Chapter 5: Multiple Access Techniques for Wireless Communications

Introduction

Why Multiple Access?

- Wireless systems must serve many users simultaneously
- Users share common wireless resources: time, frequency, and code
- Efficient resource sharing is vital for QoS and capacity

What is Duplexing?

- Duplexing allows bidirectional communication (uplink & downlink)
- Two primary techniques:
  - FDD – Frequency Division Duplexing
  - TDD – Time Division Duplexing

Frequency Division Duplexing (FDD)

- Uses two separate frequency bands:
  - One for uplink
  - One for downlink
- Requires a duplexer to isolate transmit and receive signals

Example:

- Uplink: 890–915 MHz
- Downlink: 935–960 MHz

FDD – Key Characteristics

- Full-duplex communication
- Fixed bandwidth allocation
- Low latency – simultaneous Tx and Rx
- Efficient for symmetric traffic
- Requires guard bands

Used in:

- GSM, UMTS, CDMA2000

Time Division Duplexing (TDD)

- Uses a single frequency band
- Time is divided into slots for uplink and downlink
- Tx and Rx occur at different times

Example:

- Slot 1–4: Downlink
- Slot 5–6: Uplink

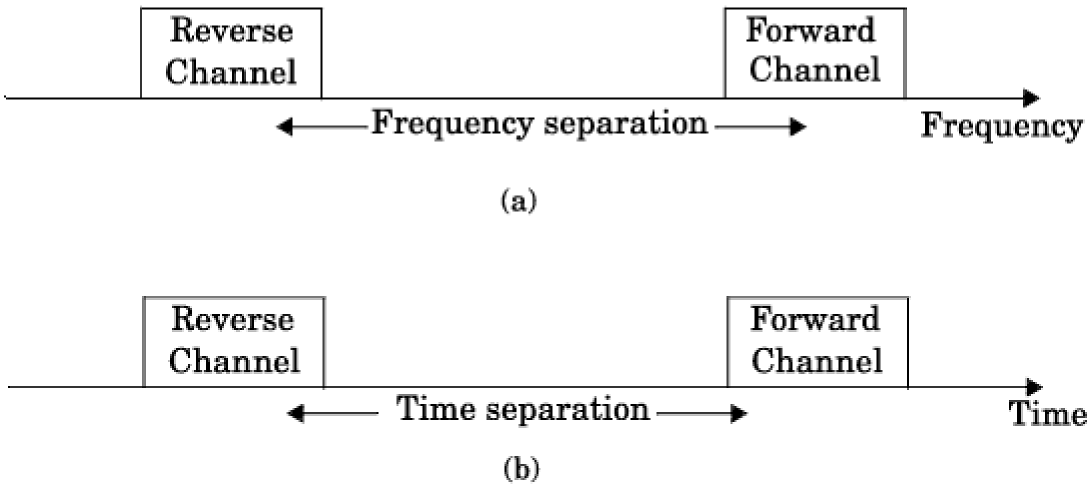
TDD – Key Characteristics

- Half-duplex operation
- Better for asymmetric traffic
- No need for guard bands
- Can adapt time slot ratios
- Synchronization is crucial

Used in:

- LTE TDD, WiMAX, DECT

FDD vs TDD



(a) FDD provides two simplex channels at the same time;
(b) TDD provides two simplex time slots on the same frequency.

FDD vs TDD – Comparison Table

Feature	FDD	TDD
Duplexing	Full-duplex	Half-duplex
Frequency	Two separate bands	One band
Hardware	Needs duplexer	No duplexer
Latency	Lower	Slightly higher
Bandwidth use	Less flexible	Flexible (asymmetric)
Guard Band	Required	Not required

When to Use What?

- Use FDD when:
  - Spectrum is allocated in paired bands
  - Symmetric traffic is expected
- Use TDD when:
  - Spectrum is unpaired
  - Traffic is asymmetric
  - Flexibility is needed (e.g., rural 5G)

Introduction to Multiple Access

What is Multiple Access?

- Multiple Access refers to the technique that allows multiple users to share the same communication resource (frequency, time, code, or space).
- Efficient resource utilization and improved system capacity.

The Problem of Resource Sharing

- Wireless spectrum is limited.
- Many users want to communicate at the same time.
- Need for organized sharing of the medium.

Classification of Multiple Access Techniques

Type	Resource Separation
FDMA	Frequency
TDMA	Time
CDMA	Code
SDMA	Space
OFDMA	Subcarriers (Orthogonal Frequency)

Importance of Multiple Access

- Avoid interference between users.
- Improve spectral efficiency.
- Increase system capacity.
- Support diverse QoS (Quality of Service) requirements.

Key Requirements of a Good Multiple Access Technique

- High capacity
- Fairness
- Low interference
- Ease of implementation
- Scalability

Centralized vs Distributed Access

- Centralized (e.g., cellular networks):
  - Base Station controls access (scheduled).
- Distributed (e.g., Wi-Fi):
  - Users contend for access (random).

Example Use-Cases

- FDMA/TDMA: Used in GSM
- CDMA: Used in IS-95 and 3G
- OFDMA: Used in LTE and 5G
- SDMA: Beamforming and MIMO in 5G

Narrowband Systems

A system in which the bandwidth of the signal is narrow compared to the coherence bandwidth of the channel.

$$\text{Bandwidth} \ll \text{Coherence Bandwidth}$$

Key Characteristics:

- Occupies a small portion of the spectrum
- Channels are well-separated
- Less frequency-selective fading
- Easy equalization
- Examples: Traditional analog voice systems, FDMA

Narrowband Systems

- The term narrowband is used to relate the bandwidth of a single channel to the expected coherence bandwidth of the channel.
- In a narrowband multiple access system, the available radio spectrum is divided into a large number of narrowband channels. The channels are usually operated using FDD.
- To minimize interference between forward and reverse links on each channel, the frequency separation is made as great as possible within the frequency spectrum, while still allowing inexpensive duplexers and a common transceiver antenna to be used in each subscriber unit.

Narrowband Systems

- In narrowband FDMA, a user is assigned a particular channel which is not shared by other users in the vicinity, and if FDD is used (that is, each duplex channel has a forward and reverse simplex channel), then the system is called FDMA/FDD.
- Narrowband TDMA, on the other hand, allows users to share the same radio channel but allocates a unique time slot to each user in a cyclical fashion on the channel, thus separating a small number of users in time on a single channel.

Wideband system

A system where the signal bandwidth is large compared to the coherence bandwidth of the channel.

$$\text{Bandwidth} \gg \text{Coherence Bandwidth}$$

Key Characteristics:

- High data rate transmission
- Frequency-selective fading present
- Requires equalization or spreading techniques
- Examples: CDMA, modern LTE/5G systems

Wideband system

- In wideband systems, the transmission bandwidth of a single channel is much larger than the coherence bandwidth of the channel.
- Thus, multipath fading does not greatly vary the received signal power within a wideband channel, and frequency selective fades occur in only a small fraction of the signal bandwidth at any instance of time.
- In wideband multiple access systems, a large number of transmitters are allowed to transmit on the same channel.

Wideband system

- TDMA allocates time slots to the many transmitters on the same channel and allows only one transmitter to access the channel at any instant of time, whereas spread spectrum CDMA allows all of the transmitters to access the channel at the same time.
- TDMA and CDMA systems may use either FDD or TDD multiplexing techniques.

Introduction to FDMA

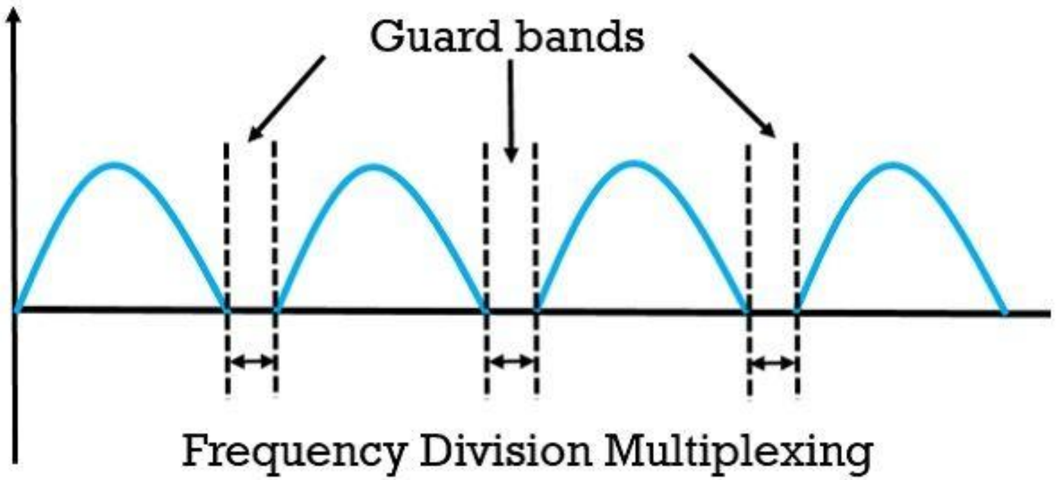
- Frequency Division Multiple Access
- FDMA: Each user is allocated a unique frequency band.
- Used in 1G analog cellular systems (e.g., AMPS).
- Each call gets a dedicated frequency until it ends.

Features of FDMA

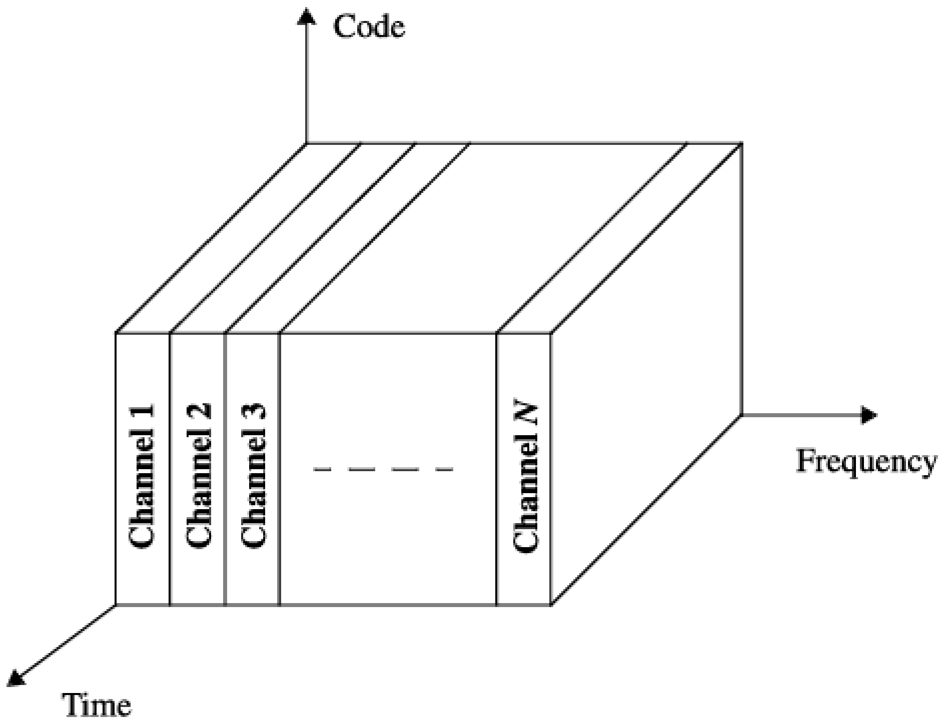
- The FDMA channel carries only one phone circuit at a time.
- If an FDMA channel is not in use, then it sits idle and cannot be used by other users to increase or share capacity. It is essentially a wasted resource.
- The bandwidths of FDMA channels are relatively narrow (30kHz in AMPS) as each channel supports only one circuit per carrier. That is, FDMA is usually implemented in narrow band systems.

Basic FDMA Principle

- The total available bandwidth is divided into non-overlapping frequency channels.
- A guard band is added between channels to prevent interference.



Basic FDMA Principle



FDMA where different channels are assigned different frequency bands.

Nonlinear Effects in FDMA

Why Do Nonlinear Effects Matter?

- FDMA systems use multiple frequency channels.
- Each user is assigned a unique frequency band.
- Signals from multiple users are amplified before transmission (especially in satellite uplinks or base stations).
- High Power Amplifiers (HPAs) exhibit nonlinear behavior when operated near saturation for efficiency.

Key Nonlinear Effects in FDMA

Effect	Description
Intermodulation Distortion (IMD)	Mixing of multiple carriers causes undesired new frequencies (intermodulation products).
Spectral Regrowth	Signal spectrum spreads beyond allocated bandwidth → adjacent channel interference.
Amplitude Compression	Higher amplitude signals are compressed → leads to distortion and degraded quality.
Phase Distortion	Causes group delay variations → affects modulation integrity.

Example: Intermodulation Products

If two carriers at frequencies f1 and f2 are amplified in a **nonlinear amplifier**, it can generate signals at:

$$2f_1 - f_2,\ 2f_2 - f_1,\ f_1 + f_2$$

These may fall into **neighboring frequency bands**, causing **interference**.

Mitigation Techniques

- Use linear amplifiers or operate with back-off (less efficiency, more linearity).
- Apply predistortion to cancel amplifier nonlinearity.
- Power control to ensure signals stay in the linear region.
- Filtering to minimize out-of-band emissions.

Numerical Example

Let:
$f1=4.0$ GHz
$f2=4.1$ GHz

Calculate third-order IMD frequencies:
$2f1-f2=3.9$ GHz
$2f2-f1=4.2$ GHz

These fall into **other user bands** — **violating FDMA channel isolation**.

Number of channels that can be simultaneously supported in a FDMA system

$$N = \frac{B_t - 2B_{guard}}{B_c}$$

- where B_t is the total spectrum allocation, B_{guard} is the guard band allocated at the edge of the allocated spectrum band, and B_c is the channel bandwidth.

Example Problem

Q) If a US AMPS cellular operator is allocated 12.5 MHz for each simplex band, and if B_t is 12.5 MHz, B_{guard} is 10 kHz, and B_c is 30 kHz, find the number of channels available in an FDMA system.

Example Problem

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$$N = \frac{12.5 \times 10^6 - 2(10 \times 10^3)}{30 \times 10^3} = 416$$

Advantages of FDMA

- Simple and reliable (used in analog systems).
- Minimal latency since the channel is dedicated.
- No synchronization needed.

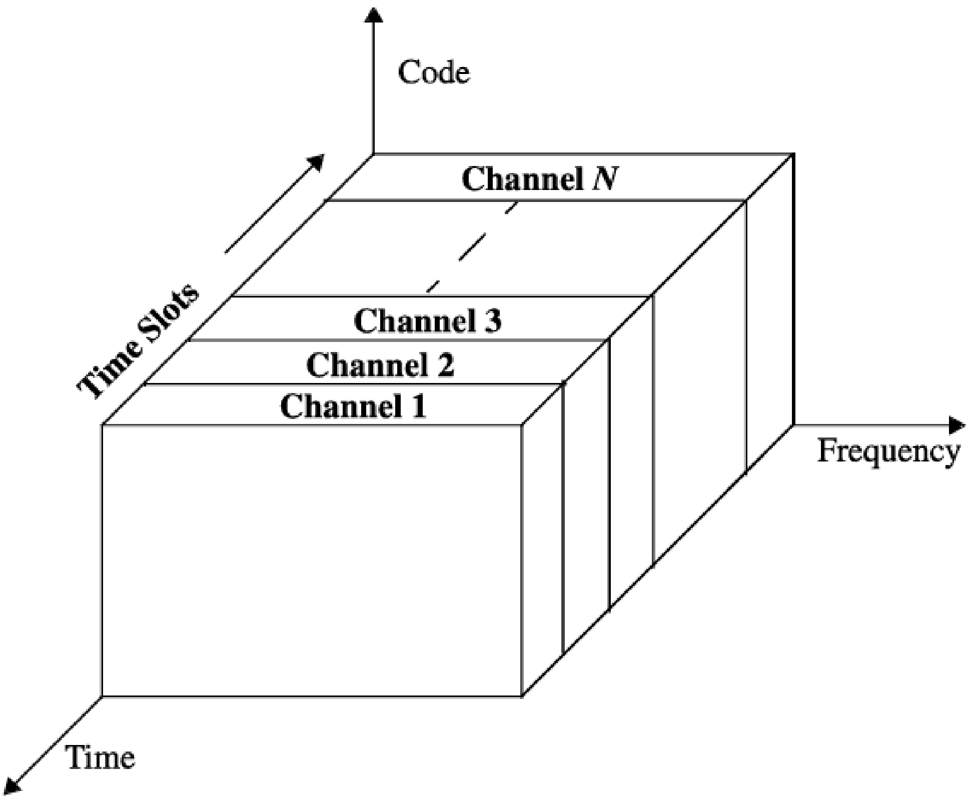
Disadvantages of FDMA

- Inefficient use of bandwidth (unused channels stay idle).
- Guard bands reduce effective spectrum usage.
- Poor scalability.
- Inflexible to dynamic user demands.

Introduction to TDMA

- Time Division Multiple Access
- TDMA divides the channel into time slots.
- Each user is allocated a specific time slot in a repeating frame.
- Used in: 2G GSM, DECT, IS-136
- Key Idea:
  - Each user gets full channel bandwidth for short time intervals → efficient use of bandwidth.

Introduction to TDMA



TDMA scheme where each channel occupies a cyclically repeating time slot.

Introduction to TDMA

- TDMA systems transmit data in a **buffer-and-burst method**, thus the transmission for any user is noncontinuous.
- This implies that, unlike in FDMA systems which accommodate analog FM, digital data and digital modulation must be used with TDMA.

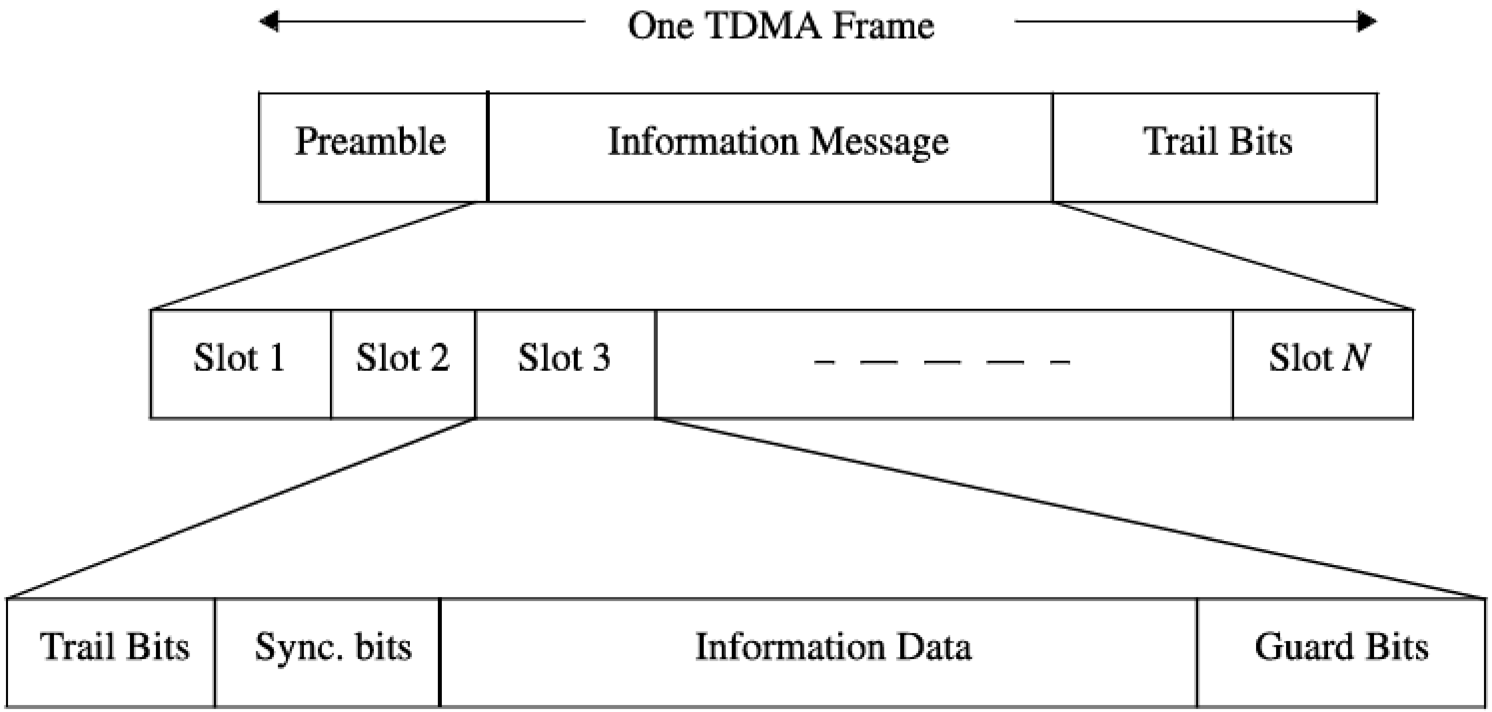
TDMA Frame Structure

Structure:

- A frame contains multiple time slots (e.g., 8 in GSM).
- Each user transmits in their assigned slot per frame.

Frame Parameters:

- **Frame Duration Tf** = Time for one full cycle.
- **Slot Duration Ts** = Time per slot = Tf/N, where N = number of slots.



TDMA frame structure. The frame is cyclically repeated over time.

What is TDMA Frame Efficiency?

TDMA Frame Efficiency (η_x) measures how much of the transmitted data per frame is actual user data vs. overhead (control bits, guards, preambles, etc.).

Frame Efficiency Formula

$$\eta_f = \left(1 - \frac{b_{OH}}{b_T}\right) \times 100\%$$

- Where:
- b_{OH}: Total overhead bits per frame
- b_T: Total bits per frame = $R \cdot T_f$
- R: Bit rate (bps)
- T_f : Frame duration (sec)

Overhead Bits in a Frame

$$b_{OH} = N_r b_r + N_t b_p + N_t b_g + N_r b_g$$

Where:

- N_r: Number of reference bursts
- N_t: Number of traffic bursts (slots per frame)
- b_r: Overhead bits per reference burst
- b_p: Preamble bits per traffic burst
- b_g: Equivalent bits of guard time per slot

GSM Frame Efficiency

Each time slot in GSM (TDMA):

- 6 tail bits
- 8.25 guard bits
- 26 training bits
- 2 traffic bursts: 58 + 58 bits

GSM Frame Efficiency

Each time slot in GSM (TDMA):

- 6 tail bits
- 8.25 guard bits
- 26 training bits
- 2 traffic bursts: 58 + 58 bits

Total bits per slot=6+8.25+26+2(58)=156.25 bits

Bits per frame (b_T)=$8\cdot156.25$=1250 bits

Overhead per frame (b_{OH})=8(6+8.25+26)=322 bits

$\eta_f=(1-322/1250)\cdot100=74.24\%$

GSM Timing Parameters

Given:

- 1 slot = 156.25 bits
- Bit rate = 270.833 kbps

(a) Bit Duration:

$T_b = 1/270.833 \approx 3.692\mu s$

(b) Slot Duration:

$T_{slot} = 156.25 \cdot T_b = 0.577 ms$

(c) Frame Duration:

$T_f = 8 \cdot T_{slot} = 4.615 ms$

(d) Slot Wait Time (for same user):
Frame duration = 4.615ms

GSM System Capacity

GSM uses:

- 25 MHz forward link
- 200 kHz per radio channel
- Each channel supports **8 users (slots)**
- No guard band assumed

Number of Channels$=25\times10^{6}/200\times10^{3}=125$

Total Users$=125\cdot8=1000$users

Channel Capacity in TDMA

- Number of channels in TDMA system:

$$N = \frac{m(B_{tot} - 2B_{guard})}{B_c}$$

Where:

- m: Slots per channel
- B_{sys}: Total allocated bandwidth
- B_c: Channel bandwidth
- B_{guard}: Guard band per edge

Spread Spectrum Multiple Access (SSMA)

What is Spread Spectrum?

- A technique in which the transmitted signal occupies a bandwidth much larger than the minimum required.
- Uses a pseudo-random noise (PN) sequence for spreading and despreading.
- Provides:
  - Resistance to jamming
  - Security
  - Multiple user access

Types of Spread Spectrum

- Frequency Hopped Multiple Access (FHMA)
- Direct Sequence Spread Spectrum (DSSS)
- Time Hopping (less common)
- Hybrid SS (e.g., FH/DSS combinations)

Frequency Hopped Multiple Access (FHMA)

- Carrier frequency changes according to a pseudo-random sequence
- Slow FHMA: Hop rate < bit rate
- Fast FHMA: Hop rate > bit rate

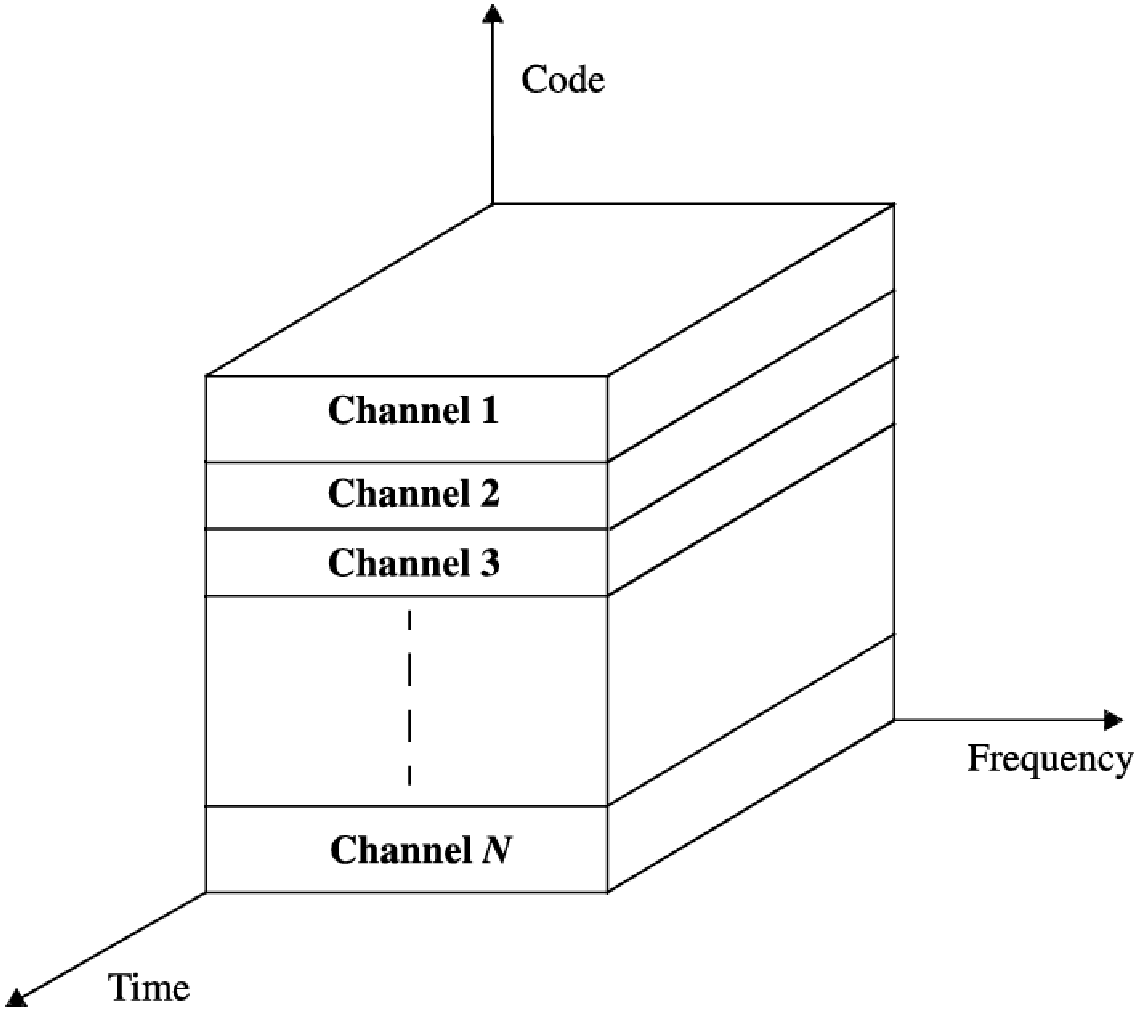
Key Formula:

Number of hops = Bandwidth of spread spectrum / Bandwidth of modulated signal

Example

- If BW_total = 10 MHz and modulated signal BW = 100 kHz, then:

No. of hops = 10 MHz / 100 kHz = 100 hops



Spread spectrum multiple access in which each channel is assigned a unique PN code which is orthogonal or approximately orthogonal to PN codes used by other users.

Direct Sequence Spread Spectrum (DSSS)

- Spreads data by multiplying it with a high-rate PN code
- Results in a higher bandwidth signal
- Robust to multipath and jamming

Processing Gain (Gp):

Gp = 10 * log10 (Spread BW / Data BW)

Example

Spread BW = 2 MHz, Data BW = 20 kHz

Gp = ?

Example

Spread BW = 2 MHz, Data BW = 20 kHz

Gp = 10 * log10(2,000,000 / 20,000) = 20 dB

Code Division Multiple Access (CDMA)

- Based on DSSS
- All users use the **same frequency band simultaneously**
- Separated by **unique orthogonal codes**

Benefits:

- Robust against interference
- Soft capacity
- Efficient bandwidth usage

What is CDMA?

- CDMA = Code Division Multiple Access
- All users share the same frequency spectrum simultaneously
- Signals are spread using unique pseudo-noise (PN) codes
- Based on spread spectrum technique

Basic Principle

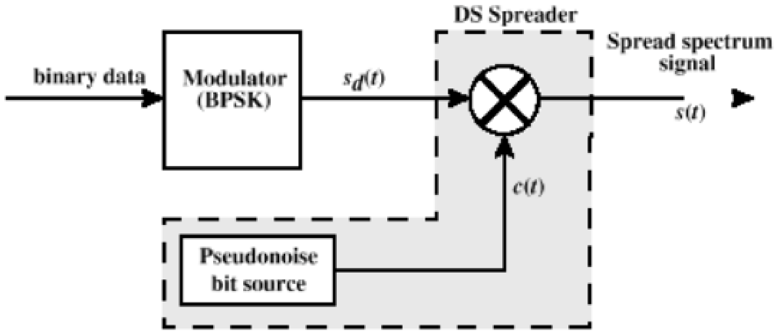
- Each user gets a unique spreading code
- Signal is spread over a wider bandwidth
- Receiver despreads using the same code
- Orthogonality of codes allows separation of users

- **Transmitted Signal:**
  $s(t)=d(t)\cdot c(t)$
  where:
- $d(t)$: user data
- $c(t)$: spreading code

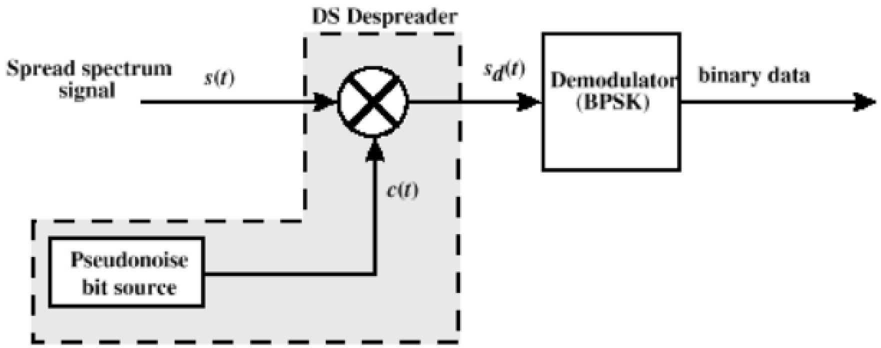
CDMA System Model

Components:

- User Data
- PN Sequence (Spreader)
- Modulation (e.g., BPSK)
- Spreading
- Summation over shared channel
- Despreading using matched PN



(a) Transmitter



(b) Receiver

Bandwidth and Processing Gain

- **Spread Spectrum** increases bandwidth
- **Processing Gain (Gp):**
- Gp=Spread bandwidth (W)/Information band width (R)
- Higher Gp → Better immunity to interference

CDMA Capacity Formula

$N \approx (W / R) / (Eb/N0)$

Where:

- N = number of users
- W = chip rate (spread BW)
- R = user data rate
- Eb/N0 = required energy per bit

Numerical Problem – CDMA Capacity

Q: A CDMA system has W = 1.25 MHz, R = 10 kbps, Eb/N0 = 6 dB.
Calculate maximum number of users.

Numerical Problem – CDMA Capacity

Q: A CDMA system has $W = 1.25$ MHz, $R = 10$ kbps, $E_b/N_0 = 6$ dB.
Calculate maximum number of users.

Convert $E_b/N_0 = 6$ dB → linear = 3.98
$N \approx (1.25\times10^6 / 10\times10^3) / 3.98$
$= 125 / 3.98 \approx$ **31 users**

Wideband CDMA (W-CDMA)

- Used in 3G networks (UMTS)
- Higher data rates (up to 2 Mbps)
- Bandwidth: ~5 MHz
- Based on CDMA principles, but adapted for broadband services

Performance Comparison

Feature	CDMA	FDMA	TDMA
Bandwidth Sharing	Code-based	Frequency-based	Time-based
Interference	Interference-limited	Less	Less
Handoff	Soft	Hard	Hard
Power Control	Essential	Less Critical	Less Critical
Security	High	Low	Low

Hybrid Spread Spectrum Techniques

- Hybrid schemes combine multiple access techniques to improve:
  - Capacity
  - Resistance to interference
  - Spectral efficiency
  - QoS in dynamic environments
- Useful in modern cellular and military applications.

Hybrid FDMA/CDMA (FCDMA)

- Total bandwidth is divided into frequency sub-bands (like FDMA).
- Each sub-band uses CDMA to allow multiple users per frequency slot.

Advantages:
- Combines frequency isolation and code multiplexing
- Reduces intra-cell interference
- Scalable with user demand

Applications of FCDMA

- Used in satellite communications and 4G LTE uplink.
- Combines benefits of spread spectrum and multichannel allocation.

Hybrid DS/FHMA (DS/FHMA)

- Combines Direct Sequence Spread Spectrum (DSSS) with Frequency Hopping (FH).

How it works:

- Signal is first spread using a pseudo-random code (DSSS).
- Then the carrier hops across frequencies at intervals (FH).

Benefits:

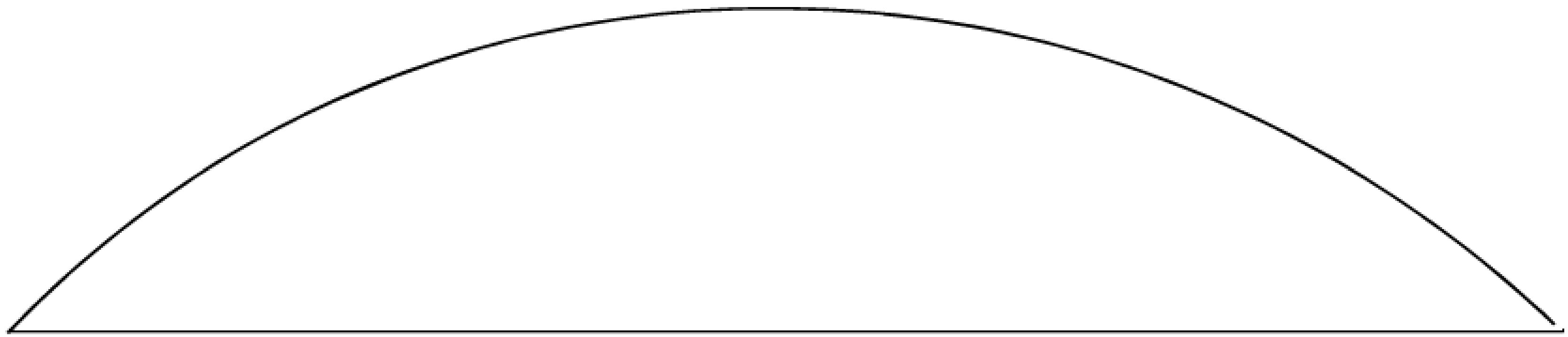
- Increased resistance to jamming and interference
- Good for secure and robust communications
- Mitigates multipath fading and Doppler effects

Time Division CDMA (TCDMA)

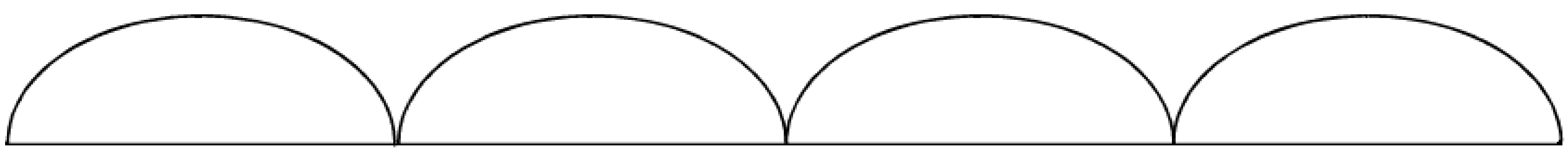
- Time is divided into slots like TDMA.
- Multiple users transmit in different time slots **with different codes**.

Use Case:
- Useful in networks where both delay and interference must be minimized.
- Can adjust time and code allocation based on QoS requirements.

Key Advantage:
- Reduces MAI (Multiple Access Interference)
- Efficient for bursty data services

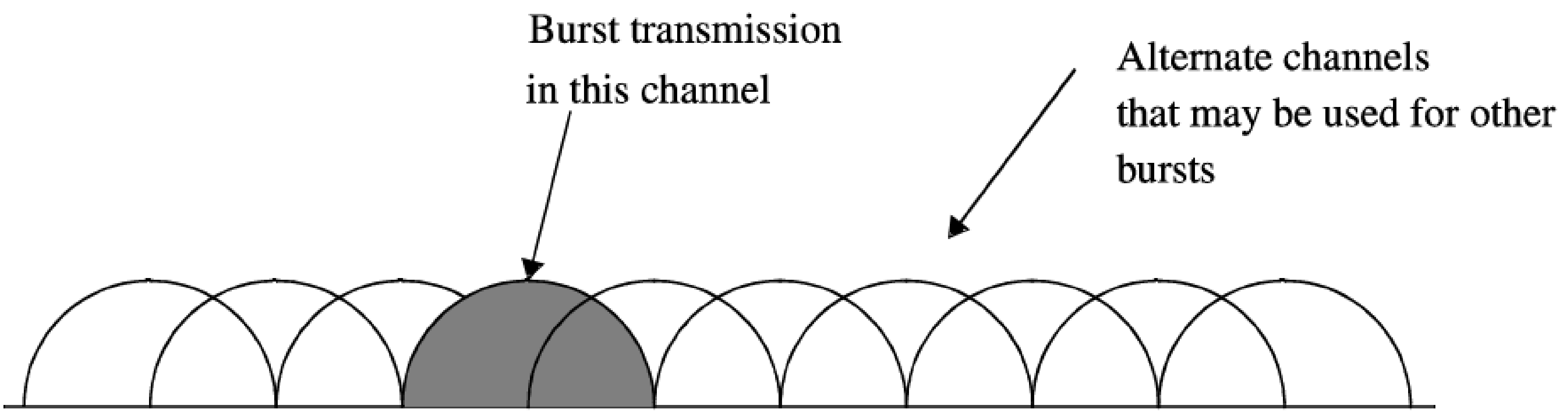


Wideband CDMA



Spectrum of Narrowband CDMA

Spectrum of wideband COMA compared to the spectrum of a hybrid, frequency division, direct sequence multiple access.



Frequency spectrum of a hybrid FH/DS system.

Time Division Frequency Hopping (TDFH)

- Combines TDMA and FHSS.
- Each user is assigned a unique frequency hopping sequence **in a time slot**.

Mechanism:

- Transmit over different frequencies in each time slot using predefined hopping sequence.

Advantages:

- High spectral efficiency
- Interference and eavesdropping resistance
- Time-synchronization allows tight control over collisions

System Comparison Table

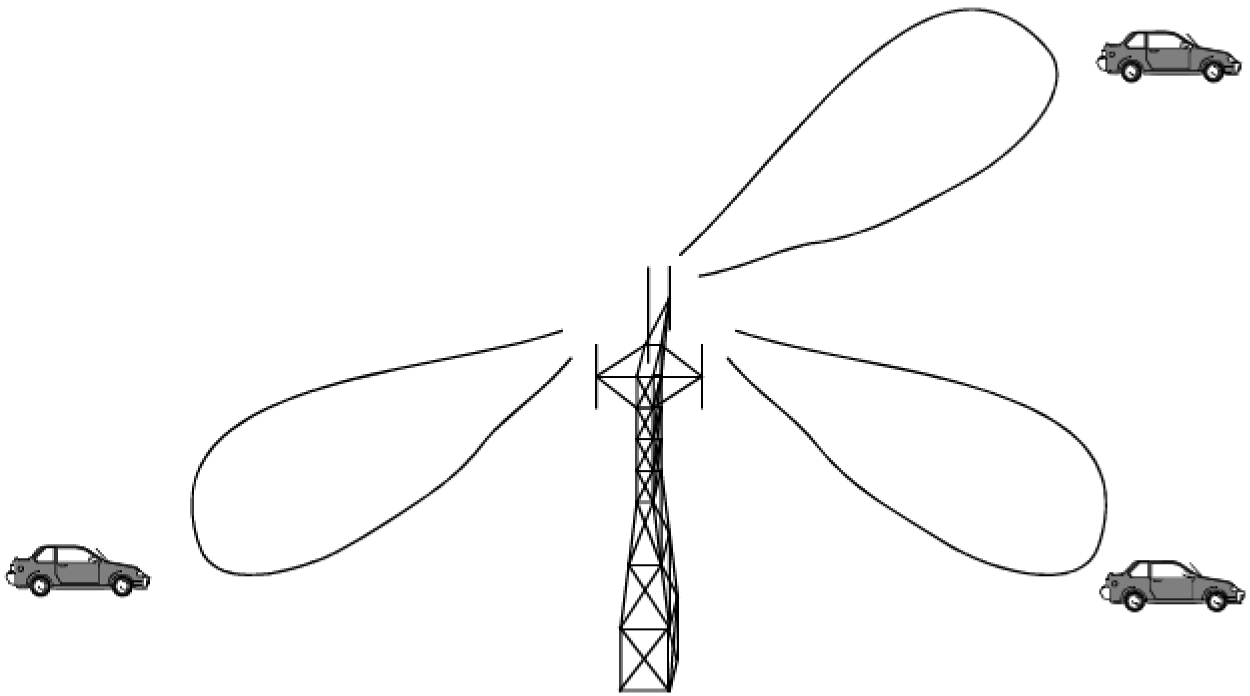
Technique	Multiple Access	Key Strength	Limitation
FCDMA	FDMA + CDMA	Scalable, Low Interference	Complex Rx processing
DSIFHMA	DSSS + FHSS	High Security, Robust	Synchronization needed
TCDMA	TDMA + CDMA	Less MAI, QoS friendly	Time sync required
TDFH	TDMA + FHSS	Interference Avoidance	Requires fast switching

Space Division Multiple Access (SDMA)

Introduction to SDMA

- Multiple access method that separates users in space using directional antennas or beamforming (spot beam antennas).
- Each user has a distinct spatial signature.
- Use physical separation (angle, location) to reuse the same frequency and time resources.

Introduction to SDMA



A spatially filtered base station antenna serving different users by using spot beams.

Principle of SDMA

- Uses smart antennas or adaptive antenna arrays to:
  - Direct beams toward intended users
  - Nullify interference from others
- Spatial separation allows frequency reuse factor = 1 in ideal case.

Advantages of SDMA

- Increased capacity without extra bandwidth
- Reduces co-channel interference
- Improves Signal-to-Interference Ratio (SIR)
- Can track moving users using adaptive beamforming
- Enhances security (signal is highly directional)

Limitations of SDMA

- Requires complex antenna and signal processing
- Performance drops in high multipath environments without MIMO compensation
- Requires accurate Direction of Arrival (DoA) estimation

SDMA in Cellular Networks

- Allows same frequency/time/code to be reused for multiple users in the same cell if spatially separated.
- Used in:
  - 4G LTE-A (Massive MIMO)
  - 5G NR (beam-based access)
  - Satellite communications

Capacity Improvement Formula

- **For ideal SDMA**:

$$C_{total} = C_{per\ beam} \times N_{beams}$$

Where N_{beams} = number of independent beams formed.

Numerical Example

Q A base station forms 4 independent beams, each supporting 25 Mbps. What is the total cell capacity?

$$C_{total} = C_{per\ beam} \times N_{beams}$$

$$C_{total} = 25 \times 4 = 100 \text{ Mbps}$$

SDMA vs Other Multiple Access

Access Method	Separation Basis	Example
FDMA	Frequency	AMPS
TDMA	Time	GSM
CDMA	Code	IS-95
SDMA	Space	Massive MIMO

Packet Radio

Introduction to Packet Radio

- A digital communication method where data is sent in discrete packets over a shared radio channel.
- Each packet contains addressing, error control, and payload data.

Applications:

- Military communications
- Amateur radio (AX.25 protocol)
- Early mobile data networks (ARQ protocols)

History and Motivation

- Originated in DARPA's PRNET (Packet Radio Network) in the 1970s
- Motivation: Enable robust, multi-hop wireless communications for mobile users
- Foundation for modern wireless data systems and mobile ad-hoc networks (MANETs)

Packet Structure

- Typical packet fields:
  - **Preamble**: Synchronization bits
  - **Header**: Addressing, control information
  - **Payload**: User data
  - **CRC**: Error detection bits

Working Principle

1) Message broken into packets
2) Packets sent individually over a shared radio channel
3) Each packet routed independently (can take different paths)
4) Receiver reassembles packets into original message

Multiple Access in Packet Radio

- Uses random access techniques:
  - ALOHA (Stations transmit whenever they have data. This is simple but has a low maximum throughput (around 18%))
  - Slotted ALOHA (Time is divided into slots, and stations can only transmit at the beginning of a slot. This improves efficiency by reducing the likelihood of collisions.)
  - CSMA (Carrier Sense Multiple Access)

- Collisions are resolved using ARQ (Automatic Repeat Request)

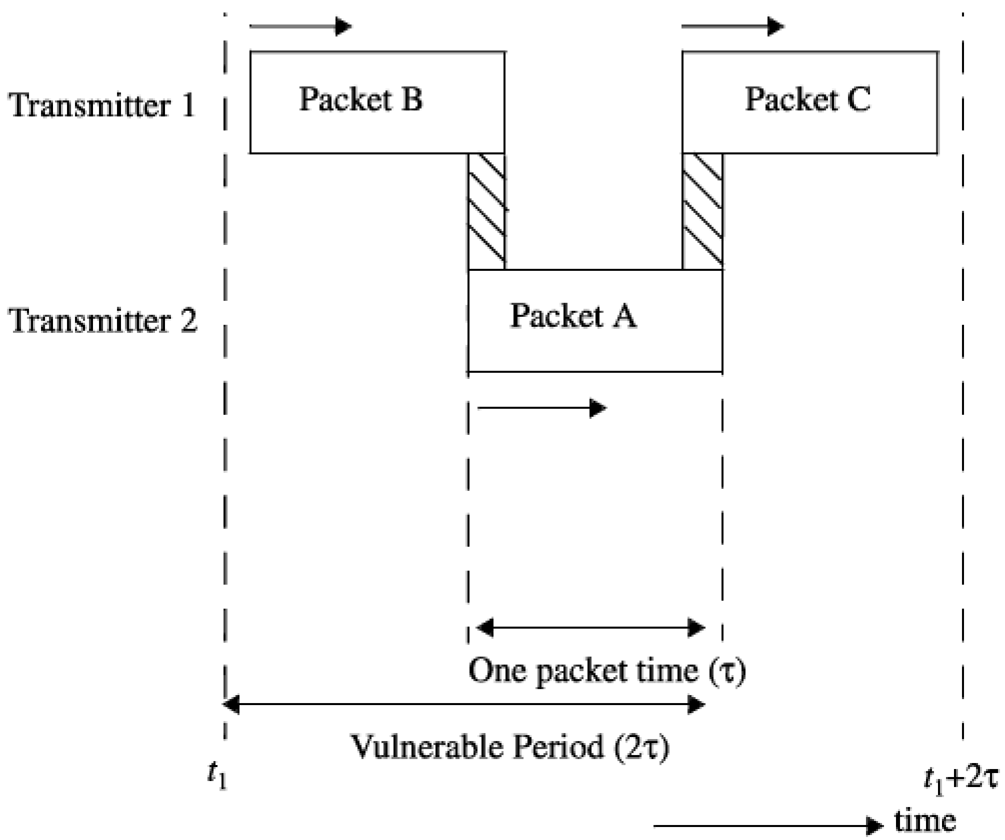
Performance Measures

- Throughput (S): Successful packet transmissions per unit time
- Delay (D): Average time between packet generation and successful reception
- Efficiency (η): Fraction of channel capacity used for actual data

Packet Radio Protocols

- In order to determine the throughput, it is important to determine the vulnerable period, Vp, which is defined as the time interval during which the packets are susceptible to collisions with transmissions from other users.
- Figure shows the vulnerable period for a packet using ALOHA. The Packet A will suffer a collision if other terminals transmit packets during the period t1 to (t1 + 2T).
- Even if only a small portion of packet A sustains a collision, the interference may render the message useless.

Vulnerable period for a packet using the ALOHA protocol.



Packet A will collide with packets B and C because of overlap in transmission time.

Pure ALOHA Throughput Formula

- The pure ALOHA protocol is a random-access protocol used for data transfer.
- A user accesses a channel as soon as a message is ready to be transmitted.
- After a transmission, the user waits for an acknowledgment on either the same channel or a separate feedback channel.
- In case of collisions, (i.e., when a NACK is received), the terminal waits for a random period of time and retransmits the message.
- As the number of users increase, a greater delay occurs because the probability of collision increases.

Pure ALOHA Throughput Formula

$$S = Ge^{-2G}$$

Where:

- S = throughput (normalized)
- G = average number of packets generated per packet time
- **Maximum throughput**: $S_{max} = 0.184$ at $G = 0.5$

Slotted ALOHA Throughput Formula

- In slotted ALOHA, time is divided into equal time slots of length greater than the packet duration T .
- The subscribers each have synchronized clocks and transmit a message only at the beginning of a new time slot, thus resulting in a discrete distribution of packets.
- This prevents partial collisions, where one packet collides with a portion of another.
- As the number of users increase, a greater delay will occur due to complete collisions and the resulting repeated transmissions of those packets originally lost.

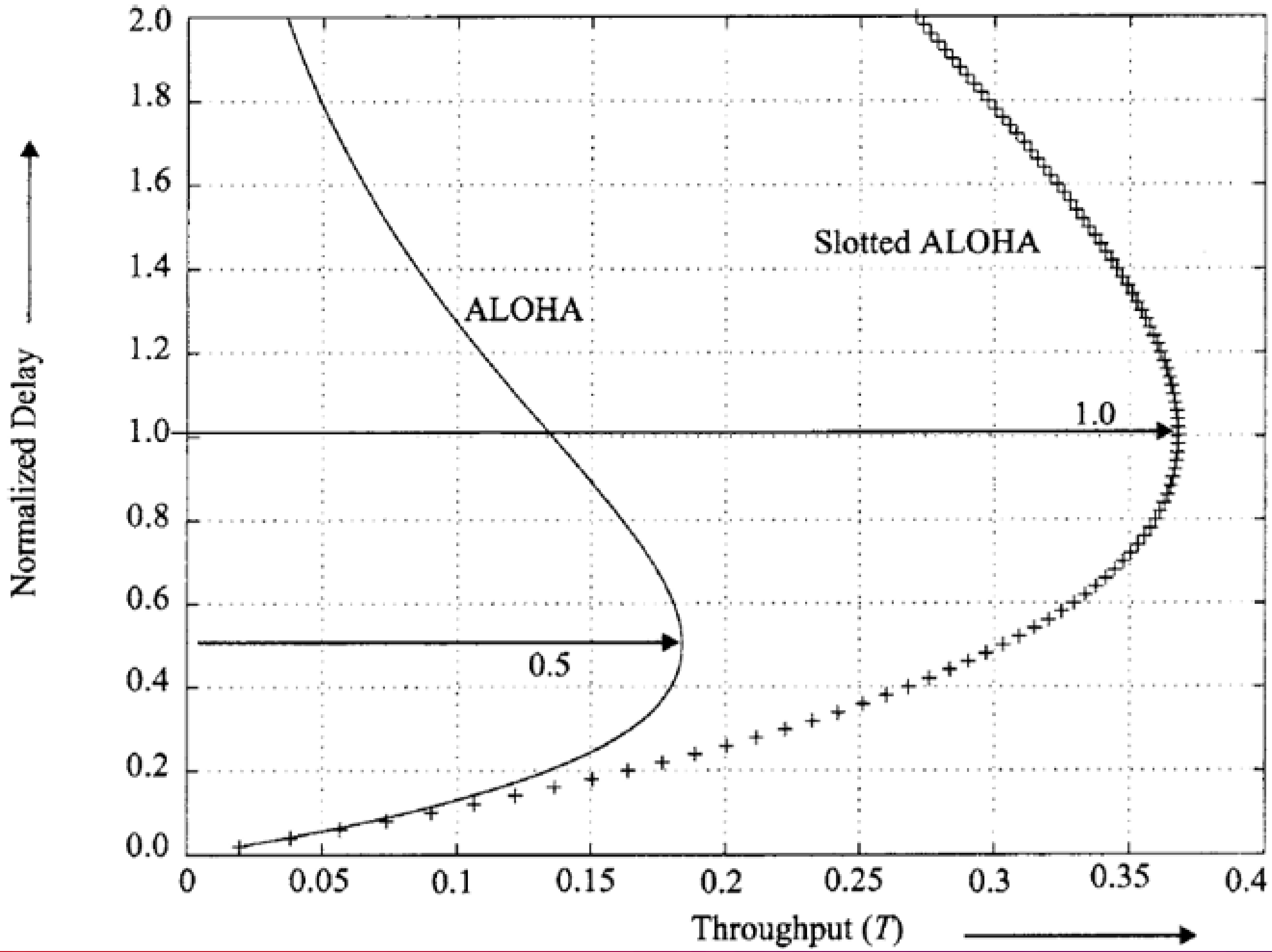
Slotted ALOHA Throughput Formula

$$S = Ge^{-G}$$

Where:

- Slots reduce collision window by 50%
- **Maximum throughput**: $S_{max} = 0.368$ at $G = 1$

Tradeoff between throughput and delay for ALOHA and slotted ALOHA packet radio protocols.



Example Problem (ALOHA)

Q: In a slotted ALOHA system, if G=0.8, find the normalized throughput.

Example Problem (ALOHA)

Q: In a slotted ALOHA system, if G=0.8, find the normalized throughput.

$S=0.8e^{-0.8}\approx 0.359$

Throughput = **35.9% of channel capacity**

Carrier Sense Multiple Access (CSMA) Protocols

- Listen to the channel before transmitting.
- Reduce collisions by avoiding transmission when the channel is busy.
- Ethernet, Wi-Fi (with modifications like CSMA/CA).

CSMA Variants

- 1-Persistent CSMA
  - Always transmit immediately after the channel becomes idle.
  - Low delay when channel is free.
  - High collision rate if many users are waiting.
- Non-Persistent CSMA
  - Wait a random time if the channel is busy, then check again.
  - Fewer collisions.
  - Higher average delay.
- p-Persistent CSMA (for slotted systems)
  - Transmit with probability p when channel is idle.
  - Balance between collision risk and delay.

CSMA Performance

- **Throughput formula** (non-persistent CSMA approximation):

$$S \approx Ge^{-aG}/(1+a-e^{-aG})$$

where:

- G = average traffic load (packets/packet time)
- a = propagation delay / packet transmission time

Example – CSMA Efficiency

- In a non-persistent CSMA system with $G=1.2$ and $a=0.01$, find the approximate throughput.

Example – CSMA Efficiency

- In a non-persistent CSMA system with G=1.2 and a=0.01, find the approximate throughput.

$$S \approx 1.2\, e^{-0.012}/(1.01-e^{-0.012})$$

(small a → high efficiency)

Efficiency close to maximum (~90%+ for small a).

Reservation Protocols in Packet Radio

Reservation-Based Access

- Reserve time slots in advance to avoid collisions.
- Steps:
  - Reservation request phase
  - Base station grants slot(s)
  - Data transmission phase

Reservation-Based Access

- Advantages:
  - Eliminates collisions during data transfer
  - Good for predictable, continuous traffic
- Disadvantages:
  - Wastes slots if reserved but unused
  - Extra overhead for reservation messages

Reservation ALOHA

- How it works:
  - Frame divided into mini-slots for reservations
  - Each user sends reservation request using ALOHA
  - Successful reservations are scheduled in next frame
- Performance: Better for moderate/high traffic than pure/slotted ALOHA.

Capture Effect in Packet Radio

- In packet radio, when two packets collide, the stronger signal may still be decoded successfully if its signal-to-interference ratio (SIR) exceeds a threshold.
- Cause:
  - Unequal received powers due to different distances, fading, or power control.
- Impact:
  - Reduces apparent collision rate.
  - Can bias channel access toward users with stronger signals.

Capture Effect Model

- **Condition for capture**:

$$P_{desired}/P_{interferer}>\beta$$

Where:

- $P_{desired}$ = received power of desired packet
- $P_{interferer}$ = received power of strongest interferer
- β = capture threshold (e.g., 10 dB)

Example – Capture Probability

Q: If capture threshold = 10 dB, desired packet power = 5 mW, interferer power = 0.2 mW, will capture occur?

Capacity of Cellular Systems

- Maximum number of simultaneous users a cellular system can support with acceptable QoS.
- Constraints:
  - Available spectrum
  - Multiple access scheme
  - Interference
  - Propagation environment
  - Frequency reuse

FDMA Capacity

- Total number of channels:

$$N_{FDMA}=B_{total}/(B_c+B_g)$$

Where:

- B_{total} = total allocated bandwidth
- B_c = channel bandwidth
- B_g = guard band per channel

System capacity:

$C_{FDMA} = N_{FDMA} \times m$

where m = frequency reuse factor (depends on cluster size).

FDMA Example

Q: A cellular system uses 25 MHz total spectrum, each channel is 30 kHz, no guard band. If cluster size N=7, find total number of channels and users.

FDMA Example

Q: A cellular system uses 25 MHz total spectrum, each channel is 30 kHz, no guard band. If cluster size N=7, find total number of channels and users.

$$N_{FDMA}=25\times10^6/30\times10^3=833.33\approx833$$

Channels per cell:

$$833/7\approx119$$

TDMA Capacity

$$C_{TDMA}=N_{FDMA}\times S$$

Where:

- N_{FDMA} = number of frequency channels from FDMA formula
- S = number of time slots per channel

TDMA Example (GSM)

Given:

- Btotal=25 MHz
- Bc=200 kHz
- S=8 time slots/channel
- Cluster size N=4

TDMA Example (GSM)

Given:

- Btotal=25 MHz
- Bc=200 kHz
- S=8 time slots/channel
- Cluster size N=4

- **Solution**:

$N_{FDMA}=25\times10^6/200\times10^3=125$

Channels per cell:

$125/4=31.25\approx31$

TDMA capacity:

$C_{TDMA}=31\times8=248$ users/cell

CDMA Capacity

- Interference-limited:

$$C_{CDMA} \approx G_p /((E_b/N_0) + i_f)$$

- Where:
- Gp=W/R (processing gain)
- E_b/N_0 = required SNR per bit
- i_f = other-cell interference factor

CDMA Example

Given:

- W=1.25 MHz
- R=9.6 kbps
- E_b/N_0 =7 dB
- i_f =0.6

CDMA Example

Given:

- $W=1.25$ MHz
- $R=9.6$ kbps
- $E_b/N_0 = 7$ dB
- $i_f = 0.6$

Solution:

$$Gp=1.25\times10^6/9600\approx130.2$$

Convert E_b/N_0 to linear: 7 dB≈5.01

$$C_{CDMA}\approx130.2/(5.01+0.6)\approx22.3 \text{ users/sector}$$

SDMA Capacity

- Uses **smart antennas** to separate users in the spatial domain.
- **Capacity gain**:

$$C_{SDMA} = C_{original} \times G_s$$

Where G_s = spatial reuse factor.

SDMA Example

Q) If original FDMA system supports 100 users and smart antennas allow 4 independent beams:

$$C_{SDMA}=100\times4=400 \text{ users}$$

Capacity Comparison Table

Access Method	Formula	Limiting Factor
FDMA	Btotal/(Bc+Bg)	Spectrum
TDMA	FDMA capacity×S	Synchronization, Guard time
CDMA	Gp /((Eb/N0) +if)	Interference
SDMA	$C_{base} \times G_s$	Antenna beamforming

End of Chapter 5