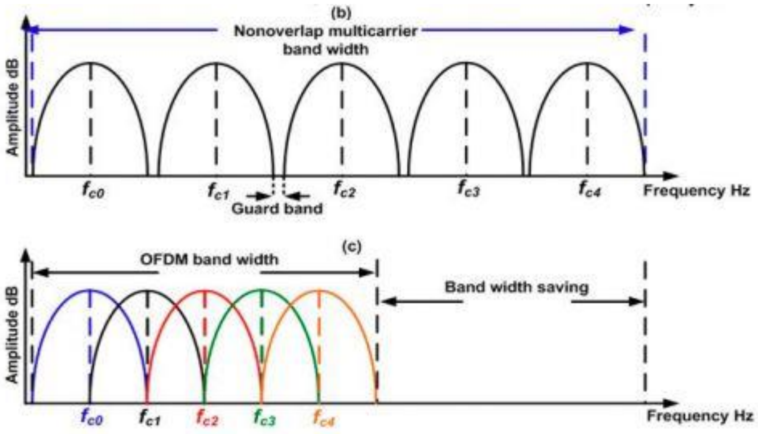






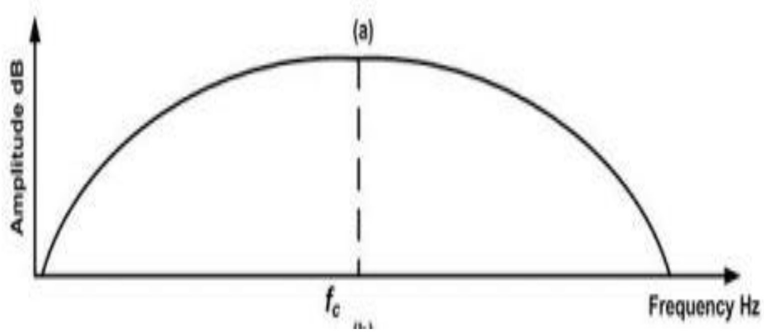
3G	4G	5G
SISO	▪ # of antennas : 2~8 ▪ Uniform linear array	▪ # of antennas : 16~256 ▪ Uniform square array

OFDMA Scheme



- Orthogonal-FDMA
- MU access scheme in 4G networks
- MU-FDMA, Guard Band removed
- Orthogonality concept
- Saving more bandwidth

NOMA Scheme



- Non-Orthogonal
- Radio Access in 5G wireless Network
- Higher SE and EE than OMA

PD(Power Domain)-NOMA

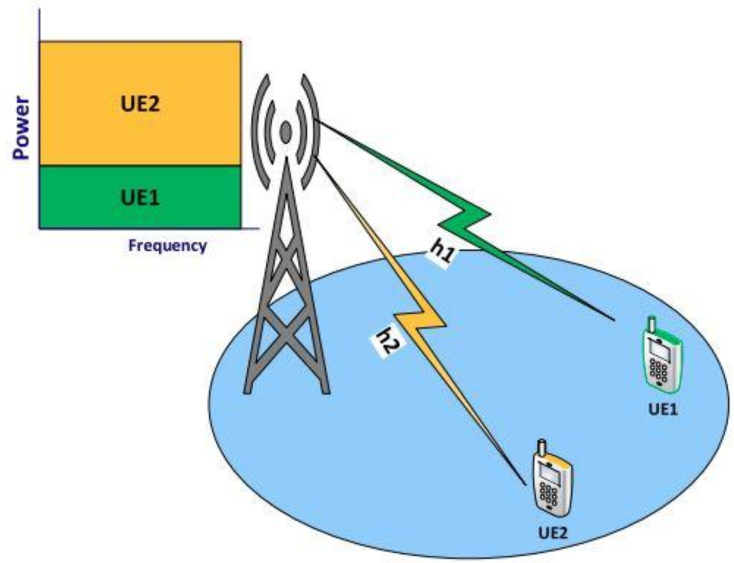


FIGURE 11. NOMA downlink transmission.

- Same Time, Same Frequency, Different Power level
- Superposition coding at the transmitter
- Successive Interference Cancellation(SIC) at the receiver
- UE1 closer than UE2 ($h_1 > h_2$)
- UE1 detect UE2's signal than extract own signal (Using SIC)
- UE2 treats UE1's signal as noise

PD-NOMA

- Transmitted Signal by the BS
  - $X(t) = \sum_{k=1}^{2} \propto_k P_t X_k(t), \begin{pmatrix} X_k(t) : \text{individual information of } k^{th} \text{user} \\ \propto_k : \text{power allocation coefficient} \\ P_t : \text{total power budget at the BS} \end{pmatrix}$
- Received Signal at k^{th} user
  - $Y_k(t) = X(t)h_k + W_k(t), \begin{pmatrix} h_k : \text{channel gain between BS and } \mathrm{UE_k} \\ W_k(t) : \text{AWGN at } \mathrm{UE_k} \end{pmatrix}$
- SNR for UE2
  - $SNR_2 = \frac{|h_2|^2 P_2}{|h_2|^2 P_1 + N_0 W}$ (W : bandwidth)
- SNR for UE1
  - $SNR_1 = \frac{|h_1|^2 P_1}{N_0 W}$
- SNR and throughput for k^{th} user
  - $SNR_k = \frac{|h_k|^2 P_k}{\sum_{i=1}^{k-1} |h_k|^2 P_i + N_0 W}, R_k = W \log_2 \left(1 + \frac{|h_k|^2 P_k}{\sum_{i=1}^{k-1} |h_k|^2 P_i + N_0 W}\right)$

Comparison between OMA and NOMA

	Advantages	**Disadvantages**
OMA	1) Low receiver complexity 2) Less interference	1) Less spectral efficiency 2) Limited number of users 3) Lack of users' fairness 4) Requires synchronization 5) Limited degrees of freedoms (DoFs) 6) Large latency
NOMA	1) High spectral efficiency 2) Supports high connection density 3) Sufficient user fairness 4) Low latency 5) Adapts with diverse QoS 6) Compatible with other multiple access techniques	1) Requires complex receivers 2) High sensitivity to channel uncertainties 3) introduces potential interference

The Concept Behind RSMA

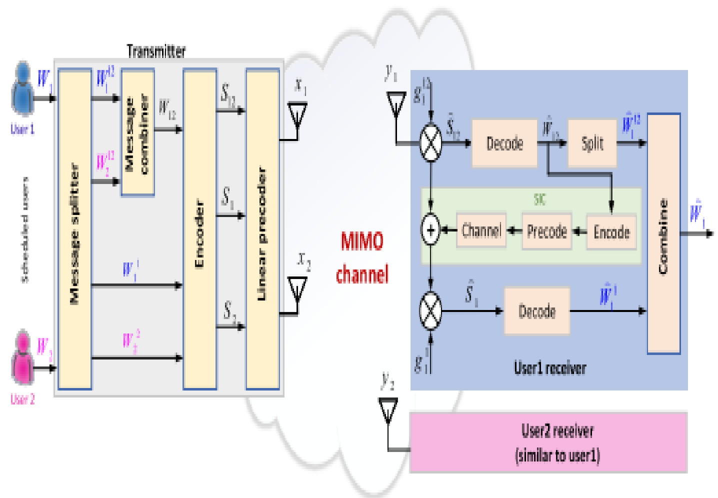


FIGURE 14. MIMO system with two users exploiting RSMA.

- In Transmitter
  - Common Stream: $\{W_1^{12}, W_2^{12}\} \rightarrow \{W_{12}\}$
  - Private Stream: $\{W_1^1, W_2^2\}$
  - Encoding
    $\{W_{12}\} \rightarrow \{S_{12}\}$, $\{W_1^1, W_2^2\} \rightarrow \{S_1, S_2\}$
  - Precoding vector P=$[p_{12}, p_1, p_2]$

- Transmitted signal
  - x = $p_{12}s_{12} + p_1 s_1 + p_2 s_2$

- In Receiver
  - First, user1 decode the common stream $\widehat{S_{12}} \rightarrow \widehat{W_{12}}$ and consider private stream as a noise.
  - Then, $\widehat{W_{12}}$ is post processed through SIC block to extract private stream $\widehat{W_1^1}$
  - Finally, user receiver combines decoded streams $\widehat{W_1^1}$ and $\widehat{W_1^{12}} \rightarrow \widehat{W_1}$

Case Study: RSMA-Enabled CRN

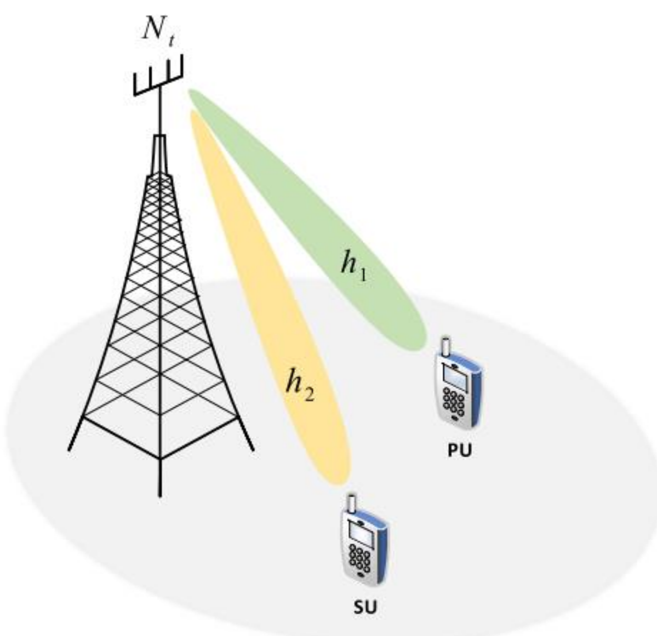


FIGURE 15. MISO-enabled CRN.

- The received signal
  - $y_{PU} = \mathbf{h_1^H x} + n_1$, $y_{SU} = \mathbf{h_2^H x} + n_2$

($\mathbf{h_1}$, $\mathbf{h_2}$=channel gain from BS to PU and SU, $\mathbf{x}$=transmitted signal, n_1, n_2 denote the AWGN $N(0, \sigma^2)$)

  - $\mathbf{x} = P_e = \mathbf{P}_c e_c + \mathbf{P}_{PU} e_{PU} + \mathbf{P}_{SU} e_{SU}$

($\mathbf{P}$: beamformer, e: data stream)

  - $\mathrm{SINR}_{c,PU}(\mathbf{P}) = \frac{|\mathbf{h_1^H P}_c|^2}{|\mathbf{h_1^H P}_{PU}|^2 + |\mathbf{h_1^H P}_{SU}|^2 + \sigma^2}$
  - $\mathrm{SINR}_{c,SU}(\mathbf{P}) = \frac{|\mathbf{h_2^H P}_c|^2}{|\mathbf{h_2^H P}_{PU}|^2 + |\mathbf{h_2^H P}_{SU}|^2 + \sigma^2}$
  - $R_{c,PU}(\mathbf{P}) = W \log_2 \left(1 + \mathrm{SINR}_{c,PU}(\mathbf{P})\right)$
  - $R_{c,SU}(\mathbf{P}) = W \log_2 \left(1 + \mathrm{SINR}_{c,SU}(\mathbf{P})\right)$
- Achievable rate
  - $R_c(\mathbf{P}) = \min(R_{c,PU}(\mathbf{P}), R_{c,SU}(\mathbf{P}))$
  - $C_{PU} + C_{SU} = R_c(P)$, (C_k is kth user's portion of the common rate)

Case Study: RSMA-Enabled CRN

- $\text{SINR}_{p,PU}(\mathbf{P}) = \frac{|\mathbf{h}_1^{\mathbf{H}}\mathbf{P}_{PU}|^2}{|\mathbf{h}_1^{\mathbf{H}}\mathbf{P}_{SU}|^2+\sigma^2}$, $\text{SINR}_{p,SU}(\mathbf{P}) = \frac{|\mathbf{h}_2^{\mathbf{H}}\mathbf{P}_{SU}|^2}{|\mathbf{h}_2^{\mathbf{H}}\mathbf{P}_{PU}|^2+\sigma^2}$
- $R_{p,PU}(\mathbf{P}) = W\log_2\left(1+\text{SINR}_{p,PU}(\mathbf{P})\right)$, $R_{p,SU}(\mathbf{P}) = W\log_2\left(1+\text{SINR}_{p,SU}(\mathbf{P})\right)$

Total achievable rate

- $R_{PU,tot} = C_{PU}(\mathbf{P})+R_{p,PU}(\mathbf{P})$, $R_{SU,tot} = C_{SU}(\mathbf{P})+R_{p,SU}(\mathbf{P})$

Weighted Sum Rate

$$\max_{(P,C)} R_{RSMA}(u) = u_1 R_{(PU,tot)} + u_2 R_{(SU,tot)}$$

$$s.t\ C_{PU} + C_{SU} \le R_c$$

$$\mathbf{tr}(PP^H) \le P_T$$

$$C \ge 0$$

$$R(SU,tot) \ge R_{SU}^{th}$$

$$P(SU,tot)h_1^H \le I_{th}$$

u=[u1,u2] : pair of weights
C=[C_{PU}, C_{SU}] : common rate vector
P : Private rate vector
tr(PP^H) : total transmit power
$R(SU,tot) \ge R_{SU}^{th}$: constraint to ensure the QoS of SU
I_{th} maximum interference level tolerable by the PU

Multiple Access and Modulation techniques