

MULTIPLE ACCESS SCHEMES IN WIRELESS NETWORKS

- Wireless communication systems support multiple users over a shared medium.
- Efficient resource allocation is essential to avoid interference and congestion.
- Multiple Access (MA) schemes enable simultaneous transmission of multiple users
- Key objectives:
 - 1-Maximize spectral efficiency
 - 2-Minimize interference
 - 3-Ensure Quality of Service (QoS)
- Evolution of MA techniques:

FDMA → TDMA → CDMA → OFDMA → NOMA
- Modern networks (4G/5G) use hybrid access schemes for improved performance

FDMA (FREQUENCY DIVISION MULTIPLE ACCESS)

-
- The total available bandwidth is divided into multiple frequency channels
- Each user is assigned a dedicated frequency band
- Users transmit simultaneously but on different frequencies
- Guard bands are placed between adjacent channels to reduce interference
- Supports continuous transmission (no time sharing required)

TOTAL BANDWIDTH:

$$B_{total} = N \times B_{user} + (N - 1) \times B_{guard}$$

WHERE:

- N : NUMBER OF USERS
- B_{user} : BANDWIDTH ALLOCATED PER USER
- B_{guard} : GUARD BAND BETWEEN CHANNELS

EXAMPLES OF FDMA

- **1G CELLULAR NETWORKS (AMPS):** THE [ADVANCED MOBILE PHONE SYSTEM \(AMPS\)](#) WAS A PURE FDMA SYSTEM WHERE EACH USER WAS GIVEN A 30 KHZ CHANNEL FOR THEIR CALL.
- **SATELLITE COMMUNICATIONS:** LARGE TRANSPONDER BANDS (E.G., 500 MHZ) ARE DIVIDED INTO SMALLER CHANNELS (E.G., 40 MHZ) TO SERVE MULTIPLE EARTH STATIONS SIMULTANEOUSLY.
- **RADIO AND TV BROADCASTING:** BOTH [AM/FM RADIO STATIONS](#) AND TERRESTRIAL DIGITAL TV USE FDMA PRINCIPLES BY OPERATING ON DISTINCT, ASSIGNED FREQUENCIES TO PREVENT OVERLAP.
- **WALKIE-TALKIES:** THESE "CLOSED-USER" SYSTEMS TYPICALLY ASSIGN A SPECIFIC CHANNEL FREQUENCY FOR A GROUP TO COMMUNICATE WITHOUT INTERFERING WITH OTHERS

TDMA (TIME DIVISION MULTIPLE ACCESS)

-
- The available channel is divided into time slots
- Each user is assigned a specific time slot for transmission
- Users transmit one after another in a cyclic manner
- Entire bandwidth is used by a user, but only for a short duration
- Requires strict time synchronization between users
- If total time frame is divided into N slots:

$$T_{\text{slot}} = \frac{T_{\text{frame}}}{N}$$

WHERE:

- T_{frame} :TOTAL FRAME DURATION
- N : NUMBER OF USERS

EXAMPLES OF TDMA

- **GSM (2G) CELLULAR NETWORKS:** THIS IS THE MOST FAMOUS EXAMPLE. A SINGLE 200 KHZ RADIO CHANNEL IS DIVIDED INTO **8 TIME SLOTS**, MEANING EIGHT DIFFERENT USERS CAN HOLD PHONE CALLS ON THAT ONE FREQUENCY SIMULTANEOUSLY .
- **SATELLITE COMMUNICATIONS:** MANY SATELLITE SYSTEMS USE TDMA TO ALLOW MULTIPLE GROUND STATIONS TO SHARE A SINGLE HIGH-POWER TRANSPONDER. EACH STATION TAKES A TURN SENDING DATA AT HIGH SPEEDS IN A COORDINATED SEQUENCE.
- **DIGITAL ENHANCED CORDLESS TELECOMMUNICATIONS (DECT):** THIS IS THE TECHNOLOGY USED BY MOST **CORDLESS HOME PHONES**. IT USES TDMA TO MANAGE MULTIPLE HANDSETS CONNECTING TO A SINGLE BASE STATION .
- **TETRA (TERRESTRIAL TRUNKED RADIO):** USED BY **EMERGENCY SERVICES** (POLICE, FIRE, AMBULANCE), THIS SYSTEM USES TDMA TO PROVIDE EFFICIENT GROUP COMMUNICATIONS AND DEDICATED "PRIORITY" SLOTS FOR CRITICAL ALERTS .
- **BLUETOOTH:** WHILE PRIMARILY A FREQUENCY-HOPPING SYSTEM, BLUETOOTH USES A TDMA STRUCTURE TO MANAGE THE DATA FLOW BETWEEN A "MASTER" DEVICE (LIKE YOUR PHONE) AND "SLAVES" (LIKE YOUR EARBUDS OR WATCH).

• CDMA (CODE DIVISION MULTIPLE ACCESS)

- All users share the same frequency band and time simultaneously
- Each user is assigned a unique spreading code (PN code)
- Signal is spread over a wide bandwidth (spread spectrum technique)
- Receiver uses the same code to extract the desired signal
- Multiple users are separated using code orthogonality

MATHEMATICAL MODEL

- TRANSMITTED SIGNAL:

$$s_i(t) = d_i(t) \cdot c_i(t)$$

- RECEIVED SIGNAL:

$$r(t) = \sum_{i=1}^N d_i(t) c_i(t) + n(t)$$

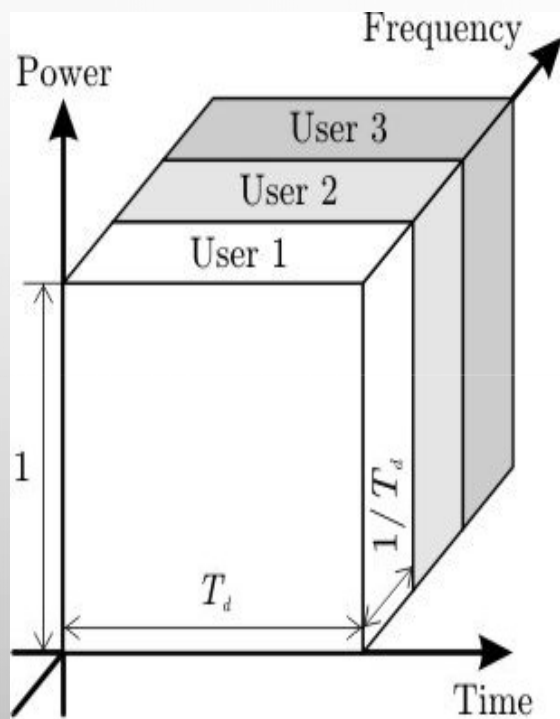
- WHERE:

- $d_i(t)$: DATA SIGNAL
- $c_i(t)$: SPREADING CODE
- $n(t)$: NOISE
- N : NUMBER OF USERS

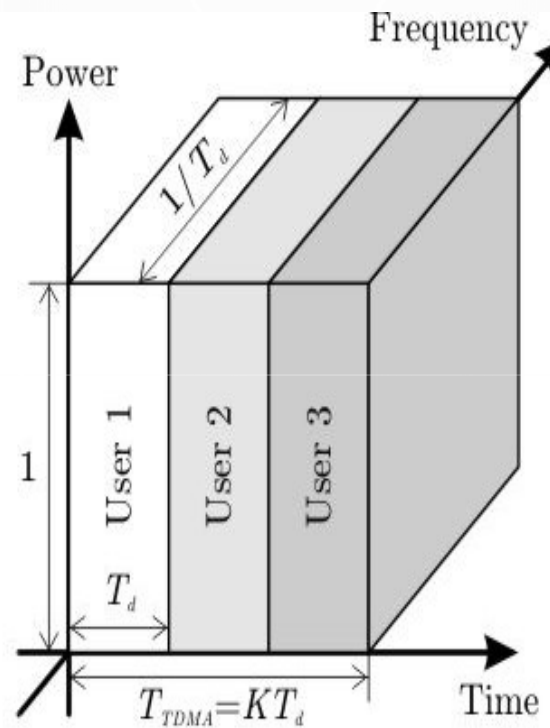
EXAMPLES OF CDMA

- **IS-95 (CDMAONE):** THE FIRST 2G CELLULAR STANDARD BASED ON CDMA, FAMOUSLY USED BY CARRIERS LIKE **VERIZON** AND **SPRINT** IN THE US AND PARTS OF ASIA.
- **W-CDMA (UMTS):** THE BACKBONE OF **3G NETWORKS**. IT USED A WIDER 5 MHZ BAND TO PROVIDE HIGHER DATA SPEEDS FOR THE FIRST WAVE OF SMARTPHONES.
- **GPS (GLOBAL POSITIONING SYSTEM):** ALL GPS SATELLITES TRANSMIT ON THE SAME FREQUENCY. YOUR PHONE OR CAR'S RECEIVER USES CDMA TO DISTINGUISH THE SIGNAL OF ONE SATELLITE FROM ANOTHER BASED ON THEIR UNIQUE "GOLD CODES."
- **CDMA2000:** AN EVOLUTION OF THE 2G SYSTEM THAT PROVIDED 3G DATA SPEEDS (EV-DO) AND WAS WIDELY USED BEFORE THE GLOBAL SHIFT TO LTE (4G)

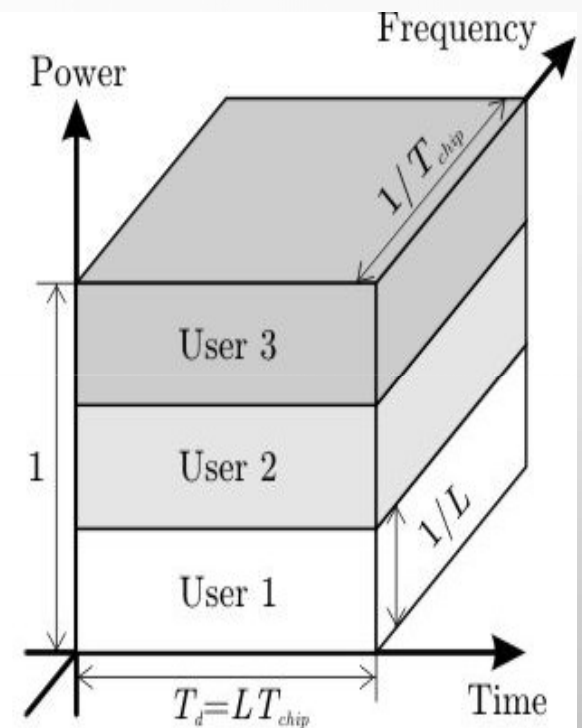
COMPARISON AMONG FDMA, TDMA, CDMA



FDMA



TDMA



CDMA

OFDMA (ORTHOGONAL FREQUENCY DIVISION MULTIPLE ACCESS)

- The available bandwidth is divided into multiple **orthogonal subcarriers**
- Data is transmitted in parallel streams over these subcarriers
- Subcarriers overlap in frequency but remain orthogonal, avoiding interference
- Uses IFFT at transmitter and FFT at receiver
- Highly robust against multipath fading and ISI (Inter-Symbol Interference)
- OFDM transmitted signal:

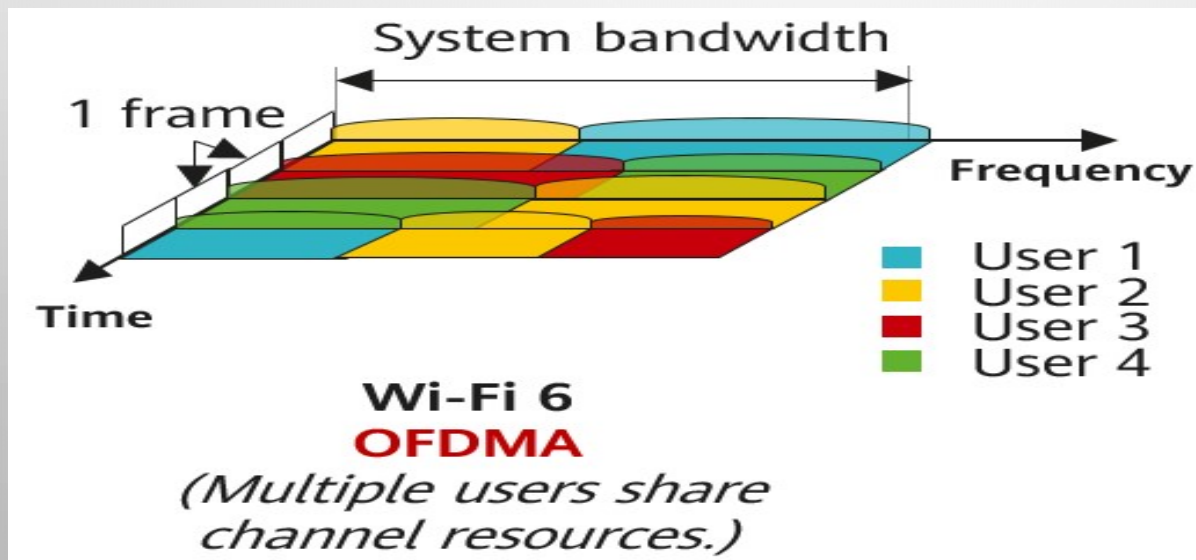
$$x(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi f_k t}$$

- Orthogonality condition:

$$\int_0^T e^{j2\pi(f_k - f_l)t} dt = 0 \quad \text{for } k \neq l$$

WHERE:

- X_k :DATA SYMBOL ON SUBCARRIER k
- f_k :SUBCARRIER FREQUENCY

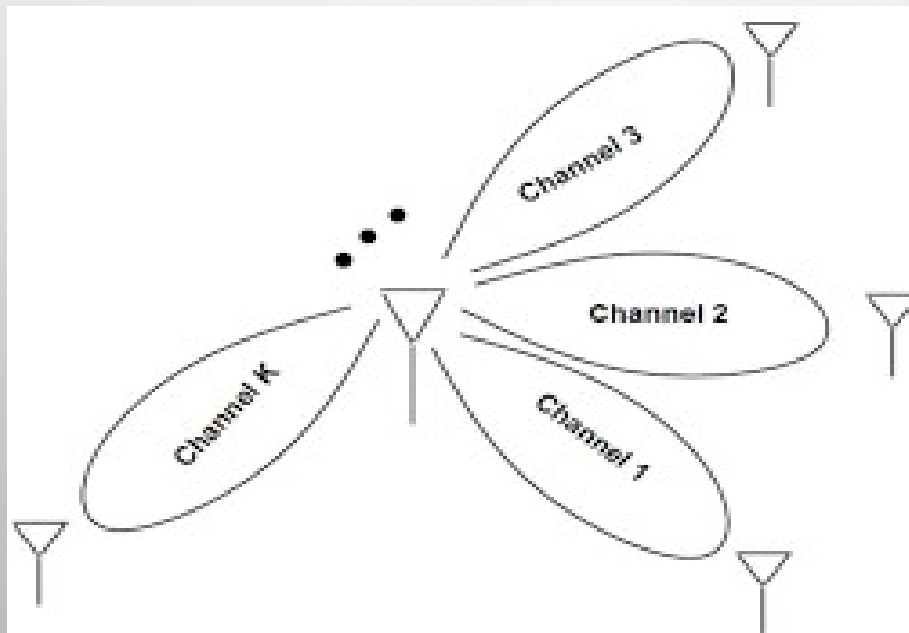


EXAMPLES OF OFDMA

- **4G LTE NETWORKS:** THIS WAS THE FIRST MAJOR MOBILE STANDARD TO ADOPT OFDMA. IT ALLOWS A CELL TOWER TO TALK TO DOZENS OF SMARTPHONES SIMULTANEOUSLY BY CARVING UP THE 20 MHZ BANDWIDTH INTO TINY SUB-CHANNELS.
- **5G NR (NEW RADIO):** 5G USES A MORE FLEXIBLE VERSION OF OFDMA. IT CAN HANDLE MASSIVE AMOUNTS OF DATA (LIKE 4K STREAMING) FOR SOME USERS WHILE PROVIDING LOW-LATENCY CONNECTIONS FOR THINGS LIKE AUTONOMOUS CARS OR INDUSTRIAL ROBOTS.
- **WI-FI 6 (802.11AX):** UNLIKE OLDER WI-FI VERSIONS WHERE ONLY ONE DEVICE COULD "TALK" TO THE ROUTER AT A TIME, WI-FI 6 USES OFDMA TO LET THE ROUTER COMMUNICATE WITH MULTIPLE DEVICES (PHONES, LAPTOPS, SMART TVS) IN A SINGLE TRANSMISSION.
- **DIGITAL VIDEO BROADCASTING (DVB-T2):** USED FOR MODERN TERRESTRIAL DIGITAL TV. IT USES THOUSANDS OF SUB-CARRIERS TO ENSURE A CLEAR HD PICTURE EVEN IF THERE ARE REFLECTIONS FROM BUILDINGS OR MOUNTAINS.

SDMA (SPACE DIVISION MULTIPLE ACCESS)

- Multiple users are separated based on spatial location
- Uses directional antennas / beamforming to serve users
- Same frequency and time resources can be reused in different directions
- Exploits spatial diversity to increase system capacity
- Widely used with MIMO (Multiple Input Multiple Output) systems



MATHEMATICAL MODEL

- RECEIVED SIGNAL:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

- BEAMFORMING OUTPUT:

$$\hat{x}_i = \mathbf{w}_i^H \mathbf{y}$$

- WHERE:

- $\mathbf{H}$: CHANNEL MATRIX
- $\mathbf{x}$: TRANSMITTED SIGNAL VECTOR
- $\mathbf{w}_i$: BEAMFORMING WEIGHT VECTOR
- $\mathbf{n}$: NOISE
- H : HERMITIAN (CONJUGATE TRANSPOSE)

OMA (ORTHOGONAL MULTIPLE ACCESS)

- USERS ARE ASSIGNED DEDICATED, ORTHOGONAL RESOURCES (TIME, FREQUENCY, OR CODES) TO AVOID INTERFERENCE, ENABLING SIMPLE, EFFICIENT, AND RELIABLE COMMUNICATION.
- BECAUSE SIGNALS DO NOT OVERLAP, THEY CAN BE DECODED SEPARATELY, SIGNIFICANTLY SIMPLIFYING RECEIVER COMPLEXITY COMPARED TO NON-ORTHOGONAL SYSTEMS.
- WHILE OMA OFFERS SIMPLICITY AND RELIABILITY, IT IS LIMITED IN SPECTRAL EFFICIENCY. NOMA IS OFTEN CONSIDERED A POTENTIAL ALTERNATIVE FOR 5G AND FUTURE SYSTEMS TO HANDLE MASSIVE CONNECTIVITY AND IMPROVE SPECTRAL EFFICIENCY



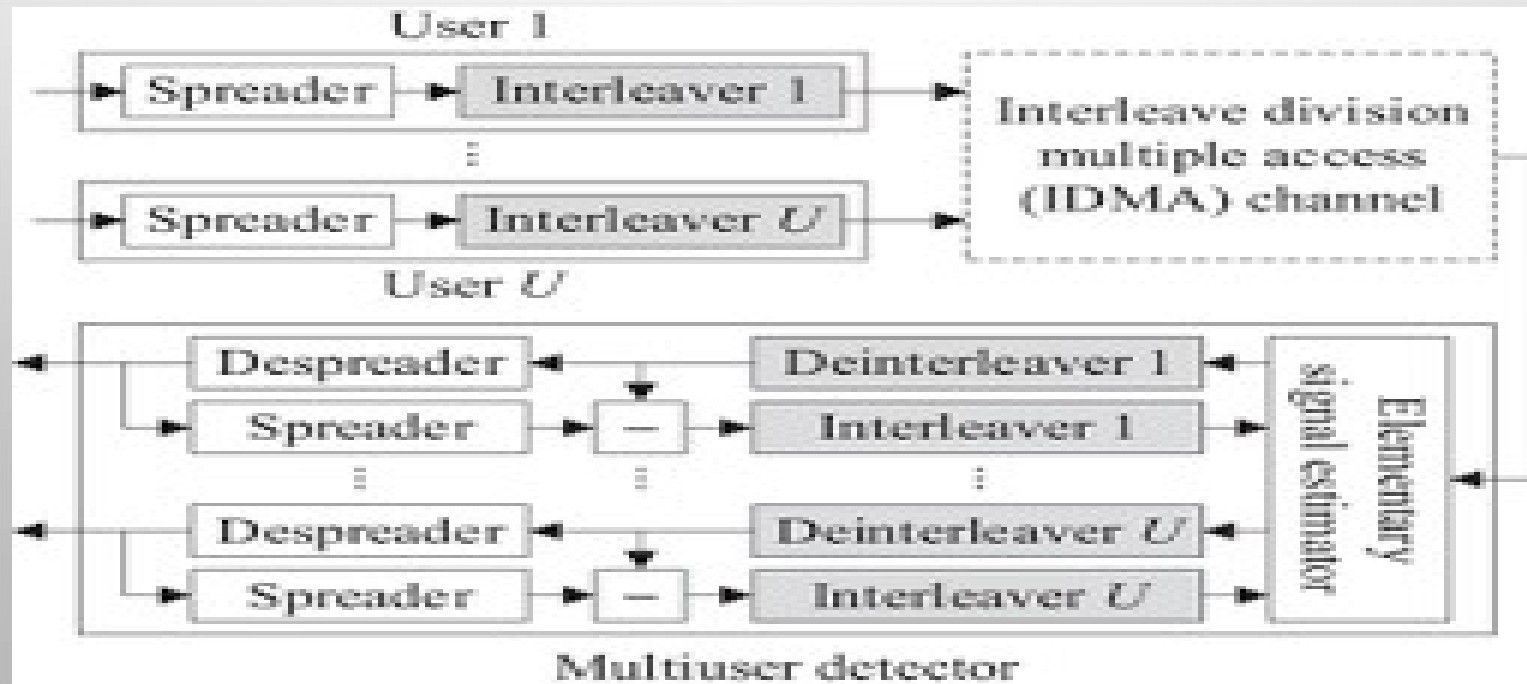
Orthogonal multiple access (OMA)



Non-orthogonal multiple access (NOMA)

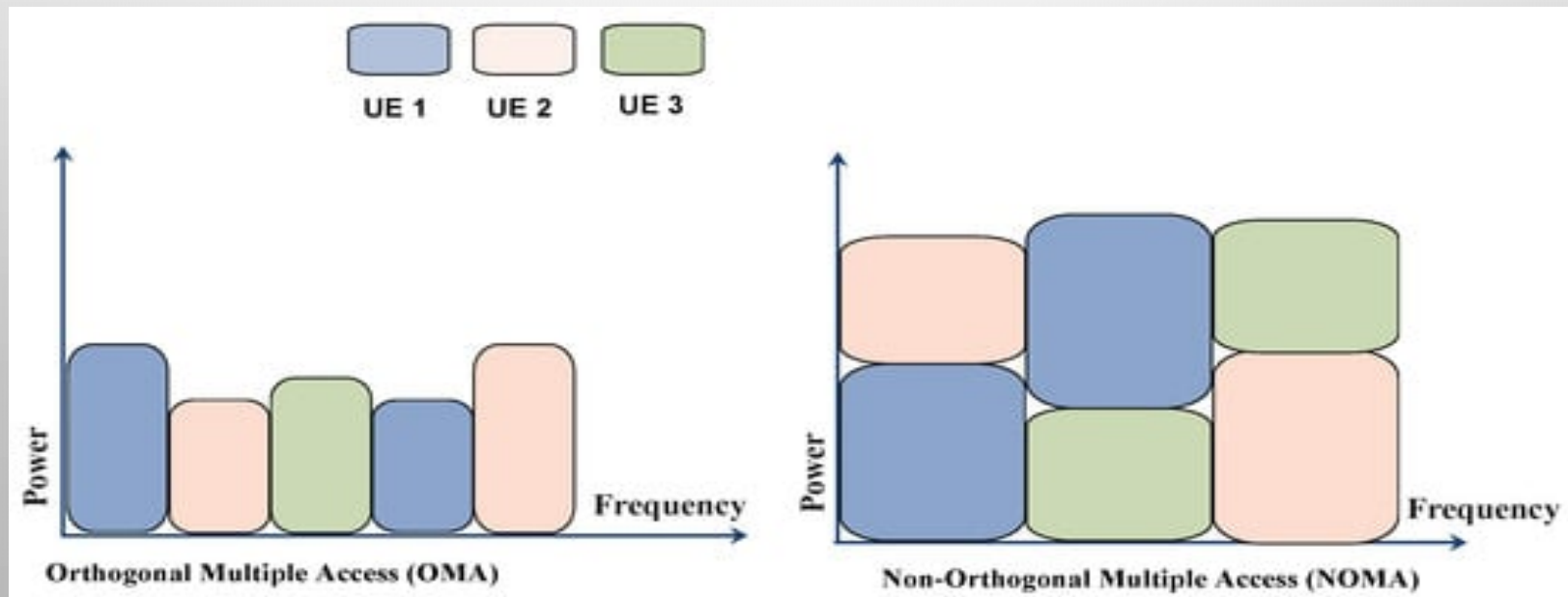
IDMA (INTERLEAVE DIVISION MULTIPLE ACCESS)

- Users are separated using **unique interleavers** instead of codes
- All users share the same **time and frequency resources**
- Based on **chip-by-chip iterative multi-user detection**
- Considered a simplified alternative to CDMA
- Provides efficient multi-user separation with **low complexity**



NOMA (NON-ORTHOGONAL MULTIPLE ACCESS)

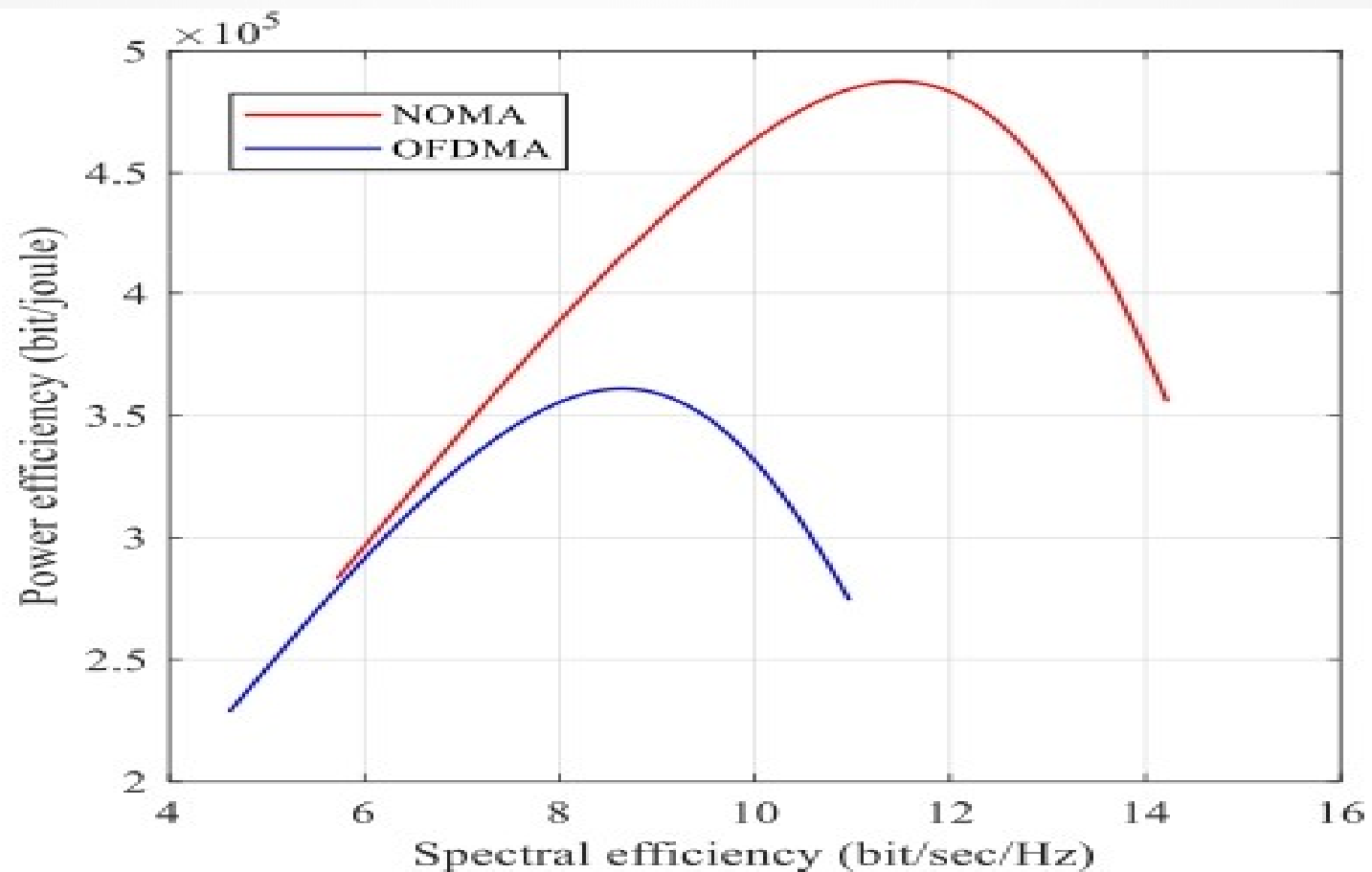
- Multiple users share the same time and frequency resources simultaneously
- Users are multiplexed in the power domain
- Different power levels are assigned based on channel conditions
- Uses Successive Interference Cancellation (SIC) at the receiver
- Strong users decode and remove signals of weaker users first



A) ADVANTAGES OF NOMA: NOMA PRESENTS PROMISING BENEFITS IN ITS APPLICATION IN WIRELESS NETWORKS IN NEW GENERATION TECHNOLOGIES, WHICH SHOW A HIGH DEMAND FOR SIMULTANEOUSLY CONNECTED USERS. THE BENEFITS OF USING NOMA IN WIRELESS NETWORKS ARE HIGH SPECTRAL EFFICIENCY ADEQUATE POWER ALLOCATION, LOW LATENCY, MASSIVE CONNECTIVITY, GOOD COMPATIBILITY, ETC.

B) DISADVANTAGES OF NOMA: THE DISADVANTAGES OF NOMA ARE DYNAMIC USER PAIRING, IMPACT OF TRANSMISSION DISTORTION, RESOURCE ALLOCATION, ETC.

SPECTRUM EFFICIENCY COMPARISON OF NOMA AND OFDMA [1]



GENERAL COMPARISONS OF 1G TO 6G [1]

Generation	MAS	Application	Frequency	Core Design	Bandwidth	Advantage	Disadvantage
1G	FDMA	AMPS	30 KHZ	PSTN	2.4 Kbps	Secrecy and safety to data and voice calls	Limited capacity
2G	TDMA	GSA	1.8 Ghz	PSTN	64 Kbps	Enabled services such as SMS and MMS (Multimedia Message)	Digital signals could be weak if there is no network coverage in any specific area
3G	CDMA	UMTS	1.6 – 2 Ghz	Packet network	2 Mbps	3G Internet allows mobile phone to use as a GPS navigation device	The frequency of 3G transmission is different, that implies that at each base station, the cellular service provider must setup the correct configuration, which can be expensive
4G	OFDMA	LTE	2 – 8 Ghz	Internet	200 Mbps	4G networks have a lot more coverage than other networks, such as Wi-Fi, which enables users to rely on hotspots in each region user visits	Multiple antennas and transmitters are used for 4G mobile networks. Therefore, consumers can experience much lower battery life on their mobile devices while on this network.
5G	NOMA – RSMA	MIMO, mm Waves	3 – 30 Ghz	Internet	1Gbps	High resolution and bi-directional large bandwidth shaping	Security and privacy issues yet to be overcome
6G	D-OMA	B5G	95 Ghz	Internet	1 Tbps	Holographic connection (Holographic connectivity) which means smooth coverage anywhere using Augmented Reality (AR)/ Virtual Reality (VR)	Many of the old devices would not be competent to 6G, hence, all of them need to be replaced with new one — expensive deal

COMPARISON OF MULTIPLE ACCESS SCHEMES

Scheme	Advantages	Disadvantages	Application Domain
FDMA	Simple, low latency	Low spectral efficiency, guard bands	1G cellular, satellite
TDMA	Better efficiency, flexible	Synchronization required, delay	2G GSM, digital communication
CDMA	High capacity, robust	Complex, near-far problem	3G, GPS, military
OFDMA	High efficiency, robust to fading	Complex, sensitive to offset	4G LTE, Wi-Fi
SDMA	High capacity, spatial reuse	Requires CSI, complex	5G MIMO, beamforming
IDMA	Low complexity, scalable	Iterative delay, less practical	Research, future systems
NOMA	Very high efficiency, massive connectivity	SIC complexity, error propagation	5G, IoT, 6G research

OPEN RESEARCH CHALLENGES IN MULTIPLE ACCESS FOR 6G

- **MASSIVE CONNECTIVITY:** DESIGNING SCALABLE ACCESS SCHEMES TO SUPPORT BILLIONS OF DEVICES IN ULTRA-DENSE NETWORKS
- **ULTRA-LOW LATENCY:** ACHIEVING SUB-MILLISECOND LATENCY DESPITE SCHEDULING (OFDMA) AND DECODING (NOMA) DELAYS
- **INTERFERENCE MANAGEMENT:** MITIGATING SEVERE INTER-USER AND INTER-CELL INTERFERENCE IN DENSE DEPLOYMENTS
- **RESOURCE ALLOCATION COMPLEXITY:** SOLVING JOINT OPTIMIZATION OF POWER, SUBCARRIERS, AND SPATIAL RESOURCES UNDER HIGH COMPUTATIONAL CONSTRAINT
- **COMPLEXITY VS PERFORMANCE TRADE-OFF:** BALANCING HIGH SPECTRAL EFFICIENCY (NOMA) WITH PRACTICAL IMPLEMENTATION COMPLEXITY
- **INTEGRATION WITH EMERGING TECHNOLOGIES:** DESIGNING UNIFIED ACCESS FRAMEWORKS FOR RIS, THZ, AND MASSIVE MIMO SYSTEMS

POTENTIAL SOLUTIONS FOR 6G MULTIPLE ACCESS CHALLENGES

- **HYBRID MULTIPLE ACCESS:** INTEGRATING OFDMA, NOMA, AND SDMA FOR ADAPTIVE AND EFFICIENT RESOURCE UTILIZATION
- **AI-DRIVEN RESOURCE ALLOCATION:** USING MACHINE LEARNING AND DEEP LEARNING FOR REAL-TIME OPTIMIZATION OF POWER, SUBCARRIERS, AND USER SCHEDULING
- **ADVANCED INTERFERENCE MANAGEMENT:** EMPLOYING INTERFERENCE COORDINATION, CANCELLATION, AND LEARNING-BASED TECHNIQUES
- **LOW-COMPLEXITY RECEIVER DESIGN:** DEVELOPING EFFICIENT SIC AND DETECTION ALGORITHMS TO REDUCE COMPUTATIONAL BURDEN
- **INTEGRATION WITH EMERGING TECHNOLOGIES:** LEVERAGING RIS, MASSIVE MIMO, AND THZ COMMUNICATION FOR ENHANCED PERFORMANCE

CONCLUSION

- Rapid evolution of cellular networks demands **high QoS, data rates, and seamless connectivity**
- Traditional multiple access techniques (**FDMA, TDMA, CDMA, OFDMA**) provide the foundation but suffer from **limited spectral efficiency**
- Orthogonal Multiple Access (OMA) ensures simplicity and reliability, but lacks scalability for future networks
- Non-Orthogonal Multiple Access (NOMA) enhances spectral efficiency and user fairness through power-domain multiplexing
- Performance of NOMA strongly depends on optimal power and resource allocation
- NOMA integrates well with advanced technologies such as MIMO, cooperative communication, and relaying
- Several challenges remain:
 1. Resource allocation complexity
 2. Inter-cell interference
 3. Scalability and QoS assurance

REFERENCES

- [1] A. F. M. S. SHAH, A. N. QASIM, M. A. KARABULUT, H. ILHAN AND M. B. ISLAM, "SURVEY AND PERFORMANCE EVALUATION OF MULTIPLE ACCESS SCHEMES FOR NEXT-GENERATION WIRELESS COMMUNICATION SYSTEMS," IN IEEE ACCESS, VOL. 9, PP. 113428-113442, 2021, DOI: 10.1109/ACCESS.2021.3104509
- [2] Z. DING, X. LEI, G. K. KARAGIANNIDIS, R. SCHÖBER, J. YUAN AND V. K. BHARGAVA, "A SURVEY ON NON-ORTHOGONAL MULTIPLE ACCESS FOR 5G NETWORKS: RESEARCH CHALLENGES AND FUTURE TRENDS," IN IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 35, NO. 10, PP. 2181-2195, OCT. 2017, DOI: 10.1109/JSAC.2017.2725519.