Wireless and Mobile Networks

Radio Access & Spectrum Efficiency

- Modulation
- Multiplexing
- Medium Access Control
- Channel Allocation

Slides prepared by Dr. Aziz Qaroush

Modulation

Modulation

- Modulation is the process of facilitating the transfer of information over a medium.
  - Sound transmission in the air has limited range for the amount of power your lungs can generate. To extend the range your voice can reach, we need to transmit it through a medium other than air, such as a phone line or radio.

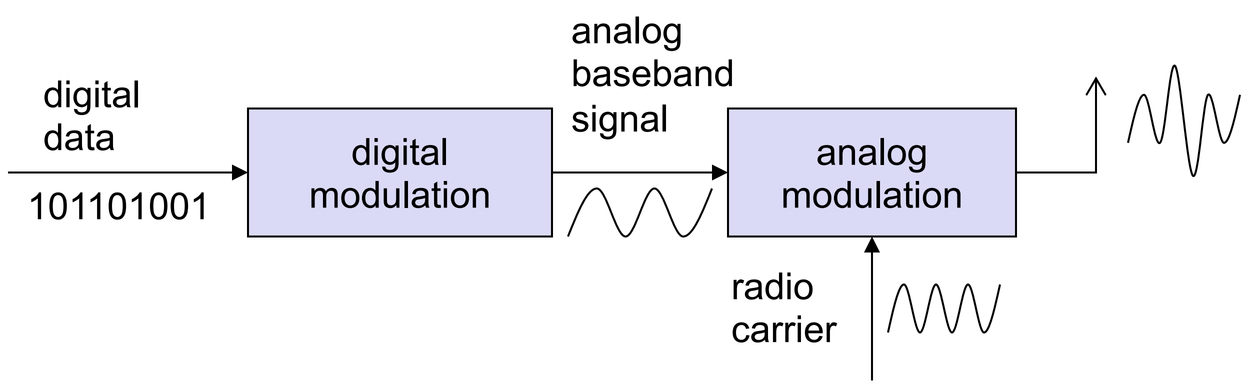
- In electronics, **modulation** is the process of varying one or more properties of high frequency periodic waveform, called the carrier signal, with respect to a modulating signal.

- In telecommunications, **modulation** is the process of conveying a message signal, for example a digital bit stream or an analog audio signal, inside another signal that can be physically transmitted.

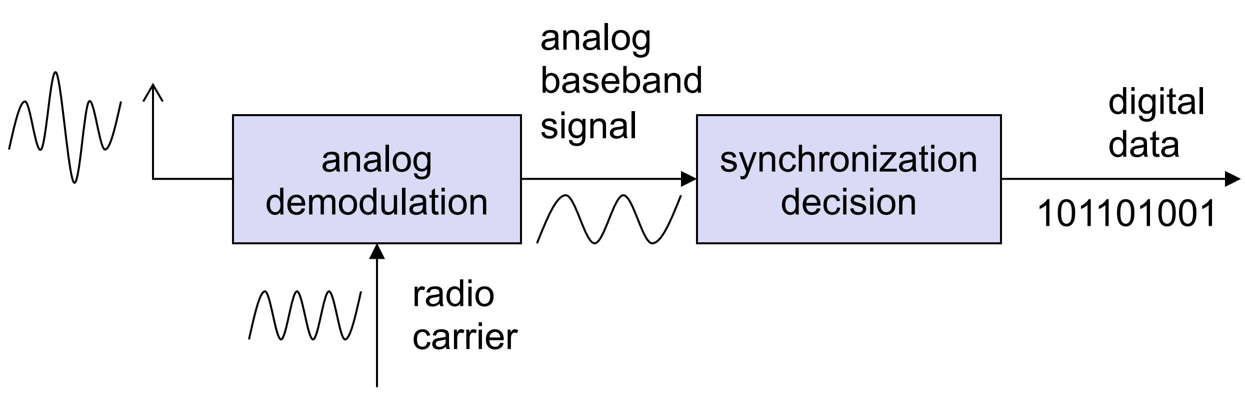
Modulation

- Digital modulation
  - digital data is translated into an analog signal (baseband)
  - ASK, FSK, PSK - main focus
  - differences in spectral efficiency, power efficiency, robustness
- Analog modulation
  - shifts center frequency of baseband signal up to the radio carrier
- Motivation
  - Large distance
  - smaller antennas (e.g., $\lambda/4$)
  - Frequency Division Multiplexing
  - Medium characteristics
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)

Modulation and demodulation



radio transmitter



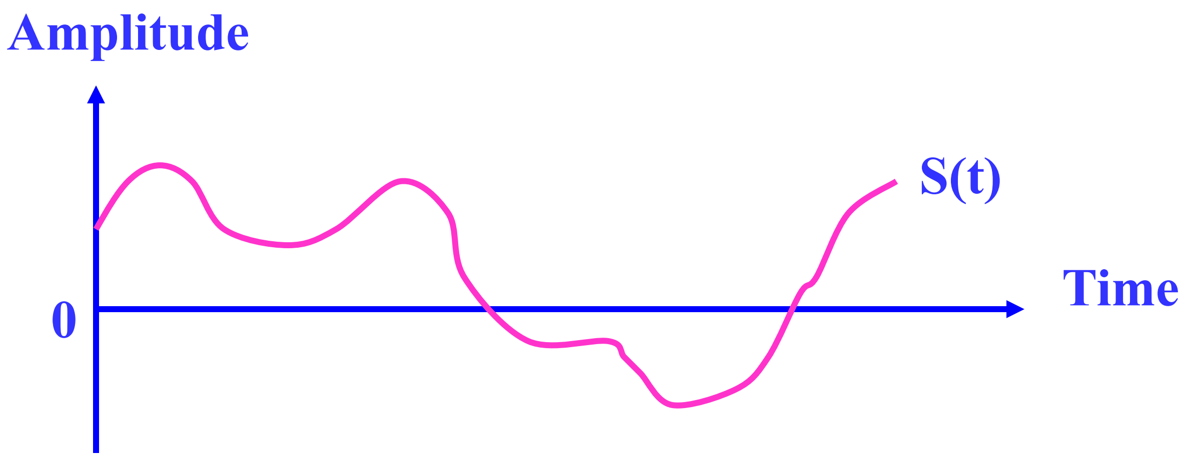
radio receiver

Modulation Techniques

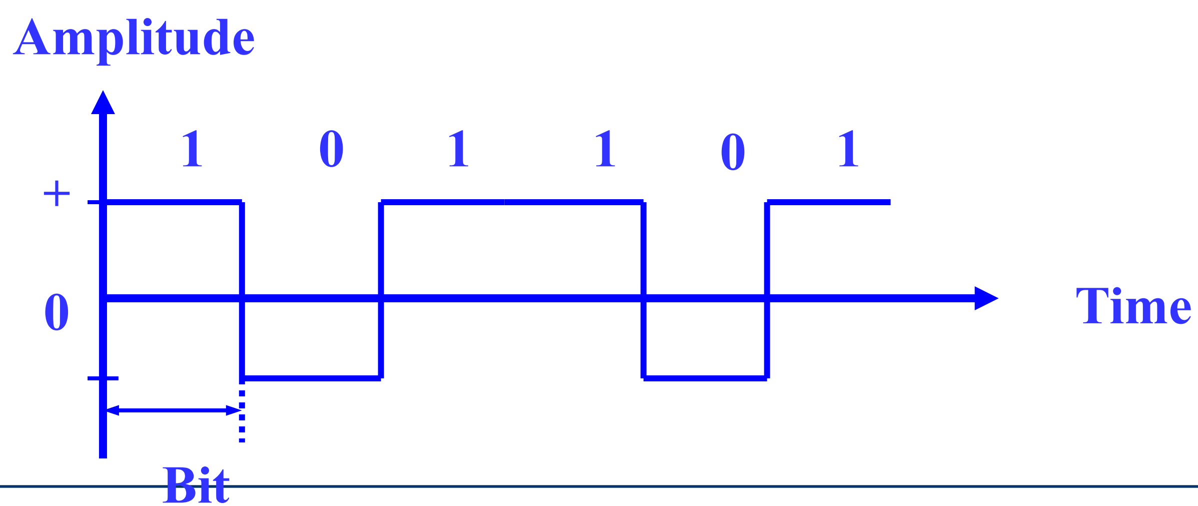
- **Analog Modulation: used for transmitting analog data**
  - **Amplitude Modulation (AM)**
  - **Frequency Modulation (FM)**
- **Digital Modulation: used for transmitting digital data**
  - **Amplitude Shift Keying (ASK)**
  - **Frequency Shift Keying (FSK)**
  - **Phase Shift Keying (PSK)**
  - **……**

Analog and Digital Signals

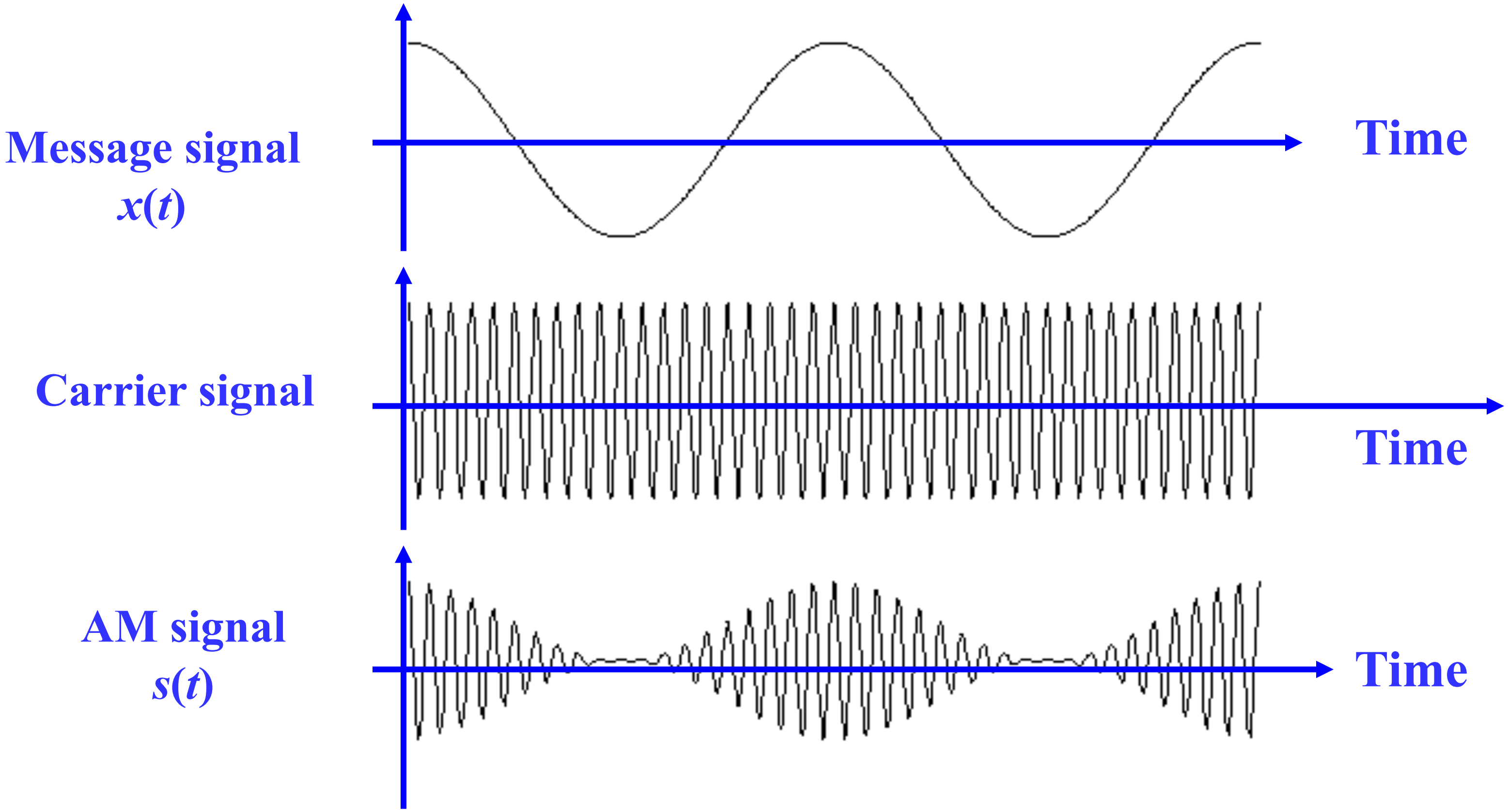
- Analog Signal (Continuous signal)



- Digital Signal (Discrete signal)



Amplitude Modulation (AM)

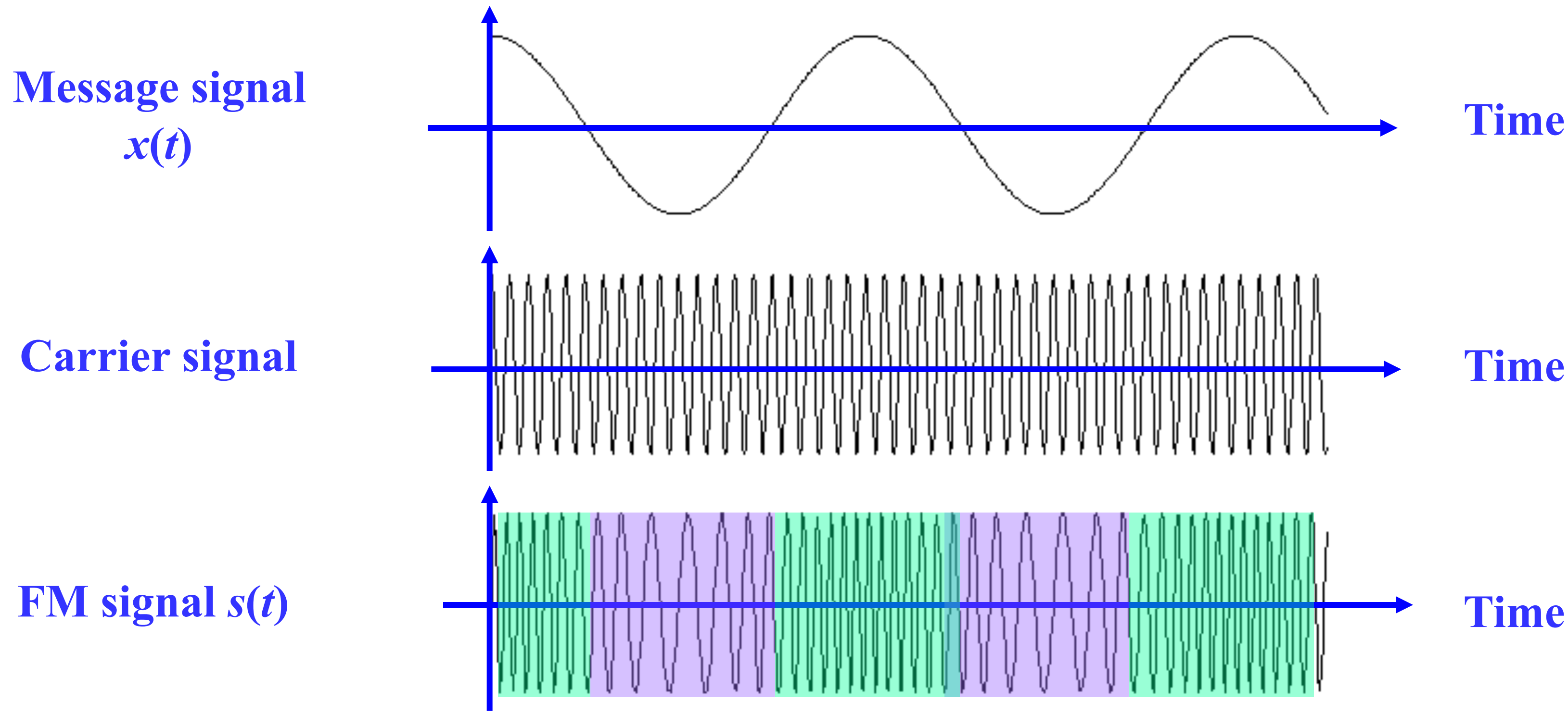


The modulated carrier signal $s(t)$ is:

$$s(t) = [A + x(t)]\cos(2\pi f_c t)$$

$\cos 2\pi f_c t$ = carrier
$x(t)$ = input signal
n_a = modulation index ≤ 1
Ratio of amplitude of input signal to carrier

Frequency Modulation (FM)



The modulated carrier signal $s(t)$ is:

$$s(t) = A\cos\left((2\pi f_c t + 2\pi f_\Delta \int_{t_0}^{t} x(\tau)d\tau + \theta_0 \right)$$

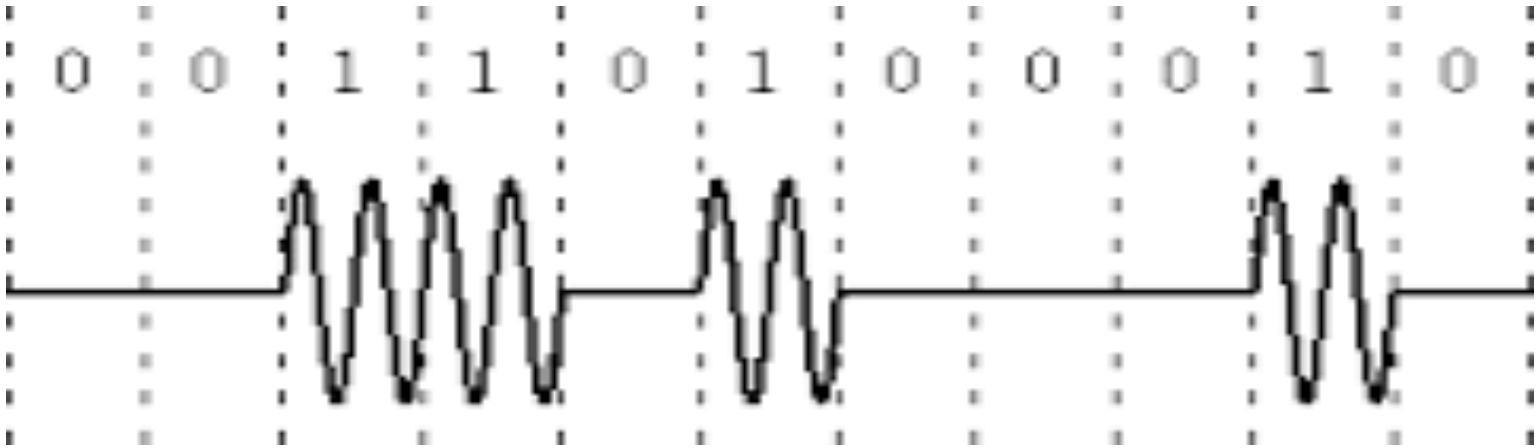
Where f_Δ is the peak frequency deviation from the original frequency and $f_\Delta << f_c$

Amplitude Shift Keying

- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

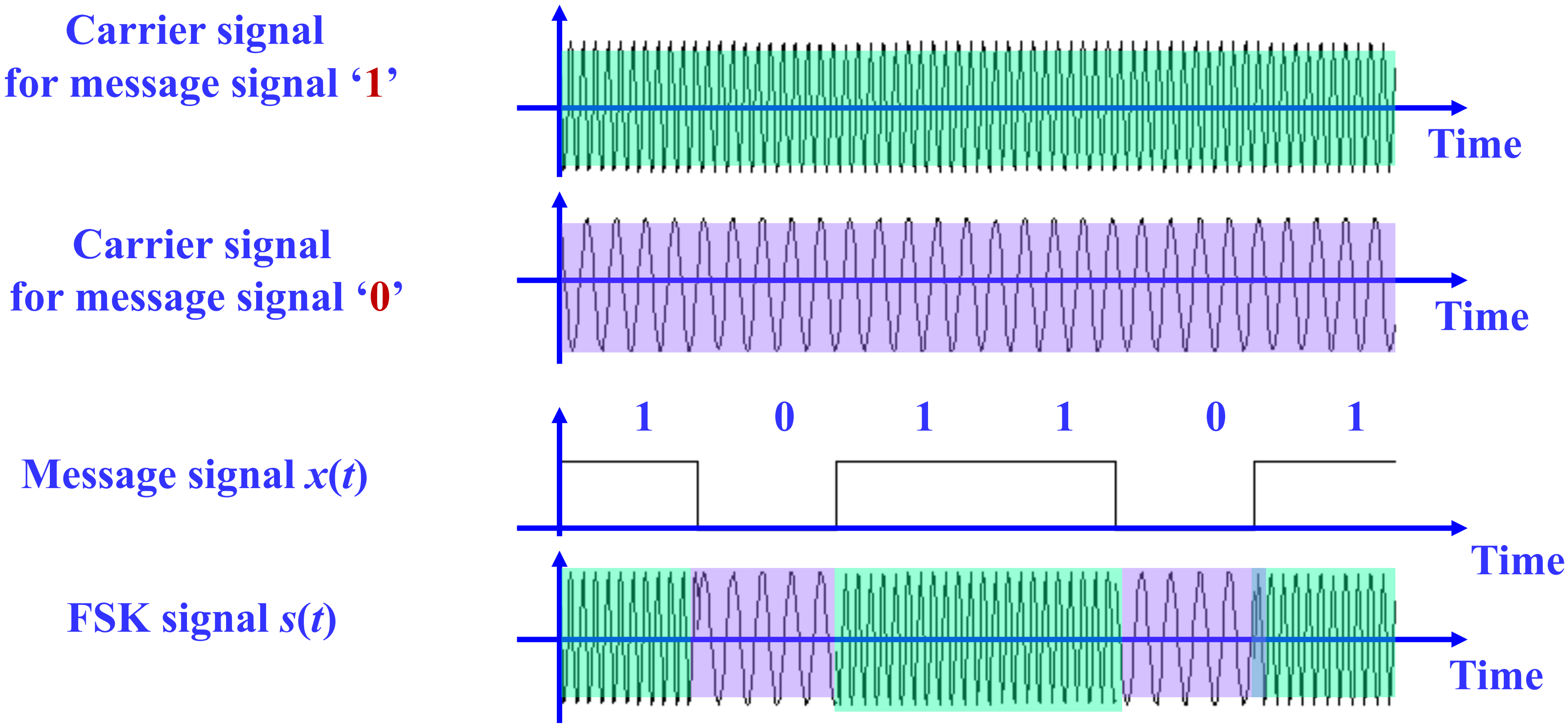
$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ 0 & \text{binary } 0 \end{cases}$$

  - where the carrier signal is $A\cos(2\pi f_c t)$



Frequency Shift Keying (FSK)

1/0 represented by two different frequencies



Binary Frequency-Shift Keying (BFSK)

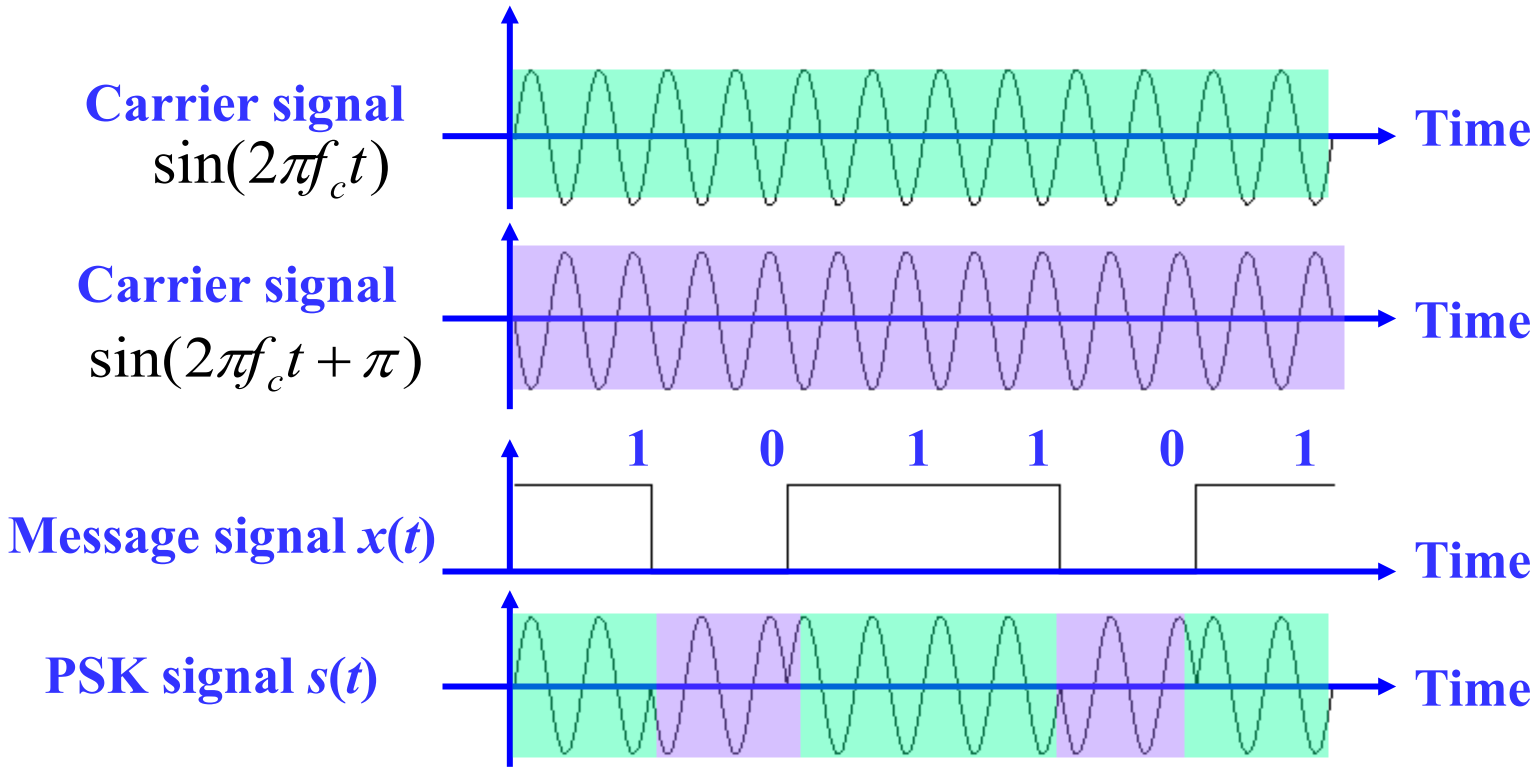
- **Two binary digits represented by two different frequencies near the carrier frequency**

$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary } 1 \\ A\cos(2\pi f_2 t) & \text{binary } 0 \end{cases}$$

- **where f_1 and f_2 are offset from carrier frequency f_c by equal but opposite amounts**

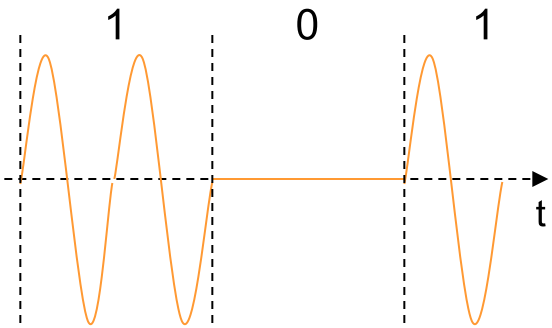
Phase Shift Keying (PSK)

- Use alternative sine wave phases to encode bits

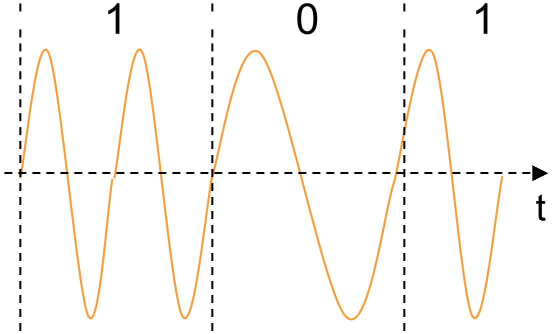


Digital modulation

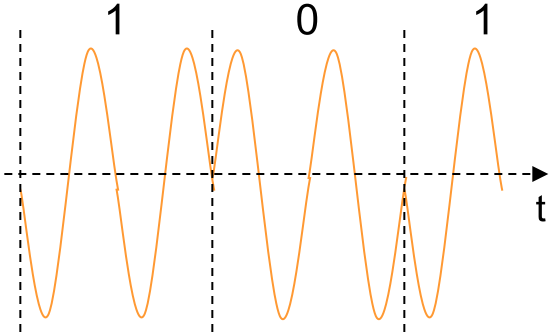
- Modulation of digital signals known as Shift Keying
- Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference
  - Optical fiber



- Frequency Shift Keying (FSK):
  - needs larger bandwidth



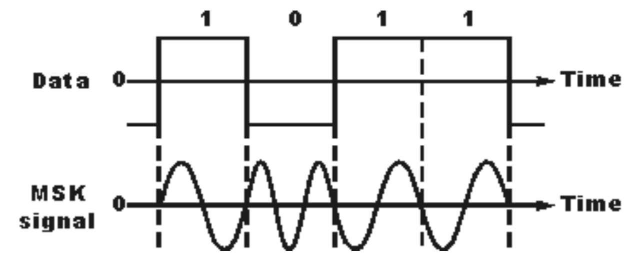
- Phase Shift Keying (PSK):
  - more complex
  - robust against interference



Minimum Shift Keying (MSK)

- A form of FSK known as continuous-phase FSK (CPFSK), in which the phase is continuous during the transition from one bit time to the next.

$$s(t)=\begin{cases} A\cos(2\pi f_1 t+\theta(0)) & \text{binary } 1 \\ A\cos(2\pi f_2 t+\theta(0)) & \text{binary } 0 \end{cases}$$



- For MSK, the two frequencies satisfy the following equations:

$$f_1 = f_c - \frac{1}{4T_b} \qquad f_2 = f_c + \frac{1}{4T_b}$$

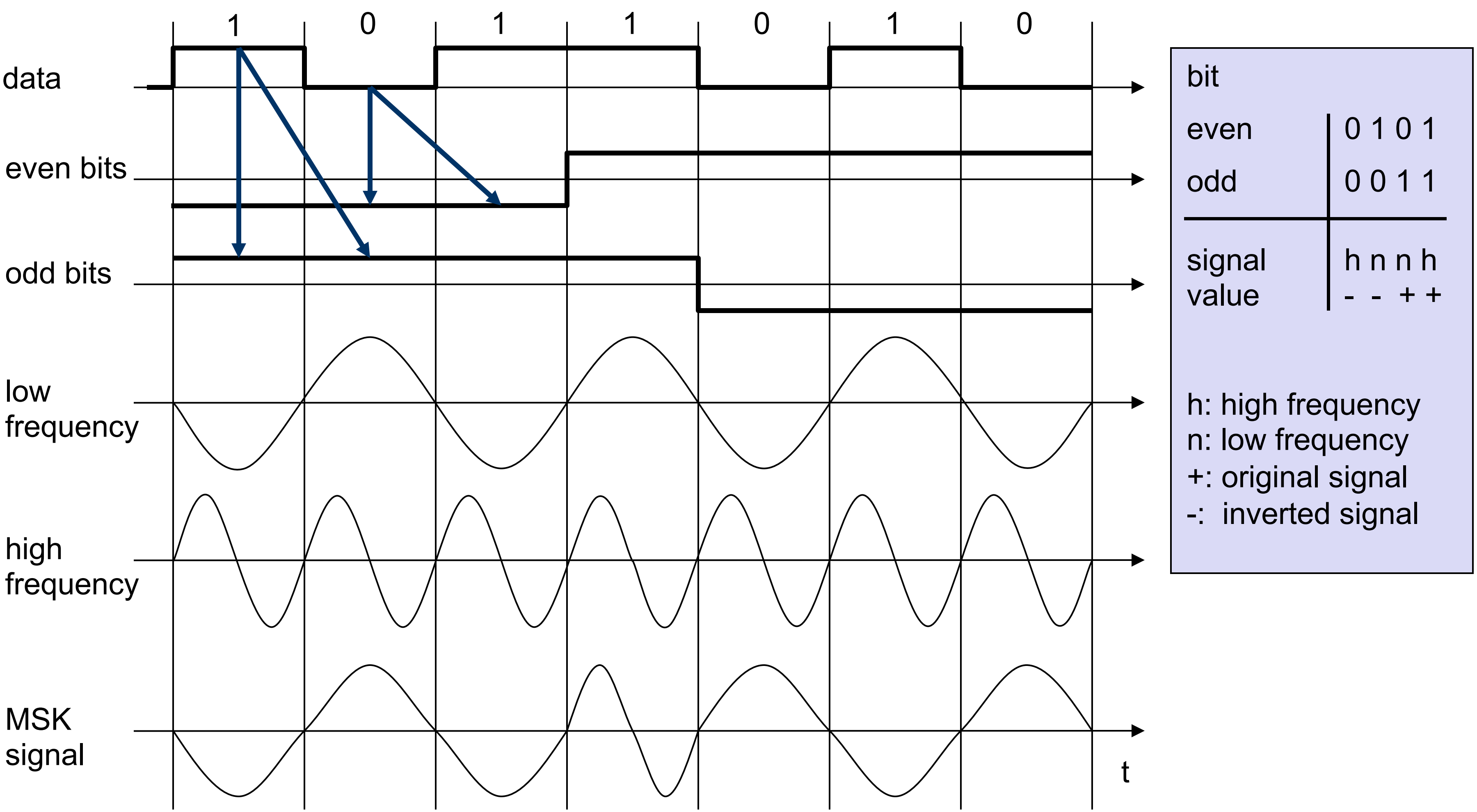
- This spacing between the two frequencies is the minimum that can be used and permit successful detection of the signal at the receiver. This is the reason for the term *minimum* in MSK.
- Provides superior bandwidth efficiency to BFSK with only a modest decrease in error performance.
- Used in some mobile commutation systems.

Minimum Shift Keying (MSK)

- special pre-computation avoids sudden phase shifts
  ➔ MSK (Minimum Shift Keying)
  - bit separated into even and odd bits, the duration of each bit is doubled
  - depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
  - the frequency of one carrier is twice the frequency of the other
  - Equivalent to offset QPSK

- even higher bandwidth efficiency using a Gaussian low-pass filter ➔ GMSK (Gaussian MSK), used in GSM

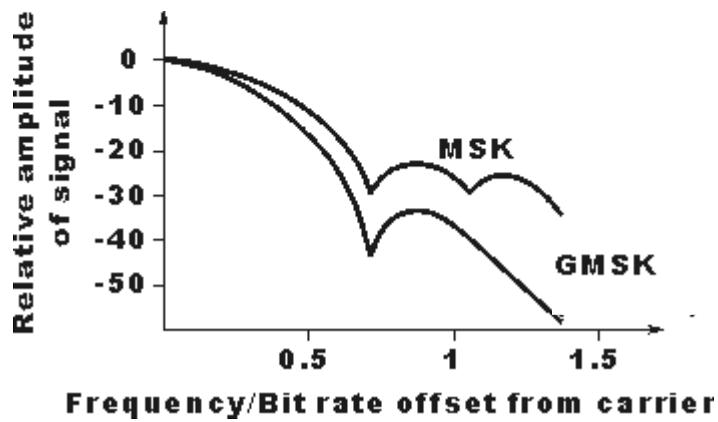
Example of MSK



No phase shifts!

Gaussian Minimum Shift Keying (GMSK)

- The spectrum of an MSK signal has sidebands extending beyond a bandwidth equals to the data rate
- This can be reduced by passing the modulating signal through a low pass filter prior to applying it to the carrier.
  - Gaussian filter
  - Its impulse response should show no overshoot with sharp cut-off



- Reduces out-of-band interference between signal carriers in adjacent frequency channels
- Used in the GSM cellular technology

Quadrature Phase Shift Keying (QPSK)

✓ Four different phase shifts used are:

$$\begin{cases} \phi_{0,0} = 0 \\ \phi_{0,1} = \pi / 2 \\ \phi_{1,0} = \pi \\ \phi_{1,1} = 3\pi / 2 \end{cases} \quad \text{or} \quad \begin{cases} \phi_{0,0} = \pi / 4 \\ \phi_{0,1} = 3\pi / 4 \\ \phi_{1,0} = -3\pi / 4 \\ \phi_{1,1} = -\pi / 4 \end{cases}$$

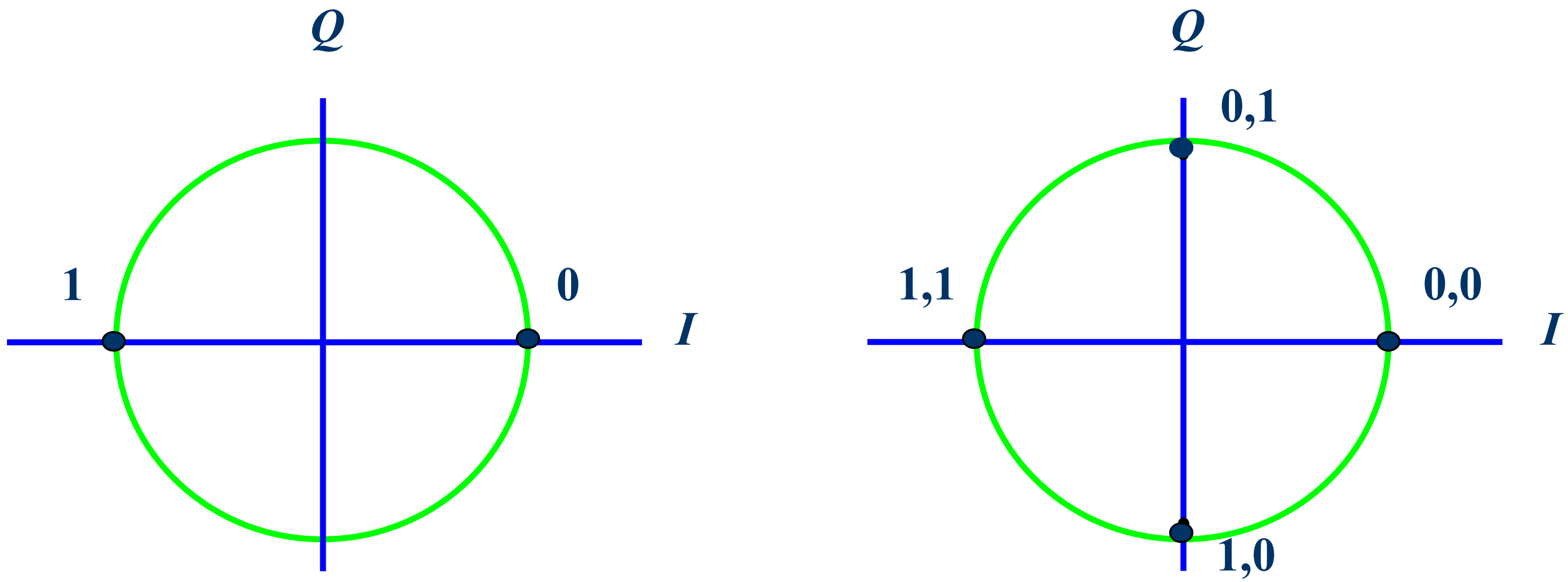
I (in-phase) and Q (quadrature) modulation used

Phase-Shift Keying (PSK)

- **Four-level PSK (QPSK)**
  - **Each element represents more than one bit**

$$
s(t) = \begin{cases}
A\cos\left(2\pi f_c t + \dfrac{\pi}{4}\right) & 11 \\
A\cos\left(2\pi f_c t + \dfrac{3\pi}{4}\right) & 01 \\
A\cos\left(2\pi f_c t - \dfrac{3\pi}{4}\right) & 00 \\
A\cos\left(2\pi f_c t - \dfrac{\pi}{4}\right) & 10
\end{cases}
$$

QPSK Signal Constellation



(a) BPSK

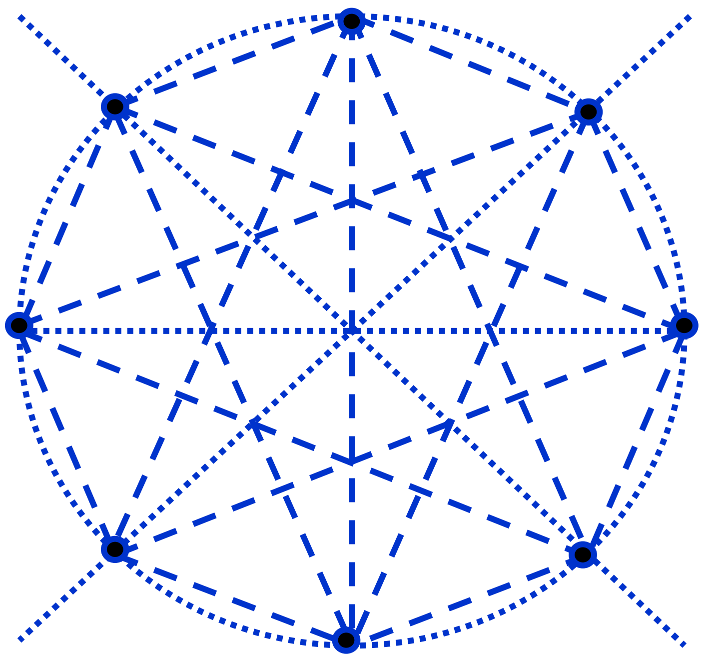
(Binary Phase Shift Keying)

(b) QPSK

(Quadrature Phase Shift Keying)

π/4 QPSK

- ✓ **The phase of the carrier is:** $\theta_k = \theta_{k-1} + \phi_k$
- ✓ **where θ_k is carrier phase shift corresponding to input bit pairs.**
- ✓ **If θ_0=0, input bit stream is [1011], then:**



All possible states in π/4 QPSK

Quadrature Amplitude Modulation (QAM)

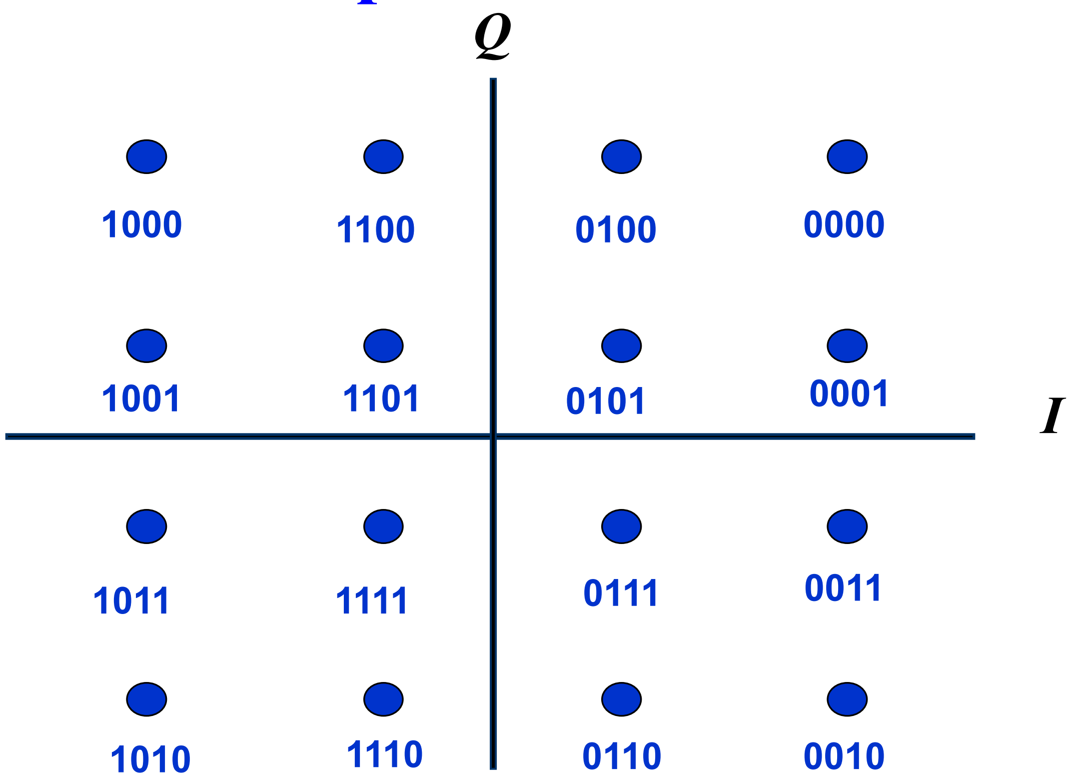
Combination of AM and PSK: modulate signals using two measures of amplitude and four possible phase shifts

A representative QAM Table

Bit sequence represented	Amplitude	Phase shift
000	1	0
001	2	0
010	1	$\pi/2$
011	2	$\pi/2$
100	1	π
101	2	π
110	1	$3\pi/2$
111	2	$3\pi/2$

Quadrature Amplitude Modulation (QAM)

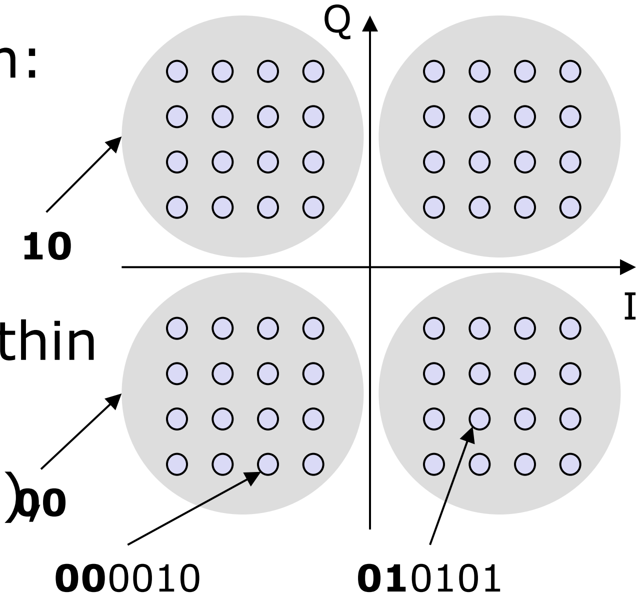
✓ **Two carriers out of phase by 90 degrees are amplitude modulated**



Rectangular constellation of 16QAM

Hierarchical Modulation

- Multi carrier system, about 2000 or 8000 carriers
- QPSK, 16 QAM, 64QAM
- Example: 64QAM
  - good reception: resolve the entire 64QAM constellation
  - poor reception, mobile reception: resolve only QPSK portion
  - 6 bit per QAM symbol, 2 most significant determine QPSK
  - High Priority (HP) embedded within a Low Priority (LP) stream
  - HP service coded in QPSK (2 bit), LP uses remaining 4 bit



Comparison of Modulation Types

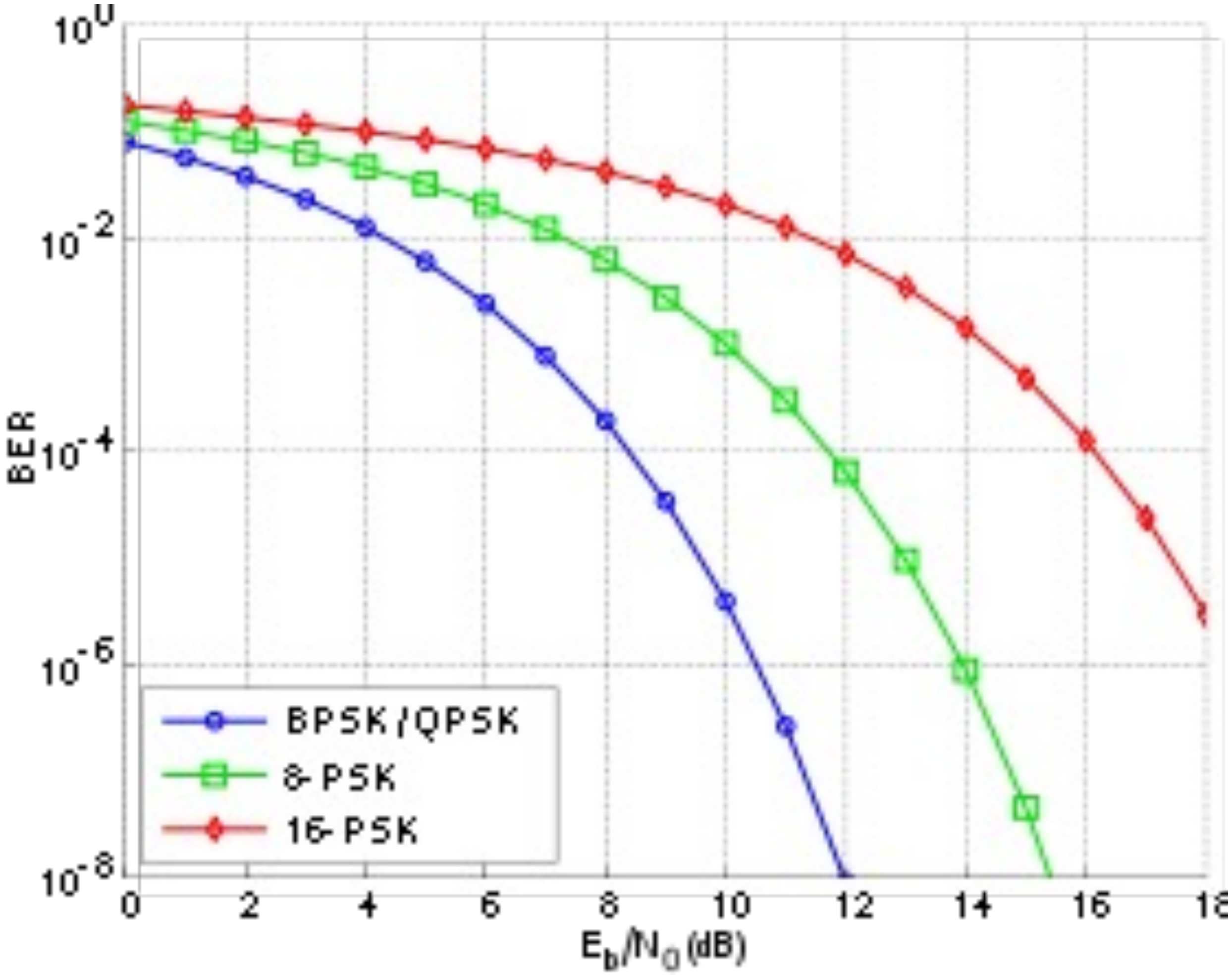
Modulation Format	Bandwidth efficiency C/B	Log2(C/B)	Error-free Eb/N0
16 PSK	4	2	18dB
16 QAM	4	2	15dB
8 PSK	3	1.6	14.5dB
4 PSK	2	1	10dB
4 QAM	2	1	10dB
BFSK	1	0	13dB
BPSK	1	0	10.5dB

$$\frac{E_b}{N_0} = \frac{S/R}{N_0}$$

- Ratio of signal energy per bit to noise power density per Hertz

S: Signal Power R: Bit Rate, $R = 1/T_b$

Comparison of Modulation Types



Bit-error rate (BER) vs E_b/N_0 curves for different digital modulation methods is a common application example of E_b/N_0. Here an AWGN channel is assumed.

Practical Applications

- BPSK:
  - WLAN IEEE802.11b (1 Mbps)
- QPSK:
  - WLAN IEEE802.11b (2 Mbps, 5.5 Mbps, 11 Mbps)
  - 3G WDMA
  - DVB-T (with OFDM)
- QAM
  - Telephone modem (16QAM)
  - Downstream of Cable modem (64QAM, 256QAM)
  - WLAN IEEE802.11a/g (16QAM for 24Mbps, 36Mbps; 64QAM for 38Mbps and 54 Mbps)
  - LTE Cellular Systems
- FSK:
  - Cordless telephone
  - Paging system

Multiplexing & Spread Spectrum Technology

Multiplexing

- In telecommunications and computer networks, **multiplexing** (also known as **muxing**) is a process where multiple analog message signals or digital data streams are combined into one signal over a shared medium. The aim is to share an expensive resource. For example, in telecommunications, several phone calls may be transferred using one wire.

- The multiplexed signal is transmitted over a communication channel, which may be a physical transmission medium. The multiplexing divides the capacity of the low-level communication channel into several higher-level logical channels, one for each message signal or data stream to be transferred.

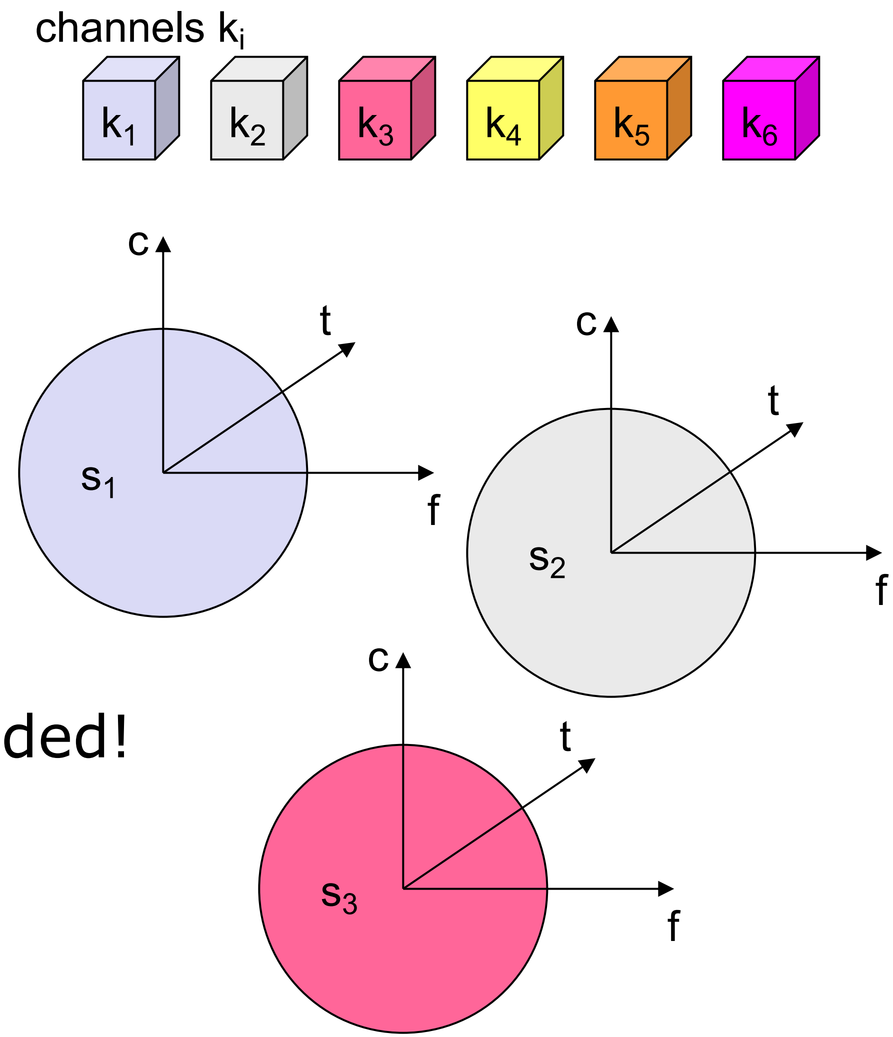
- A device that performs the multiplexing is called a multiplexer (MUX)

Multiplexing

- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)

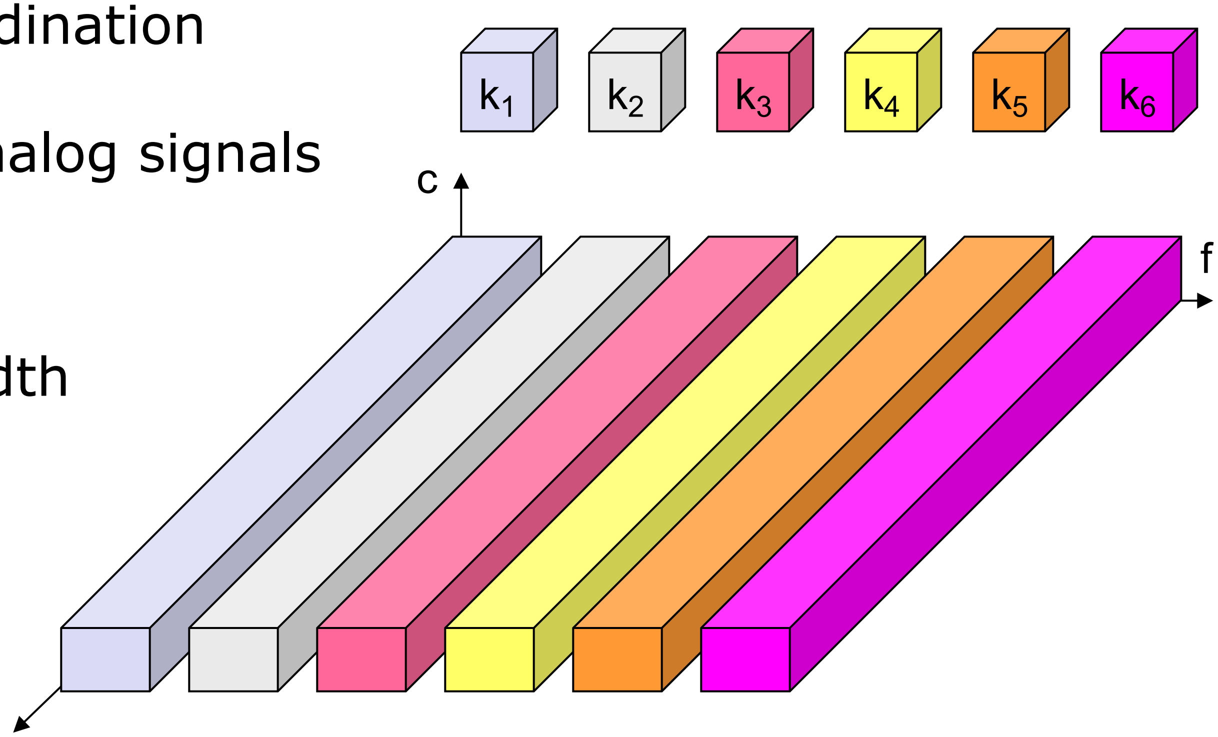
- Goal: multiple use of a shared medium

- Important: guard spaces needed!



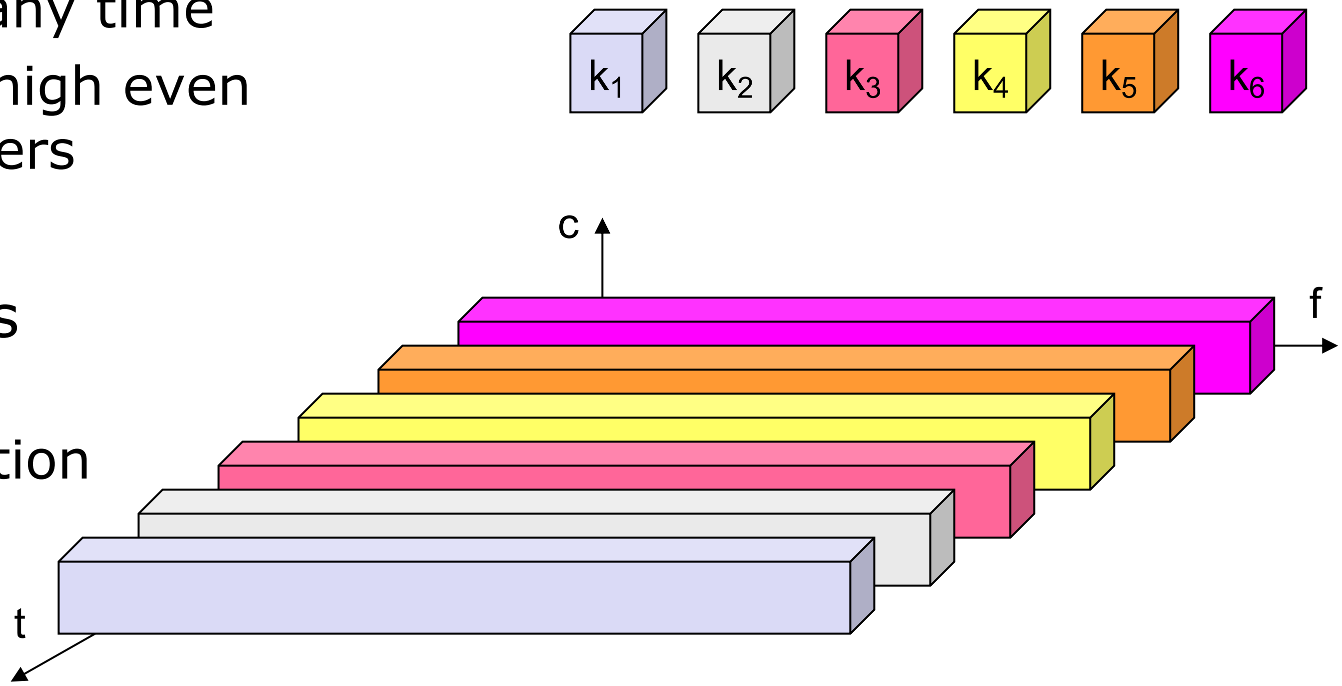
Frequency multiplex

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- Advantages
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible



Time multiplex

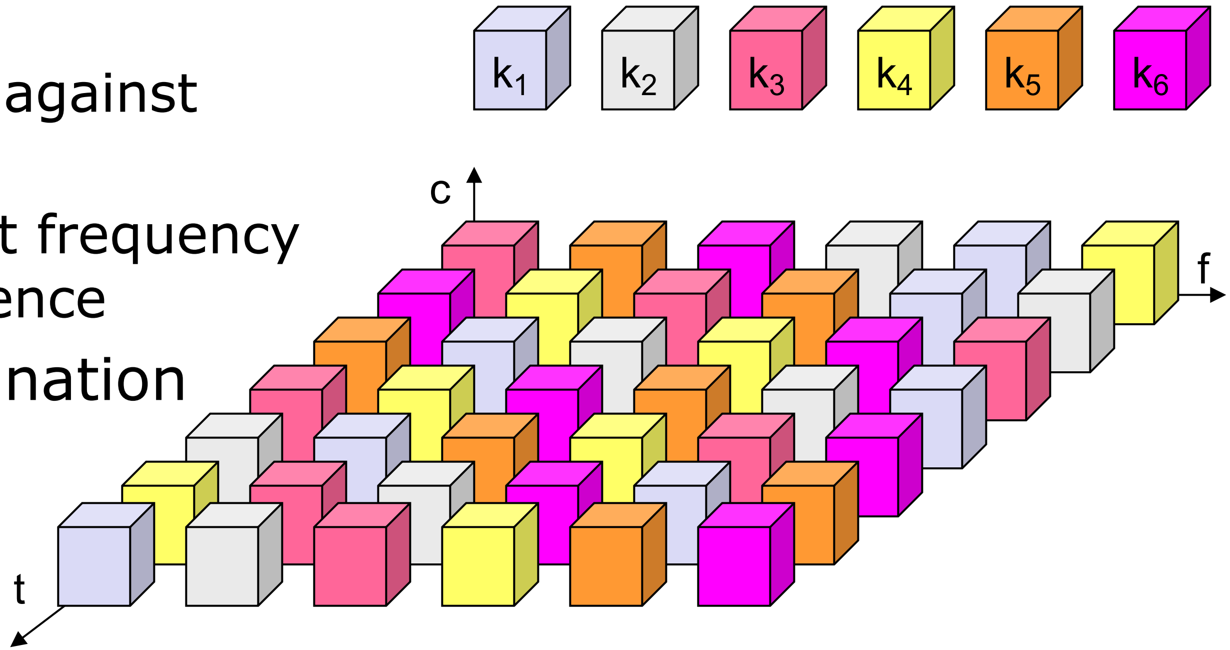
- A channel gets the whole spectrum for a certain amount of time
- Advantages
  - only one carrier in the medium at any time
  - throughput high even for many users
- Disadvantages
  - precise synchronization necessary



Time and frequency multiplex

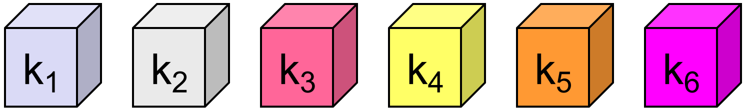
- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
- Example: GSM

- Advantages
  - better protection against tapping
  - protection against frequency selective interference
- but: precise coordination required

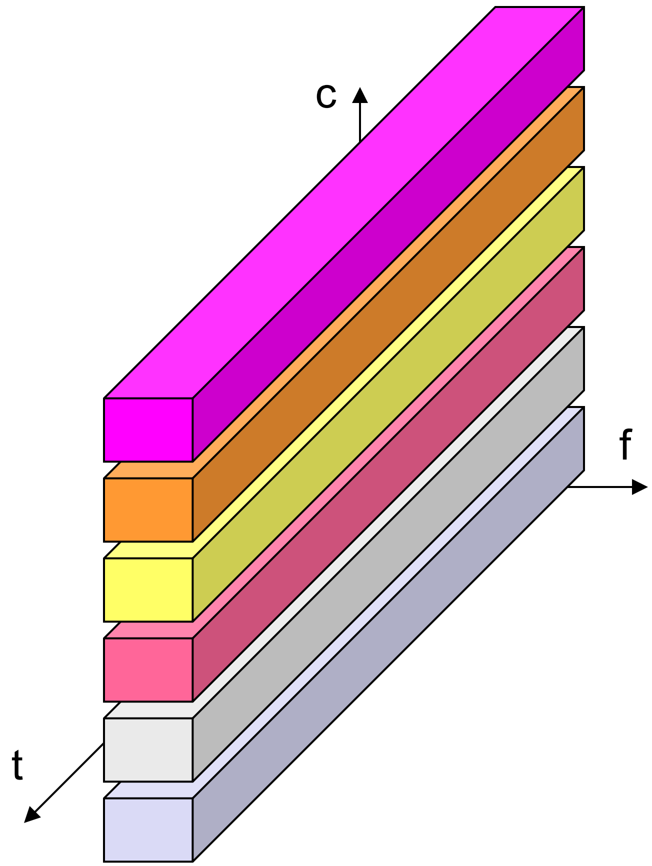


Code multiplex

- Each channel has a unique code

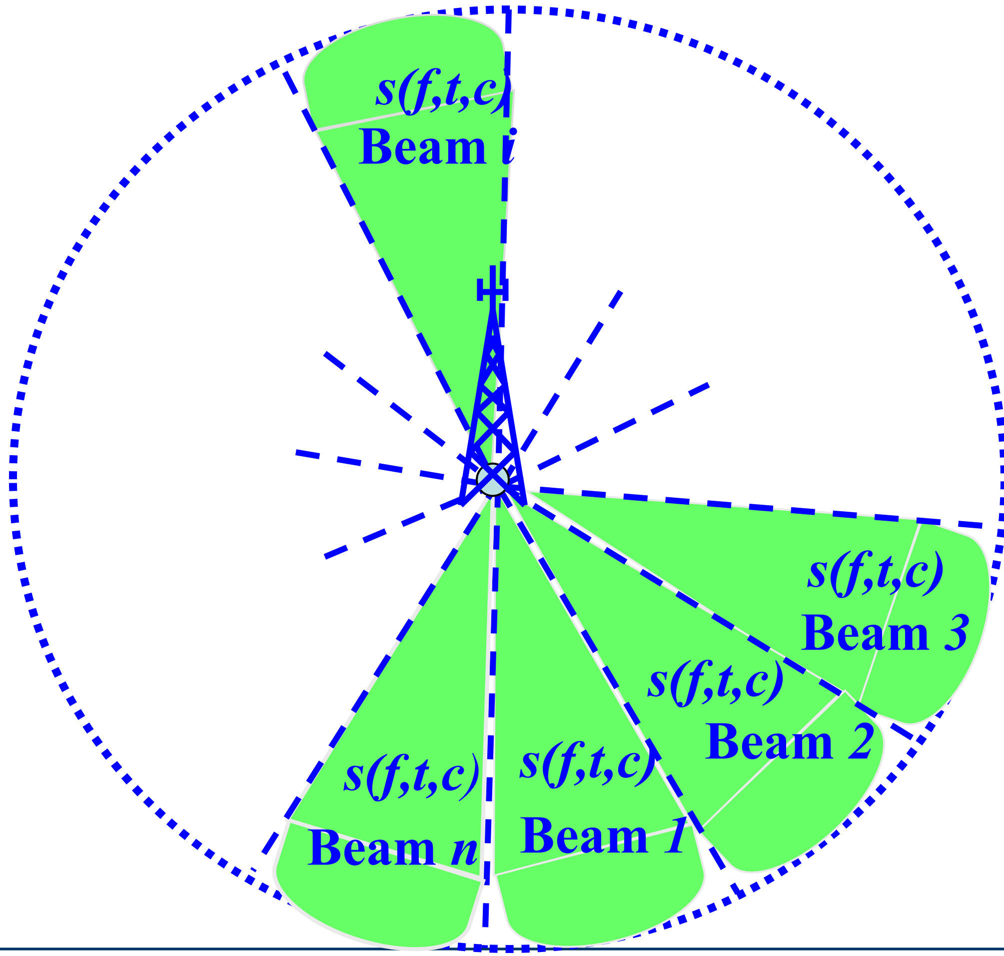


- All channels use the same spectrum at the same time
- Advantages
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages
  - varying user data rates
  - more complex signal regeneration
- Implemented using spread spectrum technology



Space Division Multiple Access (SDMA)

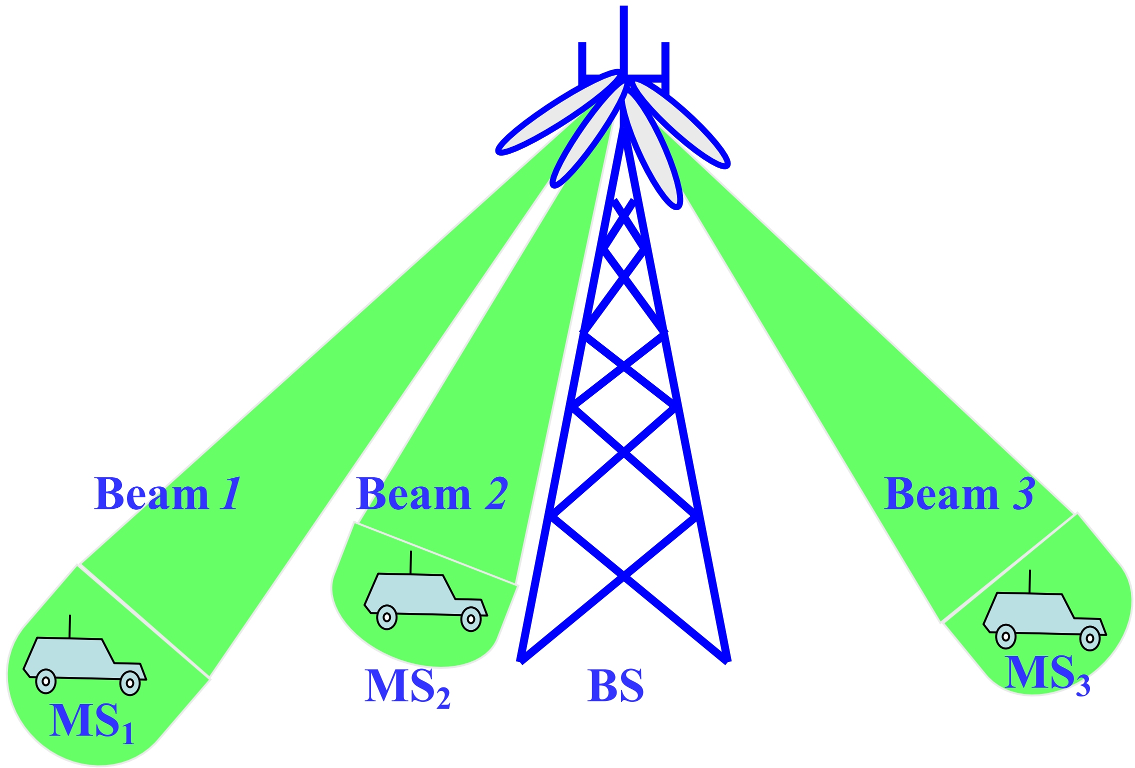
Space divided into spatially separate sectors



The concept of SDMA

Transmission in SDMA

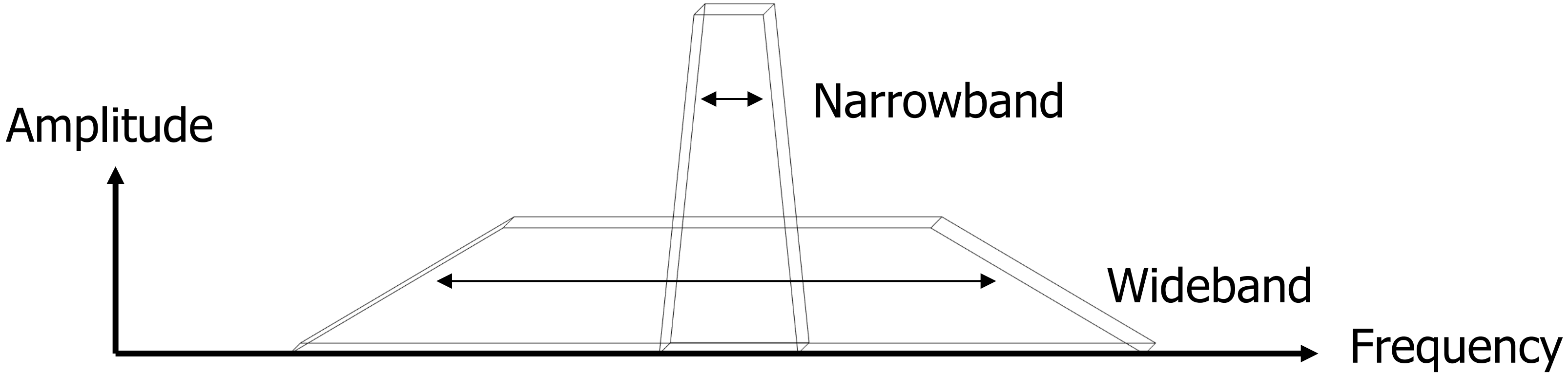
- ✓ Noise and interference for each MS and BS is minimized
- ✓ Enhance the quality of communication link and increase overall system capacity
- ✓ Intra-cell channel reuse can be easily exploited



The basic structure of a SDMA system

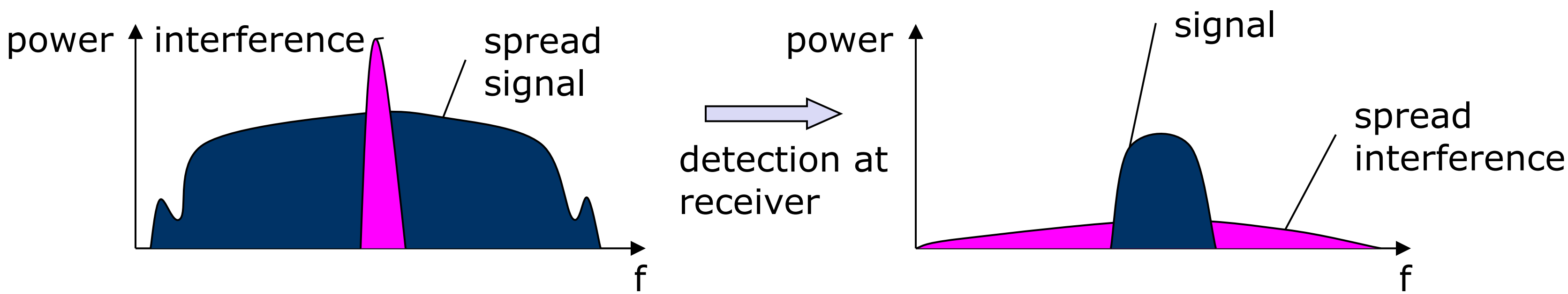
Spread Spectrum Technology

- Spread Spectrum – a telecommunications technique in which a signal is transmitted in a bandwidth considerably greater than the frequency content of the original information.
  - Narrow and Wide Band – a relative comparison of a group or range of frequencies used in a telecommunications system. Narrow Band would describe a small range of frequencies as compared to a larger Wide Band range.



Spread spectrum technology

- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code
  - protection against narrow band interference



- Side effects:
  - coexistence of several signals without dynamic coordination
  - tap-proof
- Alternatives: Direct Sequence, Frequency Hopping

Uses of Spread Spectrum

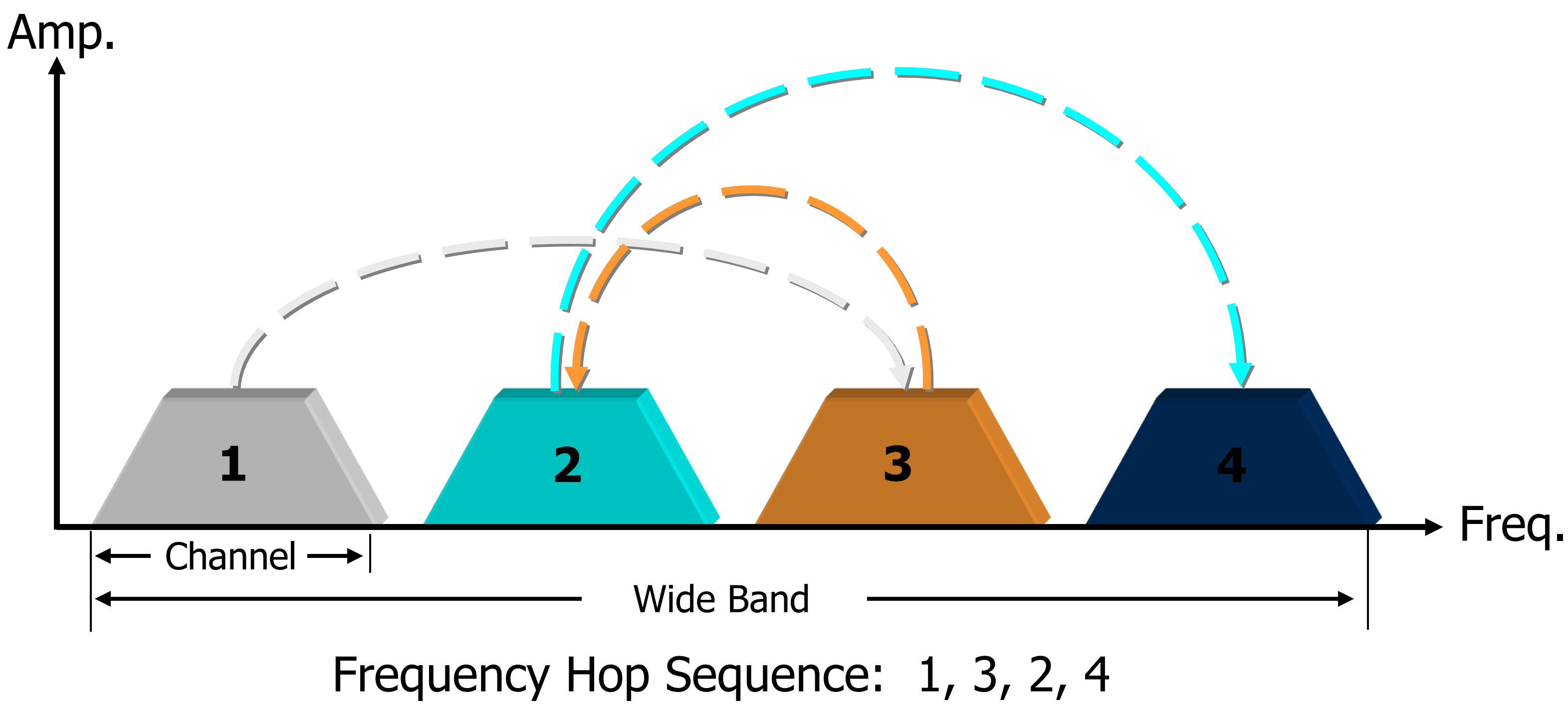
- Military - For low probability of interception of telecommunications.
- Civil/Military - Range and positioning measurements. GPS – satellites.
- Civil Cellular Telephony.
- Civil Wireless Networks – 802.11 and Bluetooth.

4-Types Spread Spectrum

- Time Hopping, (THSS)
- Frequency Hopping, (FHSS)
- Direct Sequence Spread Spectrum, (DSSS)
- Hybrid, DSSS/FHSS

FHSS

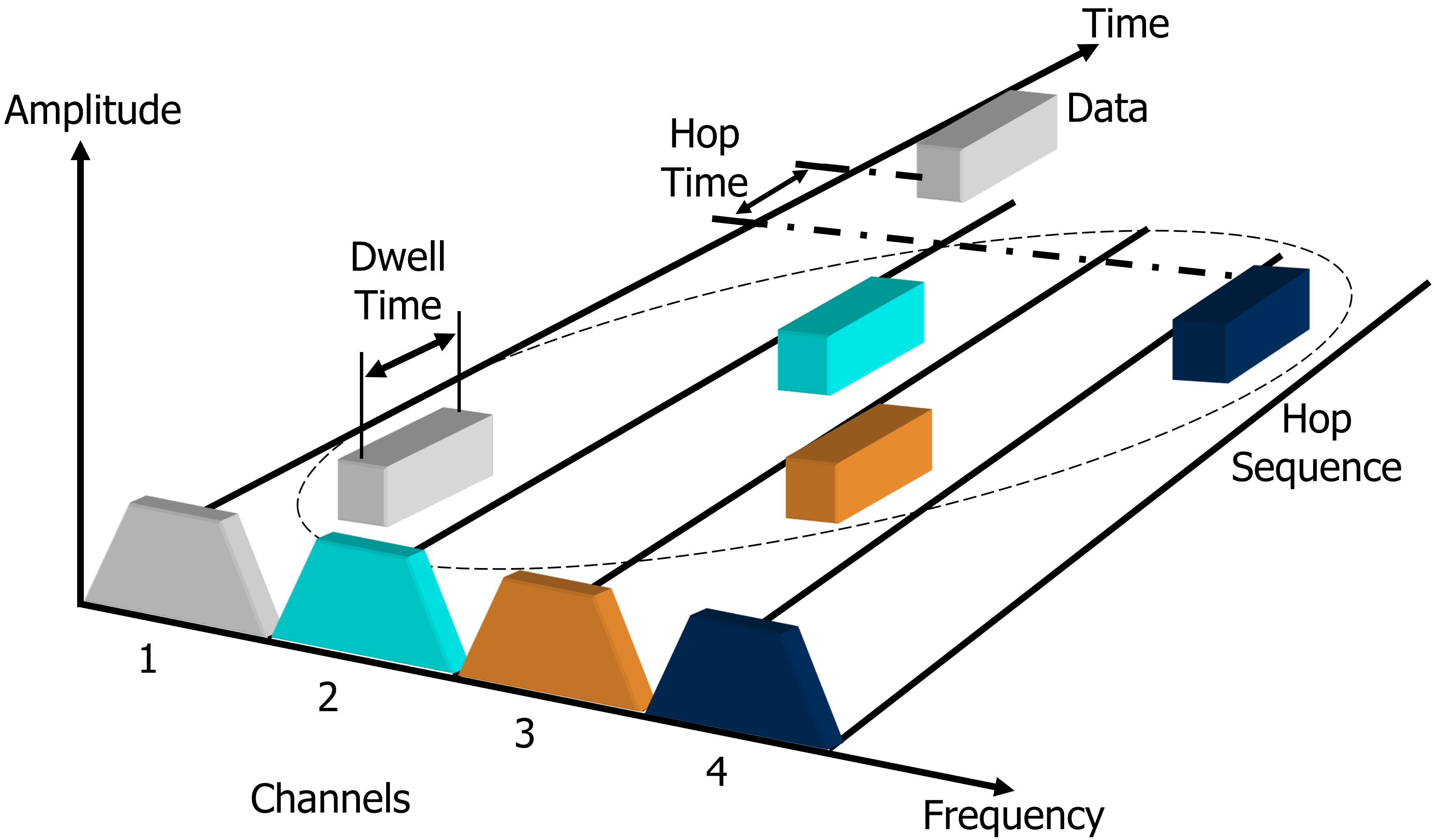
- FHSS - Acronym for ***f**requency-**h**opping **s**pread **s**pectrum.* 802.11, Bluetooth.



FHSS

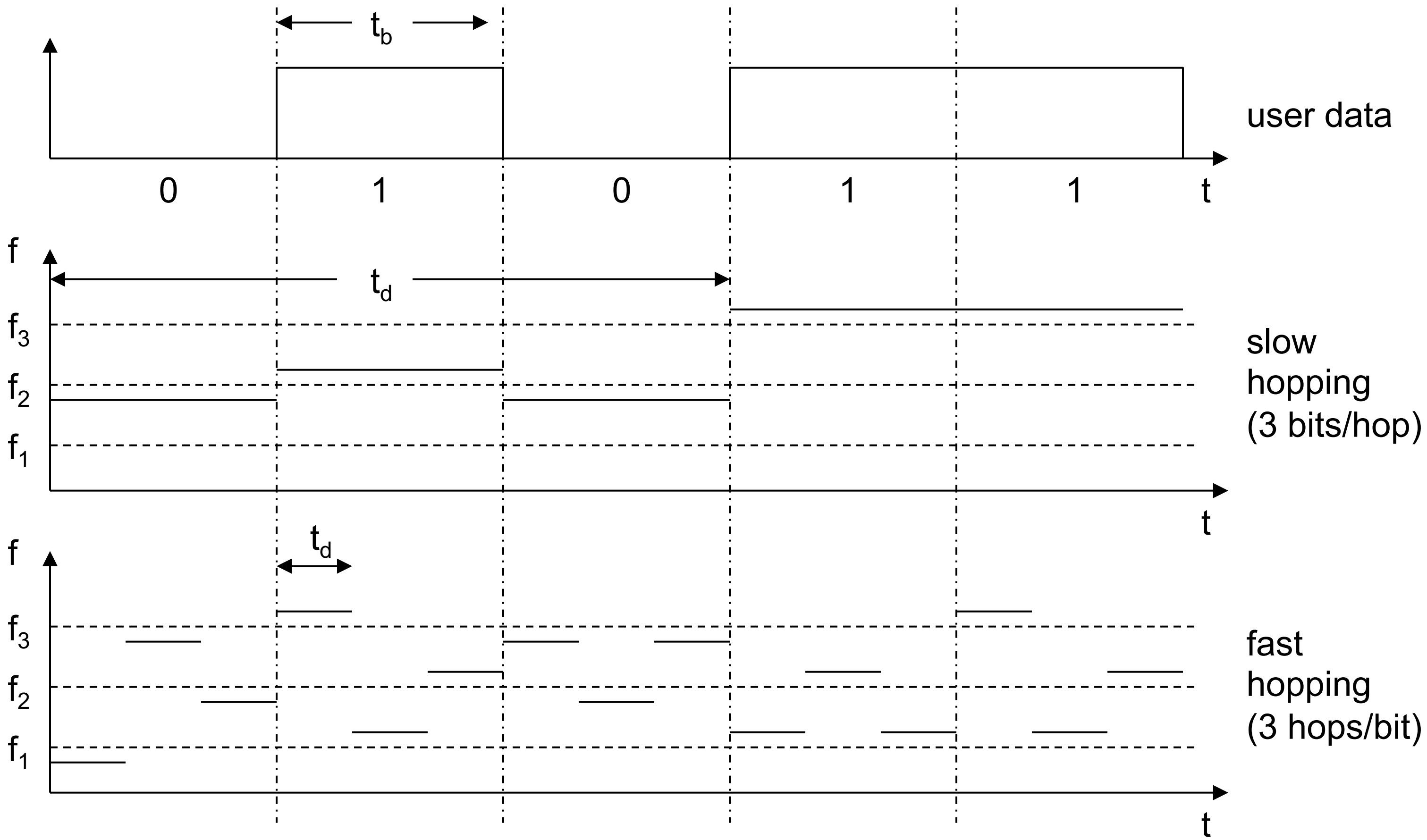
- Discrete changes of carrier frequency
  - sequence of frequency changes determined via pseudo random number sequence
- Two versions
  - Fast Hopping:
    several frequencies per user bit
  - Slow Hopping:
    several user bits per frequency
- Advantages
  - frequency selective fading and interference limited to short period
  - simple implementation
  - uses only small portion of spectrum at any time
- Disadvantages
  - not as robust as DSSS
  - simpler to detect

FHSS Timing



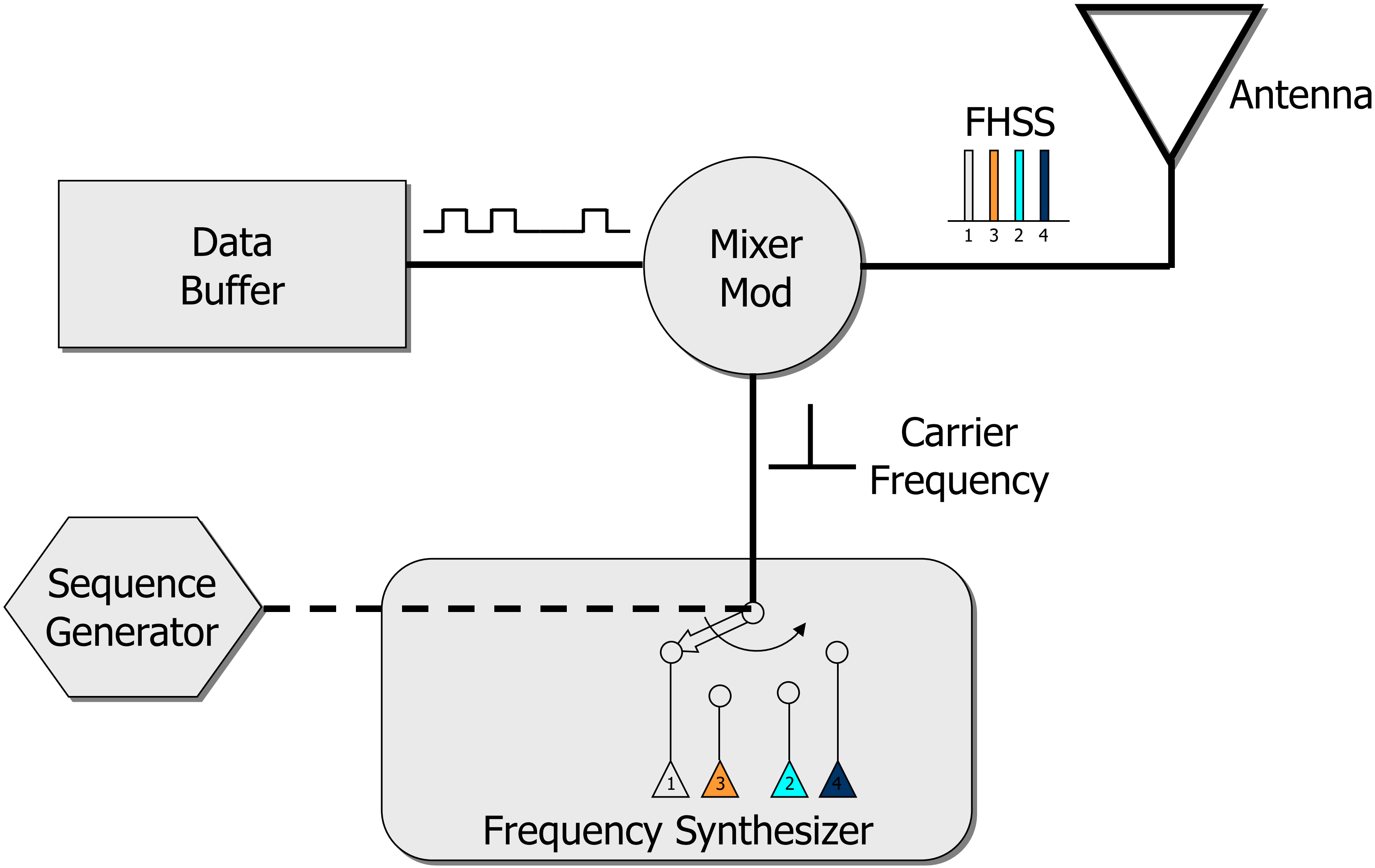
Time
Amplitude
Data
Hop
Time
Dwell
Time
Hop
Sequence
1
2
3
4
Channels
Frequency

FHSS Timing

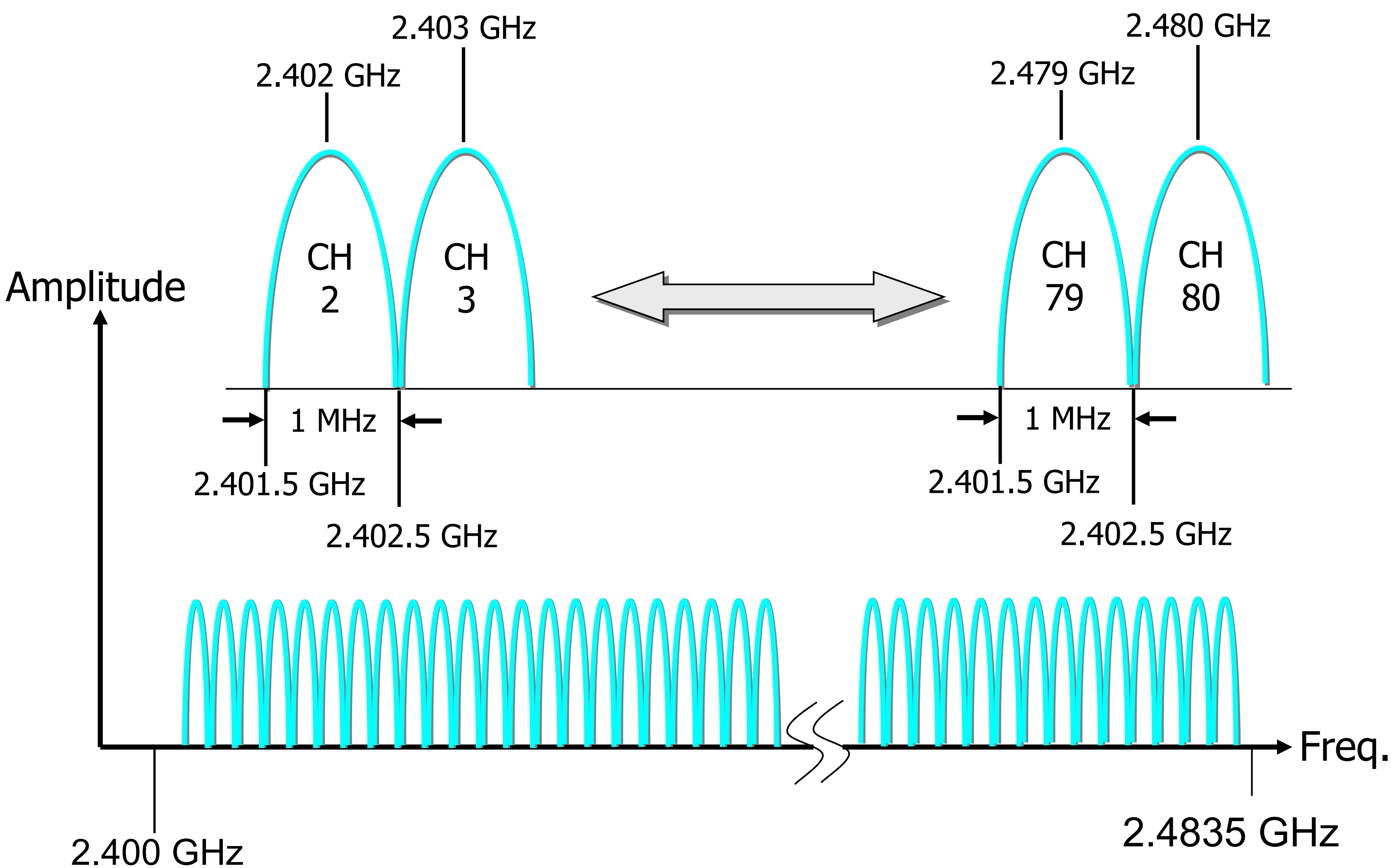


t_b: bit period t_d: dwell time

FHSS System Block Diagram

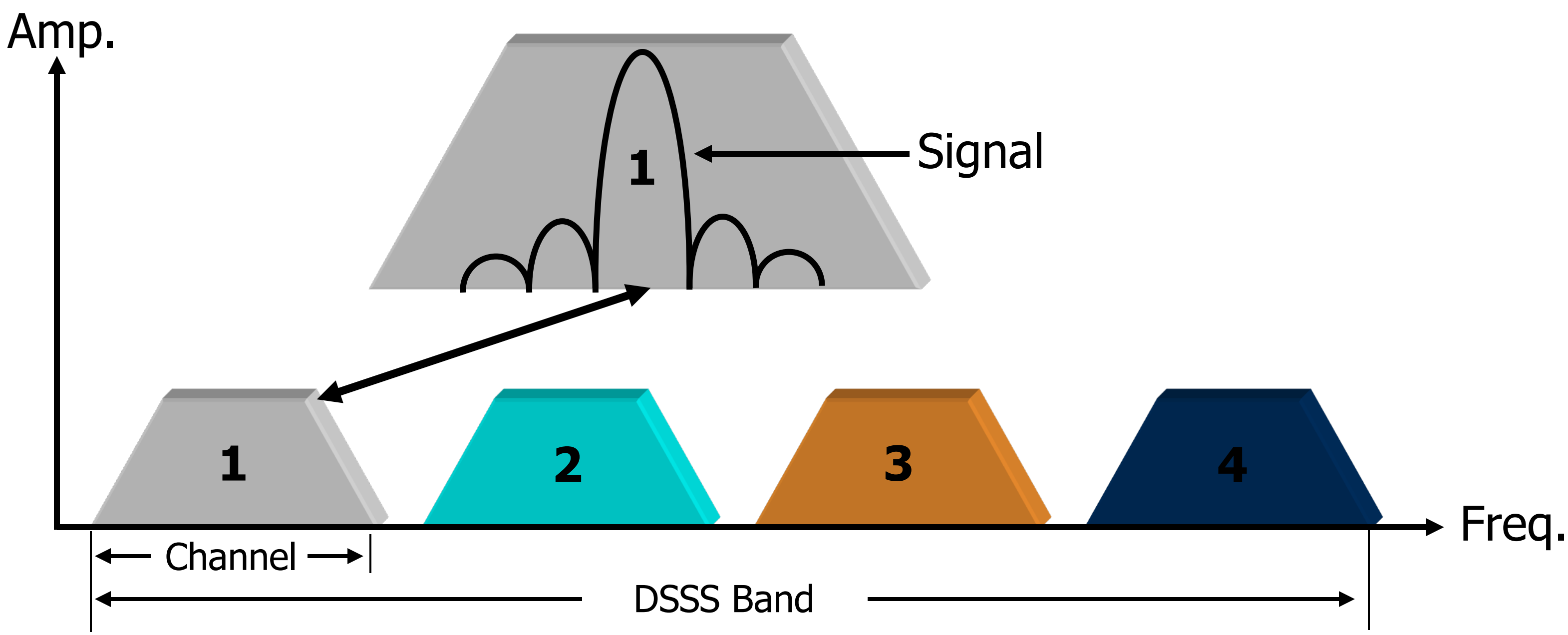


FHSS Channel Allocation in 802.11b



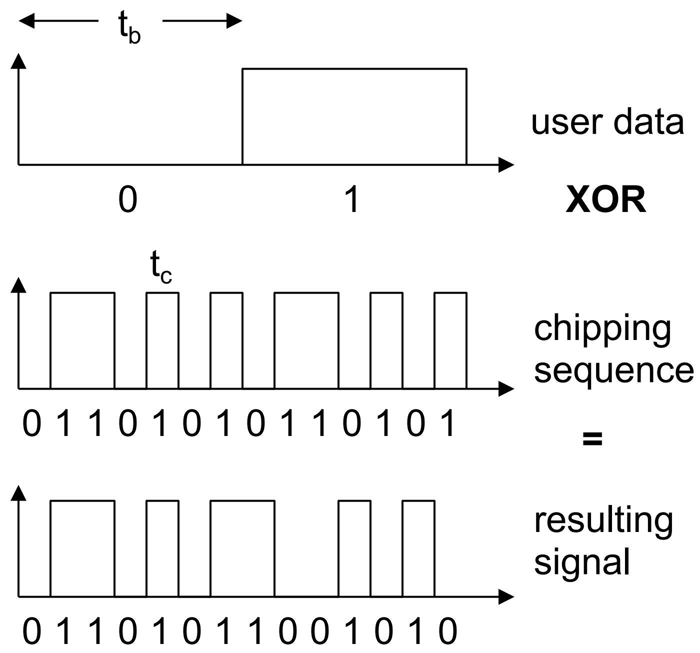
DSSS

- DSSS - Acronym for ***d****irect-****s****equence* ***s****pread* ***s****pectrum.* WLAN, 802.11.



DSSS

- DSSS: XOR of the signal with pseudo-random number (chipping sequence)
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal
- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - base stations can use the same frequency range
    - several base stations can detect and recover the signal
    - soft handover
- Disadvantages
  - precise power control necessary

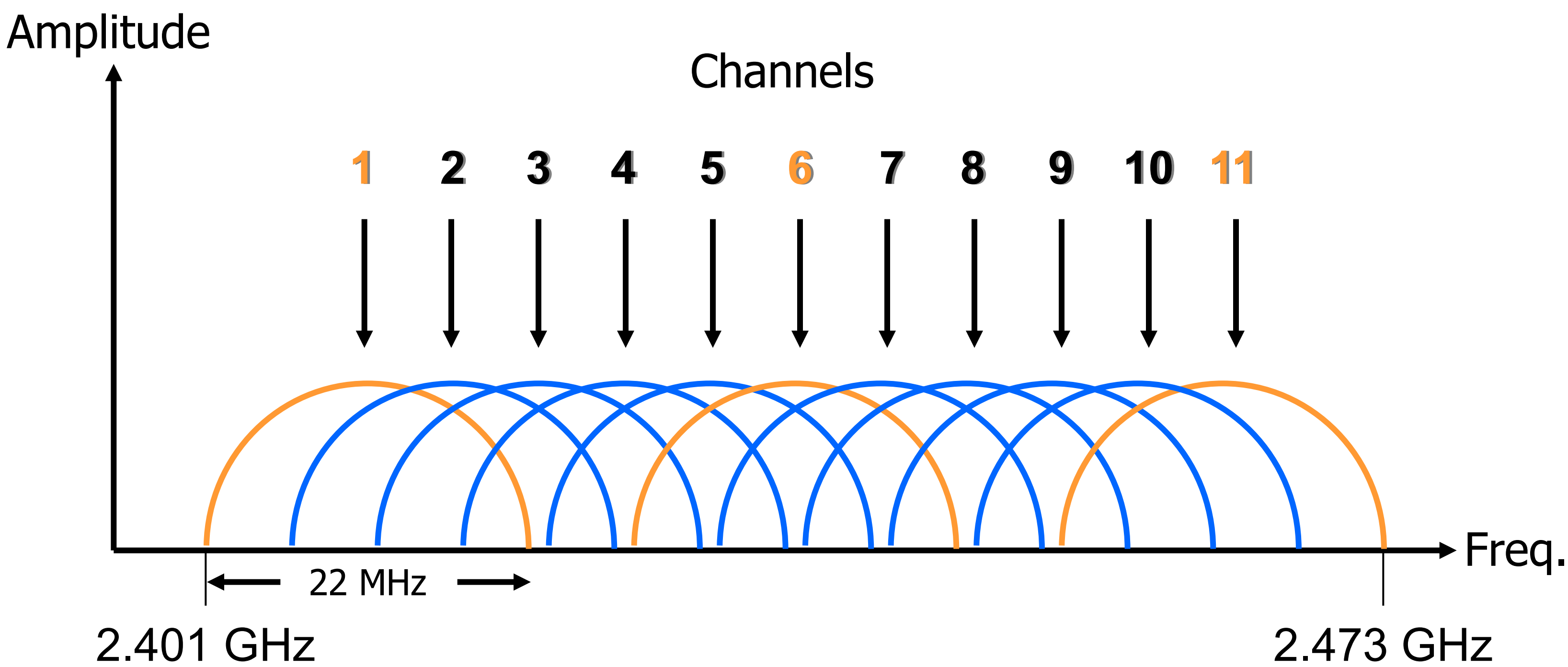


Spreading Factor $s = t_b / t_c$

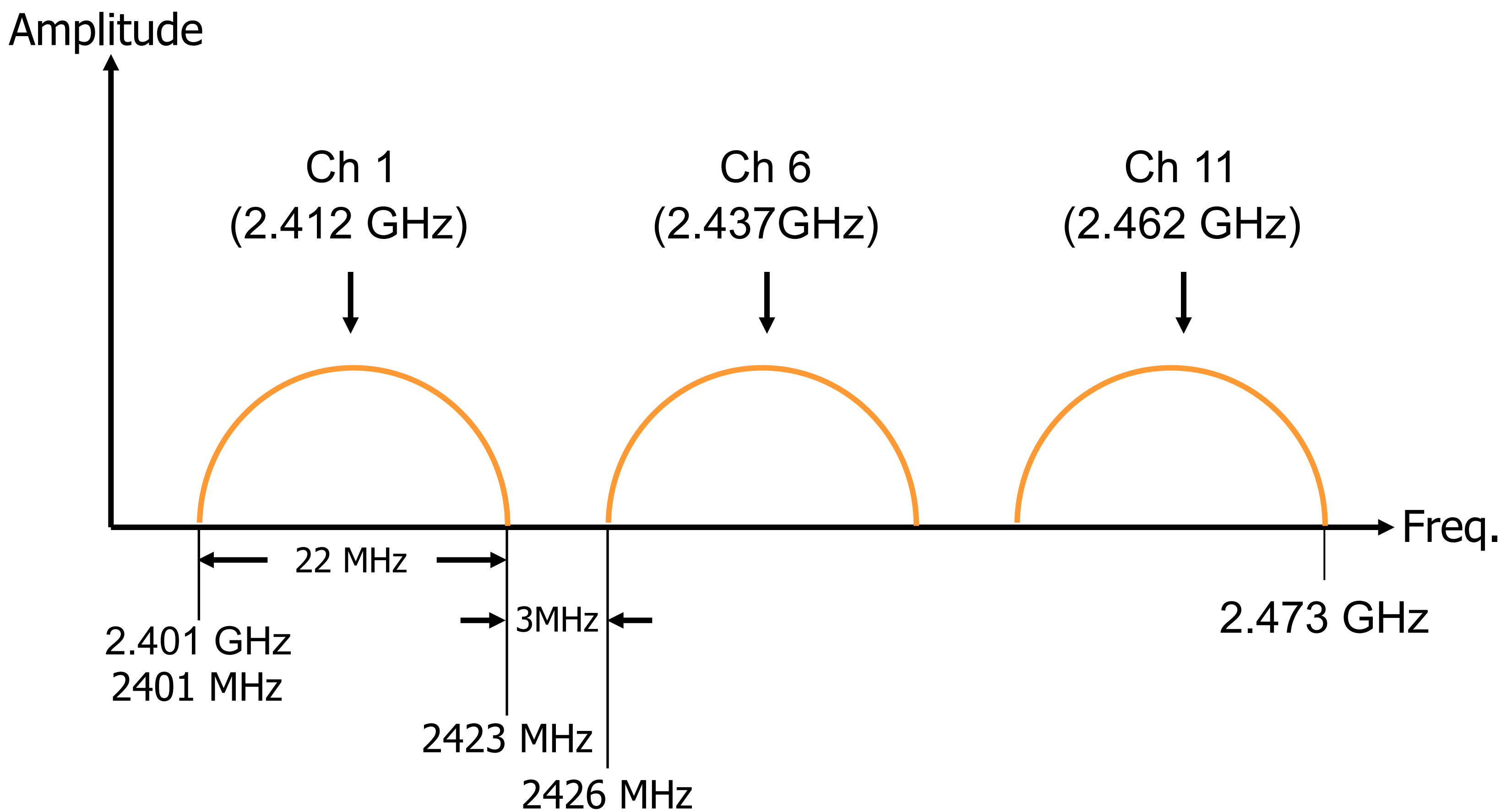
t_b: bit period

t_c: chip period

DSSS USA Channel Allocation in 802.11b



DSSS 3 Non-overlap Channels



Encoding and Modulation

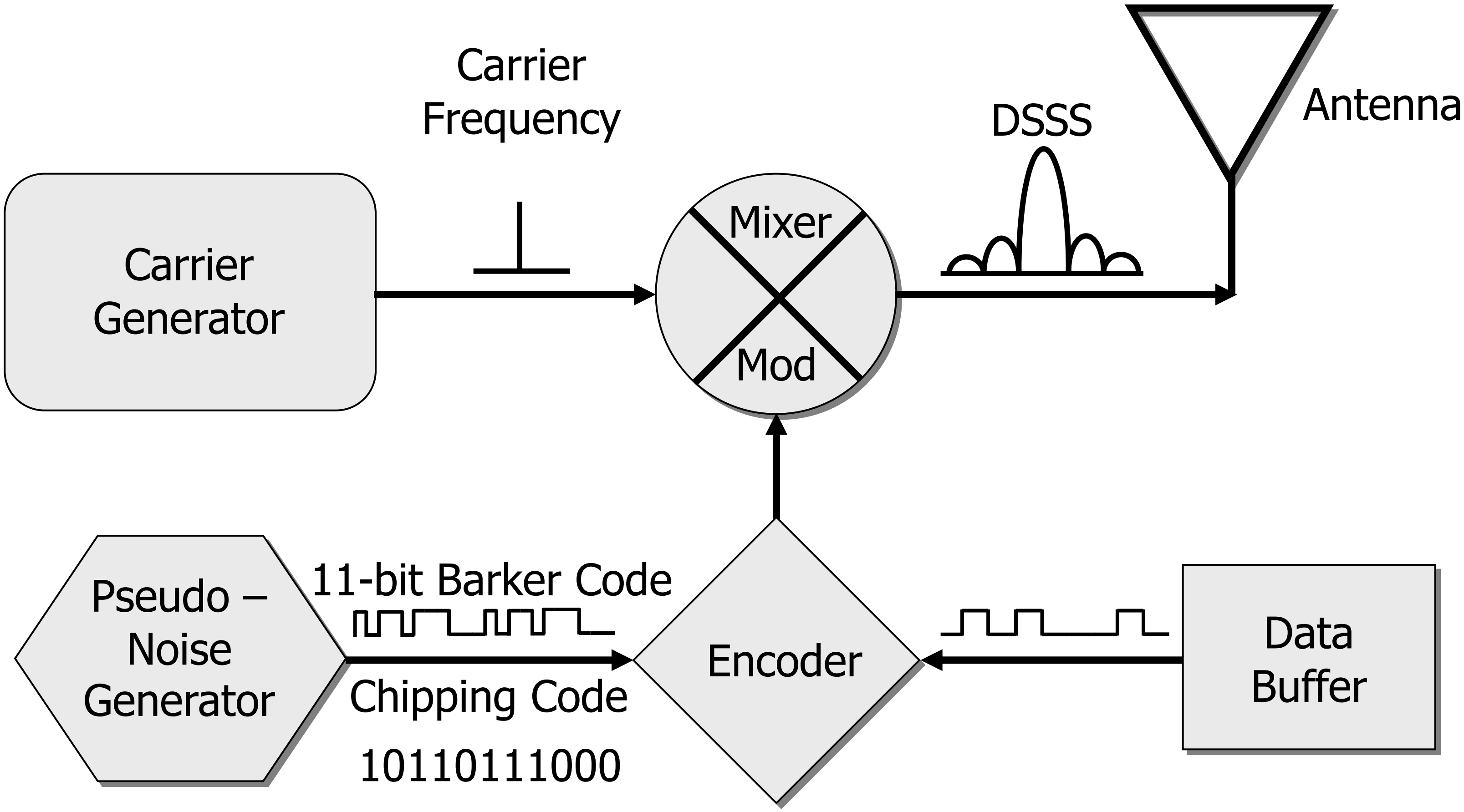
- Encoding - To change or translate one bit stream into another.

  Barker Code, Complementary Code Keying

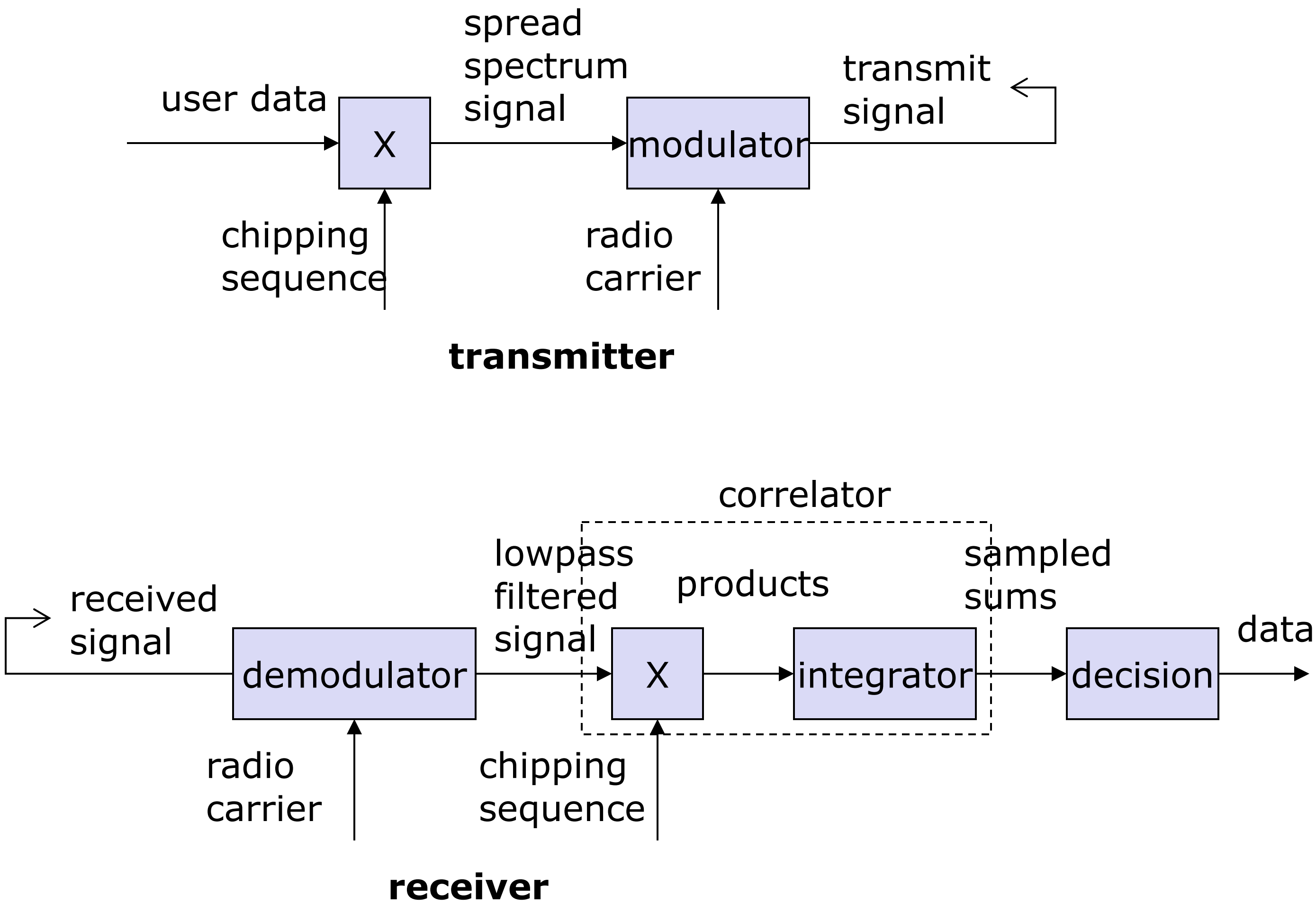
- Modulation – Appling information on a carrier signal by varying one or more of the signal's basic characteristics - frequency, amplitude and phase.

  DBPSK (Differential Binary Phase Shift Keying) DQPSK (Differential Quaternary PSK)

DSSS System Block Diagram



DSSS System Block Diagram



Security

- Neither FHSS or DSSS are inherently secure in and of themselves. Additional schemes must be employed to improve security of wireless technologies. Both systems follow published IEEE standards for intercommunications.

Co-location

- FHSS has many more frequencies / channels then DSSS which only has 3 co-location channels.
- However 3 DSSS access points co-located at 11 Mbps each would result in a maximum throughput of 33 Mbps. It would require 16 access points co-located for FHSS to achieve a throughput of 32 Mbps.

Orthogonal FDM's (OFDM) spread spectrum

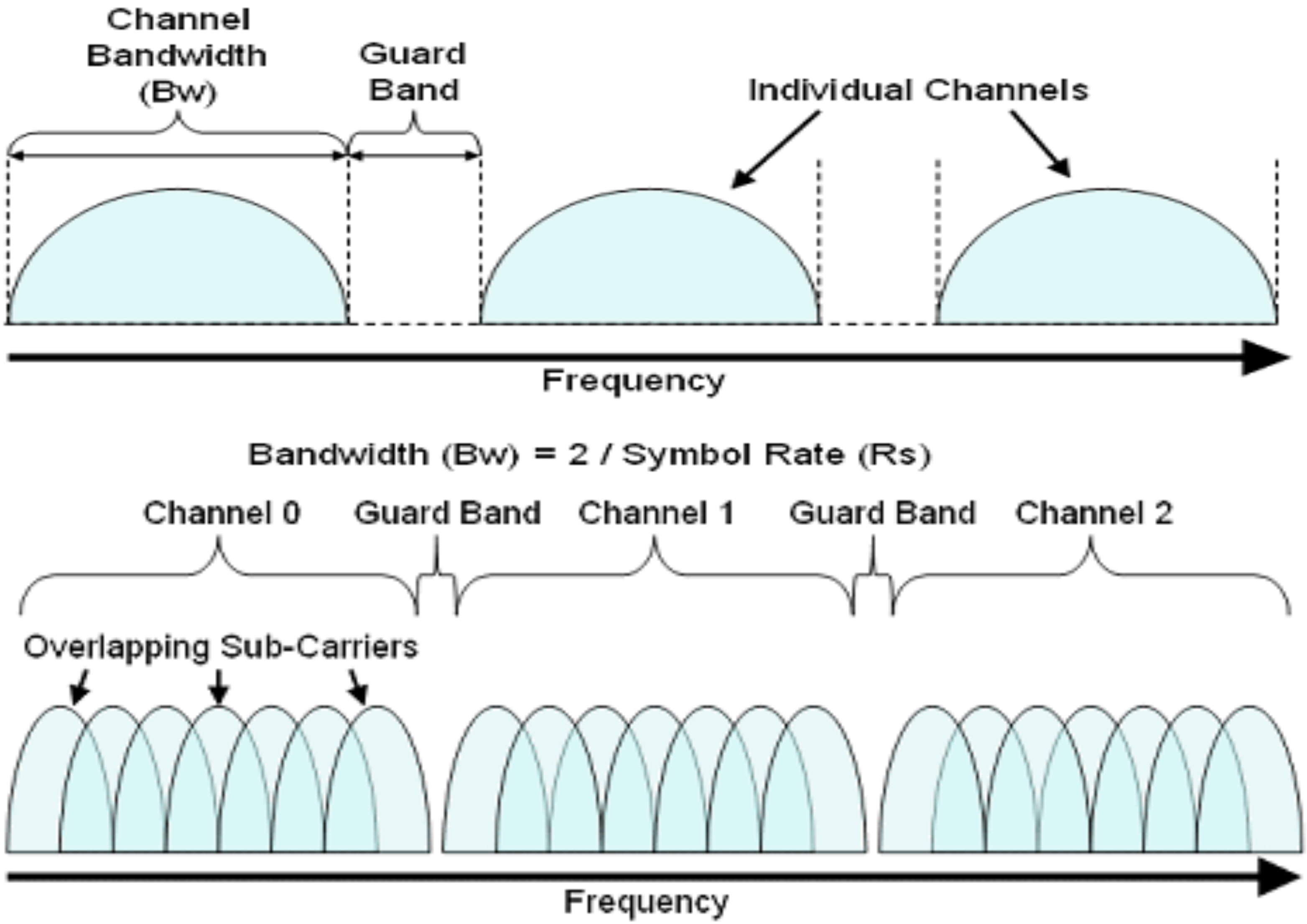
- Frequency division multiplexing (FDM) is a technology that transmits multiple signals simultaneously over a single transmission path, such as a cable or wireless system.

- Orthogonal FDM's (OFDM) spread spectrum technique distributes the data over a large number of carriers that are spaced apart at precise frequencies and null out of channel sidebands.

- OFDM allows sub-channels to overlap, providing a high spectral efficiency. The modulation technique allowed in OFDM is more efficient than spread spectrum techniques.

- OFDM works by breaking one high-speed data carrier into several lower-speed subcarriers, which are then transmitted in parallel.

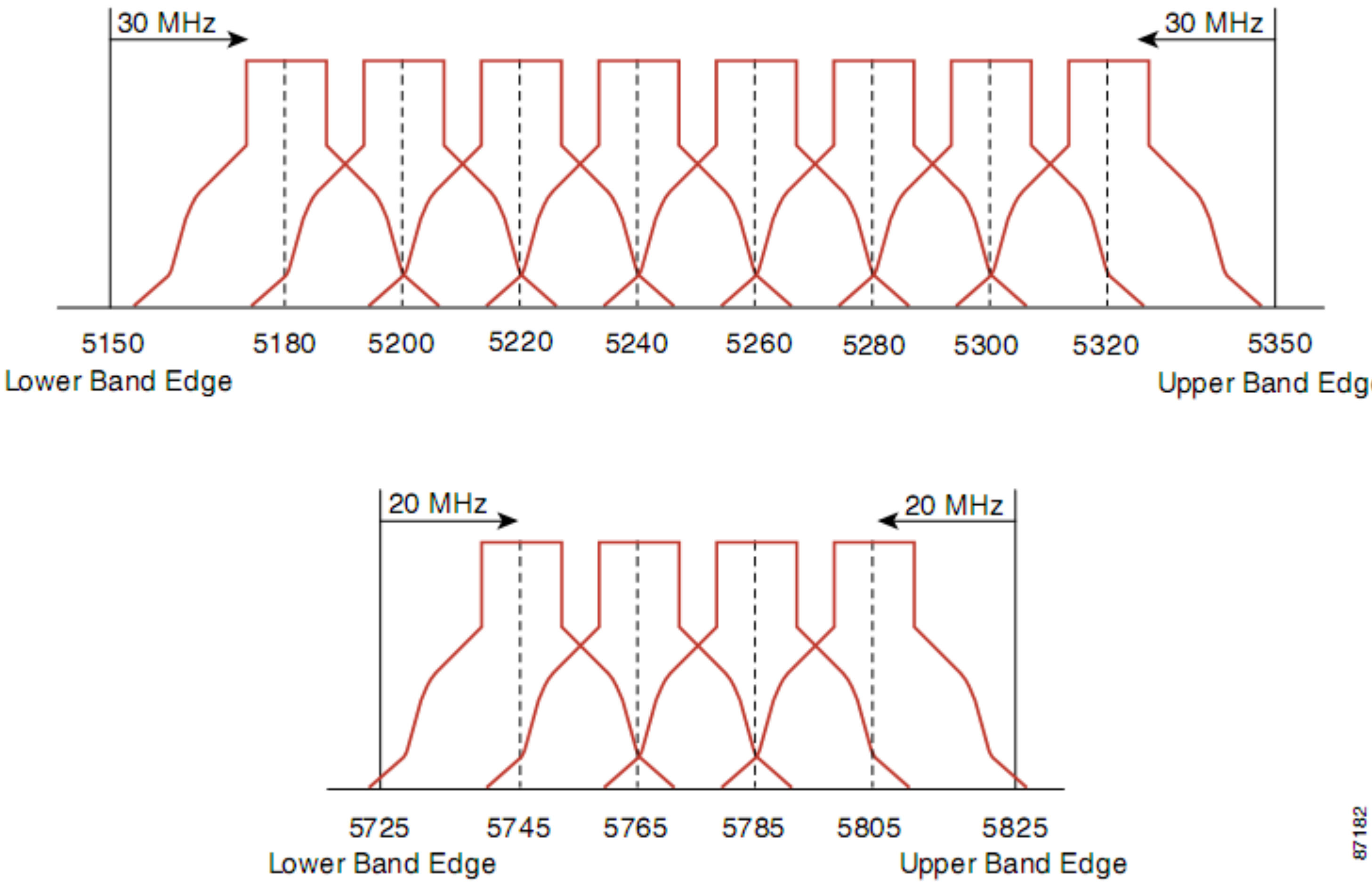
OFDM



Channel Bandwidth (Bw)
Guard Band
Individual Channels
Frequency
Bandwidth (Bw) = 2 / Symbol Rate (Rs)
Channel 0
Guard Band
Channel 1
Guard Band
Channel 2
Overlapping Sub-Carriers
Frequency

OFDM Channels in IEEE 802.11a

The frequency of the channel is 10 MHz either side of the dotted line. There is 5 MHz of separation between channels.



OFDM Channels in IEEE 802.11a

- Each high-speed carrier is 20 MHz wide and is broken up into 52 subchannels, each approximately 300 KHz wide. OFDM uses 48 of these subchannels for data, while the remaining four are used for error correction.
- Binary Phase Shift Keying (BPSK) is used to encode 125 Kbps of data per channel, resulting in a 6,000-Kbps, or 6 Mbps, data rate. Using Quadrature Phase Shift Keying (QPSK), you can double the amount of data encoded to 250 Kbps per channel, yielding a 12-Mbps data rate. And by using 16-level Quadrature Amplitude Modulation (16-QAM) encoding 4 bits per hertz, you can achieve a data rate of 24 Mbps. The 802.11a standard specifies that all 802.11a-compliant products must support these basic data rates.
- Data rates of 54 Mbps are achieved by using 64-level Quadrature Amplitude Modulation (64-QAM), which yields 8 bits per cycle or 10 bits per cycle, for a total of up to 1.125 Mbps per 300-KHz channel. With 48 channels this results in a 54 Mbps data rate.

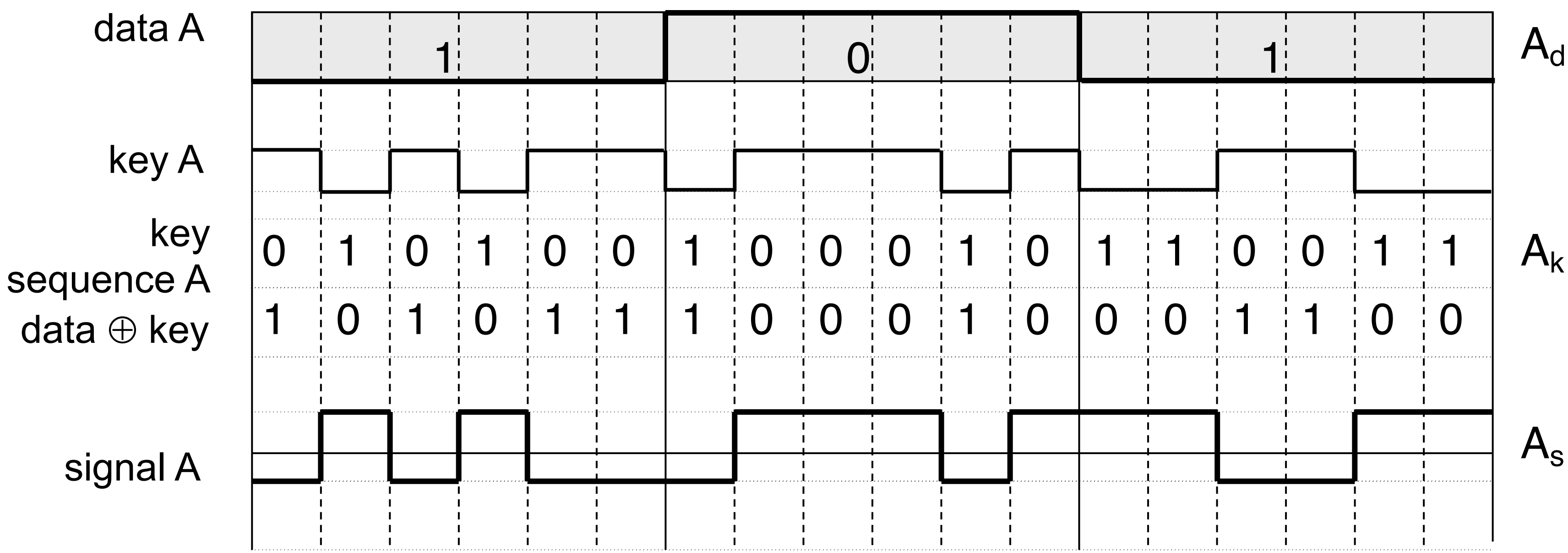
Access method CDMA

- CDMA (Code Division Multiple Access)
  - all terminals send on the same frequency probably at the same time and can use the whole bandwidth of the transmission channel
  - each sender has a unique random number, the sender XORs the signal with this random number
  - the receiver can "tune" into this signal if it knows the pseudo random number, tuning is done via a correlation function
- Disadvantages:
  - higher complexity of a receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
  - all signals should have the same strength at a receiver
- Advantages:
  - all terminals can use the same frequency, no planning needed
  - huge code space compared to frequency space
  - interferences (e.g. white noise) is not coded
  - forward error correction and encryption can be easily integrated

CDMA in theory

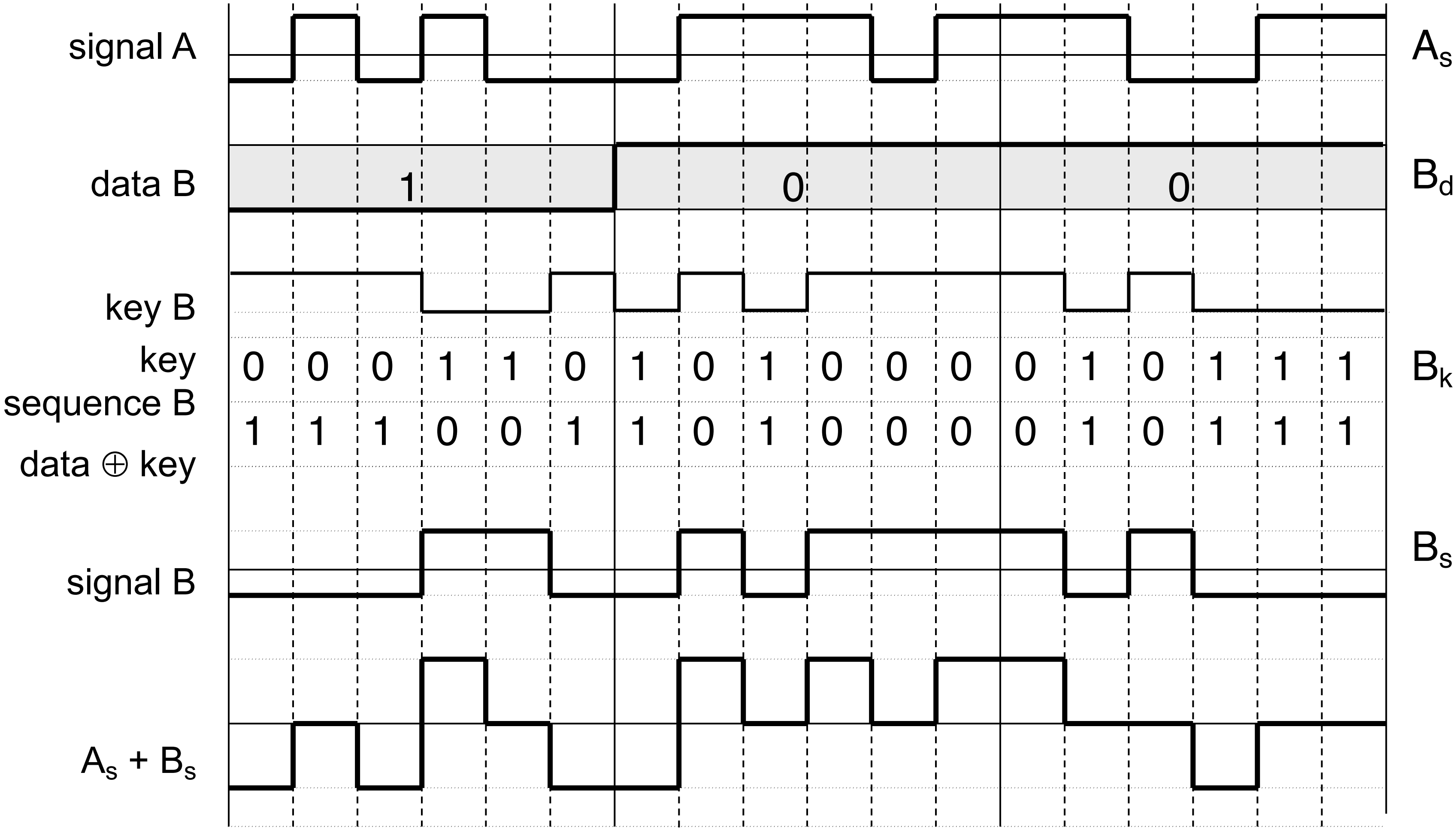
- Sender A
  - sends $A_d = 1$, key $A_k = 010011$ (assign: “0”= -1, “1”= +1)
  - sending signal $A_s = A_d * A_k = (-1, +1, -1, -1, +1, +1)$
- Sender B
  - sends $B_d = 0$, key $B_k = 110101$ (assign: “0”= -1, “1”= +1)
  - sending signal $B_s = B_d * B_k = (-1, -1, +1, -1, +1, -1)$
- Both signals superimpose in space
  - interference neglected (noise etc.)
  - $A_s + B_s = (-2, 0, 0, -2, +2, 0)$
- Receiver wants to receive signal from sender A
  - apply key A_k bitwise (inner product)
    - $A_e = (-2, 0, 0, -2, +2, 0) \bullet A_k = 2 + 0 + 0 + 2 + 2 + 0 = 6$
    - result greater than 0, therefore, original bit was “1”
  - receiving B
    - $B_e = (-2, 0, 0, -2, +2, 0) \bullet B_k = -2 + 0 + 0 - 2 - 2 + 0 = -6$, i.e. “0”

CDMA on signal level I

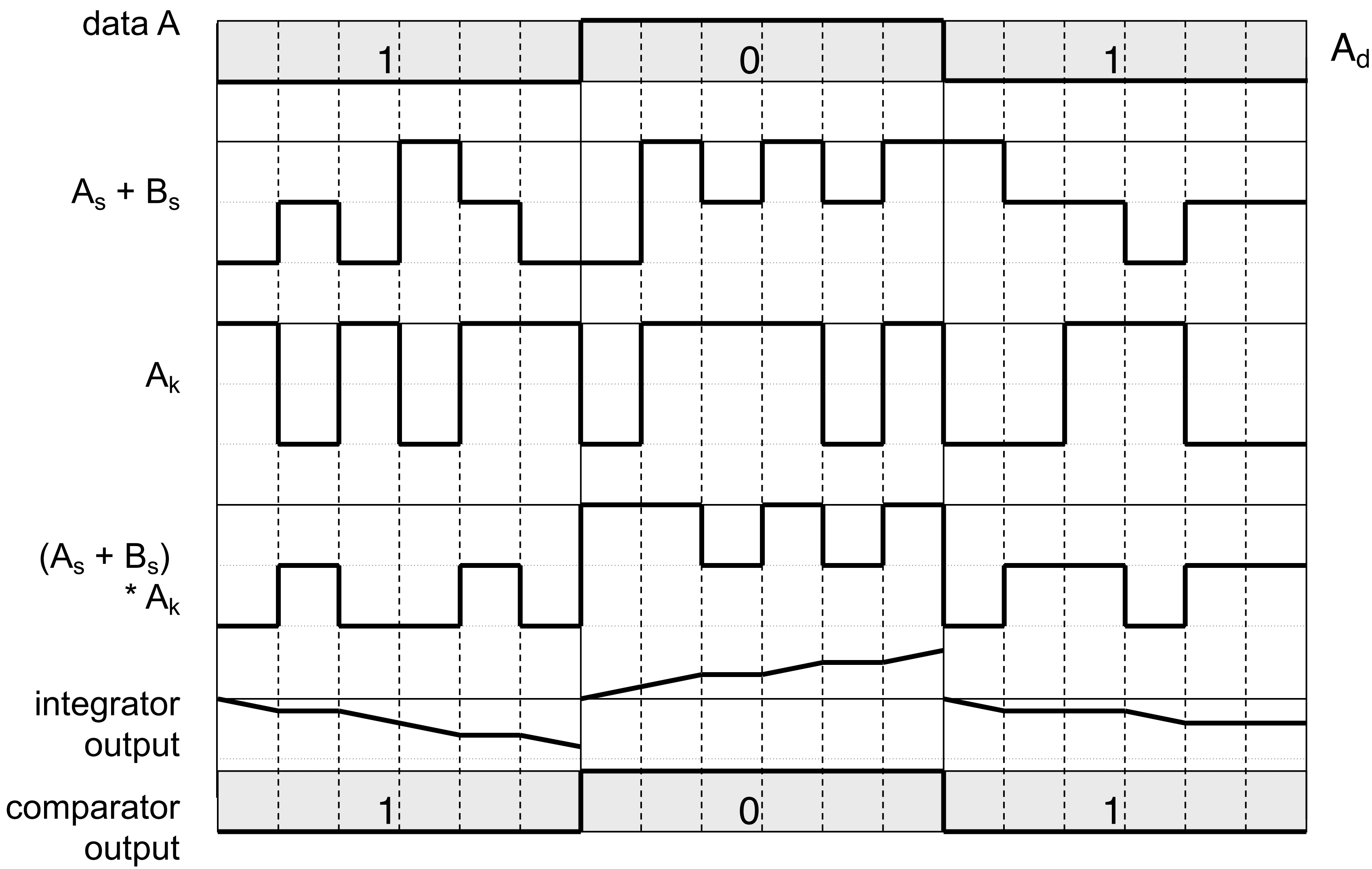


Real systems use much longer keys resulting in a larger distance between single code words in code space.

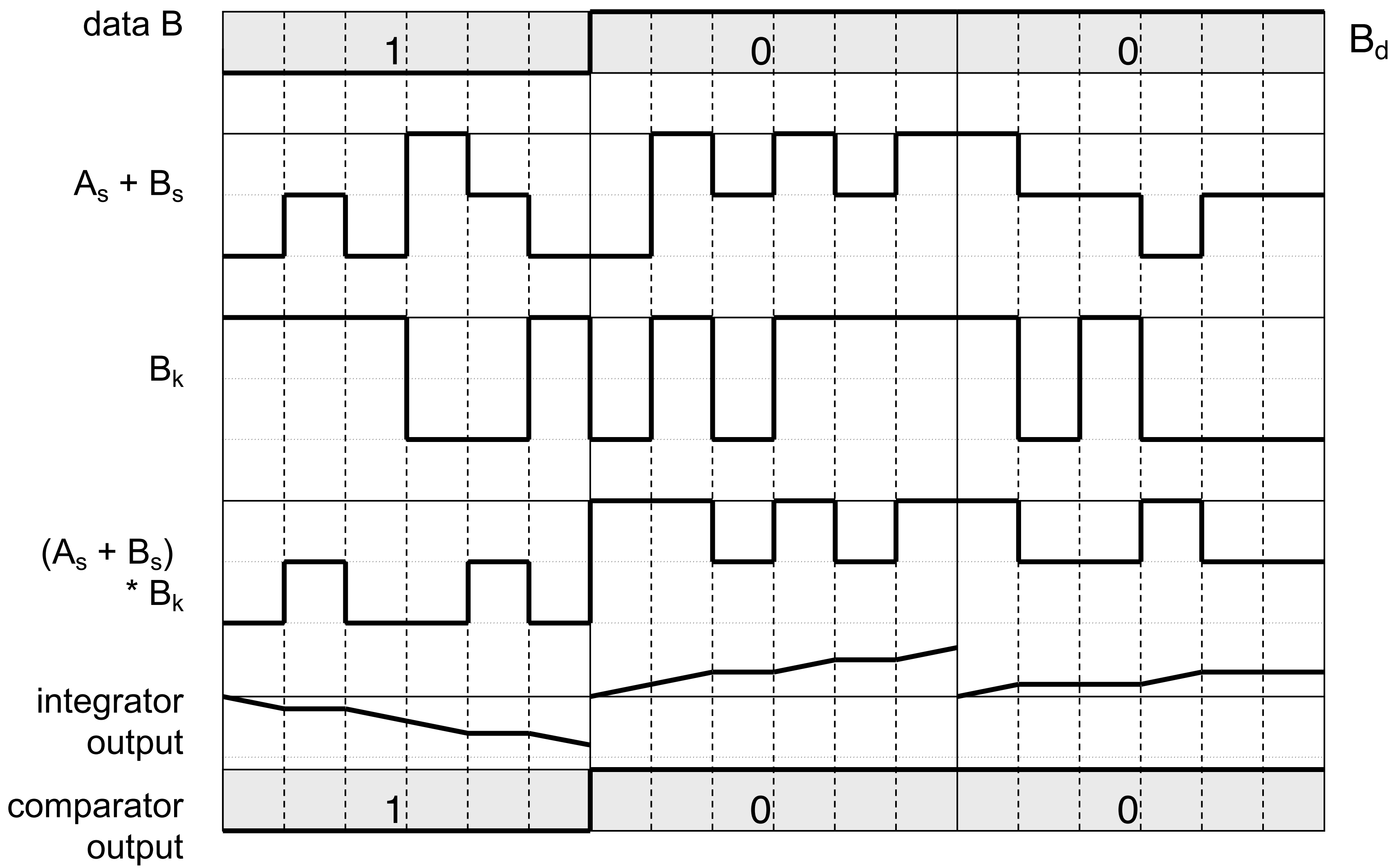
CDMA on signal level II



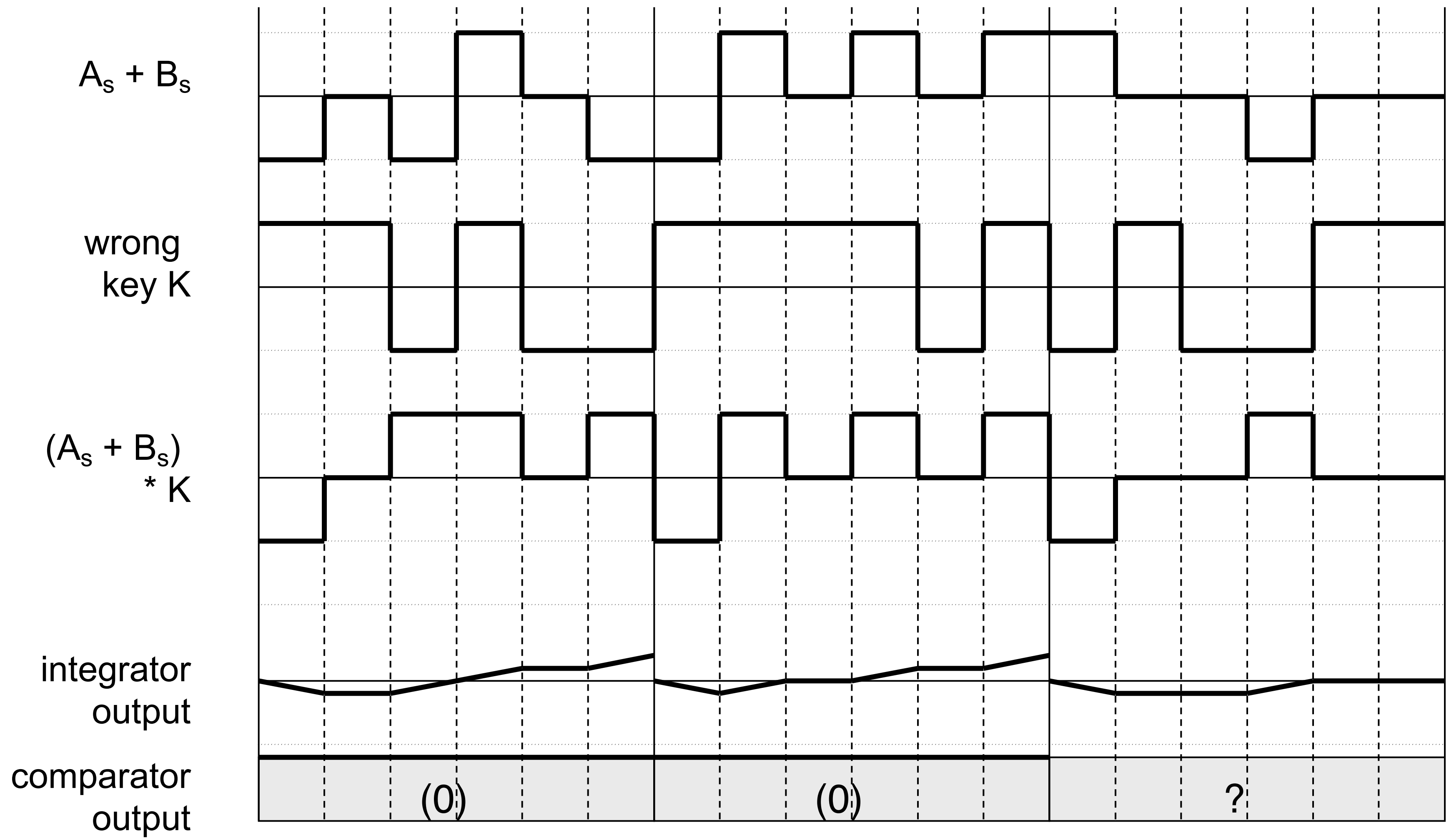
CDMA on signal level III



CDMA on signal level IV



CDMA on signal level V



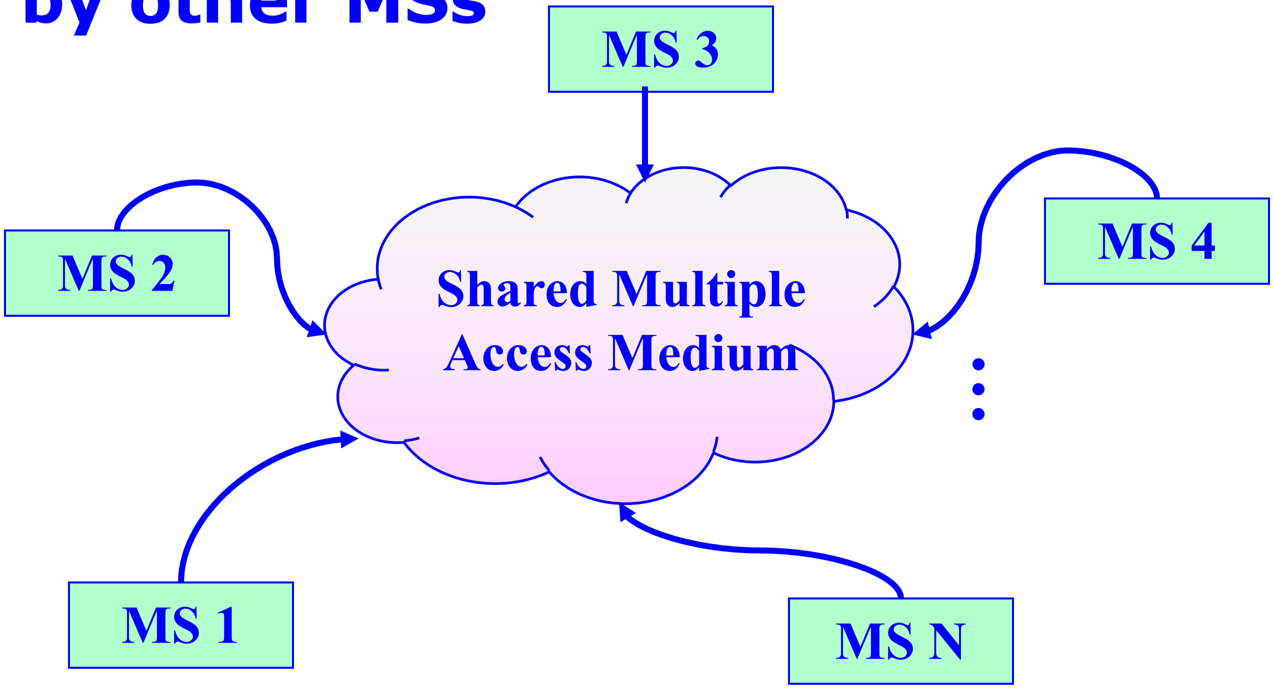
Comparison of Various Multiple Division Techniques

Technique	FDMA	TDMA	CDMA	SDMA
Concept	Divide the frequency band into disjoint subbands	Divide the time into non-overlapping time slots	Spread the signal with orthogonal codes	Divide the space into sectors
Active terminals	All terminals active on their specified frequencies	Terminals are active in their specified slot on same frequency	All terminals active on same frequency	Number of terminals per beam depends on FDMA/TDMA/ CDMA
Signal separation	Filtering in frequency	Synchronization in time	Code separation	Spatial separation using smart antennas
Handoff	Hard handoff	Hard handoff	Soft handoff	Hard and soft handoffs
Advantages	Simple and robust	Flexible	Flexible	Very simple, increases system capacity
Disadvantages	Inflexible, available frequencies are fixed, requires guard bands	Requires guard space, synchronization problem	Complex receivers, requires power control to avoid near-far problem	Inflexible, requires network monitoring to avoid intracell handoffs
Current applications	Radio, TV, and analog cellular	GSM and PDC	2.5G and 3G	Satellite systems, others being explored

Media Access Control

Introduction

- **Multiple access control channels**
  - ✓ **Each Mobile Station (MS) is attached to a transmitter / receiver which communicates via a channel shared by other nodes**
  - ✓ **Transmission from any MS is received by other MSs**



Introduction (Cont'd)

- **Multiple access issues**
  - **If more than one MS transmit at a time on the control channel to BS, a collision occurs**
  - **How to determine which MS can transmit to BS?**
- **Multiple access protocols**
  - **Solving multiple access issues**
  - **Different types:**
    - **Contention protocols resolve a collision after it occurs. These protocols execute a collision resolution protocol after each collision**
    - **Collision-free protocols ensure that a collision can never occur**

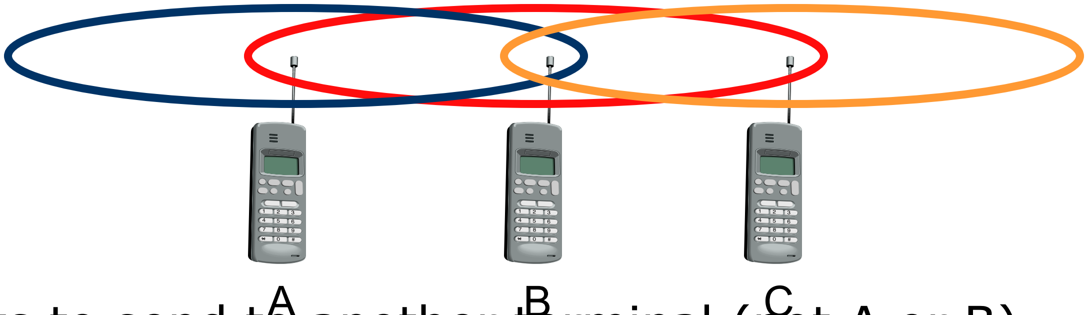
Motivation

- Can we apply media access methods from fixed networks?

- Example CSMA/CD
  - **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
  - send as soon as the medium is free, listen into the medium if a collision occurs (legacy method in IEEE 802.3)
- Problems in wireless networks
  - signal strength decreases proportional to the square of the distance
  - the sender would apply CS and CD, but the collisions happen at the receiver
  - it might be the case that a sender cannot "hear" the collision, i.e., CD does not work
  - furthermore, CS might not work if, e.g., a terminal is "hidden"

Motivation - hidden and exposed terminals

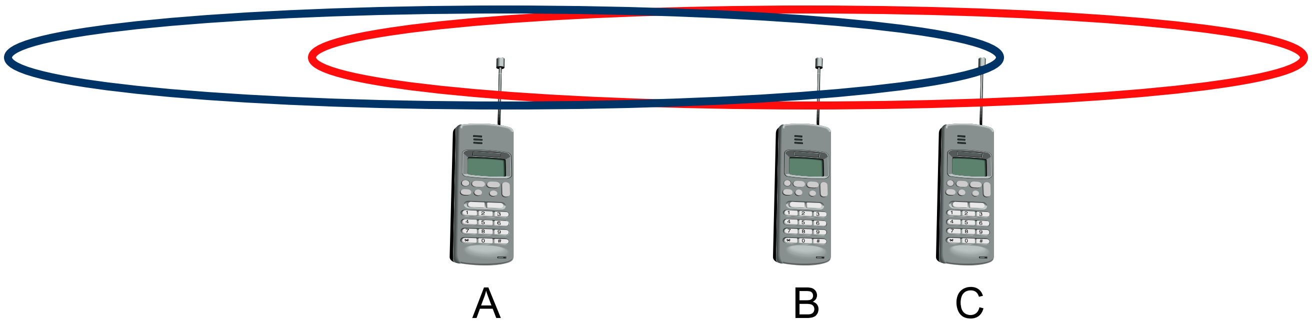
- Hidden terminals
  - A sends to B, C cannot receive A
  - C wants to send to B, C senses a "free" medium (CS fails)
  - collision at B, A cannot receive the collision (CD fails)
  - A is "hidden" for C
  - **-> Collisions**



- Exposed terminals
  - B sends to A, C wants to send to another terminal (not A or B)
  - C has to wait, CS signals a medium in use
  - but A is outside the radio range of C, therefore waiting is not necessary
  - C is "exposed" to B
  - **-> Extended delays**

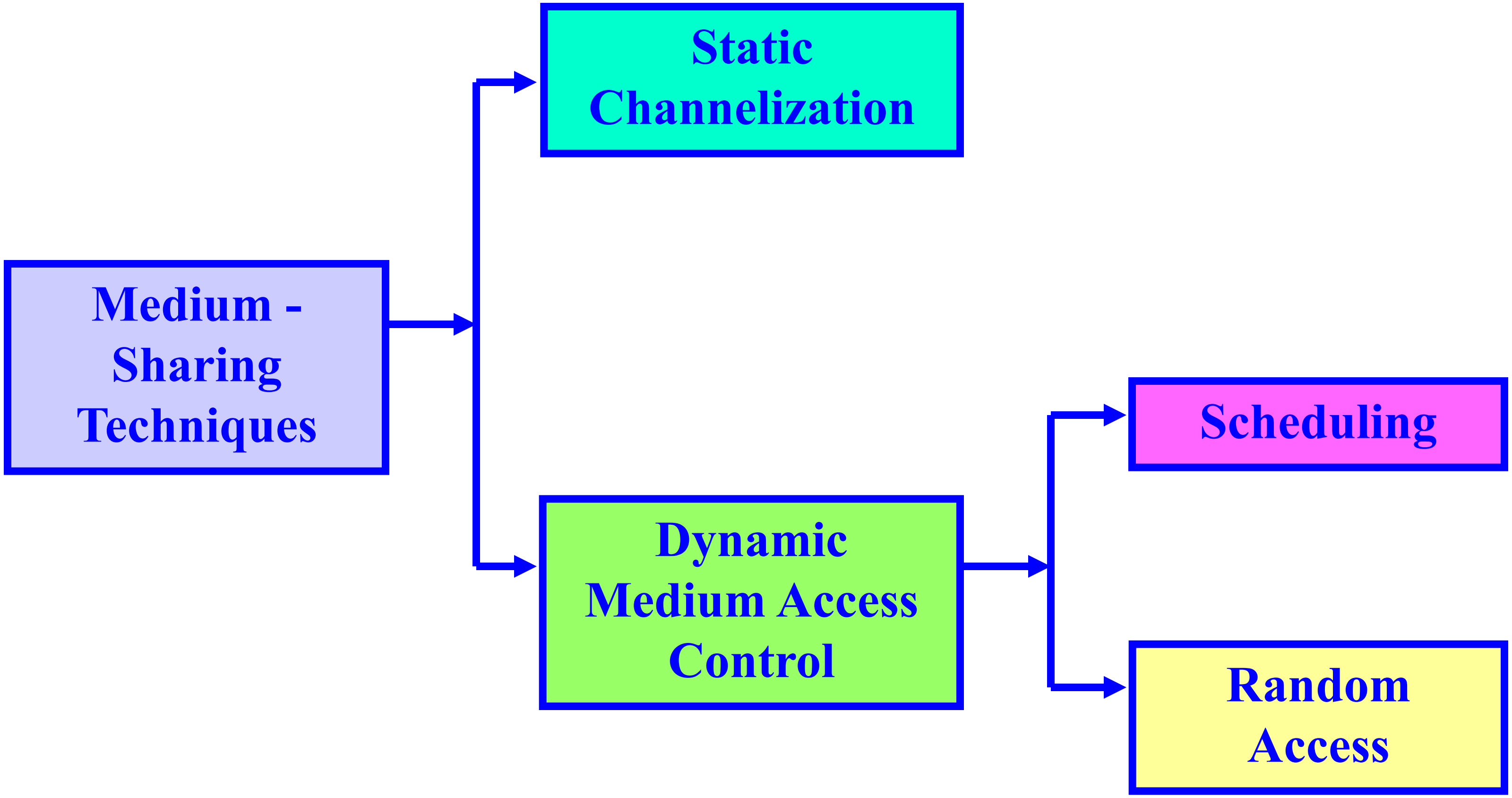
Motivation - near and far terminals

- Terminals A and B send, C receives
  - signal strength decreases proportional to the square of the distance
  - the signal of terminal B therefore drowns out A's signal
  - C cannot receive A

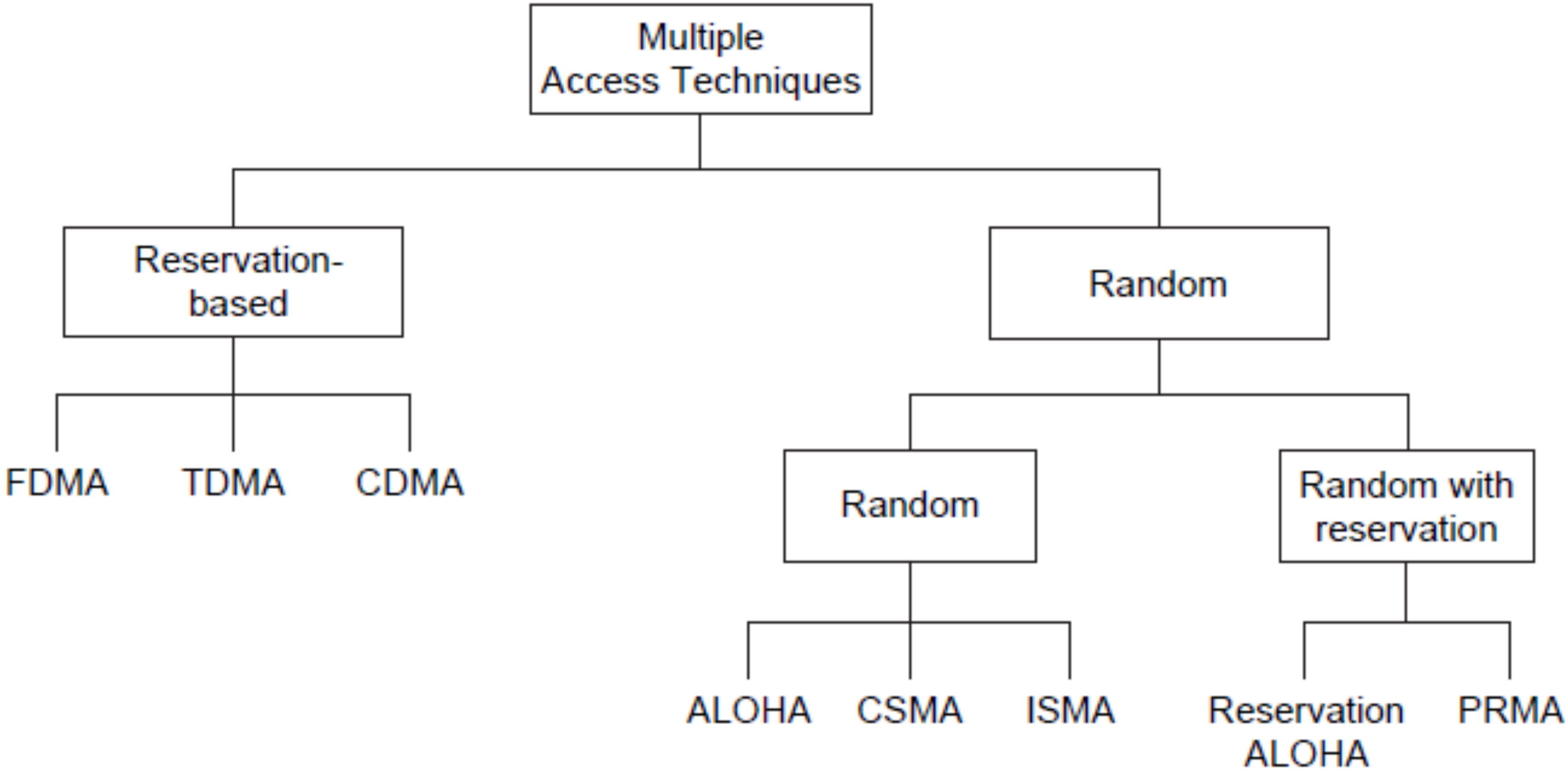


- If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer
- Also severe problem for CDMA-networks - precise power control needed!

Channel Sharing Techniques



Classification of multiple access protocols for a shared channel.



Conflict-free

- SDMA (Space Division Multiple Access)
  - segment space into sectors, use directed antennas
  - cell structure
- FDMA (Frequency Division Multiple Access)
  - assign a certain frequency to a transmission channel between a sender and a receiver
  - permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- TDMA (Time Division Multiple Access)
  - assign the fixed sending frequency to a transmission channel between a sender and a receiver for a certain amount of time
- CDMA
  - all terminals send on the same frequency probably at the same time and can use the whole bandwidth of the transmission channel

Comparison SDMA/TDMA/FDMA/CDMA

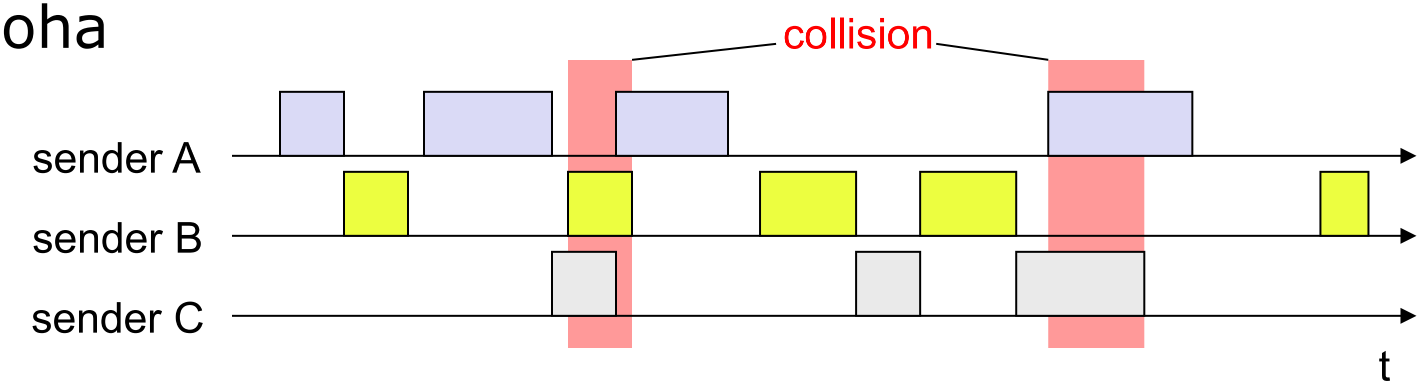
Approach	SDMA	TDMA	FDMA	CDMA
Idea	segment space into cells/sectors	segment sending time into disjoint time-slots, demand driven or fixed patterns	segment the frequency band into disjoint sub-bands	spread the spectrum using orthogonal codes
Terminals	only one terminal can be active in one cell/one sector	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

Contention-based Protocols

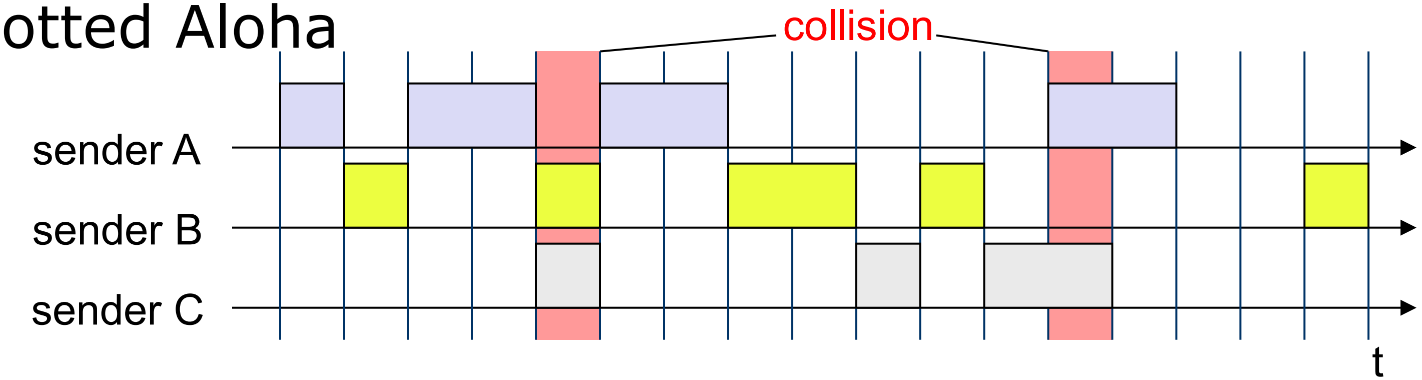
- **ALOHA**
  - **Developed in the 1970s for a packet radio network by Hawaii University**
  - **Whenever a terminal (MS) has data, it transmits. Sender finds out whether transmission was successful or experienced a collision by listening to the broadcast from the destination station. If there is a collision, sender retransmits after some random time**
- **Slotted ALOHA**
  - **Improvement: Time is slotted and a packet can only be transmitted at the beginning of one slot. Thus, it can reduce the collision duration**

Aloha/slotted aloha

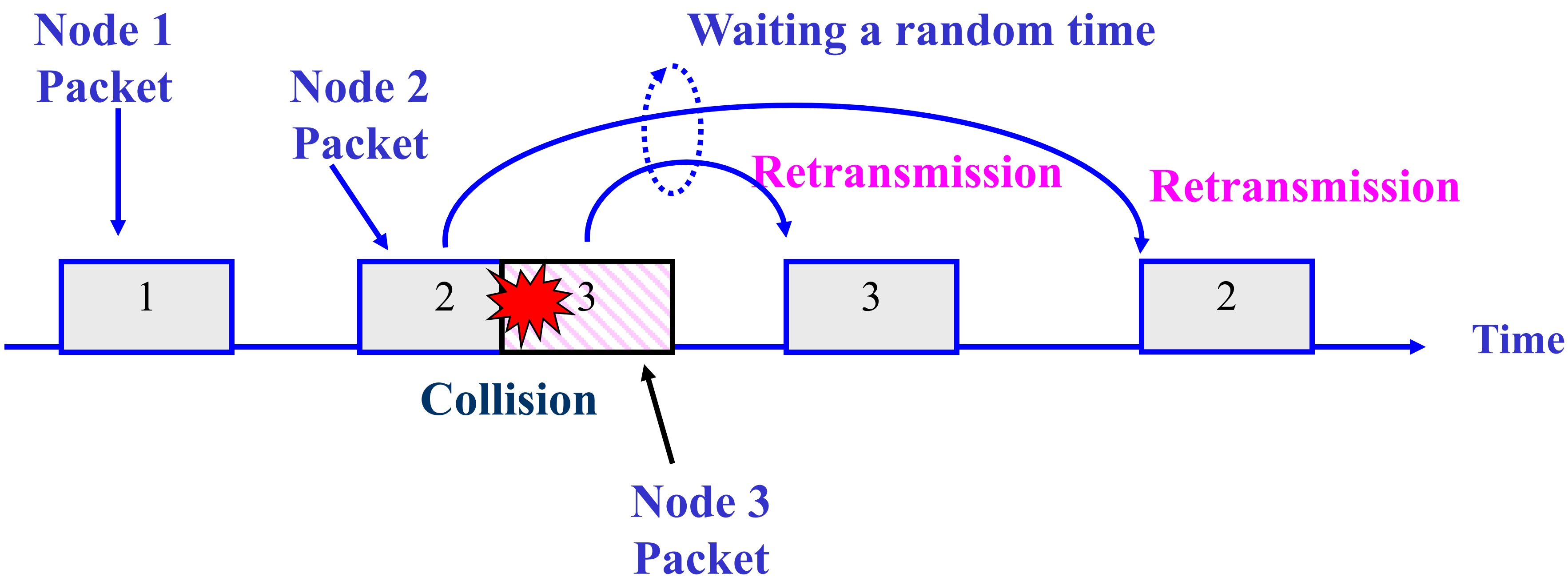
- Mechanism
  - random, distributed (no central arbiter), time-multiplex
  - Slotted Aloha additionally uses time-slots, sending must always start at slot boundaries
- Aloha



- Slotted Aloha



Pure ALOHA



Collision mechanism in ALOHA

Throughput of Pure ALOHA

- **The probability of successful transmission P_s is the probability no other packet is scheduled in an interval of length $2T$**

$$P_s = P(no\_collision)$$
$$= e^{-2gT}$$

where g is the packet rate of the traffic

- **The throughput S_{th} of pure Aloha as:** $S_{th} = gTe^{-2gT}$

- **Defining $G = gT$ to normalize offered load, we have**

$$S_{th} = Ge^{-2G}$$

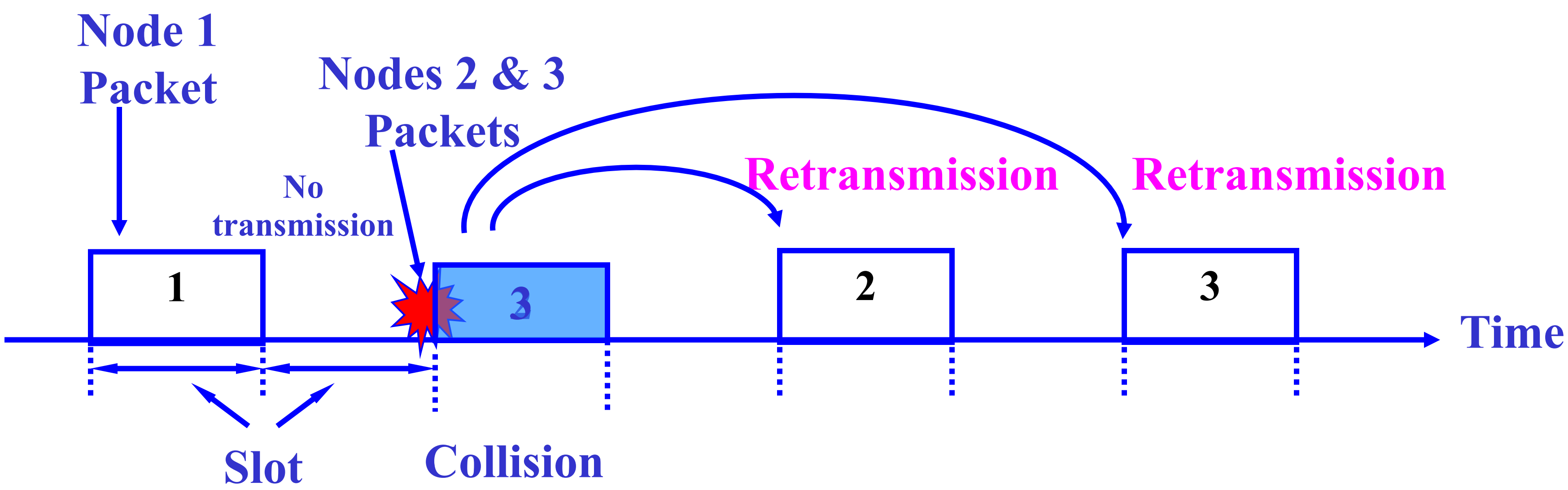
- **Differentiating S_{th} with respect to G and equating to zero gives**

$$\frac{dS_{th}}{dG} = -2Ge^{-2G} + e^{-2G} = 0$$

- **The Maximum throughput of ALOHA is**

$$S_{max} = \frac{1}{2e} \approx 0.184$$

Slotted ALOHA



Collision mechanism in slotted ALOHA

Throughput of Slotted ALOHA

- **The probability of successful transmission P_s is the probability no other packet is scheduled in an interval of length T**

$$P_s = e^{-gT}$$

where g is the packet rate of the traffic

- **The throughput S_{th} of pure Aloha as:** $S_{th} = gTe^{-gT}$

- **Defining $G = gT$ to normalize offered load, we have**

$$S_{th} = Ge^{-G}$$

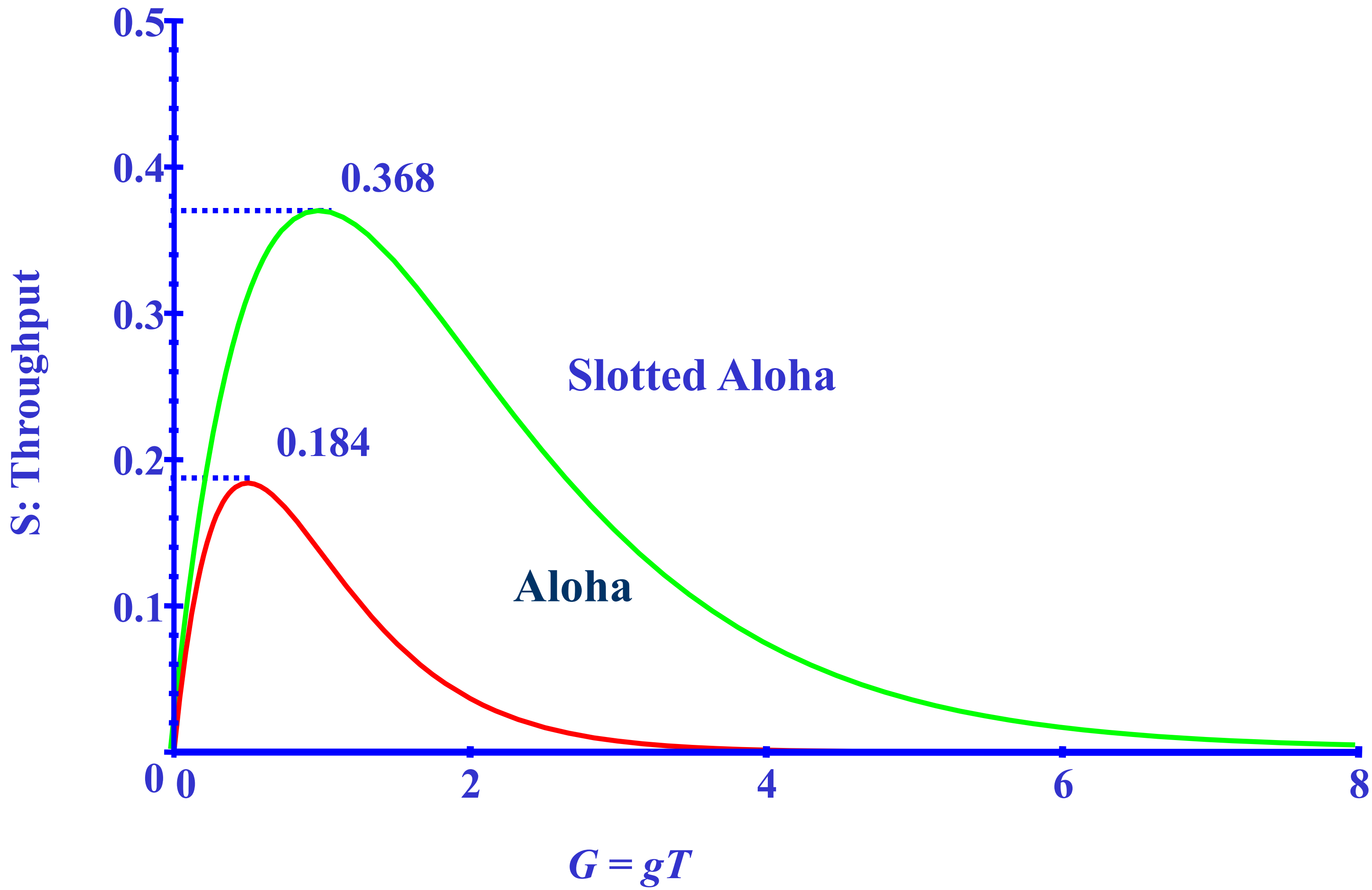
- **Differentiating S_{th} with respect to G and equating to zero gives**

$$\frac{dS_{th}}{dG} = -Ge^{-G} + e^{-G} = 0$$

- **The Maximum throughput of ALOHA is**

$$S_{\max} = \frac{1}{e} \approx 0.368$$

Throughput



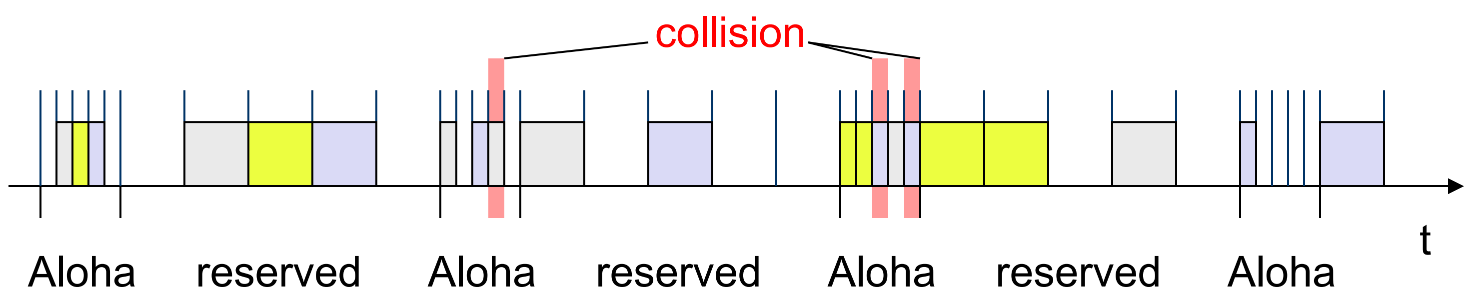
0.5
0.4
0.3
0.2
0.1
0
S: Throughput
0.368
0.184
Slotted Aloha
Aloha
0
2
4
6
8
G = gT

DAMA - Demand Assigned Multiple Access

- Channel efficiency only 18% for Aloha, 36% for Slotted Aloha (assuming Poisson distribution for packet arrival and packet length)
- Reservation can increase efficiency to 80%
  - a sender *reserves* a future time-slot
  - sending within this reserved time-slot is possible without collision
  - reservation also causes higher delays
  - typical scheme for satellite links
- Examples for reservation algorithms:
  - *Explicit Reservation according to Roberts (Reservation-ALOHA)*
  - *Implicit Reservation (PRMA)*
  - *Reservation-TDMA*

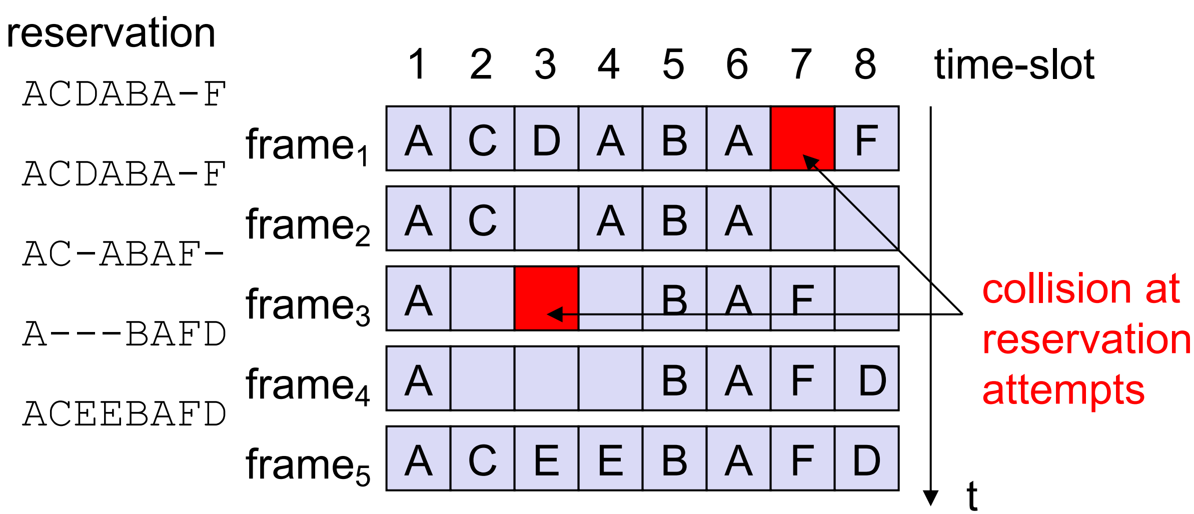
Access method DAMA: Explicit Reservation

- Explicit Reservation (Reservation Aloha):
  - two modes:
    - ALOHA mode for reservation:
      competition for small reservation slots, collisions possible
    - reserved mode for data transmission within successful reserved slots (no collisions possible)
  - it is important for all stations to keep the reservation list consistent at any point in time and, therefore, all stations have to synchronize from time to time



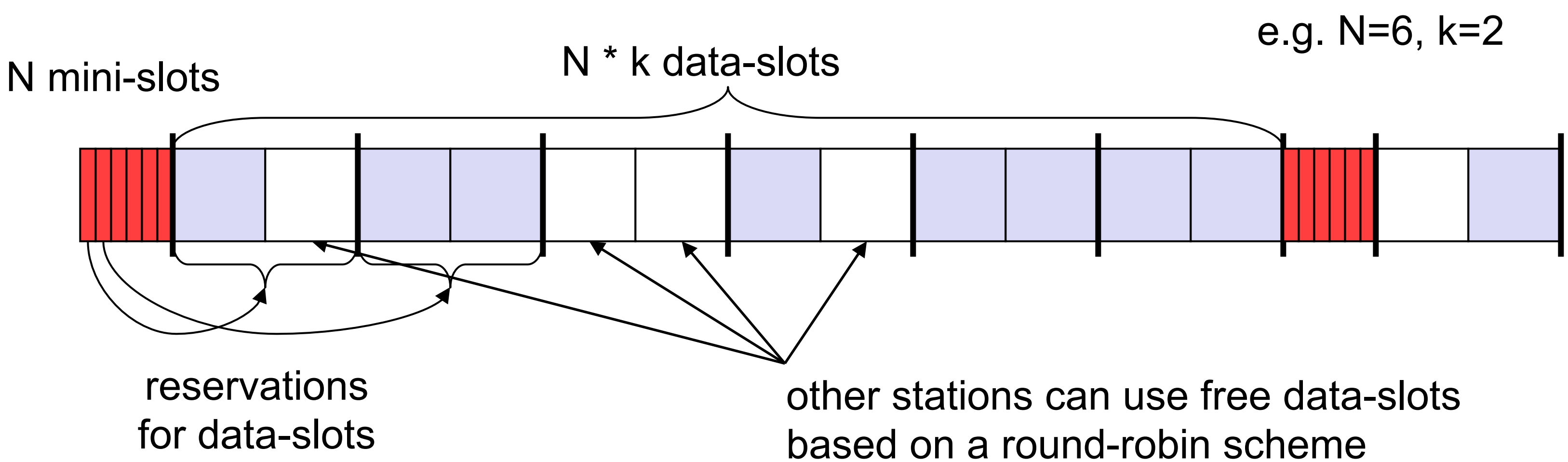
Access method DAMA: PRMA

- Implicit reservation (PRMA - Packet Reservation MA):
  - a certain number of slots form a frame, frames are repeated
  - stations compete for empty slots according to the slotted aloha principle
  - once a station reserves a slot successfully, this slot is automatically assigned to this station in all following frames as long as the station has data to send
  - competition for this slots starts again as soon as the slot was empty in the last frame



Access method DAMA: Reservation-TDMA

- Reservation Time Division Multiple Access
  - every frame consists of N mini-slots and x data-slots
  - every station has its own mini-slot and can reserve up to k data-slots using this mini-slot (i.e. x = N * k).
  - other stations can send data in unused data-slots according to a round-robin sending scheme (best-effort traffic)



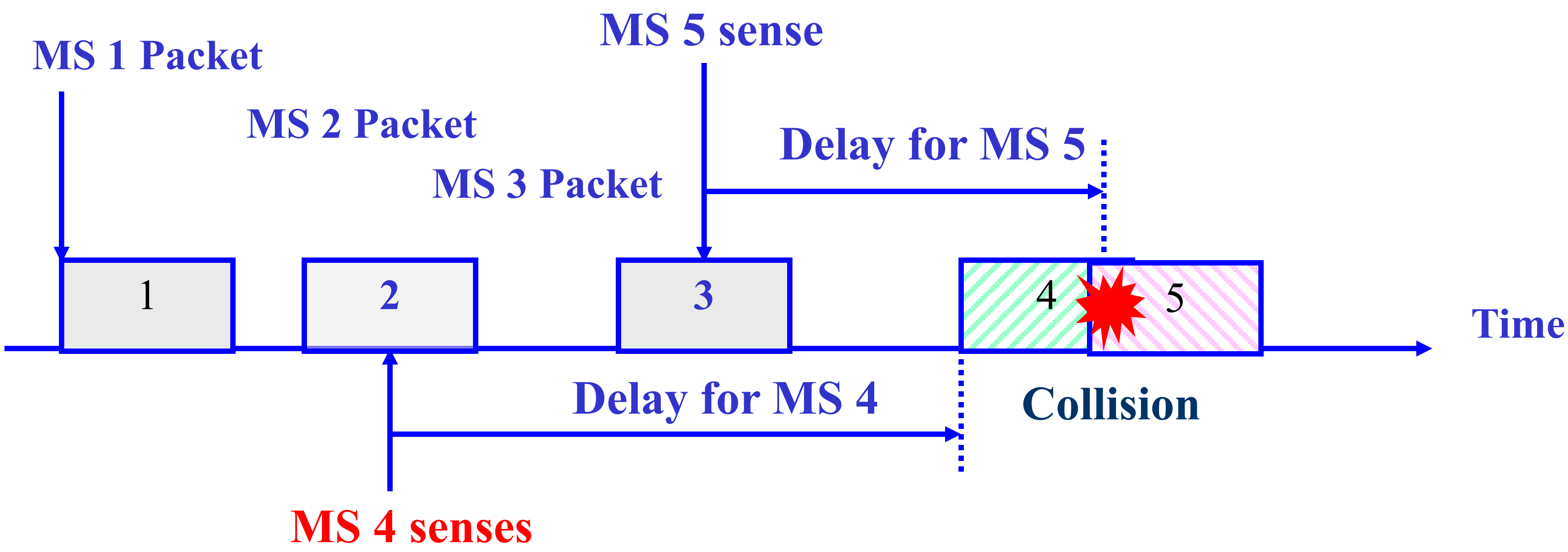
Contention Protocols (Cont'd)

- **CSMA (Carrier Sense Multiple Access)**
  - **Improvement: Start transmission only if no transmission is ongoing**
- **CSMA/CD (CSMA with Collision Detection)**
  - **Improvement: Stop ongoing transmission if a collision is detected**
- **CSMA/CA (CSMA with Collision Avoidance)**
  - **Improvement: Wait a random time and try again when carrier is quiet. If still quiet, then transmit.**
- **CSMA/CA with ACK**
- **CSMA/CA with RTS/CTS**

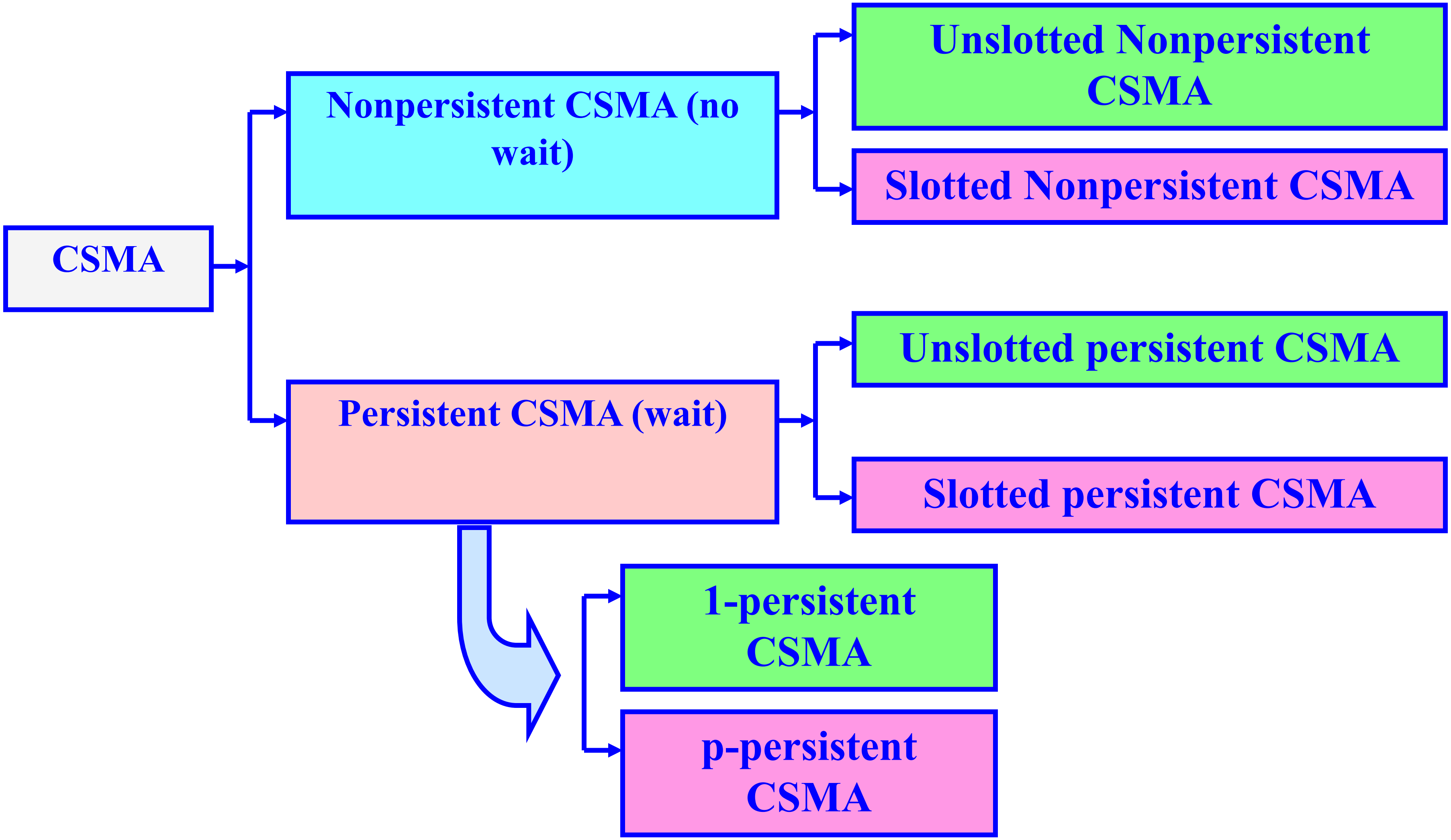
CSMA (Carrier Sense Multiple Access)

- **Max throughput achievable by slotted ALOHA is 0.368**
- **CSMA gives improved throughput compared to Aloha protocols**
- **Listens to the channel before transmitting a packet (avoid avoidable collisions)**

Collision Mechanism in CSMA



Kinds of CSMA



Nonpersistent CSMA Protocols

- **Nonpersistent CSMA Protocol:**
  - ✓ **Step 1: If the medium is idle, transmit immediately (same as *p* = 1)**
  - ✓ **Step 2: If the medium is busy, wait a random amount of time and repeat Step 1**
- **Random backoff reduces probability of collisions**
- **Waste idle time if the backoff time is too long**
- **For unslotted nonpersistent CSMA, the throughput is given by:**

$$S_{th} = \frac{Ge^{-2\alpha T}}{G(1+2\alpha)+e^{-\alpha G}}$$

- **For slotted nonpersistent CSMA, the throughput is given by:**

$$S_{th} = \frac{\alpha G e^{-2\alpha T}}{(1-e^{-\alpha G}+\alpha)}$$

1-persistent CSMA Protocols

- **1-persistent CSMA Protocol:**
  - ✓ **Step 1: If the medium is idle, transmit immediately**
  - ✓ **Step 2: If the medium is busy, continue to listen until medium becomes idle, and then transmit immediately**
  - ✓ **There will always be a collision if two nodes want to retransmit (usually you stop transmission attempts after few tries)**

- **For unslotted 1-persistent CSMA, the throughput is given by:**

$$S_{th} = \frac{G\left[1+G+\alpha G(1+G+\alpha G/2)\right]e^{-G(1+2\alpha)}}{G(1+2\alpha)-(1-e^{-\alpha G})+(1+\alpha G)e^{-G(1+\alpha)}}$$

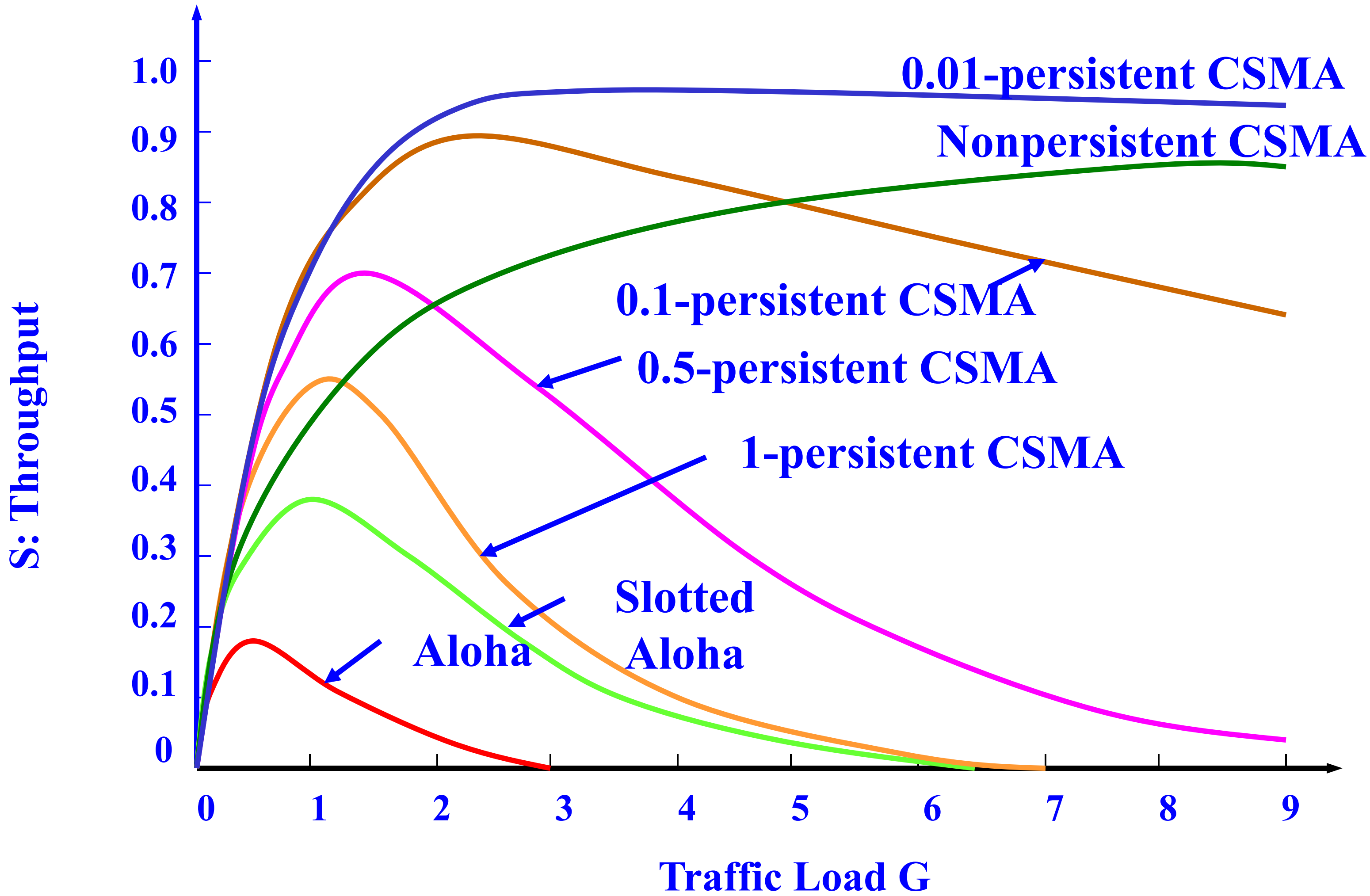
- **For slotted 1-persistent CSMA, the throughput is given by:**

$$S_{th} = \frac{G(1+\alpha-e^{-\alpha G})e^{-G(1+\alpha)}}{(1+\alpha)(1-e^{-\alpha G})+\alpha e^{-G(1+\alpha)}}$$

p-persistent CSMA Protocols

- ***p*-persistent CSMA Protocol (time is slotted):**
  - ✓ **Step 1: If the medium is idle, transmit with probability *p*, or delay the transmission with probability (1 - *p*) until the next slot**
  - ✓ **Step 2: If the medium is busy, waits until the next slot and continue to listen until medium becomes idle, then go to Step 1**
- **A good tradeoff between nonpersistent and 1-persistent CSMA**

Throughput



S: Throughput
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8
9
Traffic Load G
0.01-persistent CSMA
Nonpersistent CSMA
0.1-persistent CSMA
0.5-persistent CSMA
1-persistent CSMA
Slotted
Aloha
Aloha

CSMA/CD (CSMA with Collision Detection)

- **In CSMA, if 2 terminals begin sending packet at the same time, each will transmit its complete packet (although collision is taking place)**
- **Wasting medium for an entire packet time**
- **CSMA/CD**

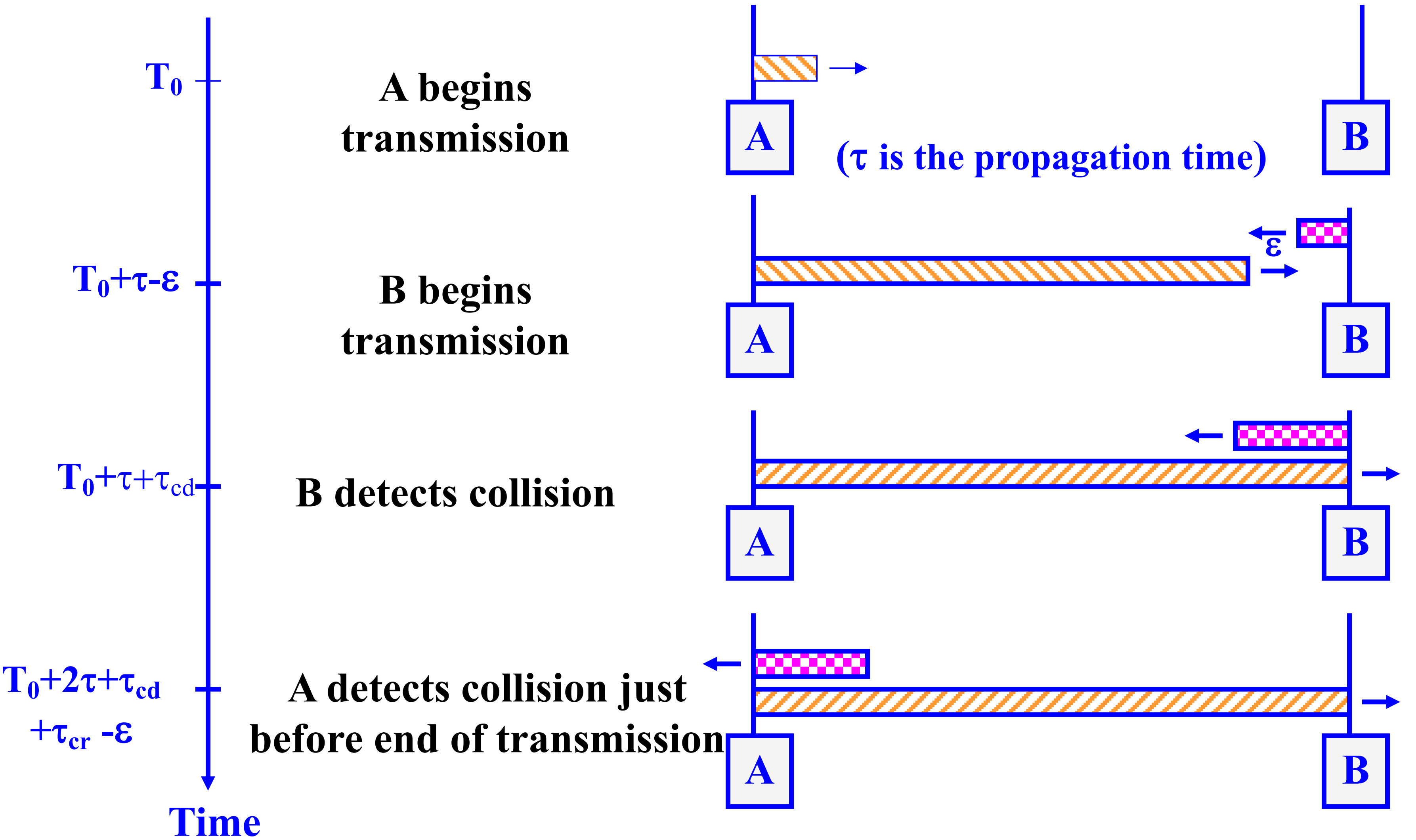
  Step 1: If the medium is idle, transmit

  Step 2: If the medium is busy, continue to listen until the channel is idle then transmit

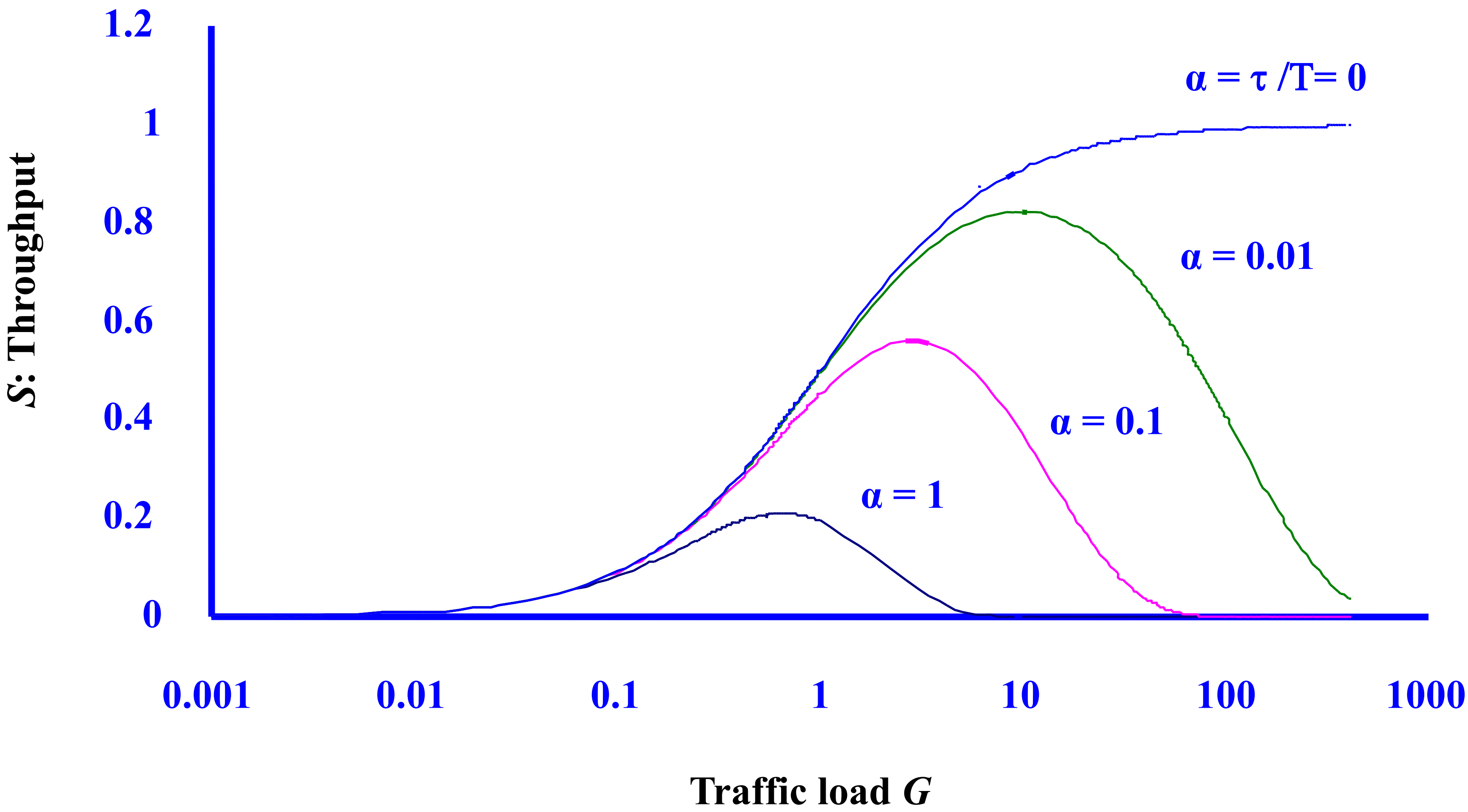
  Step 3: If a collision is detected during transmission, cease transmitting (detection not possible by wireless devices)

  Step 4: Wait a random amount of time and repeats the same algorithm

CSMA/CD in Ethernet (Cont'd)



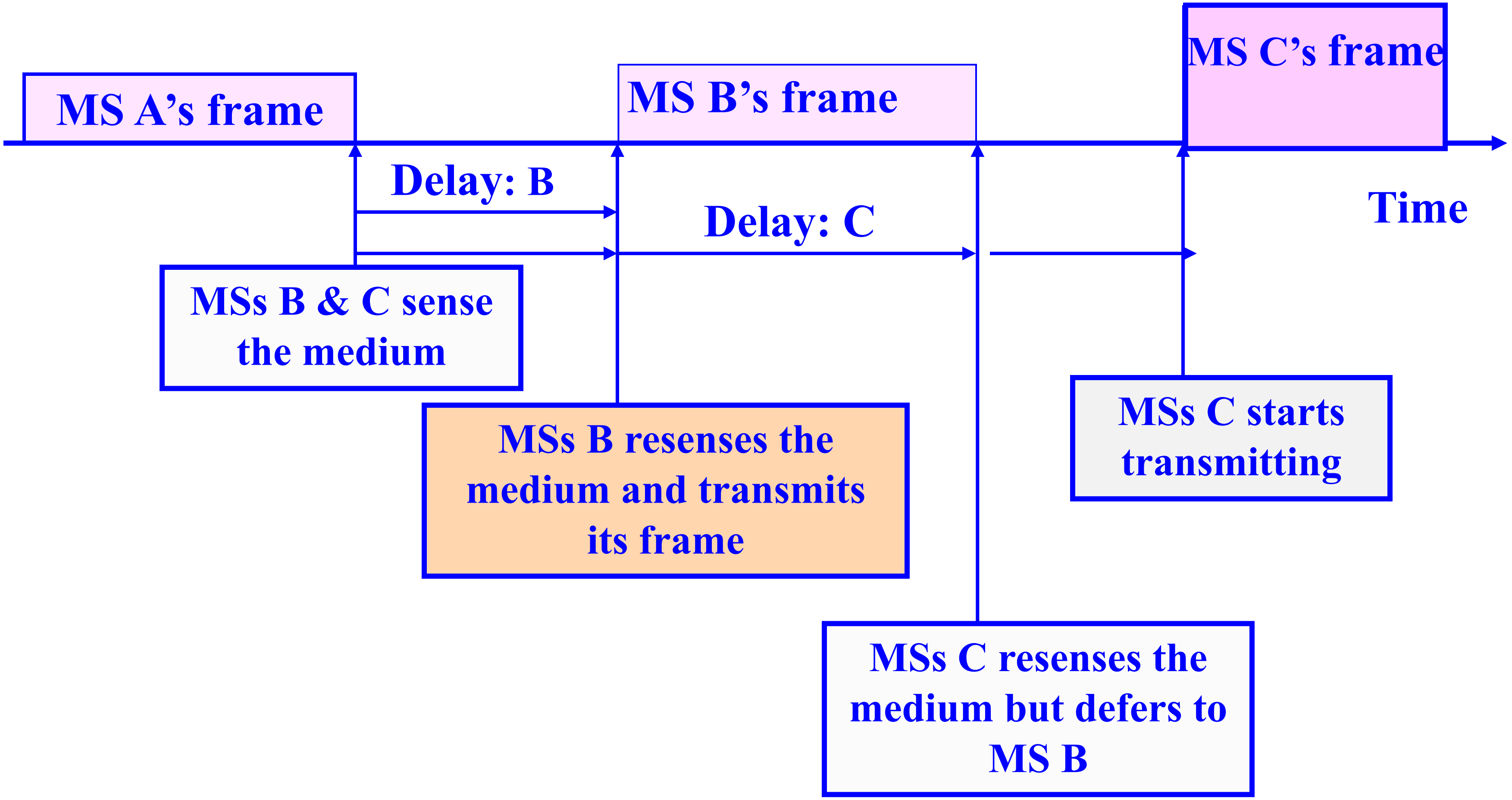
Throughput of slotted non-persistent CSMA/CD



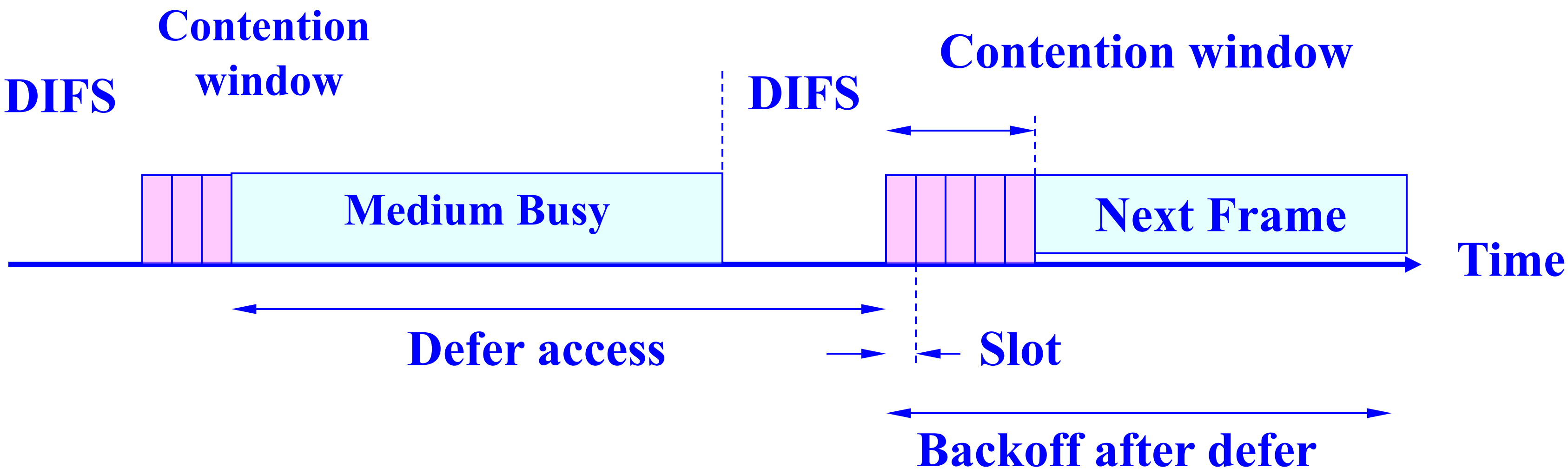
CSMA/CA (CSMA with collision Avoidance) for wireless devices

- **All terminals listen to the same medium as CSMA/CD**
- **Terminal ready to transmit senses the medium**
- **If medium is busy it waits until the end of current transmission**
- **It again waits for an additional predetermined time period DIFS (Distributed inter frame Space)**
- **Then picks up a random number of slots (the initial value of backoff counter) within a contention window to wait before transmitting its frame**
- **If there are transmissions by other MSs during this time period (backoff time), the MS freezes its counter**
- **It resumes count down after other MSs finish transmission + DIFS. The MS can start its transmission when the counter reaches to zero**

CSMA/CA (Cont'd) for Wireless Devices

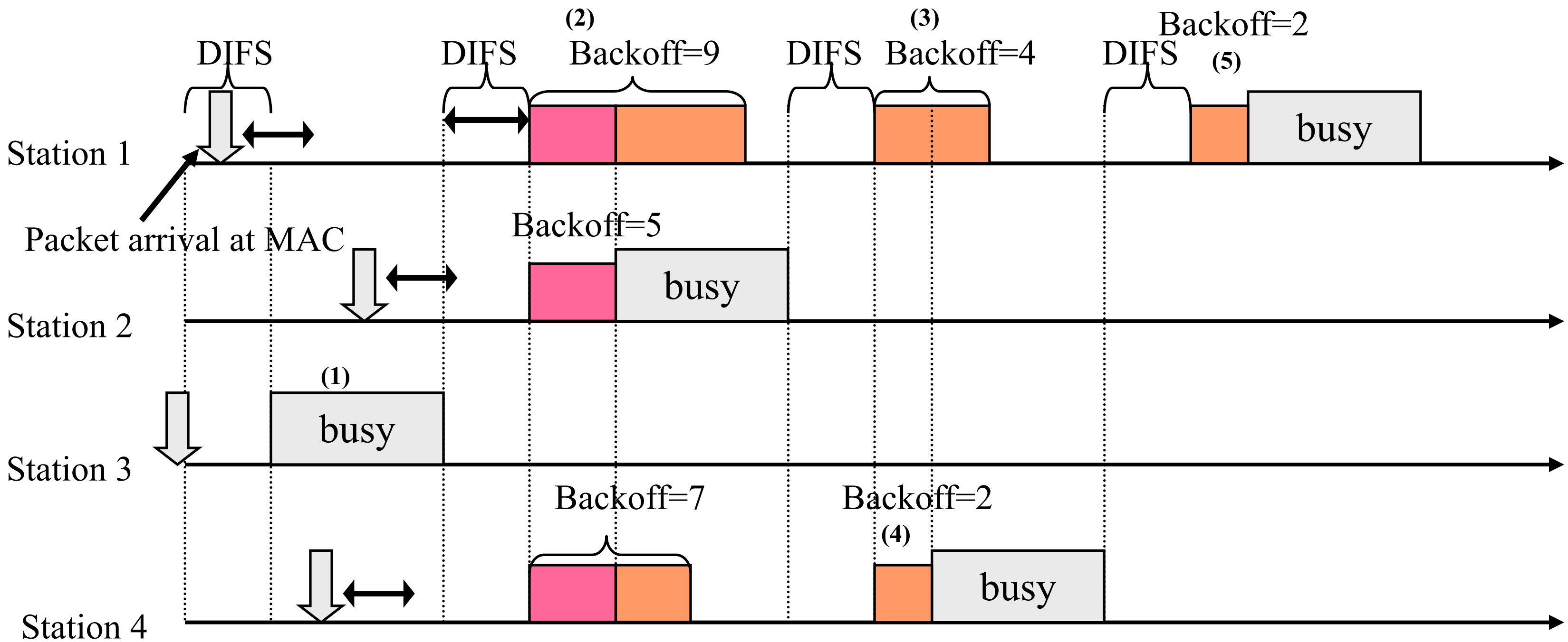


CSMA/CA Explained



DIFS – Distributed Inter Frame Spacing

Example of Backoff Intervals



(1)After packet arrival at MAC, station 3 senses medium free for DIFS, so it starts transmission immediately (without backoff interval).

(2) For station 1, 2, and 4, their DIFS intervals are interrupted by station 3. Thus, backoff intervals for station 1, 2, and 4, are generated randomly (i.e. 9, 5, and 7, respectively).

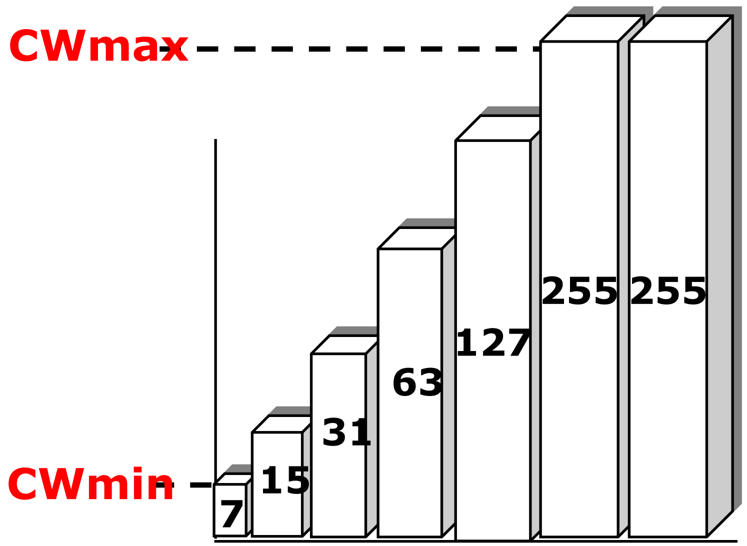
(3) After transmission of station 2, the remaining backoff interval of station 1 is (9-5)=4.

(4) After transmission of station 2, the remaining backoff interval of station 4 is (7-5)=2.

(5) After transmission of station 4, the remaining backoff interval of station 1 is (4-2)=2.

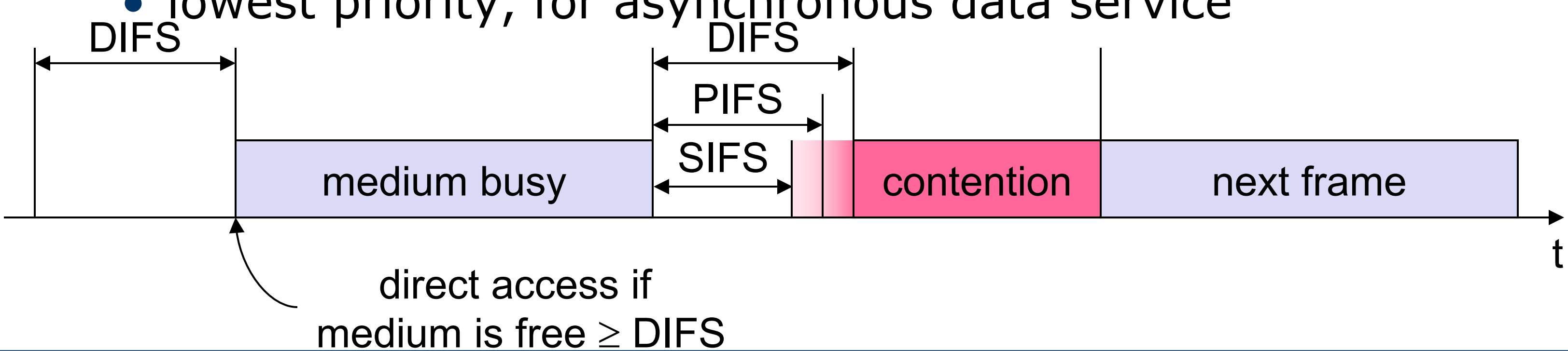
Random Backoff Time

- Backoff time = CW* Random() * Slot time
  - CW = starts at CWmin, and doubles after each failure until reaching CWmax (e.g., CWmin = 7, CWmax = 255)
  - Random() = (0,1)
  - Slot Time = Transmitter turn on delay + medium propagation delay + medium busy detect response time
  - CW : contention Window



Priorities

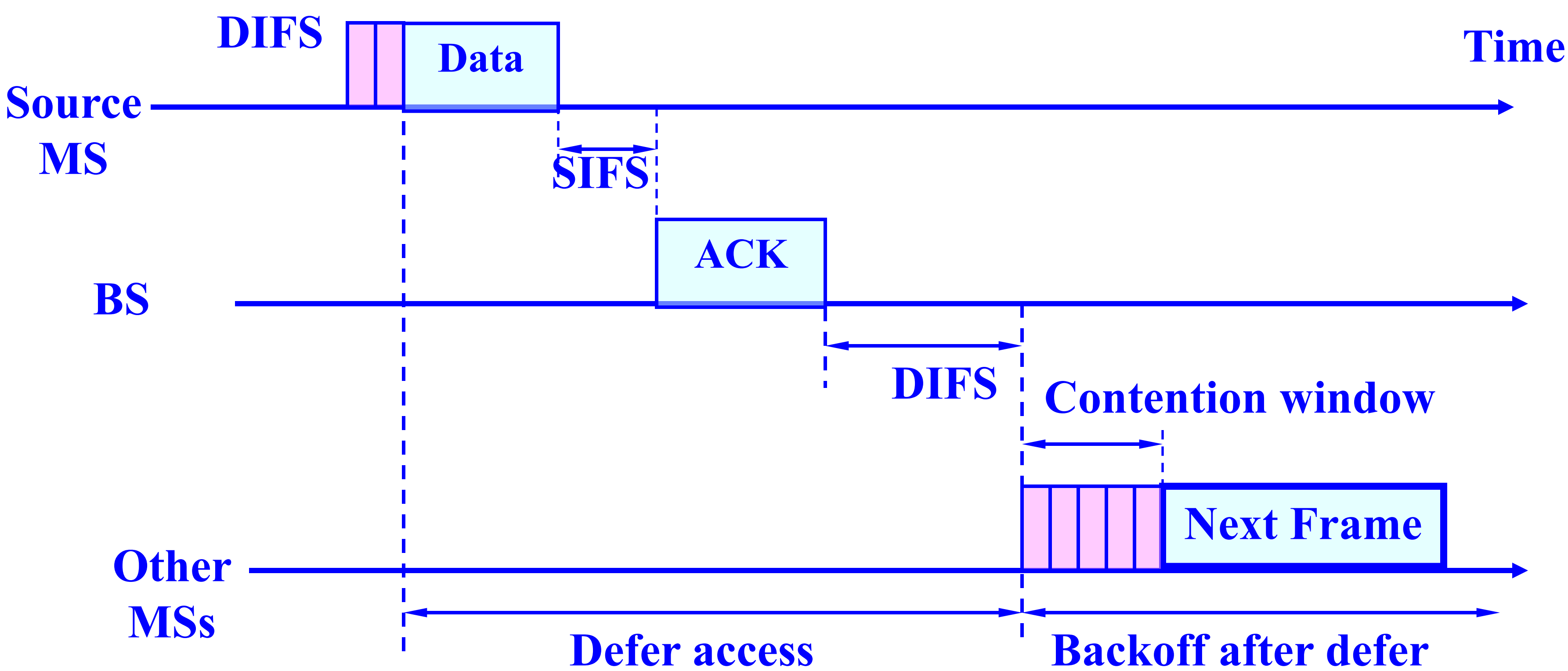
- Priorities
  - defined through different inter frame spaces
  - no guaranteed, hard priorities
  - SIFS (Short Inter Frame Spacing)
    - highest priority, for ACK, CTS, polling response
  - PIFS (PCF IFS)
    - Point coordination function (PCF) is an optional technique used to prevent collisions in centralised controlled WLANs.
    - medium priority, for time-bounded service using PCF
  - DIFS (DCF, Distributed Coordination Function IFS)
    - lowest priority, for asynchronous data service



CSMA/CA with ACK for Ad Hoc Networks

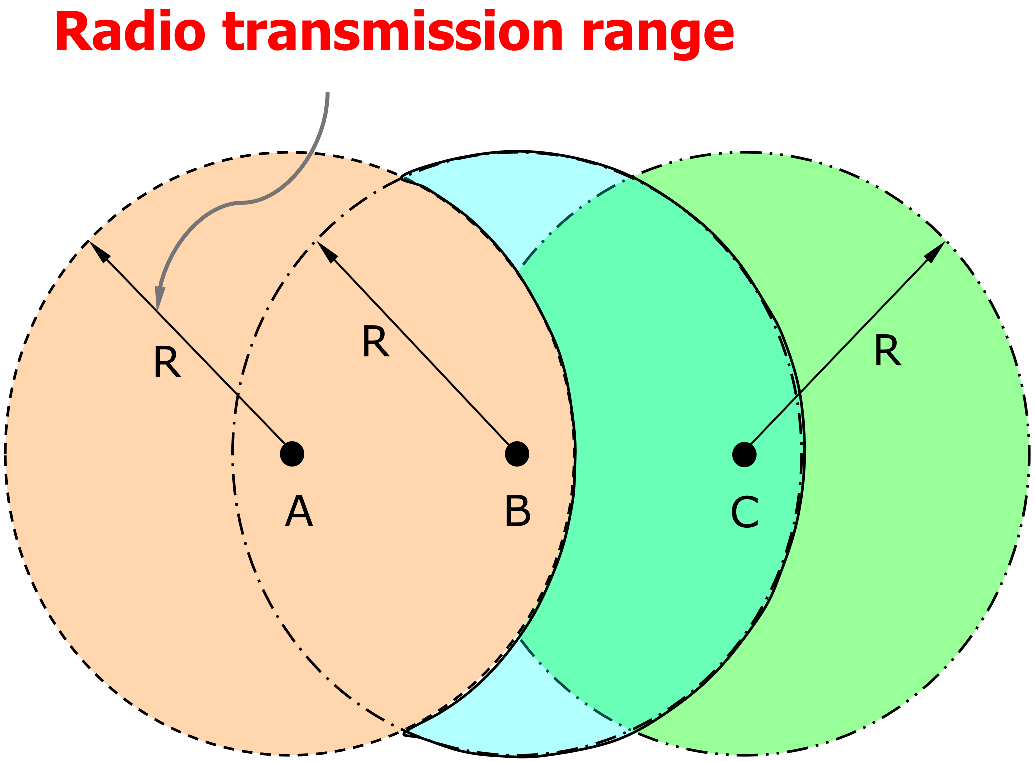
- **Immediate Acknowledgements from receiver upon reception of data frame without any need for sensing the medium**
- **ACK frame transmitted after time interval SIFS (*Short Inter-Frame Space*) (*SIFS* < *DIFS*)**
- **Receiver transmits ACK without sensing the medium**
- **If ACK is lost, retransmission done**

CSMA/CA/ACK



SIFS – Short Inter Frame Spacing

Hidden Terminal Problem

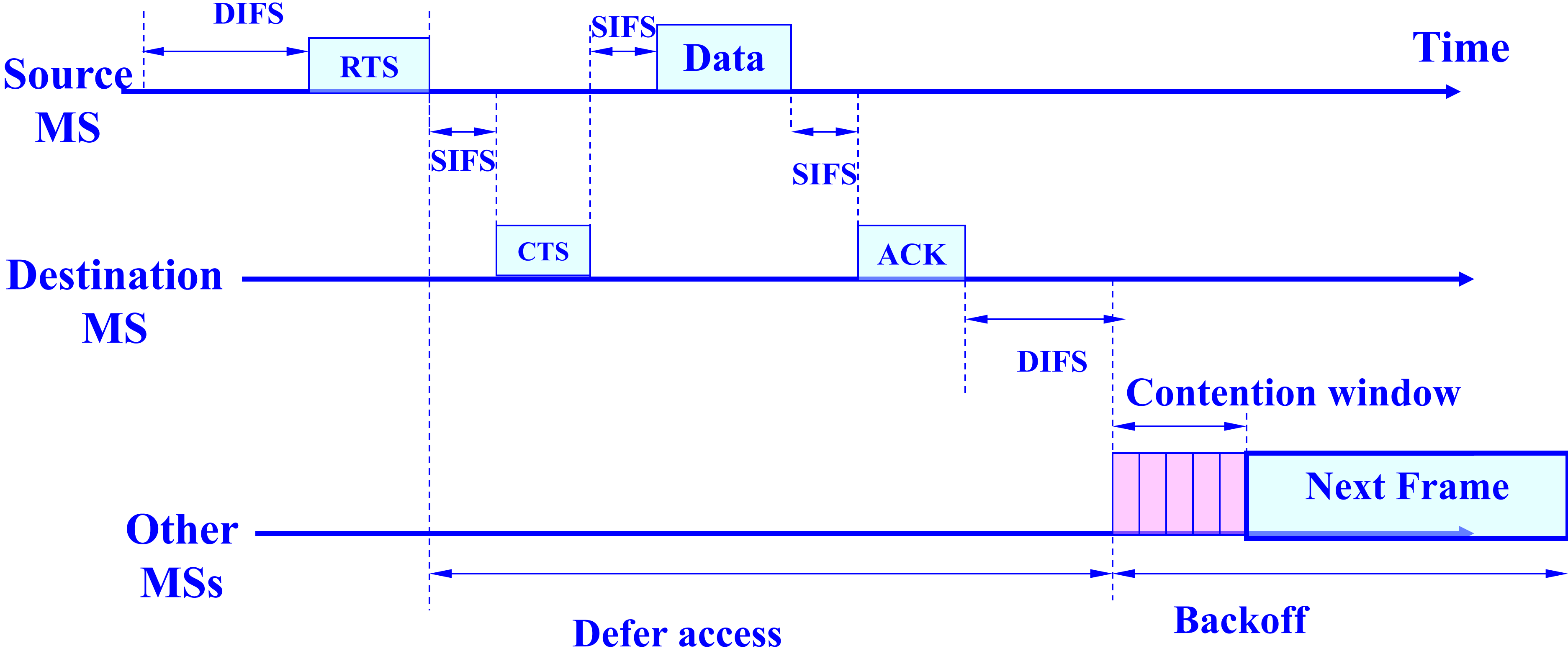


A and C are hidden with respect to each other

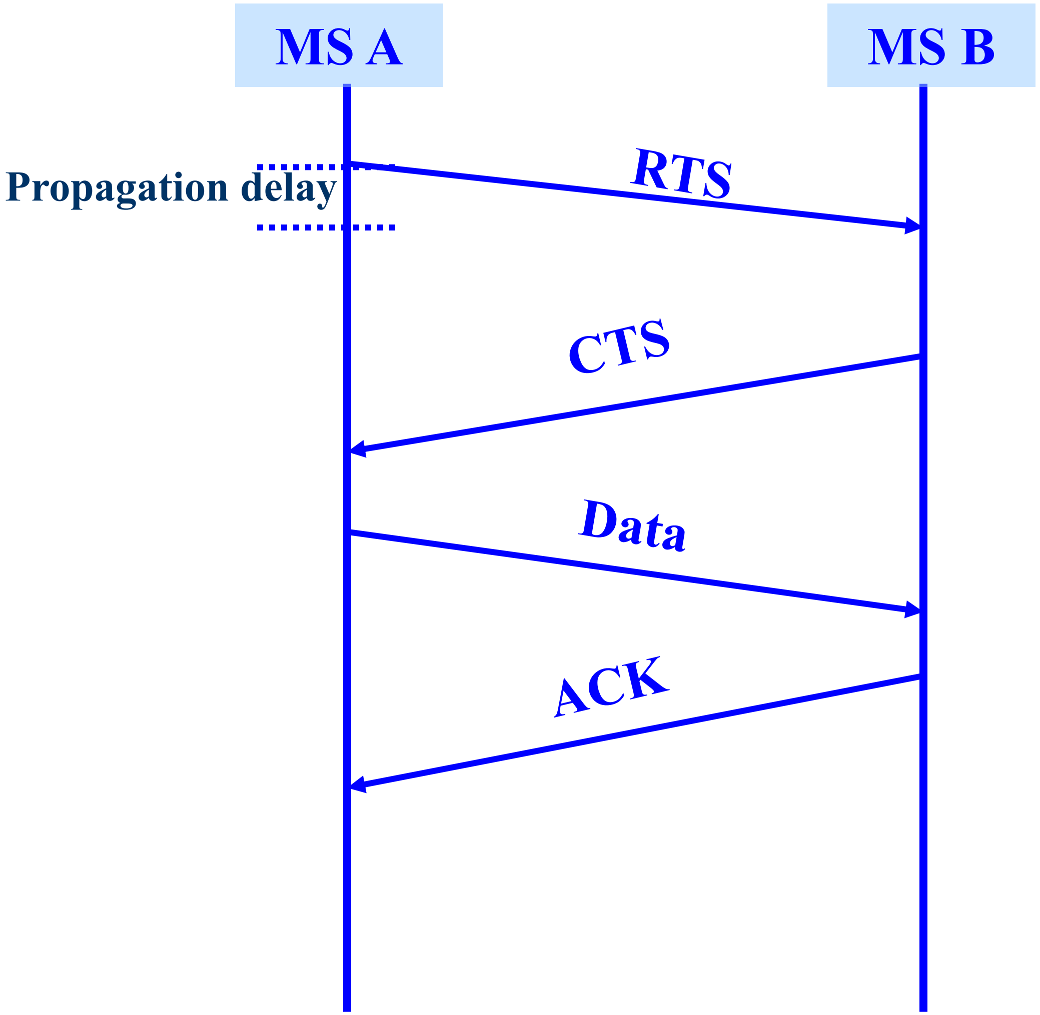
CSMA/CA with RTS/CTS for Hidden Terminal Problem

- **Transmitter sends an RTS (request to send) after medium has been idle for time interval more than DIFS**
- **Receiver responds with CTS (clear to send) after medium has been idle for SIFS**
- **Then Data is exchanged**
- **RTS/CTS is used for reserving channel for data transmission so that the collision can only occur in control message**

CSMA/CA with RTS/CTS

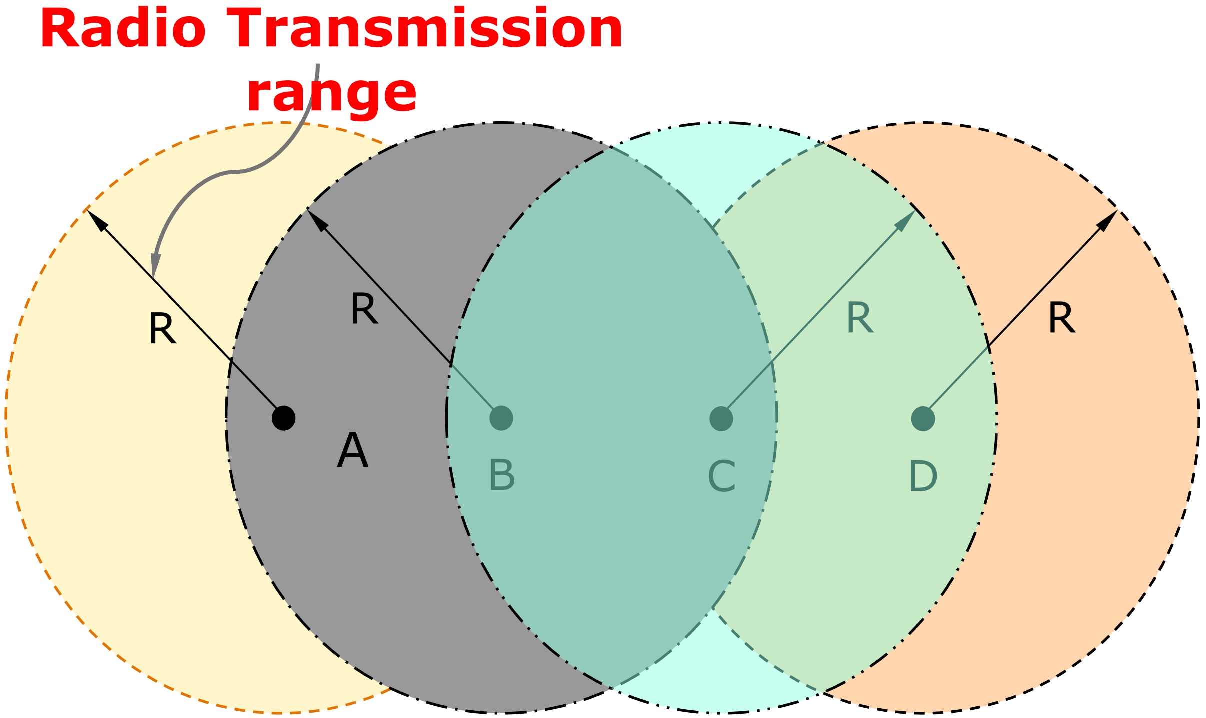


RTS/CTS



This helps avoid hidden terminal problem in Ad hoc networks

Exposed Terminal Problem



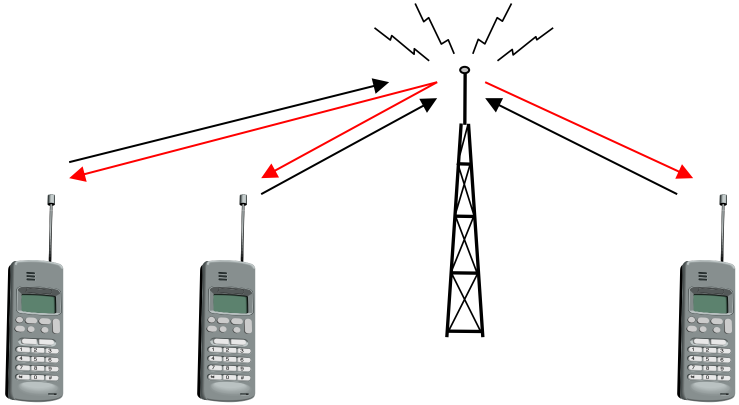
Transmission at B forces C (Exposed) to stop transmission to D

Polling mechanisms

- If one terminal can be heard by all others, this “central” terminal (a.k.a. base station) can poll all other terminals according to a certain scheme
  - now all schemes known from fixed networks can be used (typical mainframe - terminal scenario)
- Example: Randomly Addressed Polling
  - base station signals readiness to all mobile terminals
  - terminals ready to send can now transmit a random number without collision with the help of CDMA or FDMA (the random number can be seen as dynamic address)
  - the base station now chooses one address for polling from the list of all random numbers (collision if two terminals choose the same address)
  - the base station acknowledges correct packets and continues polling the next terminal
  - this cycle starts again after polling all terminals of the list

ISMA (Inhibit Sense Multiple Access)

- Current state of the medium is signaled via a "busy tone"
  - the base station signals on the downlink (base station to terminals) if the medium is free or not
  - terminals must not send if the medium is busy
  - terminals can access the medium as soon as the busy tone stops
  - the base station signals collisions and successful transmissions via the busy tone and acknowledgements, respectively (media access is not coordinated within this approach)
  - mechanism used, e.g., for CDPD (USA, integrated into AMPS)



Traffic Channel Allocation

Introduction

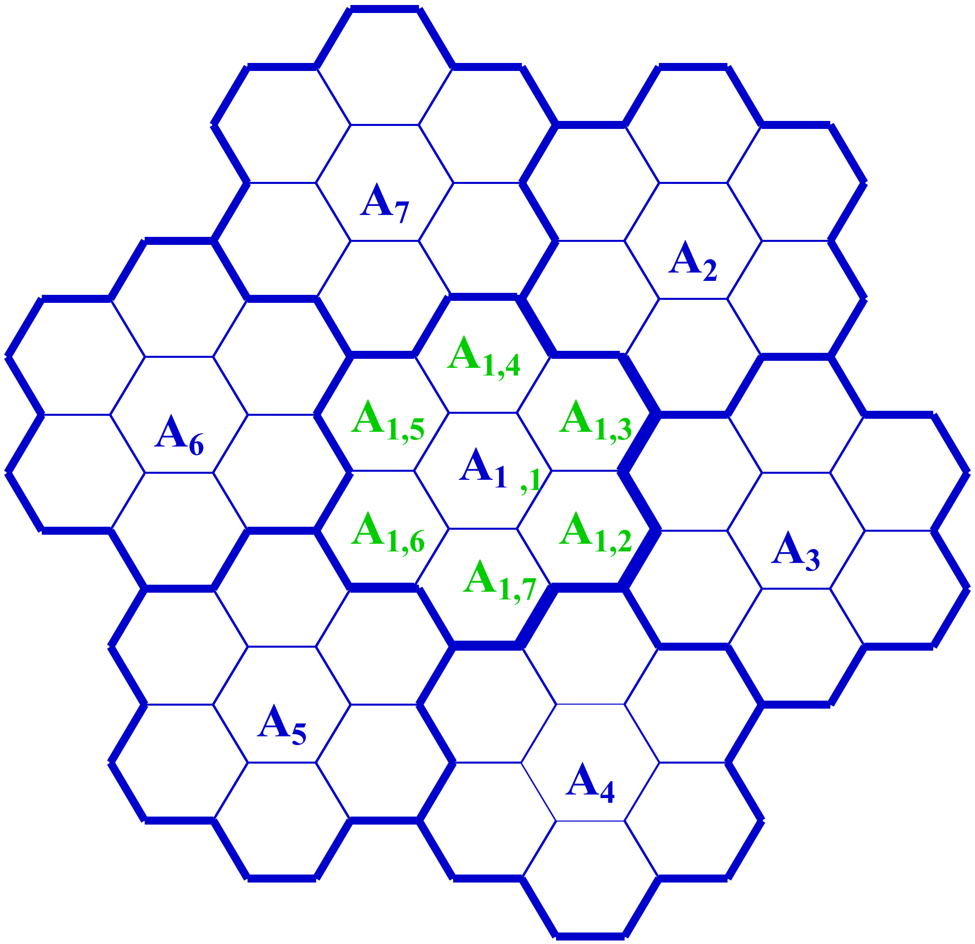
- **What is channel allocation?**
- **A given radio spectrum is to be divided into a set of disjointed channels that can be used simultaneously while minimizing interference in adjacent channel by allocating channels appropriately (especially for traffic channels)**
- **S_{total} channels equally partitioned among N cells and each cell with S channels as**

  $$S = S_{total}/N, \ \text{e.g., } 140/7=20$$

  - ✓ **$A_{1,1}$: Channels 1-20, $A_{1,2}$: Channels 21-40**
  - ✓ **$A_{1,3}$: Channels 41-60, $A_{1,4}$: Channels 61-80**
  - ✓ **$A_{1,5}$: Channels 81-100, $A_{1,6}$: Channels 101-120**
  - ✓ **$A_{1,7}$: Channels 120-140**

Introduction

- **Channel allocation schemes can be divided in general into Static versus Dynamic**
  - **Fixed Channel Allocation (FCA);**
  - **Dynamic Channel Allocation (DCA);**
  - **Hybrid Channel Allocation (HCA).**



Fixed Channel Allocation (FCA)

- In FCA, a set of channels is permanently allocated to each cell
- Number of available channels *S* is divided into sets, the minimum number of channel sets *N* required is related to the frequency reuse distance *D* as follows:

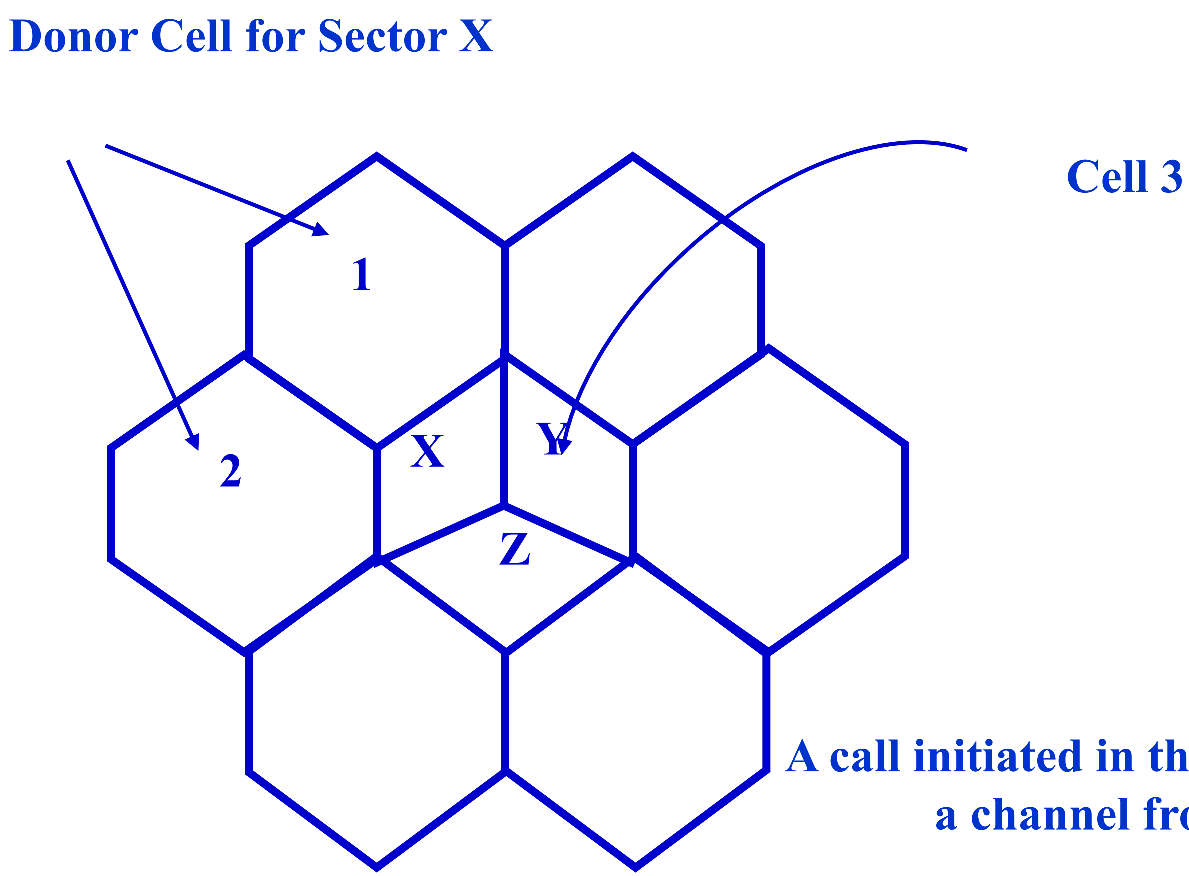
$$N = D^2 / 3R^2 \quad or \quad \sqrt{N} = \frac{D}{\sqrt{3}R}$$

- If a cell of cluster A_1 borrows channel, there should not be interference with cells A_2, A_3, A_4, A_5, A_6, and A_7

Simple Borrowing Schemes

- **In SB schemes, cell (*acceptor cell*) that has used all its nominal channels can borrow free channels from its neighboring cell (*donor cell)* to accommodate new calls.**
- **Borrowing can be done from an adjacent cell which has largest number of free channels (*borrowing from the richest*)**
- **Select the first free channel found for borrowing using a search algorithm (*borrow first available scheme*)**
- **Return the borrowed channel when channel becomes free in the cell (*basic algorithm with reassignment*)**
- **To be available for borrowing, the channel must not interfere with existing calls, as shown in the next figure**

Simple Channel Borrowing Schemes

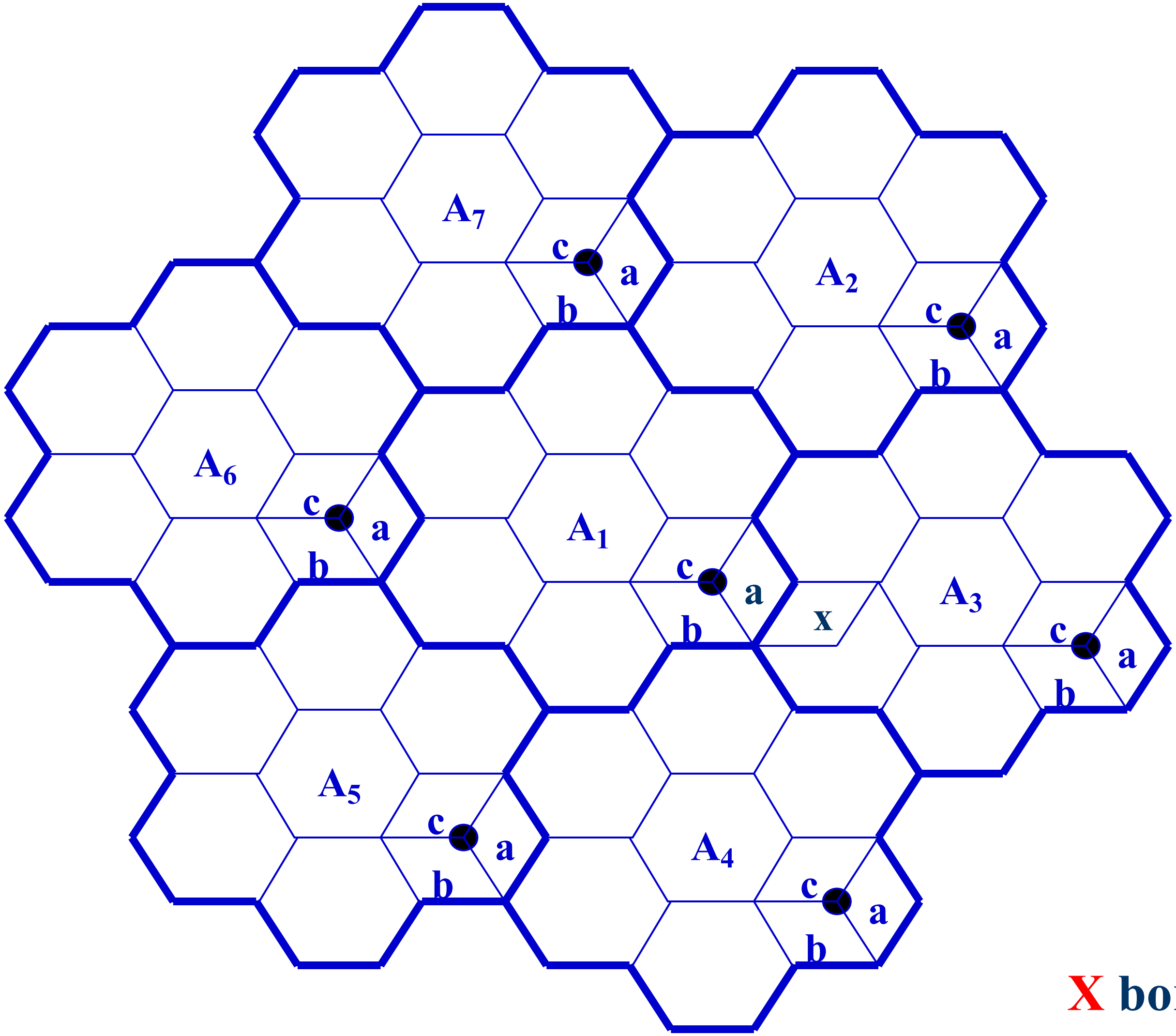


A call initiated in the sector X of cell 3 can borrow a channel from adjacent cells 1 or 2

Complex Borrowing Scheme

- **Partition the traffic channels into two groups, one group assigned to each cell permanently and the second group to be borrowed by neighboring cells**
- **The ratio between the two groups is determined a priori**

Complex Channel Borrowing using Sectored Cell-based Wireless System



X borrows some channels from a

Simple Channel Borrowing Schemes

Scheme	Description
Simple Borrowing (SB)	A nominal channel set is assigned to a cell, as in the FCA case. After all nominal channels are used, an available channel from a neighboring cell is borrowed
Borrow from the Richest (SBR)	Channels that are candidates for borrowing are available channels nominally assigned to one of the adjacent cells of the acceptor cell. If more than one adjacent cell has channels available for borrowing, a channel is borrowed from the cell with the greatest number of channels available for borrowing
Basic Algorithm (BA)	This is an improved version of the SBR strategy which takes channel blocking into account when selecting a candidate channel for borrowing. This scheme tried to minimize the future call blocking probability in the cell that is most affected by the channel borrowing
Basic Algorithm with Reassignment	This scheme provides for the transfer of a call from a borrowed channel to a nominal channel whenever a nominal channel becomes available
Borrow First Available	Instead of trying to optimize when borrowing, this algorithm selects the first candidate channel it finds

Dynamic Channel Allocation (DCA)

- **In DCA schemes, all channels are kept in a central pool and are assigned dynamically to new calls as they arrive in the system**
- **After each call is completed, the channel is returned to the central pool. Select the most appropriate channel for any call based simply on current allocation and current traffic, with the aim of minimizing the interference**
- **DCA scheme can overcome the problem of FCA scheme. However, variations in DCA schemes center around the different cost functions used for selecting one of the candidate channels for assignment**

Dynamic Channel Allocation (DCA)

- DCA schemes can be centralized or distributed
- The centralized DCA scheme involves a single controller selecting a channel for each cell
- The distributed DCA scheme involves a number of controllers scattered across the network (MSCs)
- Centralized DCA schemes can theoretically provide the best performance. However, the enormous amount of computation and communication among BSs leads to excessive system latencies and render centralized DCA schemes impractical. Nevertheless, centralized DCA schemes often provide a useful benchmark to compare practical decentralized DCA schemes

Centralized DCA

- **For a new call, a free channel from the central pool is selected that would maximize the number of members in its co-channel set**

- **Minimize the mean square of distance between cells using the same channel**

Centralized DCA Schemes

Scheme	Description
First Available (FA)	Among the DCA schemes the simplest one is the FA strategy. In FA, the first available channel within the reuse distance encountered during a channel search is assigned to the call. The FA strategy minimizes the system computational time
Locally Optimized Dynamic Assignment (LODA)	The channel selection is based on the future blocking probability in the vicinity of the cell where a call is initiated
Selection with Maximum Usage on the Reuse Ring (RING)	A candidate channel is selected which is in use in the most cells in the co-channel set. If more than one channel has this maximum usage, an arbitrary selection among such channel is made to serve the call. If none is available, then the selection is made based on the FA scheme

Centralized DCA Schemes

Scheme	Description
Mean Square (MSQ)	The MSQ scheme selects the available channel that minimizes the mean square of the distance among the cells using the same channel
1-clique	This scheme uses a set of graphs, one for each channel, expressing the non co-channel interference structure over the whole service area for that channel

Distributed DCA Schemes

- **Based on one of the three parameters:**
  - **Co-channel distance**
    - co-channel cells in the neighborhood not using the channel
    - sometimes adjacent channel interference taken into account
  - **Signal strength measurement**
    - expected CCIR (co-channel interference above threshold

Comparison between FCA and DCA

FCA	DCA
▪ Performs better under heavy traffic	▪ Performs better under light/moderate traffic
▪ Low flexibility in channel assignment	▪ Flexible channel allocation
▪ Maximum channel reusability	▪ Not always maximum channel reusability
▪ Sensitive to time and spatial changes	▪ Insensitive to time and spatial changes
▪ Unstable grade of service per cell in an interference cell group	▪ Stable grade of service per cell in an interference cell group
▪ High forced call termination probability	▪ Low to moderate forced call termination probability
▪ Suitable for large cell environment	▪ Suitable in microcellular environment
▪ Low flexibility	▪ High flexibility

Comparison between FCA and DCA

FCA	DCA
▪ Radio equipment covers all channels assigned to the cell	▪ Radio equipment covers the temporary channel assigned to the cell
▪ Independent channel control	▪ Fully centralized to fully distributed control dependent on the scheme
▪ Low computational effort	▪ High computational effort
▪ Low call set up delay	▪ Moderate to high call set up delay
▪ Low implementation complexity	▪ Moderate to high implementation complexity
▪ Complex, labor intensive frequency planning	▪ No frequency planning
▪ Low signaling load	▪ Moderate to high signaling load
▪ Centralized control	▪ Centralized, distributed control depending on the scheme

Other Channel Allocation Schemes

- **Based on different criterion being used as a potential way of optimizing the performance, many other channel allocation schemes have been suggested**
  - **Hybrid Channel Allocation (HCA)**
  - **Flexible Channel Allocation (FCA)**
  - **Handoff Channel Allocation (HCA)**

Hybrid Channel Allocation (HCA)

- HCA schemes are the combination of both FCA and DCA techniques
- In HCA schemes, the total number of channels available for service is divided into fixed and dynamic sets
  - The fixed set contains a number of nominal channels that are assigned to cells as in the FCA schemes and, in all cases, are to be preferred for use in their respective cells
  - The dynamic set is shared by all users in the system to increase flexibility

Example: When a call requires service from a cell and all of its nominal channels are busy, a channel from the dynamic set is assigned to the call

Hybrid Channel Allocation (HCA)

- **Request for a channel from the dynamic set is initiated only when the cell has exhausted using all its channels from the fixed set**
- **Optimal ratio: ratio of number of fixed and dynamic channels**
  - ✓ **3:1 (fixed to dynamic), provides better service than fixed scheme for traffic load up to 50% (105 versus 35 channels)**
  - ✓ **Beyond 50% traffic load fixed scheme perform better**
  - ✓ **For dynamic, with traffic load of 15% to 40%, better results are found with HCA**

Flexible Channel Allocation (FCA)

- **Similar to hybrid scheme with channels divided into fixed and flexible (emergency) sets**
- **Fixed sets used to handle lighter loads**
- **Variations in traffic (peaks in time and space) are needed to schedule emergency channels**
- **Two types: Scheduled and Predictive**
- ***Scheduled*: Prior estimate is done about traffic change**
- ***Predictive*: Traffic intensity and blocking probability is monitored in each cell all the time**