Basics of Wireless Communications

- Analog vs. Digital transmission
- Frequency, Spectrum, Bandwidth
- Modulation Techniques
- Multiplexing Techniques
- Medium Access Control (MAC)

Networking Layers

Application layer	service location new applications, multimedia adaptive applications
Transport layer	congestion and flow control quality of service
Network layer	addressing, routing, device location hand-over authentication
Data link layer	media access multiplexing media access control encryption
Physical layer	modulation interference attenuation frequency

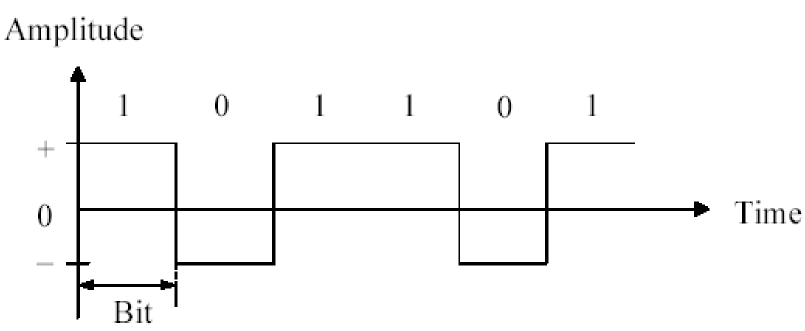
Analog vs. digital data

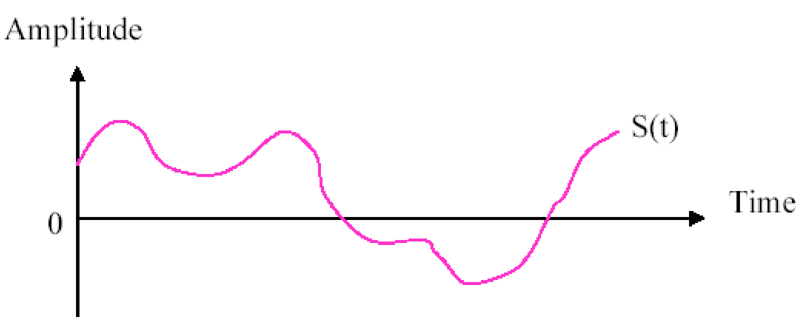
- **Data can be digital or analog**
  - ***Digital data*** appears as a sequence of bits, each of it taking on one of two discrete values: the binary 0 and the binary 1.
    - e.g., text
  - ***Analog data*** is characterized by a continuous value range at some interval.
    - e.g., human speech.

Analog vs. digital signal

Signals can also be digital or analog:

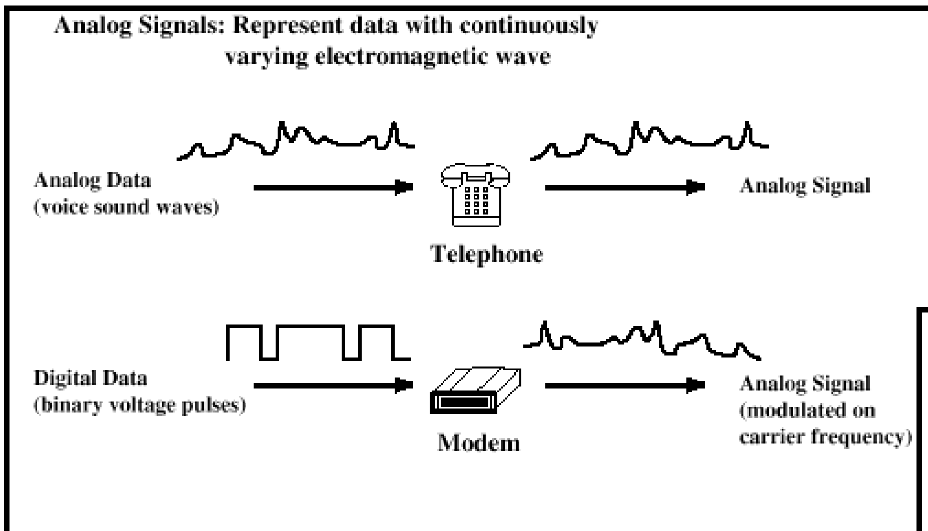
- ***Digital signal*** - signal strength (voltage pulses) maintains a constant level for some period of time and then changes to another constant level
- ***Analog signal*** - signal strength varies in a smooth (continuously varying) fashion over time

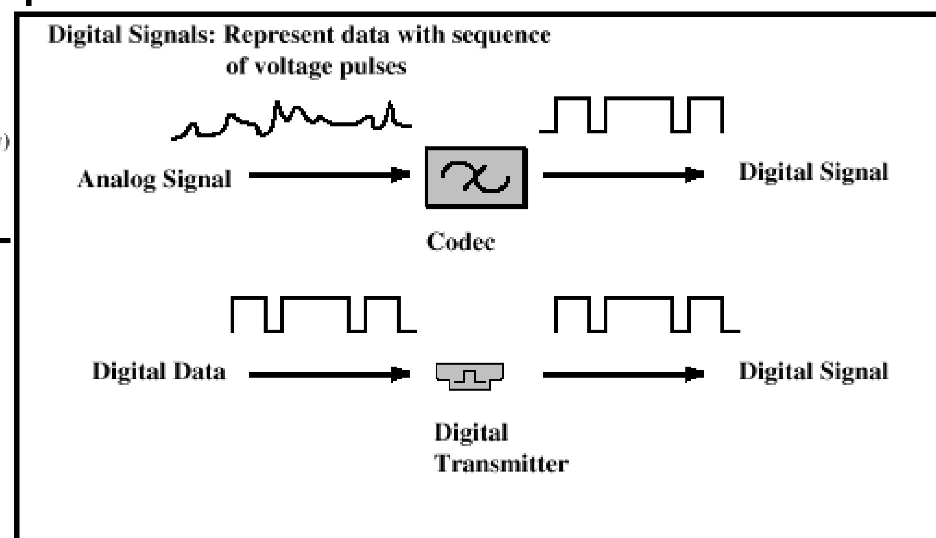




Analog vs. digital signal

- Both analog and digital data can be propagated by analog and digital signals



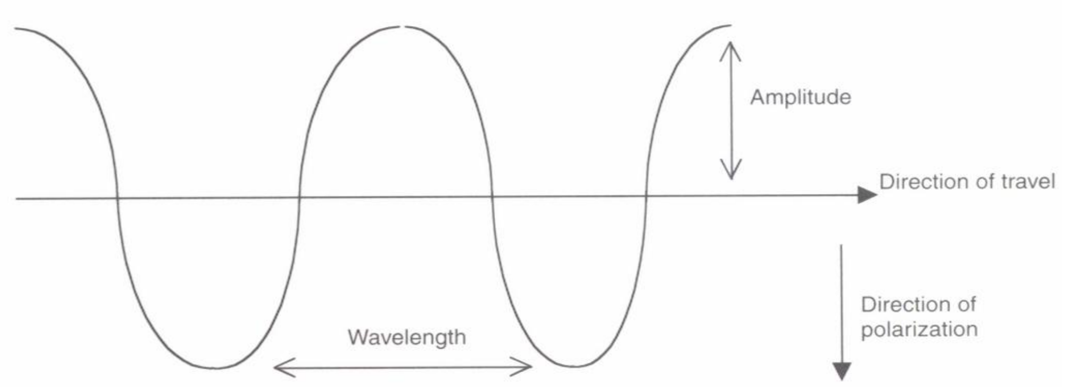


Analog vs. digital signal

- **Digital signal**
  - generally cheaper than analog signaling
  - less susceptible to noise interference
  - allow better utilization of the bandwidth
  - suffer more from attenuation, which endangers integrity of data
    - repeaters can be used to recover the signal and retransmit for longer distance (in wired networks)

Frequency

- An electromagnetic wave is characterized by:
  - **Amplitude (*A*) -** maximum strength of the signal over time; typically measured in *volts*
  - **Frequency (*f*) -** rate at which the signal repeats, measured by cycles per second (called Hertz (Hz))
  - **Phase (ϕ) -** denotes the relative position in time within a single cycle of a signal
  - **Wavelength (λ) -** distance occupied by a single cycle of the signal - the distance between two points of corresponding phase of two consecutive cycles

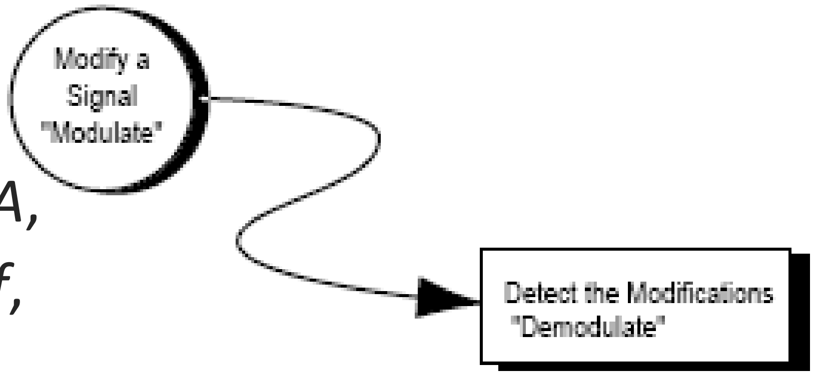


Frequency

- **The higher the frequency, the shorter the wavelength.**
  - In vacuum, all electromagnetic waves transmit at the same constant speed C (speed of light: $C \cong 3\text{x}10^8$m/s), independent of their frequencies: $C = \lambda f$
- **The higher the frequency, the higher the bit rate.**
  - More changes can be expressed
  - e.g., under low frequency, only several bits can be encoded, but under high frequency, sometimes can encode up to 40 bits.
- **The higher the frequency, the smaller the components become (e.g., antennas)**
  - Today's cellular phone are so small because they operate at frequencies high enough to allow components inside to be made small enough

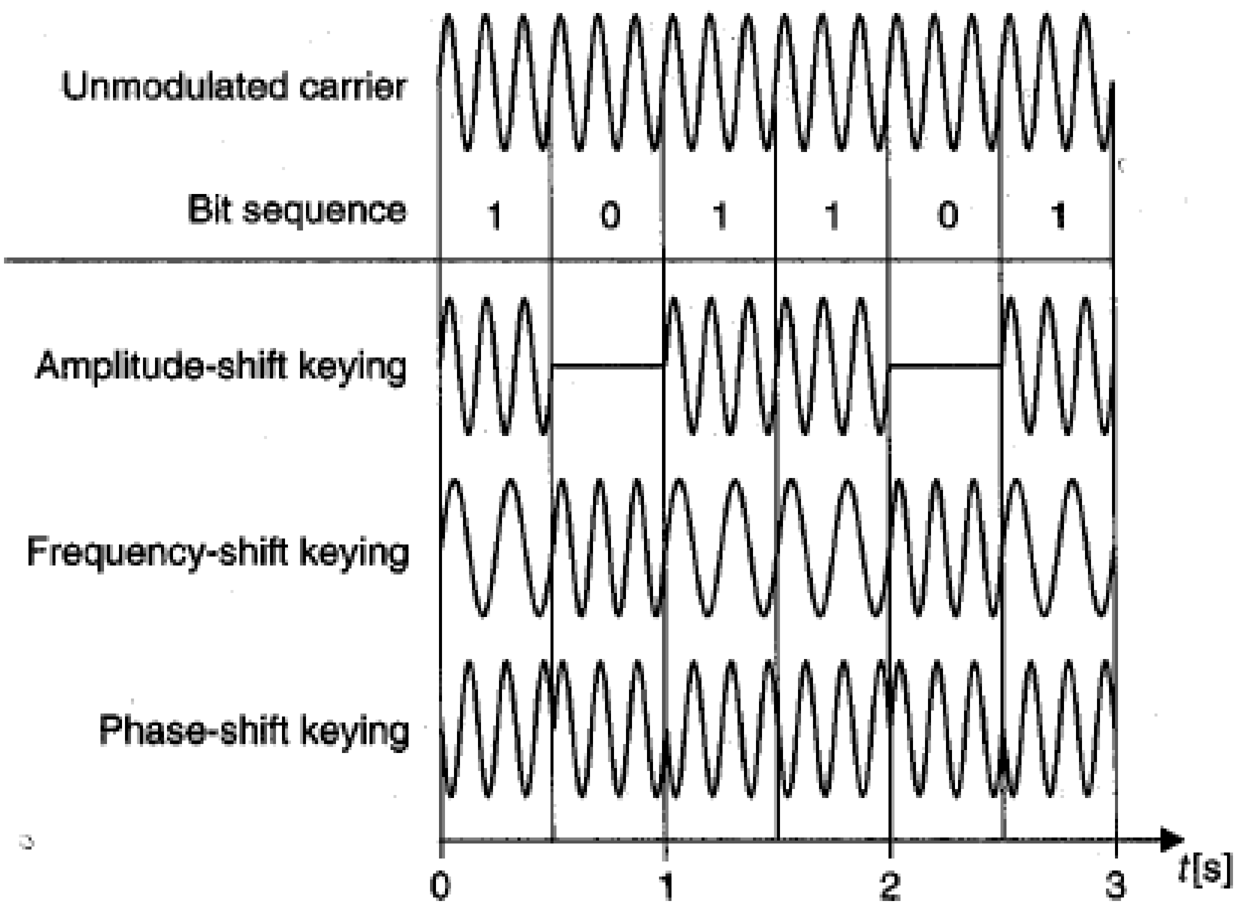
Modulation

- **An electromagnetic wave does not carry any information in its pure form. In order to represent data, one or more of its parameters *A*, *f*, and ϕ need to be varied over time.**
  - This is called modulation: signals are manipulated to carry information, or data is superimposed onto the carrier signal
- **Conventional standard modulation methods are:**
  - Amplitude modulation – varying *A*,
  - Frequency modulation – varying *f*,
  - Phase modulation – varying ϕ



Any reliably detectable change in signal characteristics can carry information

Modulation



Unmodulated carrier
Bit sequence
1
0
1
1
0
1
Amplitude-shift keying
Frequency-shift keying
Phase-shift keying
0
1
2
3
t[s]

Spectrum, Bandwidth

- The original carrier signal consists of only a single frequency but, when modulating data onto it, the modulated carrier signal can be spread over a range of several frequencies.
- **Spectrum** - range of frequencies adopted by a modulated carrier signal [f_{min}, f_{max}].
- **Bandwidth** - width of the spectrum, or the difference between the highest and lowest frequencies available in a band ($f_{min} - f_{max}$)

Channel capacity

- **The following two terms have benn used interchangeably for describing the information transmission capability of a network.**
- ***Bandwidth*** **:** ***range of signal frequencies*** **that can be supported**
  - Used in analog networks - unit is Hz, KHz, MHz and GHz
  - e.g. telephone lines carrying analog signals have a bandwidth from 300 Hz to 3.4 KHz
- ***Data rate*** **: number of bits that be transmitted in a unit of time**
  - Used in digital networks - unit is bps, Kbps, Mbps, and Gbps
  - e.g. digital voice signal passes at a speed of 64Kbps; optical fiber can carry digital signals at a speed of 20 Gbps.

Channel capacity

- **The greater the bandwidth, the higher the information-carrying capacity (transmission rate, or data rate)**
- **Any digital waveform has infinite bandwidth, but it is the transmission system that limits the bandwidth that can be transmitted**
  - For any given medium, the greater the bandwidth transmitted, the greater the cost
  - On the other hand, limiting the bandwidth creates distortions

Channel capacity

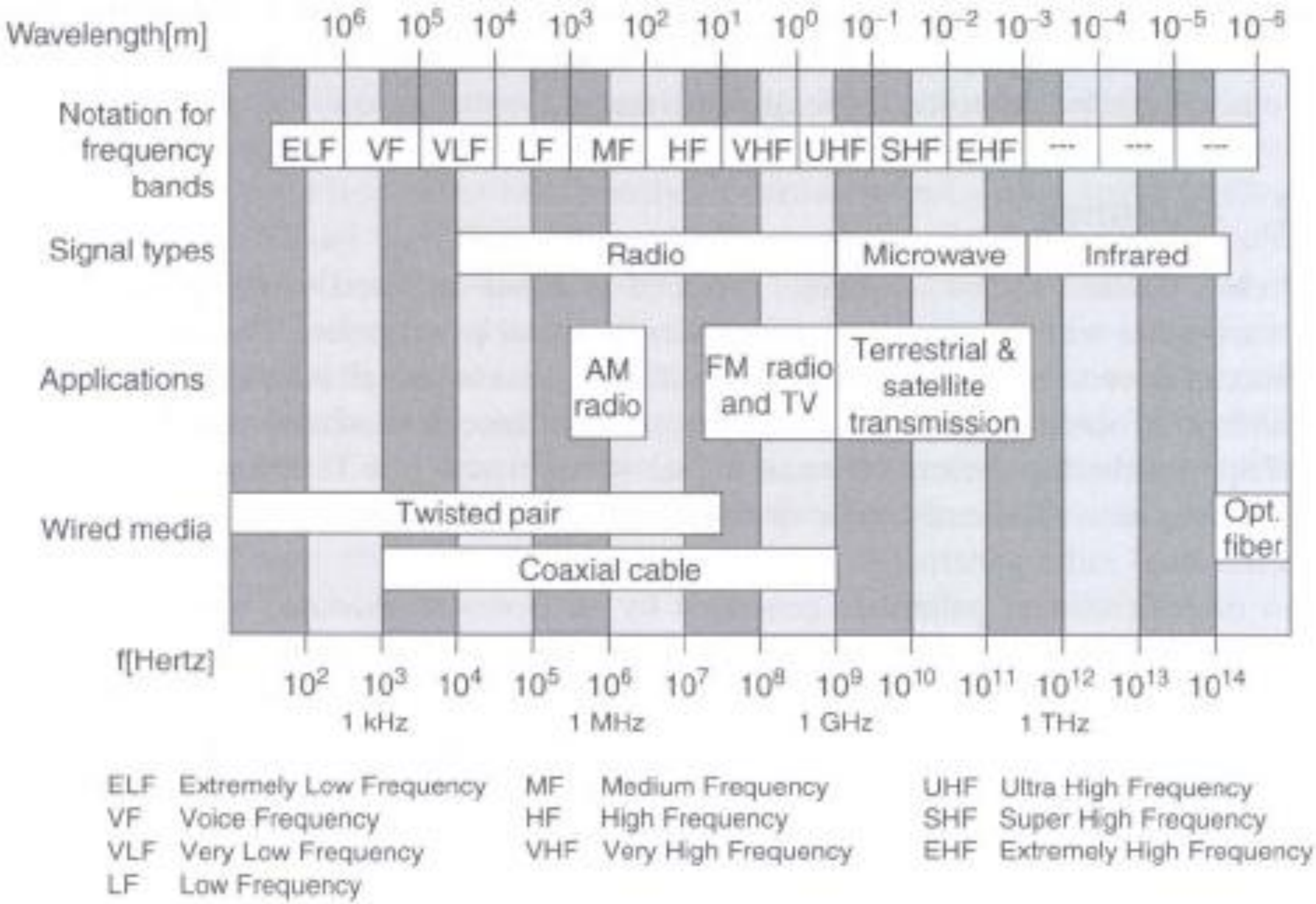
- **Narrowband (or *Voiceband*)**
  - Used for regular telephone communications
  - Transmission rate < 100 kilobits per second
- **Mediumband**
  - Used for long-distance data transmission or to connect mainframe and midrange computers
  - Transmission rate 100 kb to 1 megabit per second
- **Broadband**
  - For high-speed data and high-quality audio and video
  - Transmission rate 1 megabit per second to 100 megabits per second

Electromagnetic spectrum

- **Wireless networks may use different *bands* in the *electromagnetic spectrum***
  - Each band consists of a range of *frequencies*
  - Majority of wireless networks use the bands of *radio waves* and *microwaves*
  - Some use *Infrared* (e.g., for household devices)

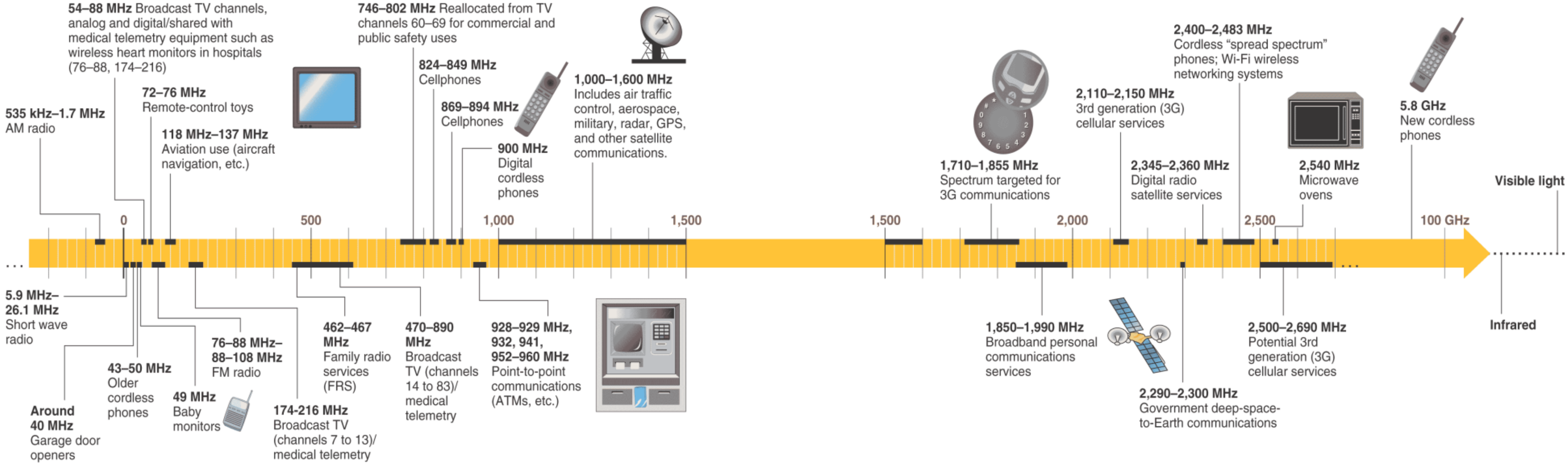
☛ The spectrum is a continuum; the boundaries between different bands don't exist naturally, but were invented by scientists trying to classify them

Electromagnetic spectrum



Signals for wireless communications are classified into ***radio, microwave, infrared***

Electromagnetic spectrum



Frequency bands for wireless communications

- ***Radio frequency range***
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications
- ***Microwave frequency range***
  - 1 GHz to 40 GHz
  - Higher-frequency bands are suitable for point-to-point transmission
  - Used for satellite / radar communications
  - Also used for heating
- ***Infrared frequency range***
  - Roughly, 3×10^{11} to 2×10^{14} Hz
  - Useful in local point-to-point / multipoint applications within confined areas
  - Remote control, optical networks
- **These bands are relevant to telecommunications (ELF – EHF) and fixed by ITU – Int’l Telecom Union.**

Modulation in wireless networks

- **Special transmission techniques are used in wireless communications.**
  - e.g., WLANs, mobile phone networks, digital radio system DAB (Digital Audio Broadcast), etc.
  - Unlike in narrowband technology (data is transmitted on designated carrier frequency), here multiple frequencies are used.
- **Different techniques are available, differing in efficiency, power requirements, and complexity.**
  - **Spread spectrum**
  - **Orthogonal Frequency Division Multiplexing (OFDM)**

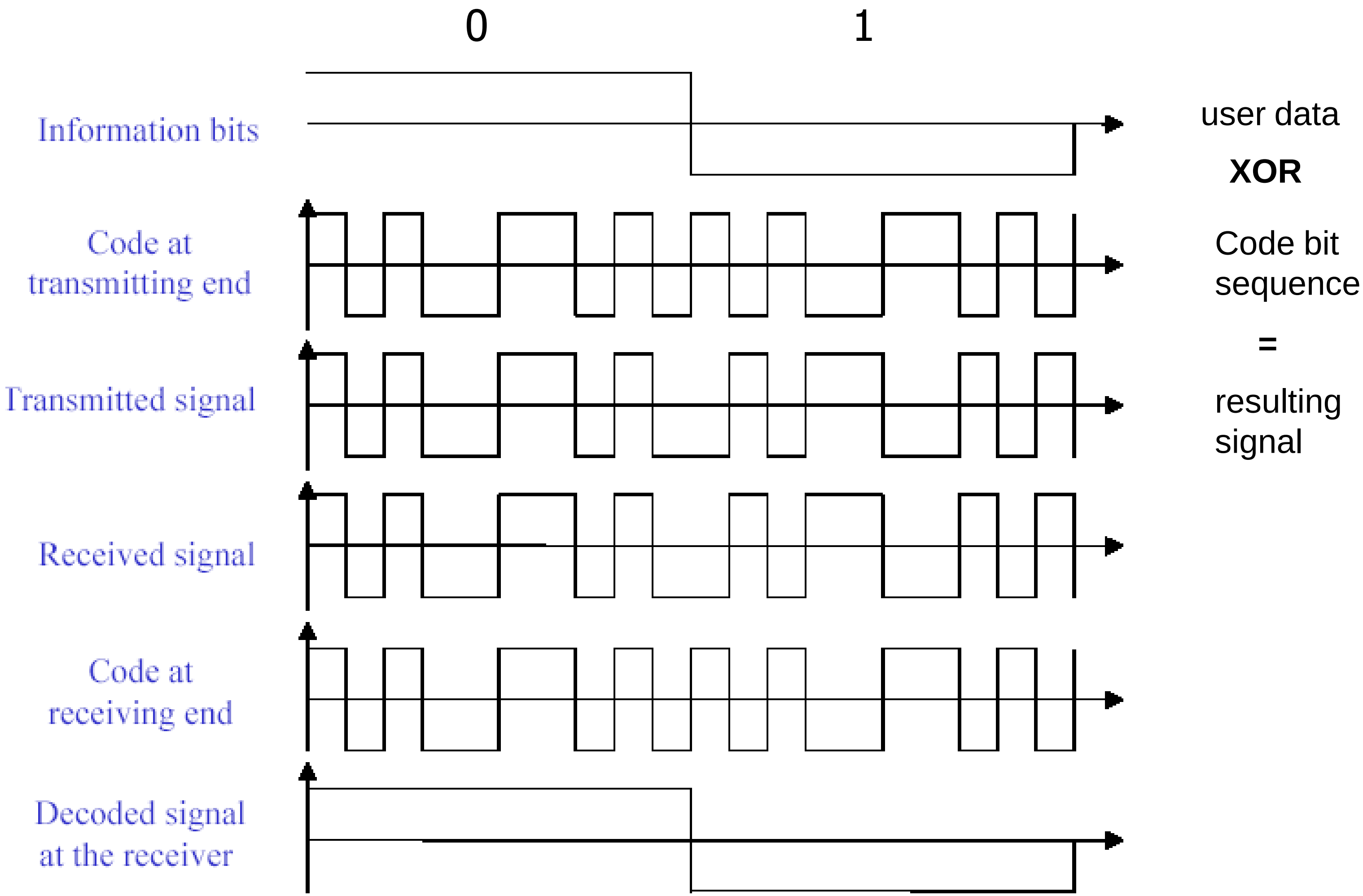
Spread spectrum

- Distribute a signal over a wide range of frequencies for transmission
- Two variations exist:
  - DSSS (Direct Sequence Spread Spectrum)
  - FHSS (Frequency Hopping Spread Spectrum)

DSSS

- **Each bit in original signal is represented by multiple bits in the transmitted signal**
  - **Spreading code** is used to mix with each message bit before it is transmitted – the effect is spreading the signal across a wider frequency band.
    - Spread is in direct proportion to number of bits used
  - The same code is used to decode these encoded bits.
- **One technique combines digital data stream with the spreading code bit stream using *exclusive-OR***

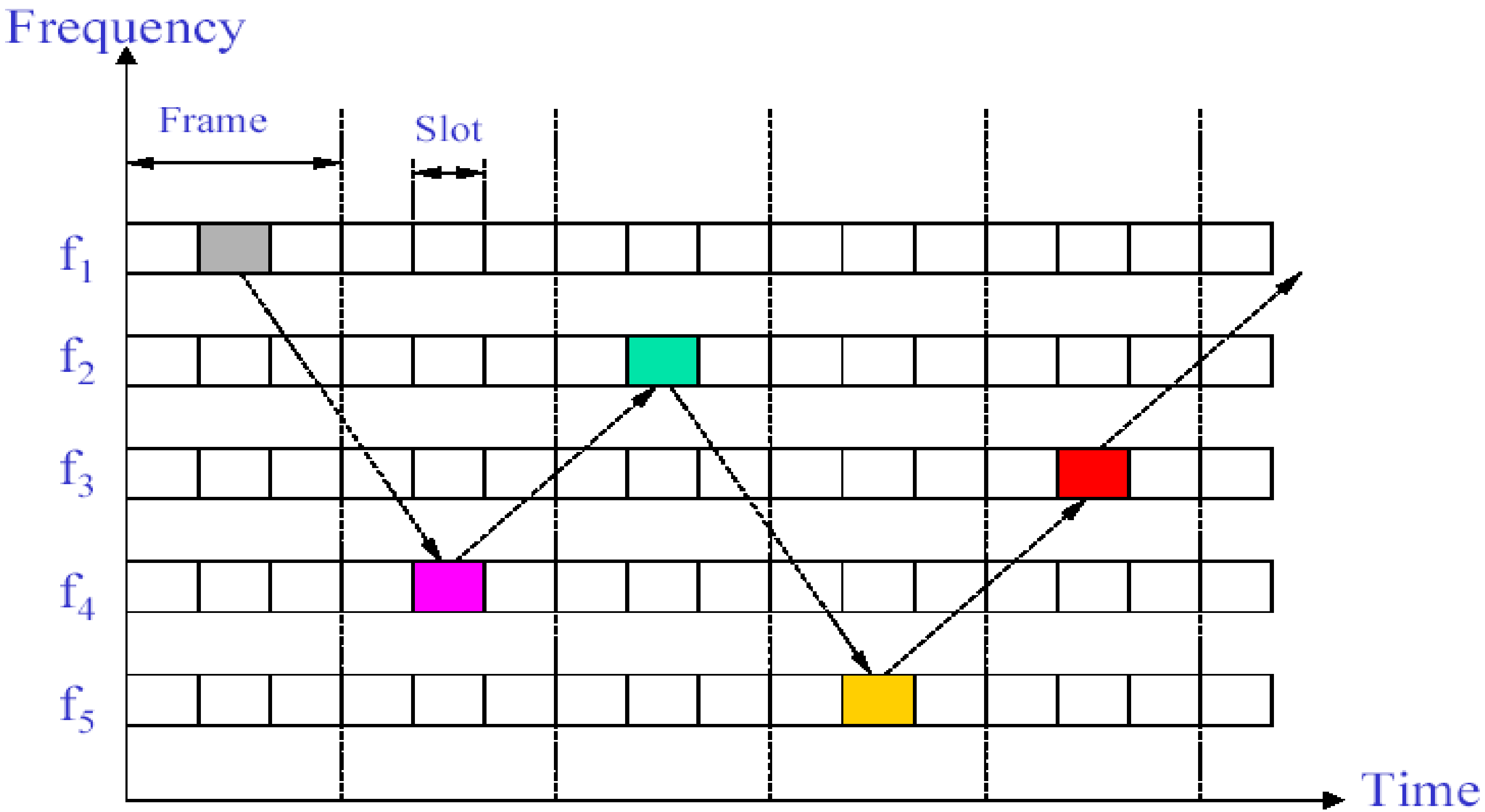
DSSS


0
1
Information bits
Code at transmitting end
Transmitted signal
Received signal
Code at receiving end
Decoded signal at the receiver
user data
XOR
Code bit sequence
=
resulting signal

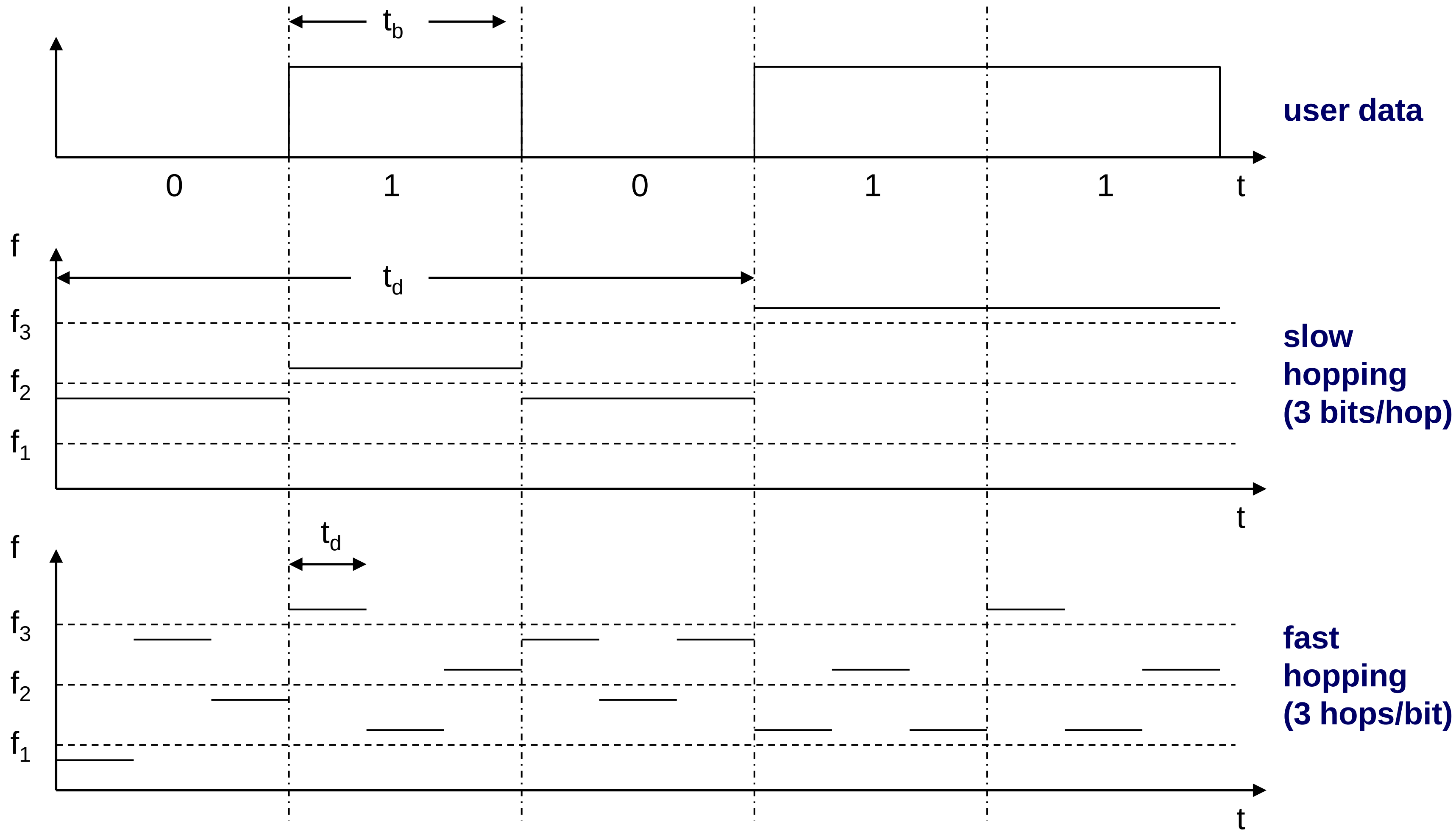
FHSS

- **Signal is broadcast over seemingly random series of radio frequencies**
  - A number of channels are allocated for the FH signal
  - Width of each channel corresponds to bandwidth of input signal
  - Signal hops from frequency to frequency at fixed intervals
- **Transmitter operates in one channel at a time**
  - Bits are transmitted using some encoding scheme
  - At each successive interval, a new carrier frequency is selected
- **Receiver, hopping between frequencies in synchronization with transmitter, picks up message**

FHSS



FHSS



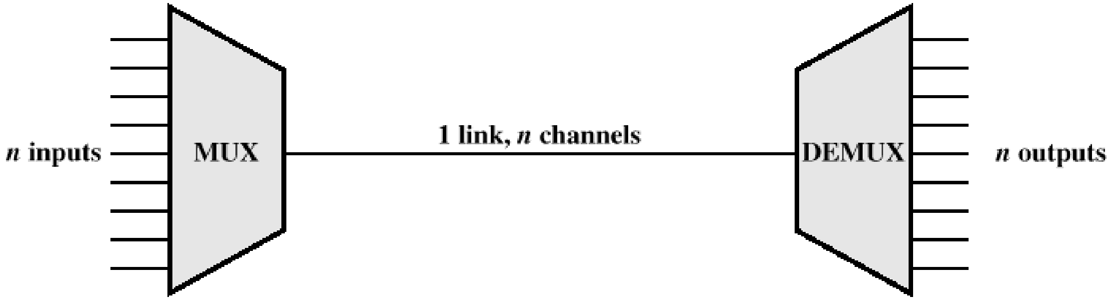
t_b: bit period t_d: dwell time

Features of spread spectrum

- **Allow multiple users to use the same frequency band**
  - Easily detected by receivers that know the parameters (patterns) of the signal being broadcast.
  - To everyone else the spread-spectrum signal looks like background noise
- **Higher reliability and security**
- **Used in most mobile data transmission systems, including Bluetooth, 3G cellular networks, and WLAN**

Multiplexing

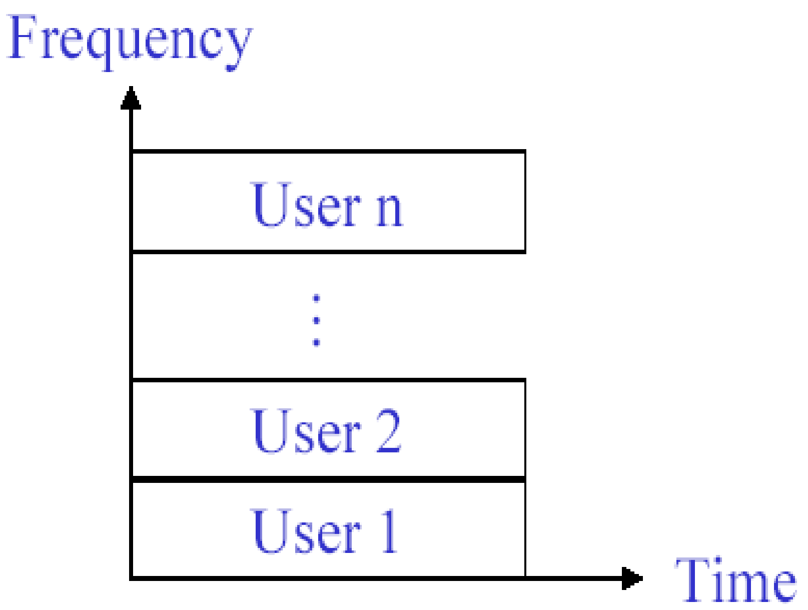
- **Multiplexing - carrying multiple users' signals over a single medium**
  - Capacity of transmission medium usually exceeds capacity required for transmission of a single user – *how to make more efficient use of transmission medium*
  - The medium is always shared in wireless communication – *how to ensure low interference*.
  - Divide medium into several channels that can be used independently of each other without interferences.



Multiplexing techniques

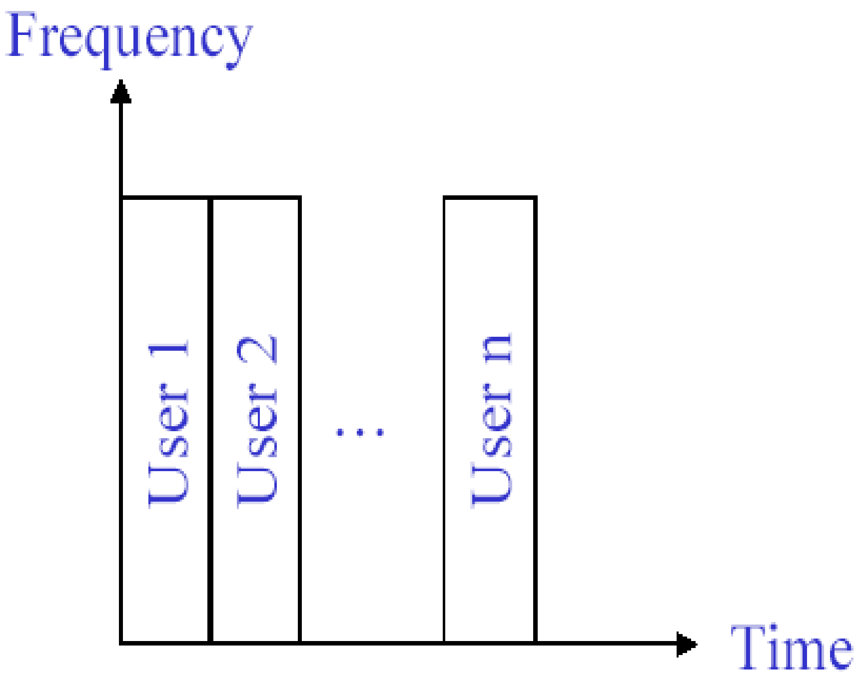
Frequency-division multiplexing (FDM)

- Takes advantage of the fact that the useful bandwidth of the medium exceeds the required bandwidth of a given signal
- Advantages:
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages:
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible



Multiplexing techniques

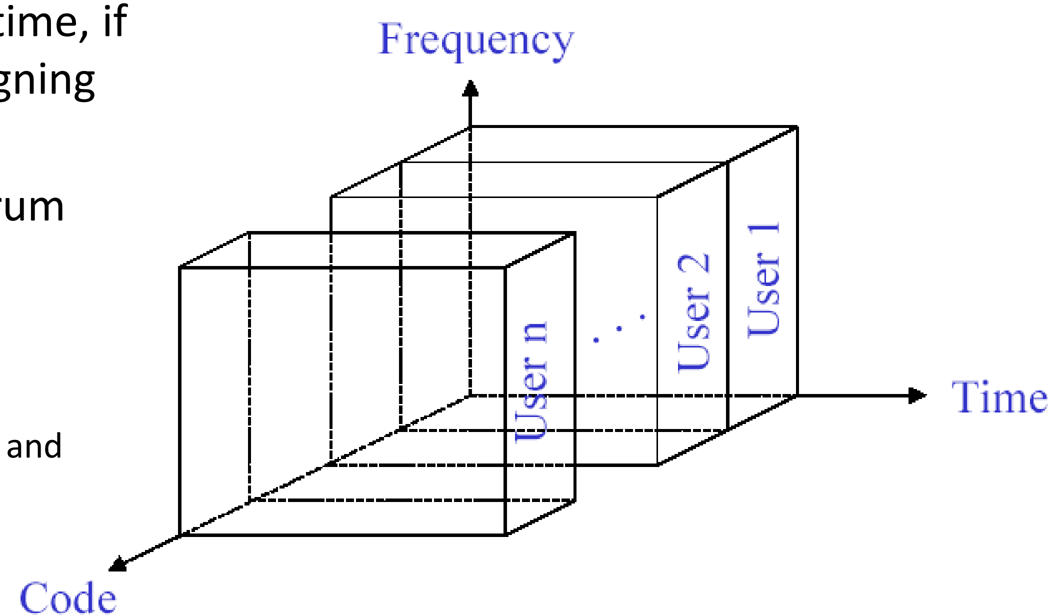
- **Time-division multiplexing (TDM)**
  - Takes advantage of the fact that the achievable bit rate of the medium exceeds the required data rate of a digital signal
  - Advantages:
    - only one carrier in the medium at any time
    - high throughput even for many users
  - Disadvantages:
    - Precise coordination and synchronization necessary



Multiplexing techniques

Code-division multiplexing (CDM)

- Takes advantage of the fact that multiple channels can take place using the same frequency at the same time, if we separate the channels by assigning them their own ‘code’
- Implemented using spread spectrum technology - DSSS
- Advantages:
  - Bandwidth efficient
  - Good protection against interference and tapping
- Disadvantages:
  - More complex signal regeneration
  - Precise power control needed



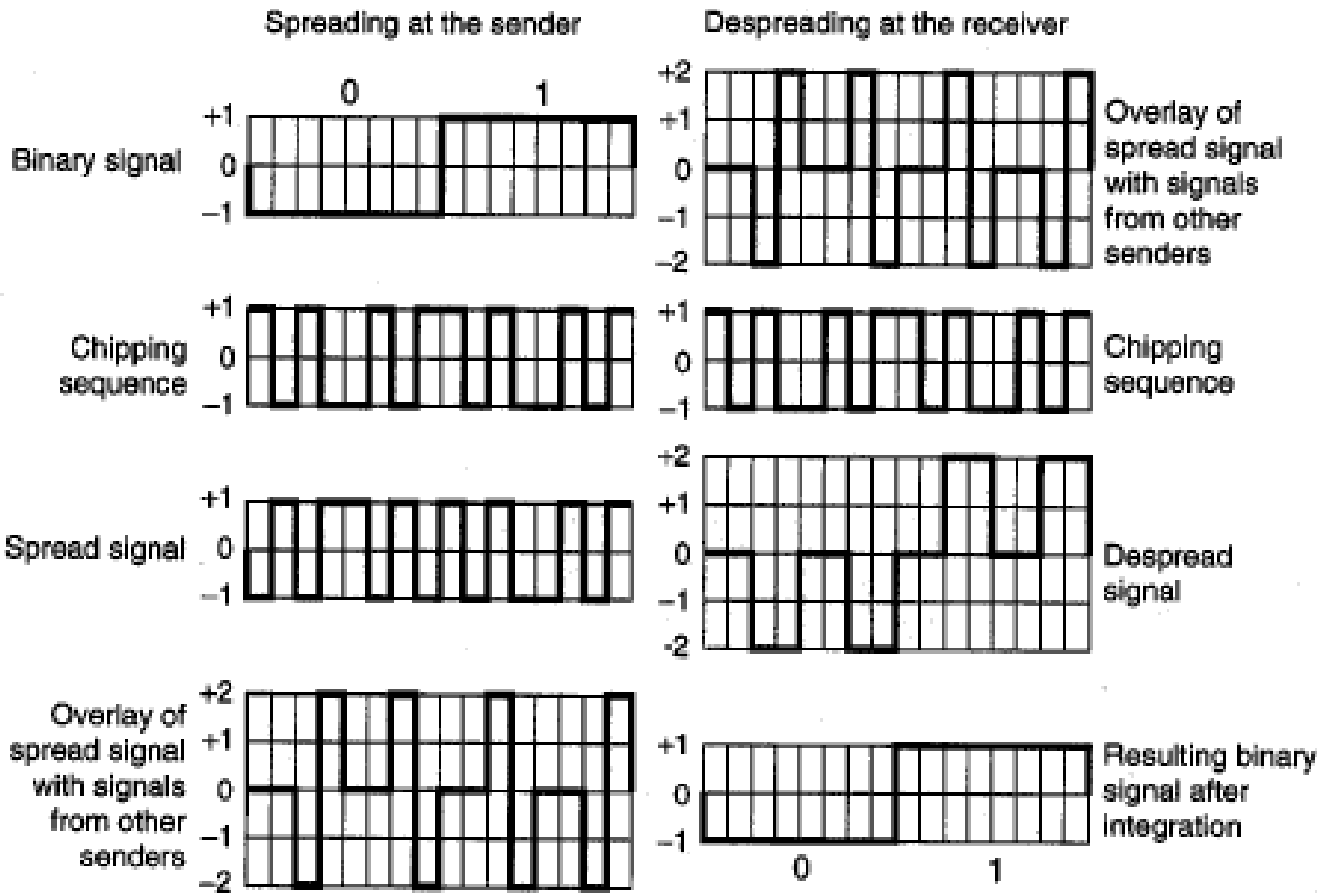
CDM examples

- **Sender A**
  - sends **Ad** = 1, Code **Ac** = 010011 (Let "0"= -1, "1"= +1, **Ak** = -1 +1 -1 -1 +1 +1)
  - sending signal **As** = Ad * Ak = (+1) * (-1, +1, -1, -1, +1, +1)

    = **(-1, +1, -1, -1, +1, +1)**
- **Sender B**
  - sends **Bd** = 0, Code **Bc** = 110101 (Let "0"= -1, "1"= +1, **Bk** = +1 +1 -1 +1 -1 +1)
  - sending signal **Bs** = Bd * Bk = (-1) * (+1, +1, -1, +1, -1, +1)

    = **(-1, -1, +1, -1, +1, -1)**
- **Both signals superimpose in space**
  - interference neglected (noise etc.)
  - **As** + **Bs** = **(-2, 0, 0, -2, +2, 0)**
- Receiver **wants to receive signal from sender A**
  - apply code **Ac** bitwise (inner product)
    - **Ae** = (-2, 0, 0, -2, +2, 0) • **Ak** = 2 + 0 + 0 + 2 + 2 + 0 = 6
    - result greater than 0, therefore, original bit was "1"
  - receiving B
    - **Be** = (-2, 0, 0, -2, +2, 0) • **Bk** = -2 + 0 + 0 - 2 - 2 + 0 = -6, i.e. "0"

CDM examples

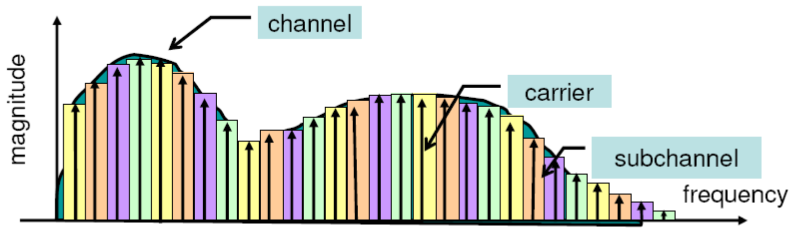


Multiplexing techniques

- **Space-division multiplexing (SDM)**
  - Allow the establishment of several channels in the same frequency range for simultaneous use, assuming that they are sufficiently separated in space.
  - Define frequency reuse distance (e.g., Cell structure, where signals are attenuated as farther away they travel from the source). or
  - Propagate signals as highly directed beams (e.g., Segment space into sectors, use directed antennas)

OFDM

- **Transmits data over parallel frequencies**
  - A special method of implementing MCM (**m**ulti-**c**arrier **m**odulation)
    - Channel bandwidth is divided into multiple sub-carrier frequencies called tones (sub-channels)
    - Fast serial data stream is converted into slow parallel streams (longer symbol durations), and then distributed over different sub-carriers for transmission.



Channel impulse response

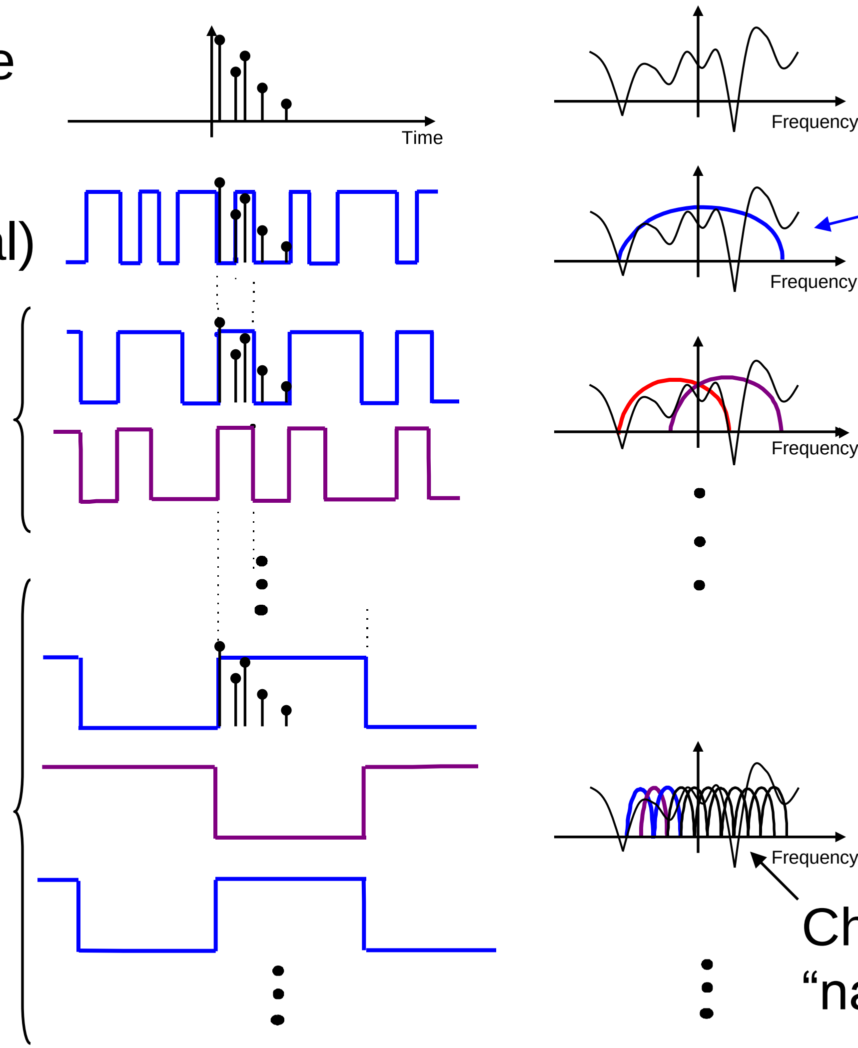
Channel transfer function

1 Channel (serial)

Signal is "broadband"

2 Channels

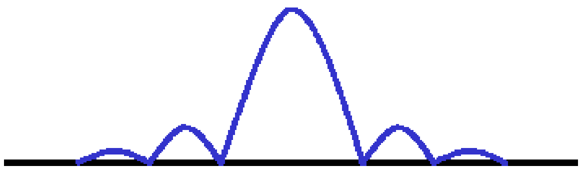
8 Channels



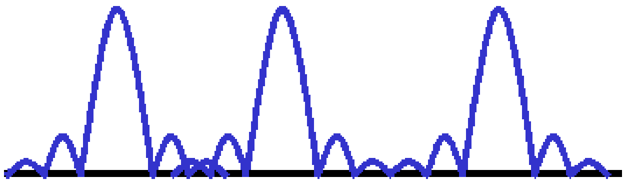
Channels are "narrowband"

OFDM

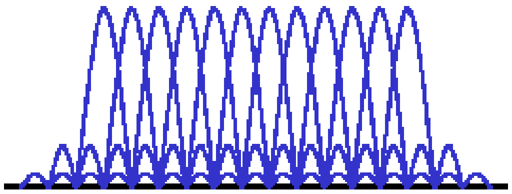
- **Same as in traditional FDM, sub-carriers are spaced apart, but in OFDM they can be overlapped to be independent & unrelated, hence orthogonal.**



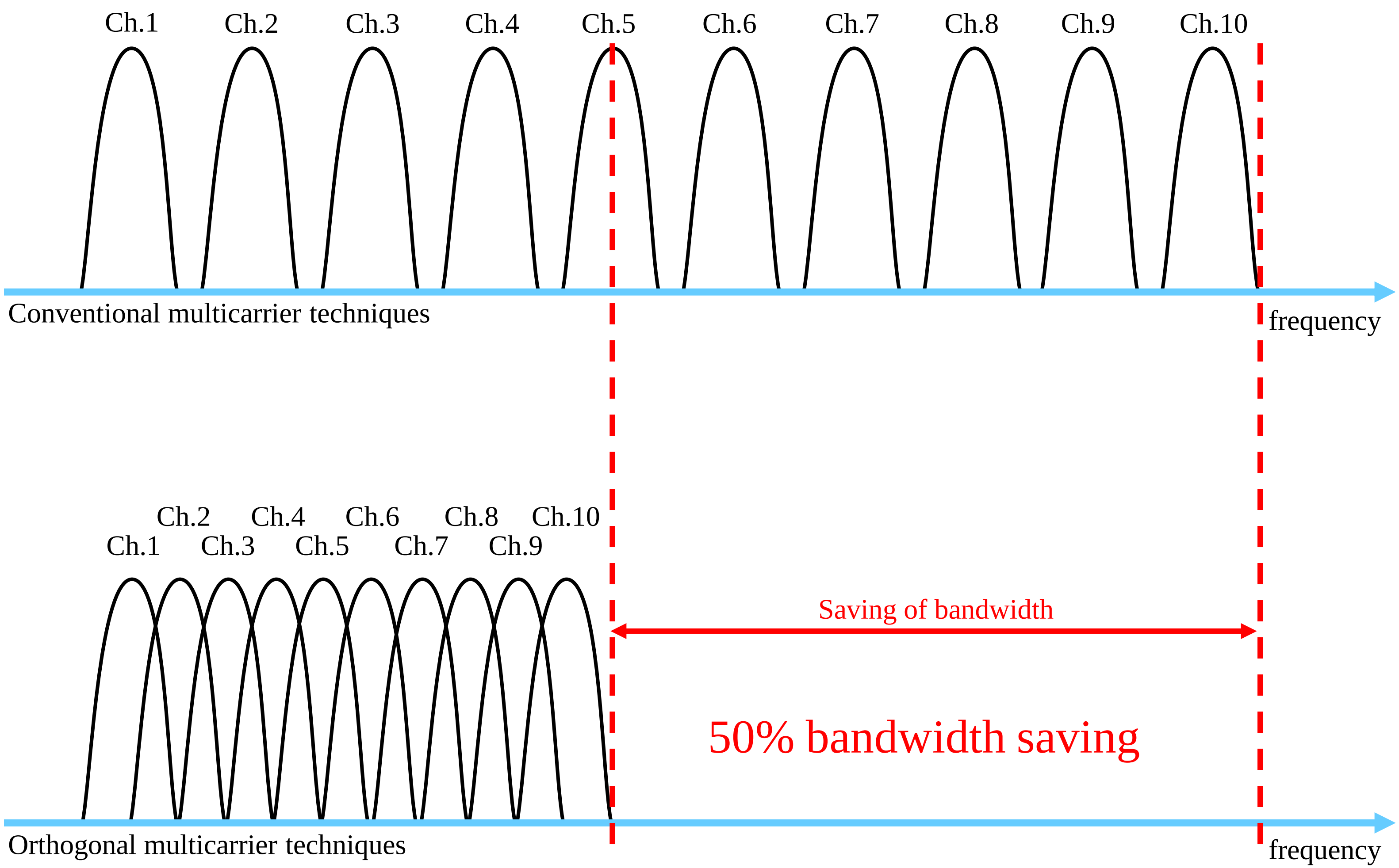
Spectrum of normal time domain sequence



Spectrum of classical FDM



Spectrum of OFDM


Ch.1
Ch.2
Ch.3
Ch.4
Ch.5
Ch.6
Ch.7
Ch.8
Ch.9
Ch.10
Conventional multicarrier techniques
frequency
Ch.2
Ch.4
Ch.6
Ch.8
Ch.10
Ch.1
Ch.3
Ch.5
Ch.7
Ch.9
Saving of bandwidth
50% bandwidth saving
Orthogonal multicarrier techniques
frequency

OFDM

- **Used by IEEE 802.11a/g & 802.16**
- **Advantages:**
  - Protecting signal from interference
  - High spectrum efficiency – more data can travel over a smaller amount of bandwidth

Multiple access methods

- ***Multiplexing*** **is about how to share the medium by dividing the medium into multiple channels**
- **But how to use multiplexing ?**
  This is by *multiple access methods* :
  - Segmenting available spectrum into frequencies,
  - planning frequency for reuse,
  - allocating time slots, or
  - defining spreading codes, etc..

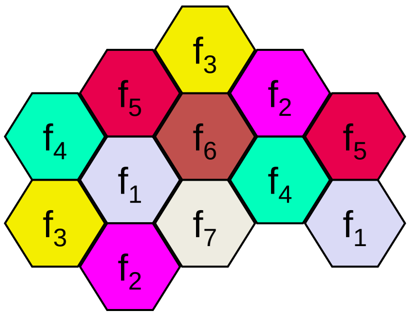
Multiple access methods

- **FDMA (Frequency Division Multiple Access)**
  - Based on FDM – Allocate frequencies to channels or define a frequency hopping pattern
  - E.g., used for simultaneous communication between base station and mobile unit (uplink and downlink)
- **TDMA (Time Division Multiple Access)**
  - Based on TDM – Allocate time slots for channels in a fixed pattern;
- **CDMA (Code Division Multiple Access)**
  - Based on CDM – Assign codes to allow for separation of different users in code space;
  - Power control (the problem of "near and far terminals").
- **SDMA (Space Division Multiple Access)**
  - Based on SDM

Multiple access methods

Approach	SDMA	TDMA	FDMA	CDMA
Idea	segment space into cells/sectors	segment sending time into disjoint time-slots, demand driven or fixed patterns	segment the frequency band into disjoint sub-bands	spread the spectrum using orthogonal codes
Terminals	only one terminal can be active in one cell/one sector	all terminals are active for short periods of time on the same frequency	every terminal has its own frequency, uninterrupted	all terminals can be active at the same place at the same moment, uninterrupted
Signal separation	cell structure, directed antennas	synchronization in the time domain	filtering in the frequency domain	code plus special receivers
Advantages	very simple, increases capacity per km²	established, fully digital, flexible	simple, established, robust	flexible, less frequency planning needed, soft handover
Dis-advantages	inflexible, antennas typically fixed	guard space needed (multipath propagation), synchronization difficult	inflexible, frequencies are a scarce resource	complex receivers, needs more complicated power control for senders
Comment	only in combination with TDMA, FDMA or CDMA useful	standard in fixed networks, together with FDMA/SDMA used in many mobile networks	typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)	still faces some problems, higher complexity, lowered expectations; will be integrated with TDMA/FDMA

Comparison of FDMA, TDMA, CDMA (example: Cellular system)



Operation	FDMA	TDMA	CDMA
Allocated Bandwidth	12.5 MHz	12.5 MHz	12.5 MHz
Frequency reuse	7	7	1
Required channel BW	0.03 MHz	0.03 MHz	1.25 MHz
No. of RF channels	12.5/0.03=416	12.5/0.03=416	12.5/1.25=10
Channels/cell	416/7=59	416/7=59	12.5/1.25=10
Control channels/cell	2	2	2
Usable channels/cell	57	57	8
Calls per RF channel	1	4*	40**
Voice channels/cell	57x1=57	57x4=228	8x40=320
Sectors/cell	3	3	3
Voice calls/sector	57/3=19	228/3=76	320
Capacity vs FDMA	1	4	16.8

* Depends on the number of slots

** Depends on the number of codes

Call Admission Control

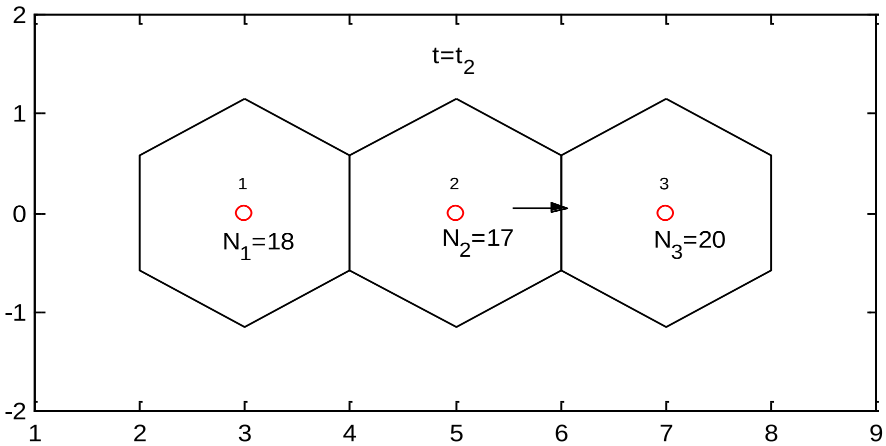
- **Given the number of channels available, the network needs to determine whether a newly arrived transmission request should be admitted.**
- **This is especially important for calls in cellular phone networks - the Call Admission Control (CAC) problem**
  - The number of channels allocated to each BS is limited
  - Maximized channel utilization while guaranteeing QoS

Call Admission Control

- CAC is a process for managing the arriving traffic (at the call, session, or connection level) based on some predefined criteria
- When necessary, some call requests need to be blocked
  - New call blocking
  - Handoff call blocking
- Example: TDMA network

- Number of channels per cell=20.
- The network consists of 3 cells.
- At instant (t0), number of users Ni(t0) (i=1,2,3) is equal to (18, 17, 19)
- At instant (t1), a new user arrived at cell 3. Then Ni(t2) will be (18, 17,20).

- At instant (t_2), one of the 17 active users in cell 2 is leaving cell 2 heading cell 3.
- This user has to be handed over to cell 3, but cell 3 is fully loaded.
- Result: This user will be rejected by cell 3 and the call will be dropped.
- Conclusion: Admitting the new user in cell 2 at instant (t_1) was not a good decision.



The Guard Channel Scheme

- Parameter to consider: new and handoff call arrival rates and mean call residency time

Call Admission Control

- *Naïve solution:* **for no hand-off drops, reserve bandwidth in all cells a mobile/connection might pass through**
- *Problem:* **bandwidth quickly consumed and new connection blocking probability increases**
- *Proposed solution:* **a cell estimates aggregate bandwidth for hand-offs from adjacent cells, to be reserved and used solely for hand-offs, not new connection requests**
  - Predictive: estimate directions and hand-off times of ongoing connections in each cell
  - Adaptive: dynamically adjust amount of reserved bandwidth to account for estimation inaccuracies and varying traffic/mobility conditions

Medium Access Control (MAC)

- **Multiplexing allows terminals to share medium, assuming each terminal can be assigned a separate channel in the medium for transmission (e.g. by CAC).**
- **But in some networks, channels are accessed by terminals *on demand* - there is no admission control and no dedicated channel for each terminal. Then terminals need to compete for the use of channels and collision may occur.**
- **MAC protocols are used to *regulate* multiple terminals for *randomly* access to the shared medium.**
  - Need to resolve collisions - can be centralized and distributed
  - Needed for wireless networks that are designed to carry data: IEEE 802.11 Wireless LANs, ad hoc networks, bluetooth, ...

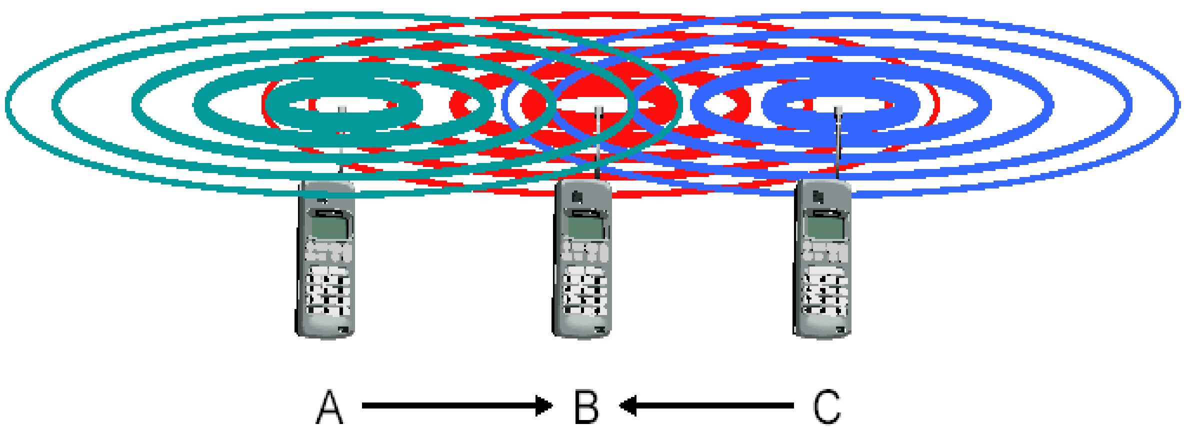
Medium Access Control (MAC)

- **MAC in wireless networks is more difficult than in wired network**
  - Signal strength decreases proportional to square of distance, so no use for sender to apply CS
  - Collisions happen at receivers, so no use for sender to apply CD
- **Protocols (centralized vs distributed; schedule-based vs. conflict-based)**
  - ALOHA,
  - CSMA/CA (Carrier Sense MA with Collision Avoidance),
  - MACA (MA with Collision Avoidance),
  - DAMA (Demand Assignment MA – for Satellites),
  - ...

Medium Access Control (MAC)

Hidden terminal problem

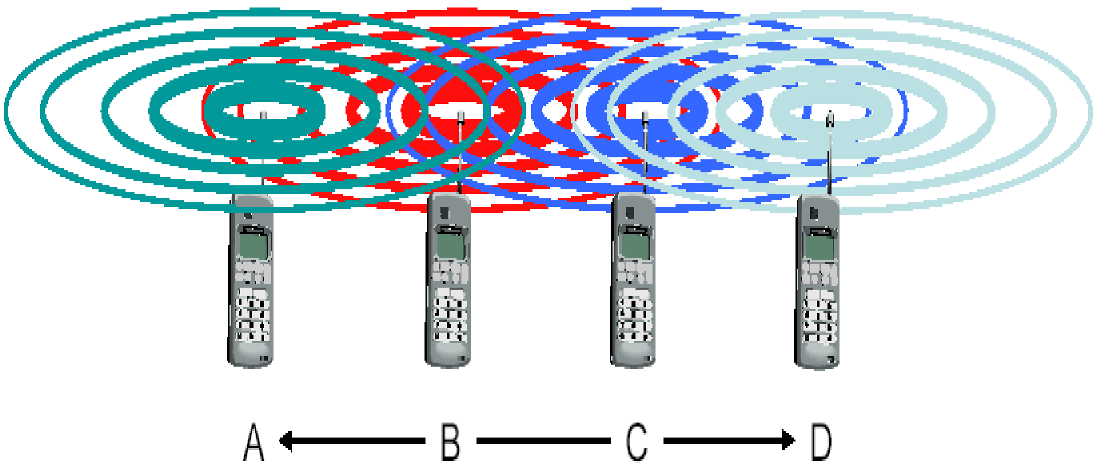
- A sends to B, C cannot receive A
- C wants to send to B, C senses a “free” medium (CS fails)
- Collision at B, A cannot receive the collision (CD fails)
- A is “hidden” for C -> cause collisions



Medium Access Control (MAC)

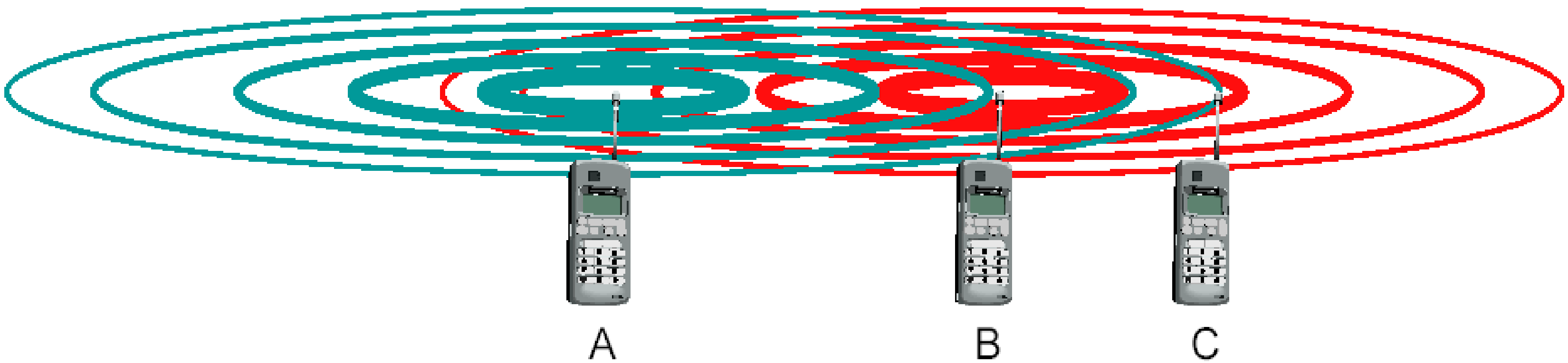
Exposed terminal problem

- B sends to A, C wants to send to D
- C has to wait, CS signals a medium in use
- Since A is outside radio range of C, waiting is not necessary
- C is “exposed” to B –> unnecessary blocking



Medium Access Control (MAC)

- **Near and far terminal problem**
  - The signal of terminal B hides A's signal
  - C cannot receive A as B can keep occupying the channel
  - This is also a severe problem for CDMA networks - precise power control is needed

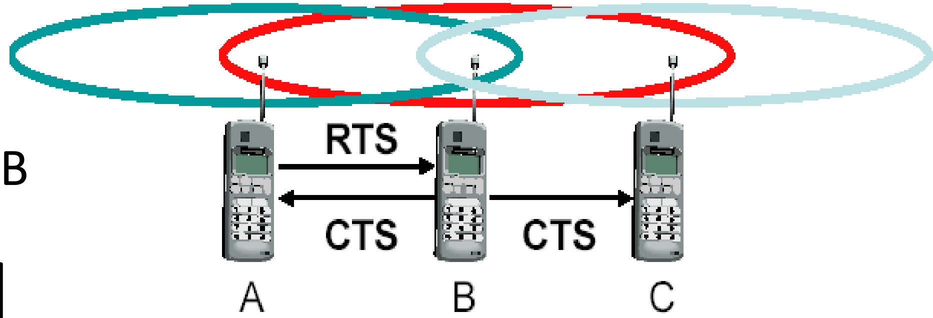


Medium Access Control (MAC)

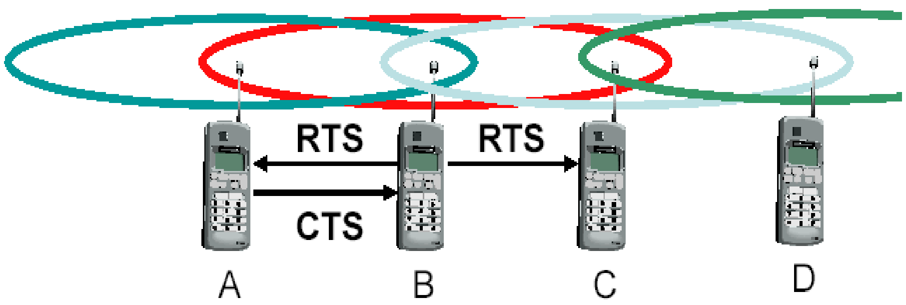
- **Example: MACA (Multiple Access with Collision Avoidance)**
  - Use short signaling packets for collision avoidance;
  - **Request (or Ready) to send** (**RTS**): sender requests the right to send from a receiver with a short RTS packet before it sends a data packet;
  - **Clear to send** (**CTS**): receiver grants the right to send as soon as it is ready to receive
  - Signaling packets contain:
    - Sender address
    - Receiver address
    - Packet size

Medium Access Control (MAC)

- **MACA avoids hidden terminal problem**
  - A and C want to send to B
  - A sends RTS first
  - C waits until receiving CTS from B



- **MACA avoids exposed terminal problem**
  - B wants to send to A and C wants to send to D
  - Now C does not have to wait as it cannot receive CTS from A



Research on MAC

- Energy efficiency
- Improving throughput (channel utilization)
- Improving fairness
- …