Telecom Systems (Week 4)

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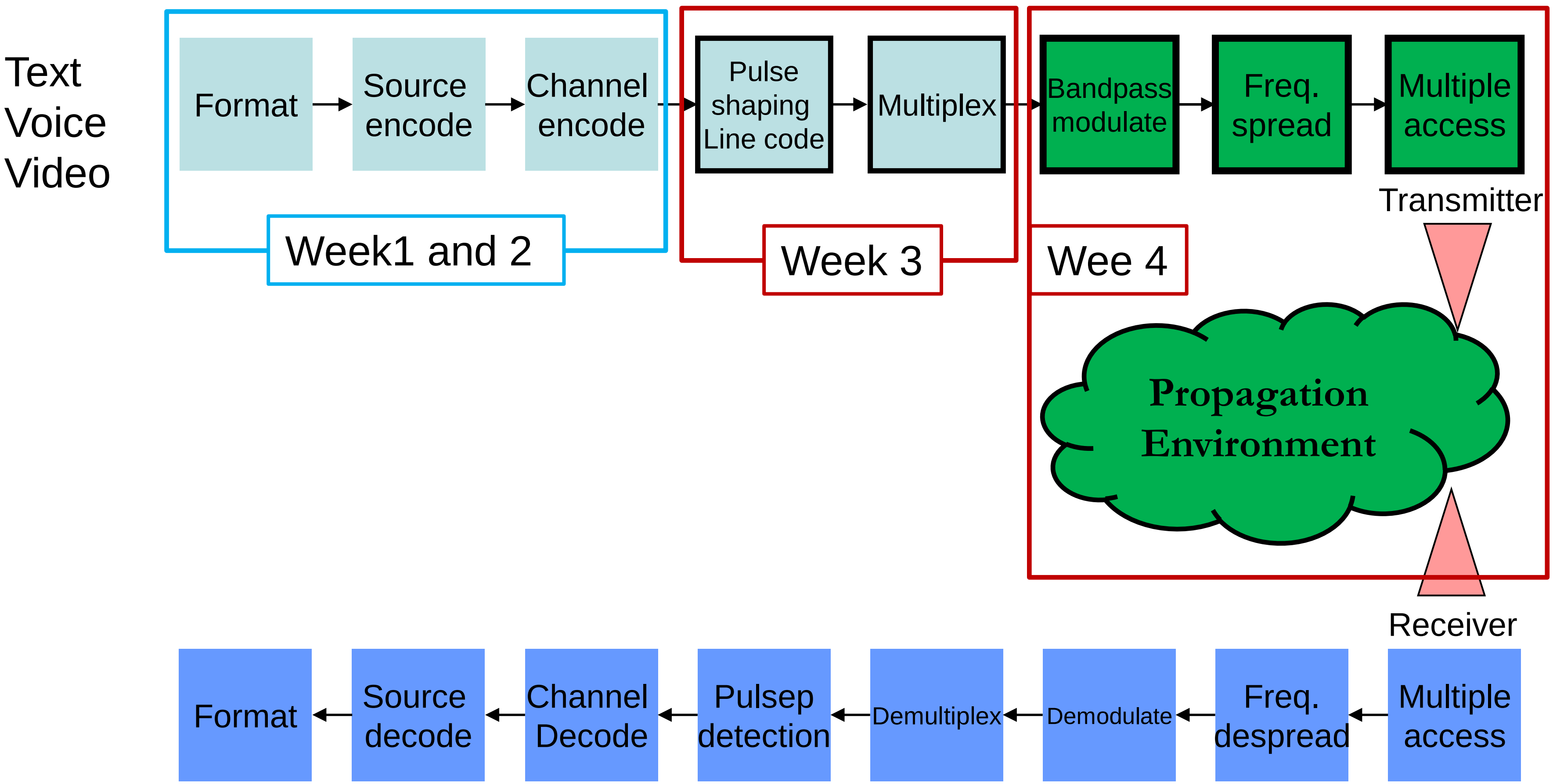
Overview of Wireless Communication System



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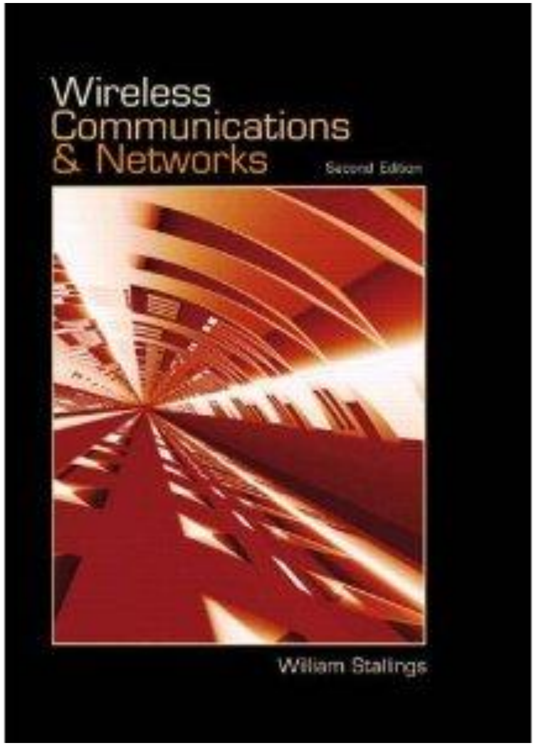
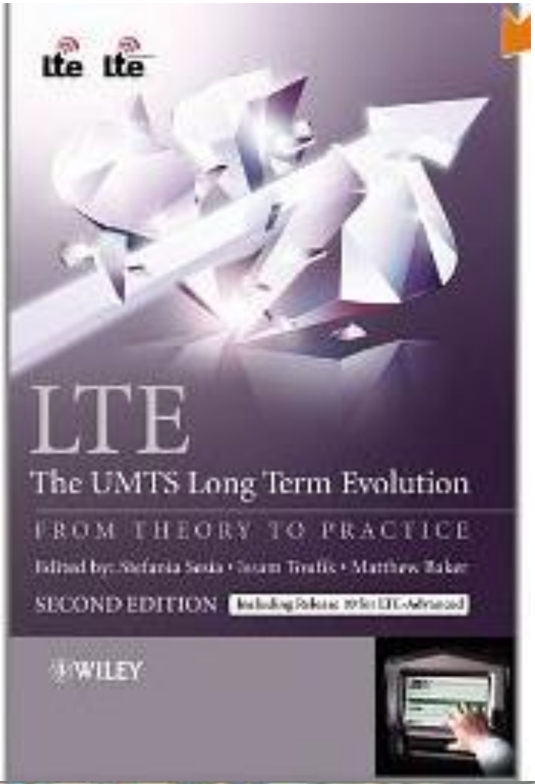
Reference books for week 4

Wireless Communications and Networks, Second Edition. by ***William Stallings***



LTE: The UMTS Long Term Evolution: from Theory to Practice ***by Stefania Sesia, Matthew Baker and Mr Issam Toufik***



Modulation Techniques

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Reasons for Choosing Encoding Techniques

- Digital data, digital signal
  - Equipment less complex and expensive than digital-to-analog modulation equipment
- Analog data, digital signal
  - Permits use of modern digital transmission and switching equipment
- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - E.g., optical fiber and unguided media
- Analog data, analog signal
  - Analog data in electrical form can be transmitted easily and cheaply
  - Done with voice transmission over voice-grade lines

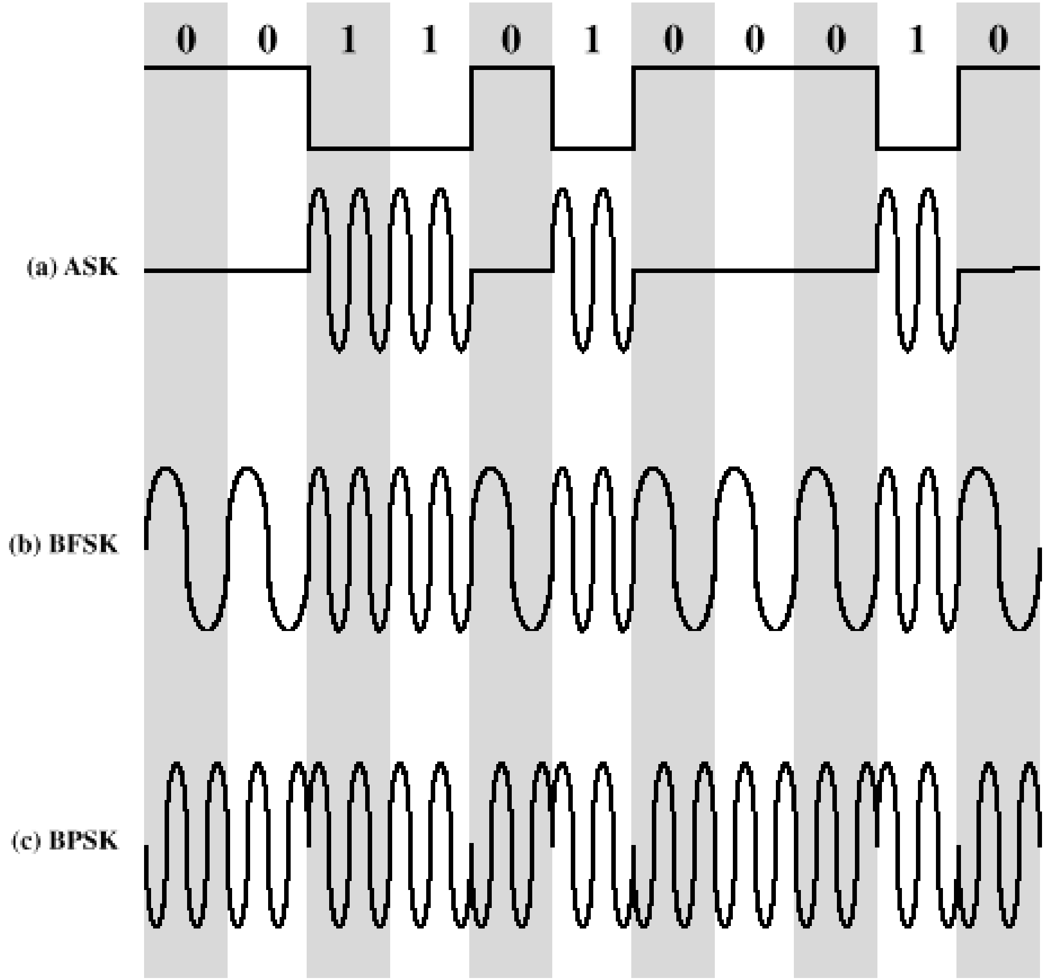
Signal Encoding Criteria

- What determines how successful a receiver will be in interpreting an incoming signal?
  - Signal-to-noise ratio
  - Data rate
  - Bandwidth
- An increase in data rate increases bit error rate
- An increase in SNR decreases bit error rate
- An increase in bandwidth allows an increase in data rate

Basic Encoding Techniques

- Digital data to analog signal
  - Amplitude-shift keying (ASK)
    - Amplitude difference of carrier frequency
  - Frequency-shift keying (FSK)
    - Frequency difference near carrier frequency
  - Phase-shift keying (PSK)
    - Phase of carrier signal shifted

Basic Encoding Techniques



Modulation of Analog Signals for Digital Data

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 $A\cos(2\pi f_c t)$

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

Multiple Frequency-Shift Keying (MFSK)

- More than two frequencies are used
- More bandwidth efficient but more susceptible to error

$$s_i(t) = A\cos 2\pi f_i t \quad 1 \le i \le M$$

- $f_i = f_c + (2i - 1 - M)f_d$
- f_c = the carrier frequency
- f_d = the difference frequency
- M = number of different signal elements = 2^L
- L = number of bits per signal element

Multiple Frequency-Shift Keying (MFSK)

- To match data rate of input bit stream, each output signal element is held for:

  $T_s = LT$ seconds

  where T is the bit period (data rate = $1/T$)

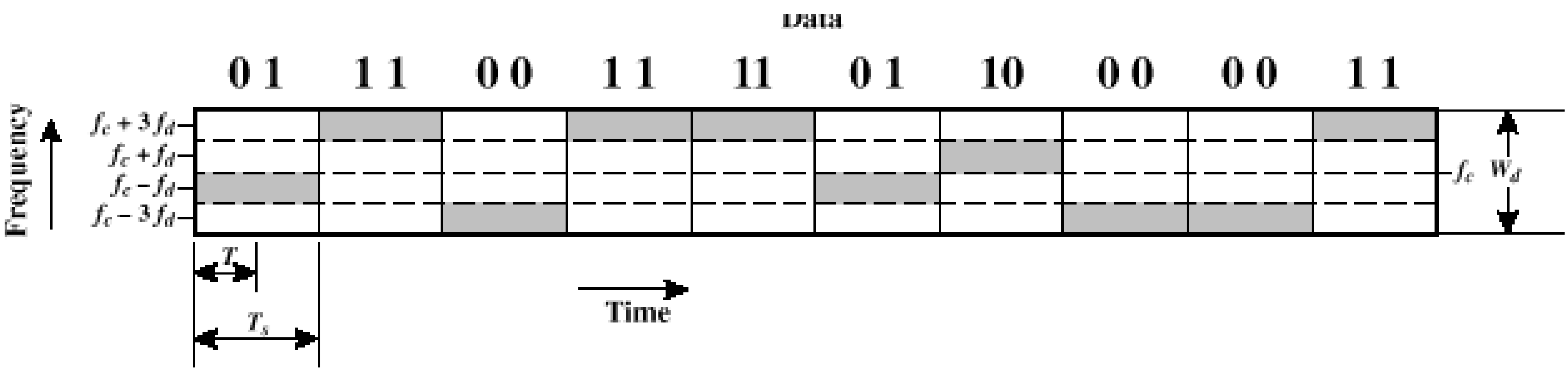
- So, one signal element encodes L bits, total bandwidth required

$$2Mf_d$$

- Minimum frequency separation required $2f_d = 1/T_s$
- Therefore, modulator requires a bandwidth of

$$W_d = 2^L/LT = M/T_s$$

Multiple Frequency-Shift Keying (MFSK)



MFSK Frequency Use (M=4)

Phase-Shift Keying (PSK)

- Two-level PSK (BPSK)
  - Uses two phases to represent binary digits

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

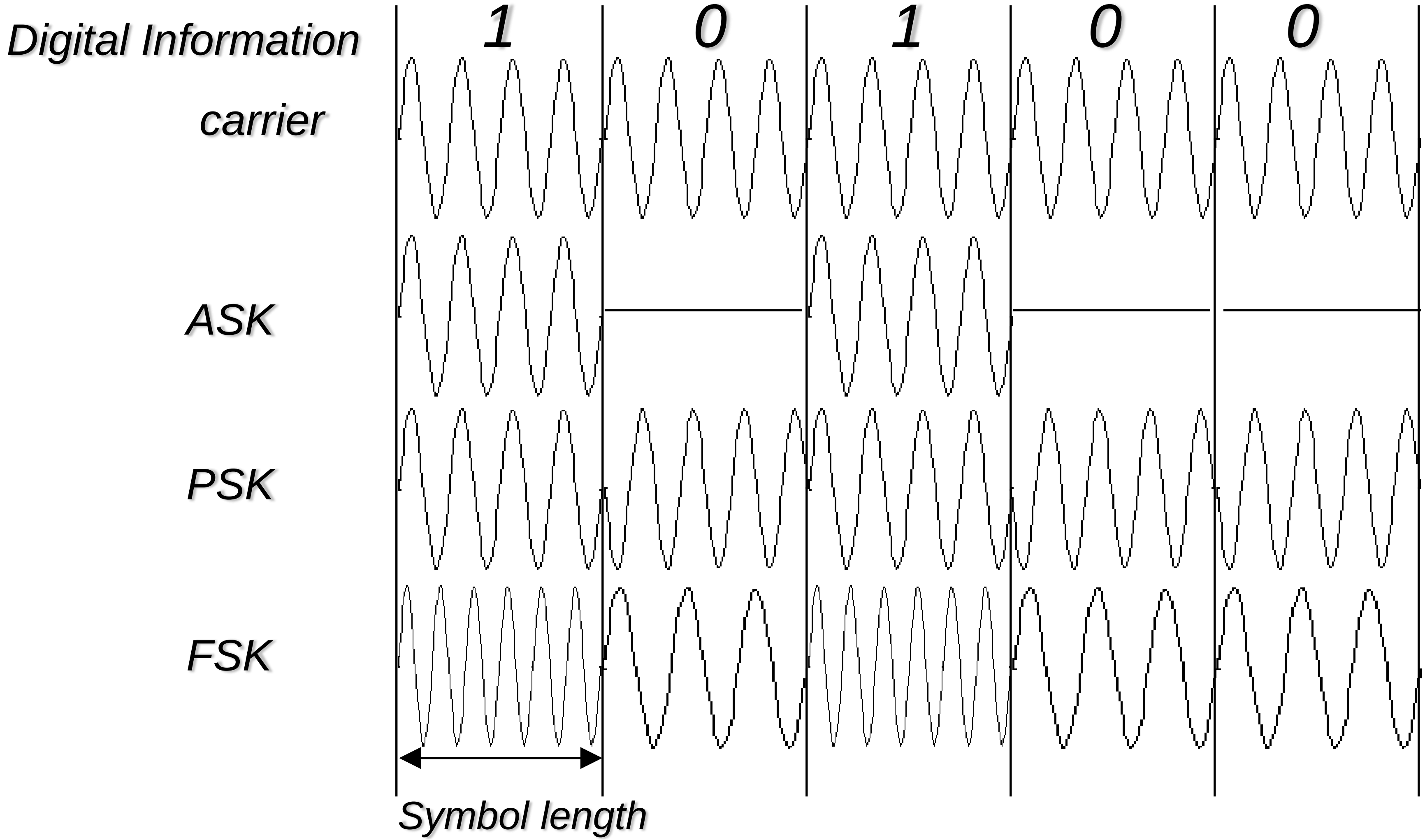
$$= \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ -A\cos(2\pi f_c t) & \text{binary } 0 \end{cases}$$

Phase-Shift Keying (PSK)

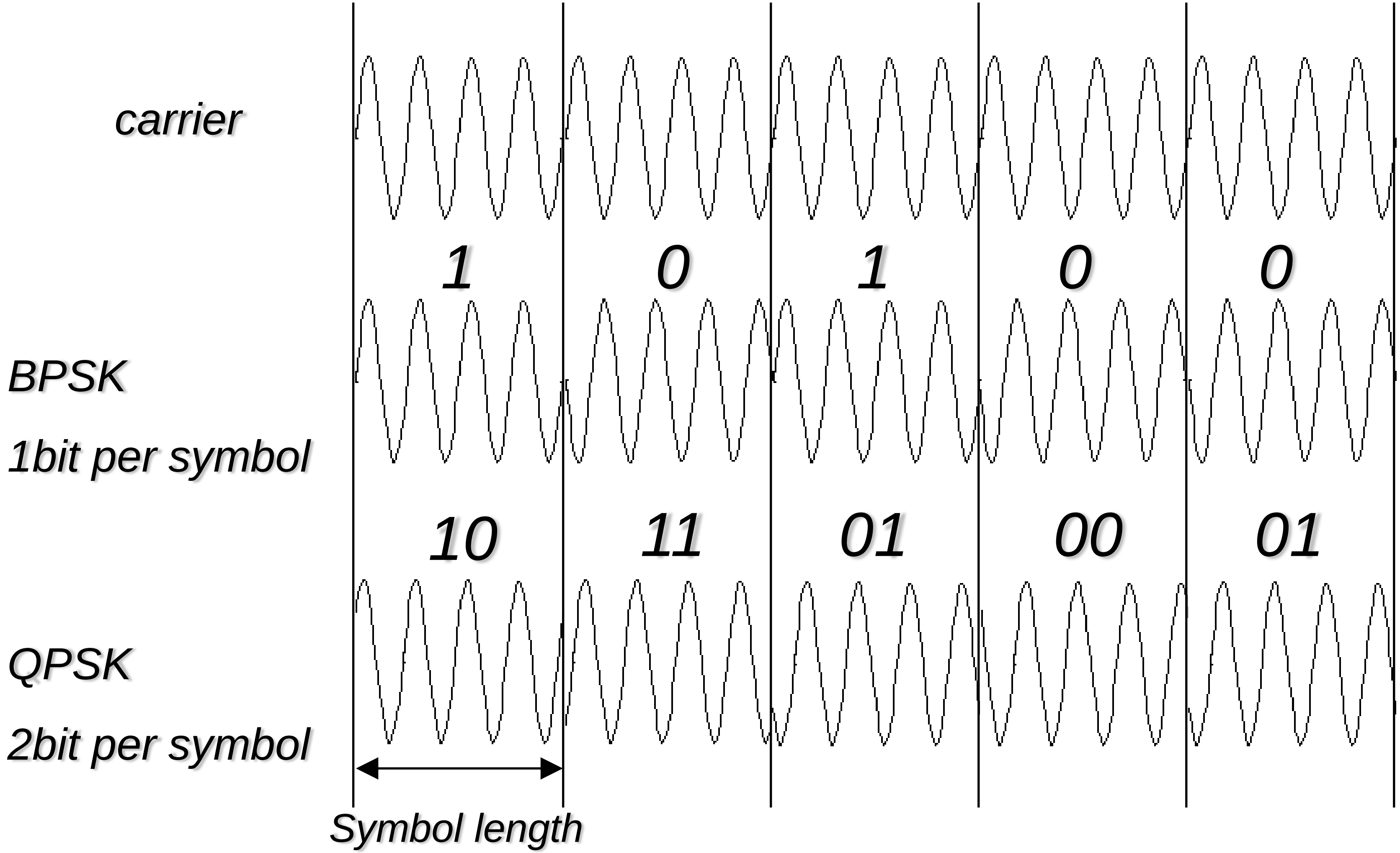
- Four-level PSK (QPSK)
  - Each element represents more than one bit

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

Symbol Waveform



Multi bit modulation



Mathematical expression of digital modulation

- Transmission signal can be expressed as follows

$$s(t) = \cos(2\pi \cdot f_c \cdot t + \theta_k)$$

$$= \cos\theta_k \cdot \cos(2\pi \cdot f_c \cdot t) - \sin\theta_k \cdot \sin(2\pi \cdot f_c \cdot t)$$

$$a_k = \cos\theta_k, \quad b_k = \sin\theta_k$$

$$s(t) = \mathrm{Re}[(a_k + jb_k)e^{j2\pi fc \cdot t}]$$

- s(t) can be expressed by complex base-band signal $(a_k + jb_k)e^{j2\pi fc \cdot t}$

$e^{j2\pi fc \cdot t}$ *Indicates carrier sinusoidal*

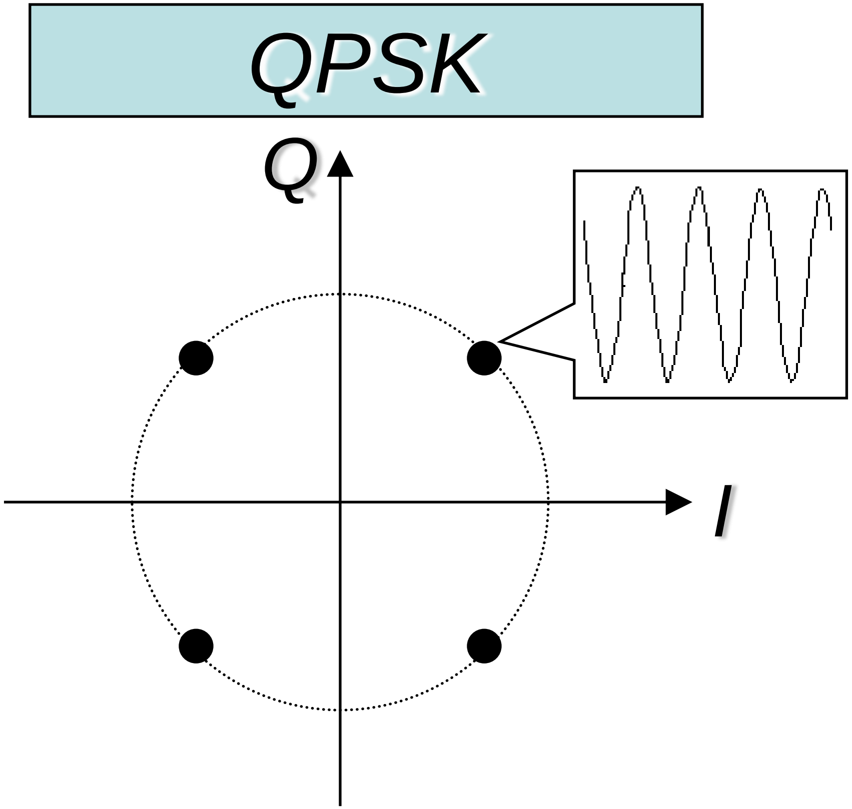
$(a_k + jb_k)$ *Digital modulation*

Digital modulation can be expressed by the complex number

Constellation map

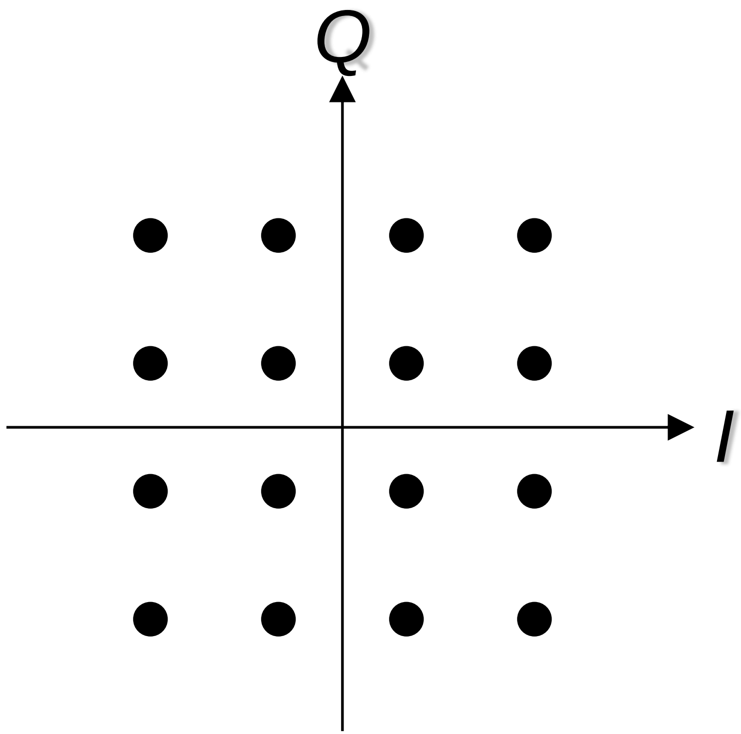
- $(a_k + jb_k)$ is plotted on I(real)-Q(imaginary) plane

data	Phase	a_k	b_k
00	π/4	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
01	3π /4	$-\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
11	5π /4	$-\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$
10	7π /4	$\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$

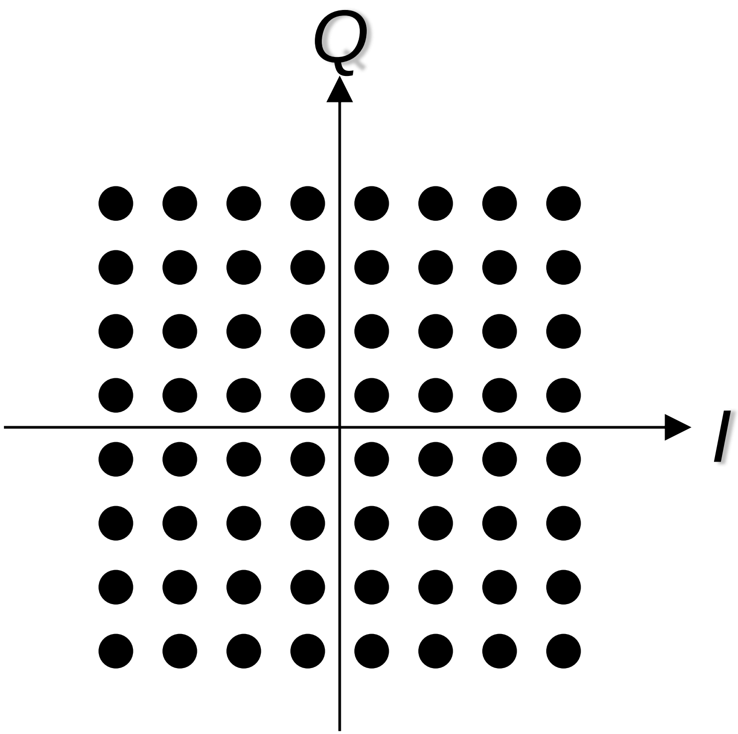


Quadrature Amplitude Modulation (QAM)

16QAM



64QAM

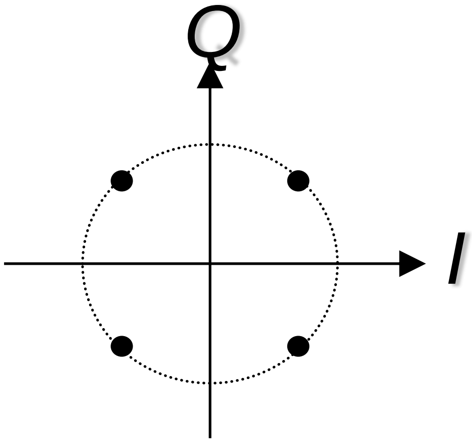


Summary of digital modulation

- Type of modulation: ASK,PSK,FSK,QAM
- OFDM uses PSK and QAM
- Digital modulation is mathematically characterized by the coefficient of complex base-band signal

$$(a_k + jb_k)$$

- Plot of the coefficients gives the constellation map



Spread Spectrum (Freq. Spread)

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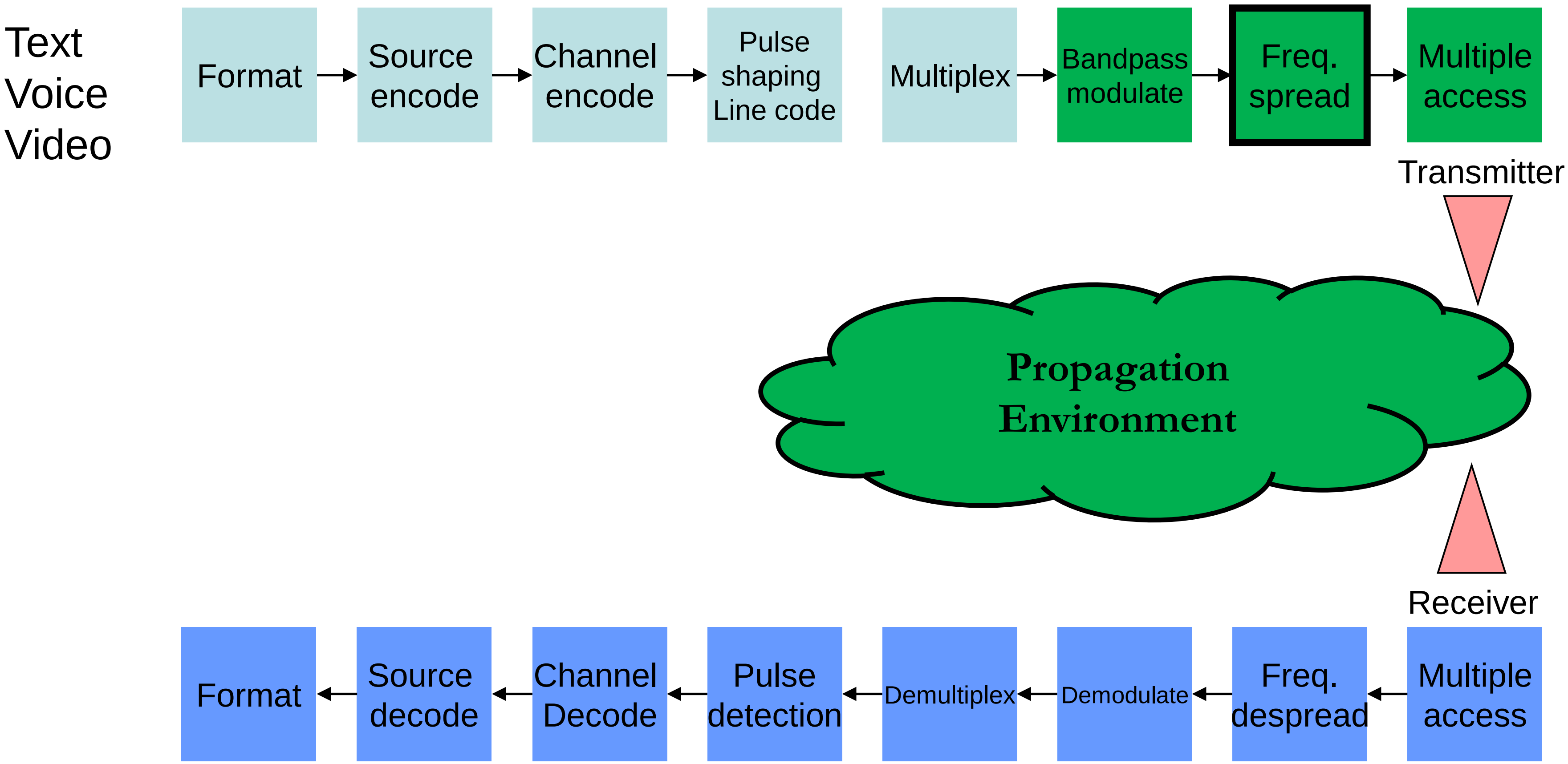
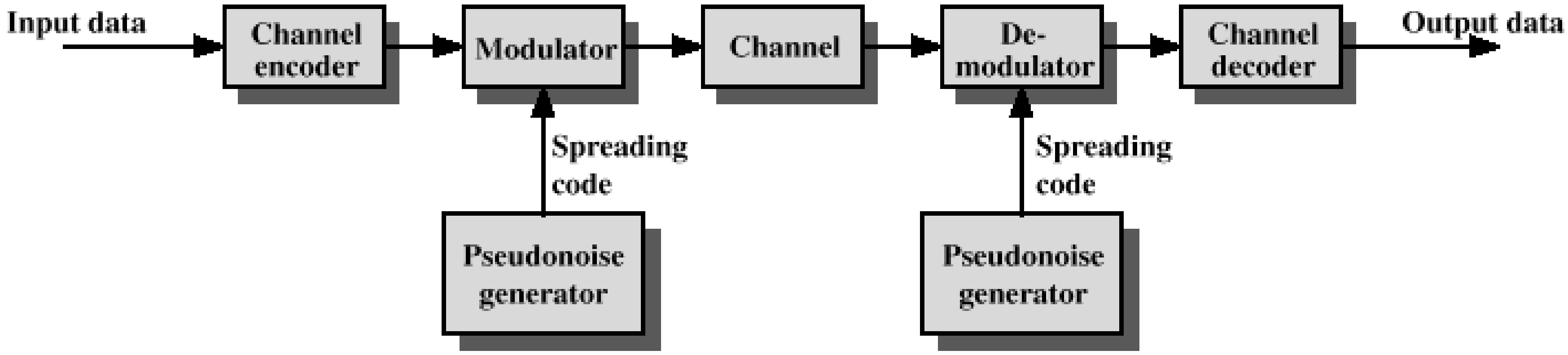
Overview of Wireless Communication System



Spread Spectrum

- Input is fed into a channel encoder
  - Produces analog signal with narrow bandwidth
- Signal is further modulated using sequence of digits
  - Spreading code or spreading sequence
  - Generated by pseudonoise, or pseudo-random number generator
- Effect of modulation is to increase bandwidth of signal to be transmitted

Spread Spectrum



General Model of Spread Spectrum Digital Communication System

1. Frequency Hoping Spread Spectrum (FHSS)
2. Direct Sequence Spread Spectrum (DSSS)

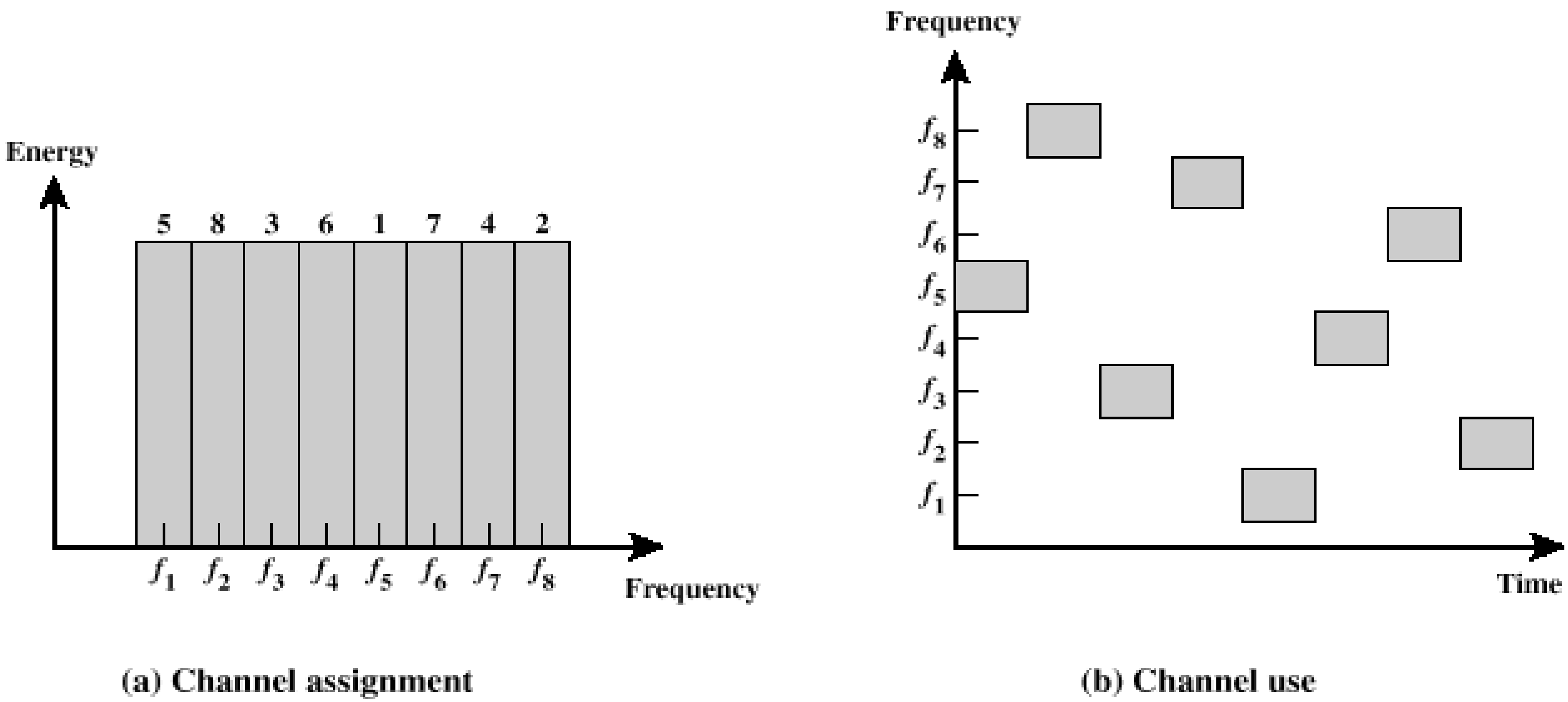
Frequency Hoping Spread Spectrum (FHSS)

- Signal is broadcast over seemingly random series of radio frequencies
  - A number of channels 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

Frequency Hoping Spread Spectrum

- Channel sequence dictated by spreading code
- Receiver, hopping between frequencies in synchronization with transmitter, picks up message
- Advantages
  - Eavesdroppers hear only unintelligible blips
  - Attempts to jam signal on one frequency succeed only at knocking out a few bits

Frequency Hoping Spread Spectrum

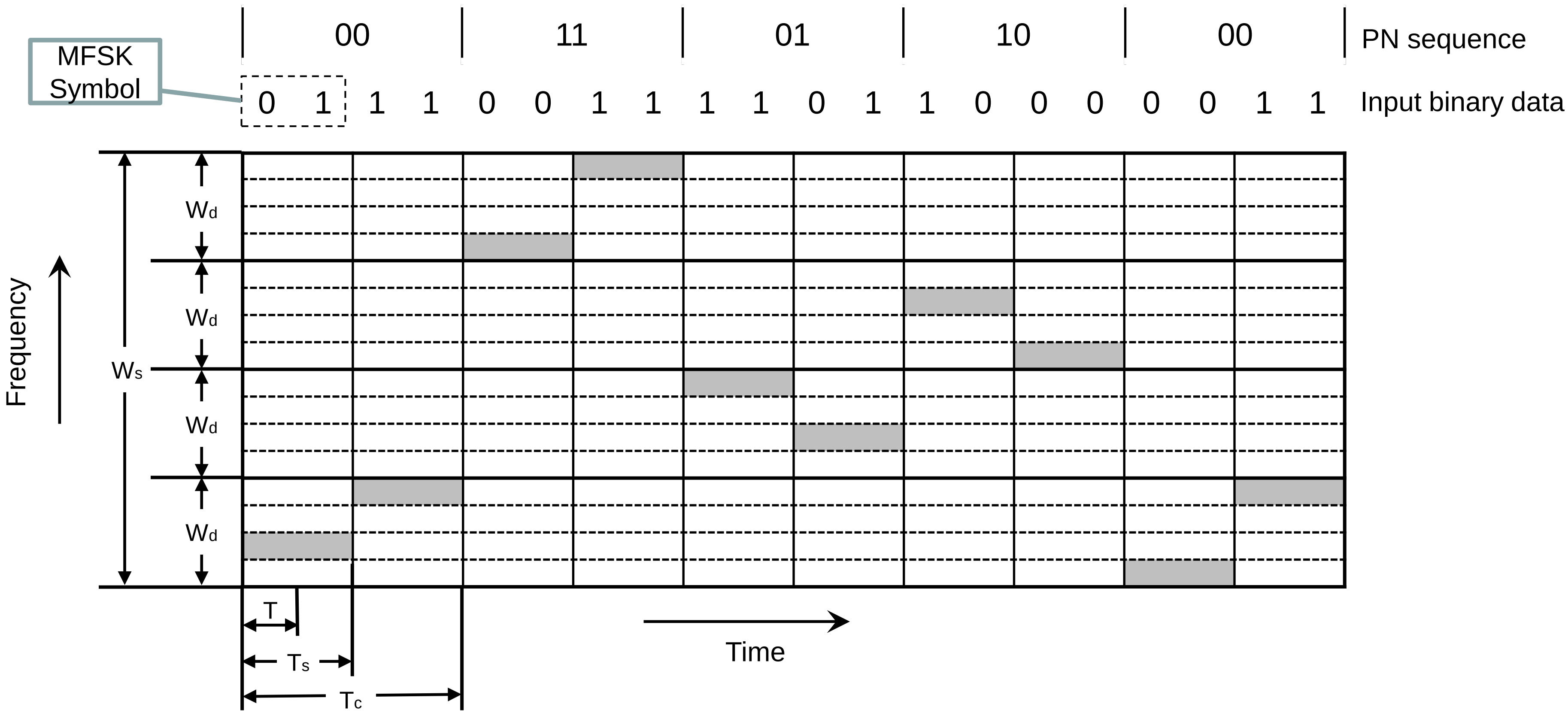


Frequency Hopping Example

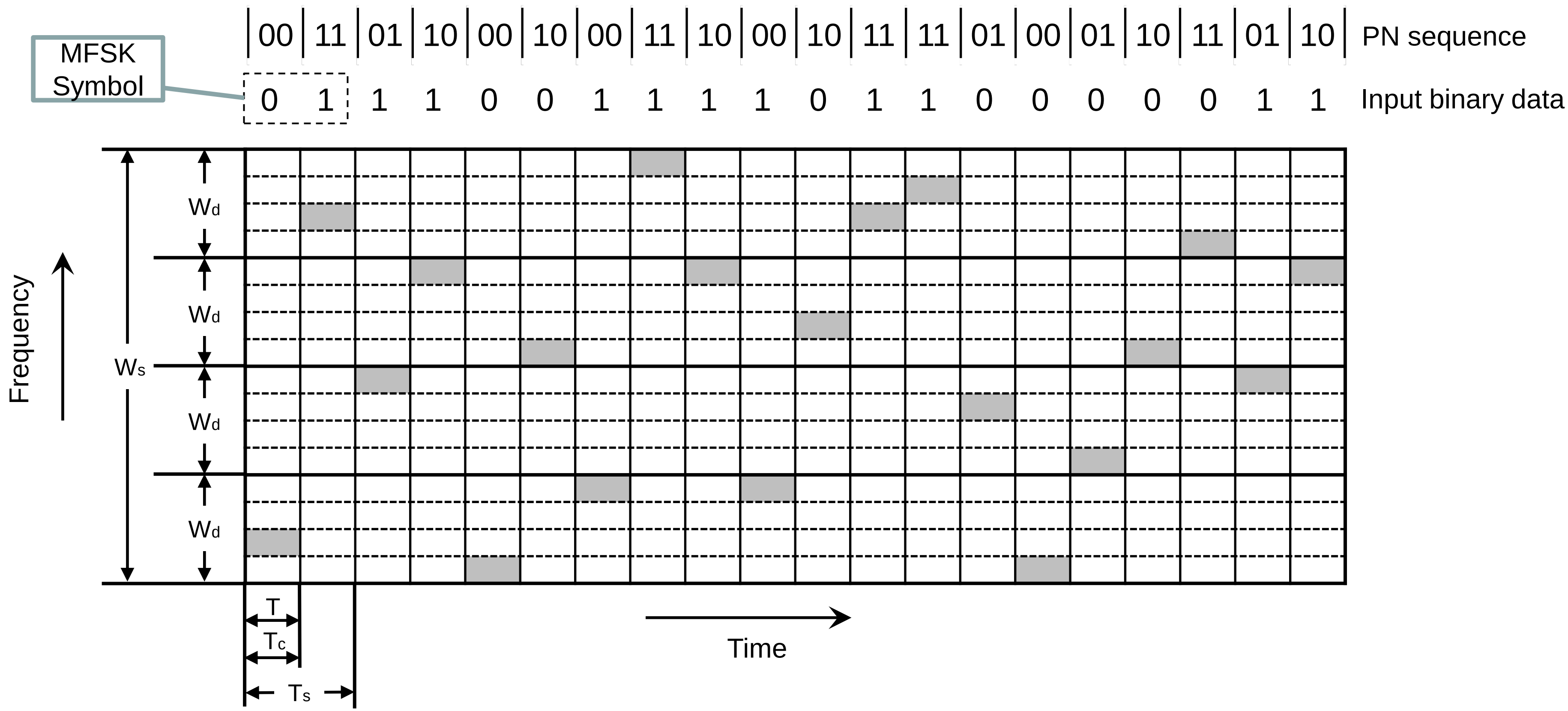
FHSS Using MFSK

- MFSK signal is translated to a new frequency every T_c seconds by modulating the MFSK signal with the FHSS carrier signal
- For data rate of R:
  - duration of a bit: $T = 1/R$ seconds
  - duration of signal symbol: $T_s = LT$ seconds
- $T_c \geq T_s$ – slow-frequency-hop spread spectrum
- $T_c < T_s$ - fast-frequency-hop spread spectrum

Slow FHSS Using MFSK (M = 4, k = 2)



Fast FHSS Using MFSK (M = 4, k = 2)



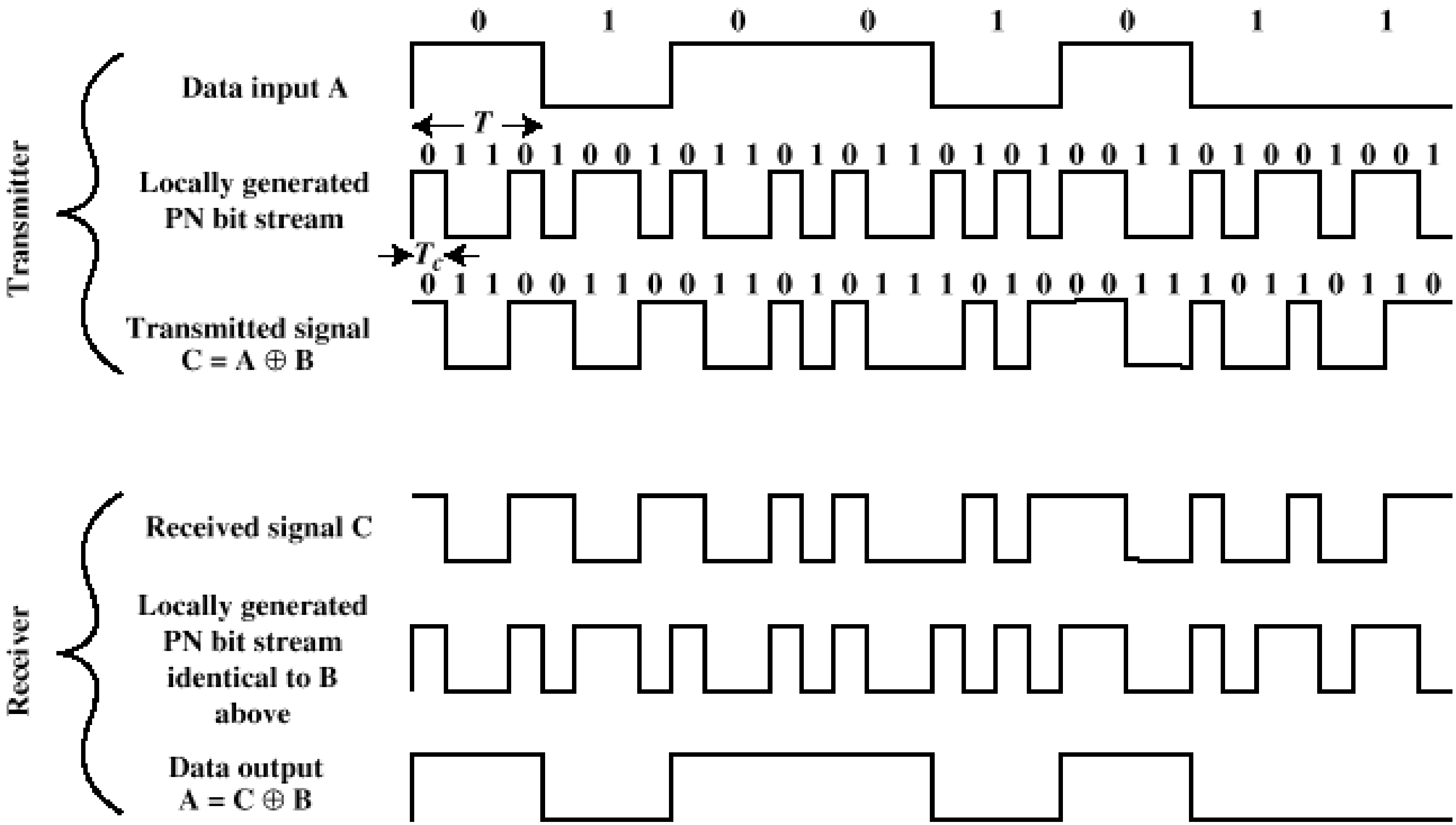
FHSS Performance Considerations

- Large number of frequencies used
- Results in a system that is quite resistant to jamming
  - Jammer must jam all frequencies
  - With fixed power, this reduces the jamming power in any one frequency band

Direct Sequence Spread Spectrum (DSSS)

- Each bit in original signal is represented by multiple bits in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - Spread is in direct proportion to number of bits used
- One technique combines digital information stream with the spreading code bit stream using exclusive-OR (Figure in next slide)

Direct Sequence Spread Spectrum (DSSS)



DSSS Using BPSK

- Multiply BPSK signal,

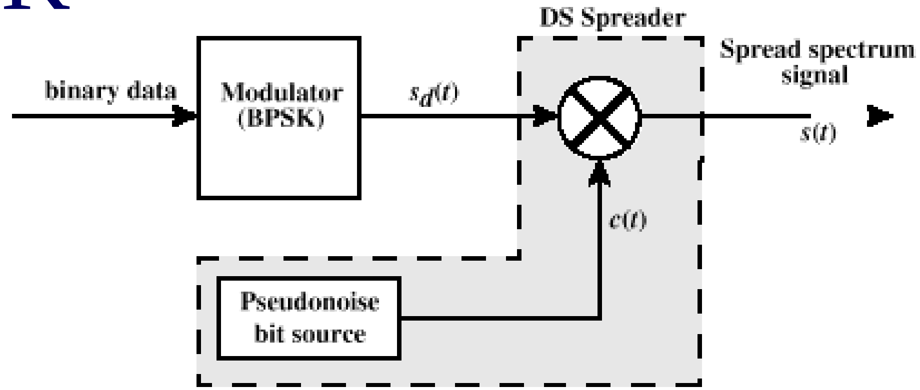
$$s_d(t) = A\, d(t) \cos(2\pi f_c t)$$

  by $c(t)$ [takes values +1, -1] to get

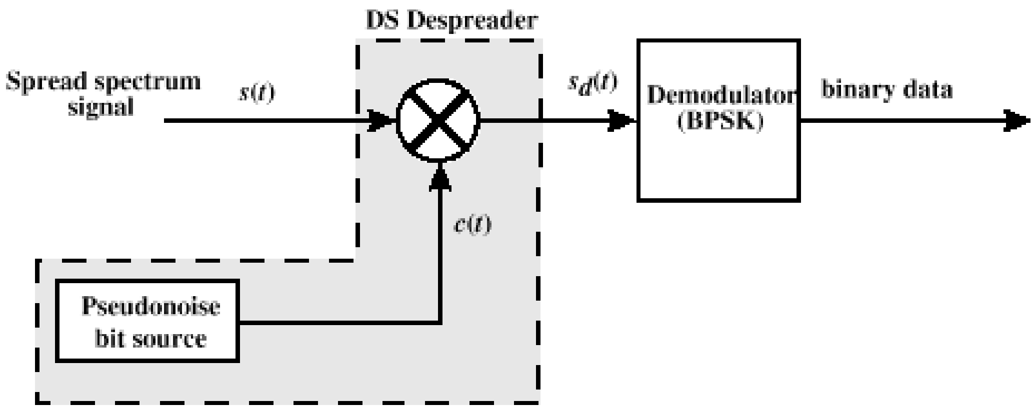
$$s(t) = A\, d(t)c(t) \cos(2\pi f_c t)$$

  - A = amplitude of signal
  - f_c = carrier frequency
  - d(t) = discrete function [+1, -1]
- At receiver, incoming signal multiplied by $c(t)$
  - Since, $c(t)$ x $c(t)$ = 1, incoming signal is recovered

DSSS Using BPSK



(a) Transmitter



(b) Receiver

Direct Sequence Spread Spectrum

Code-Division Multiple Access (CDMA)

- Basic Principles of CDMA
  - D = rate of data signal
  - Break each bit into *k chips*
    - Chips are a user-specific fixed pattern
  - Chip data rate of new channel = kD

CDMA Example

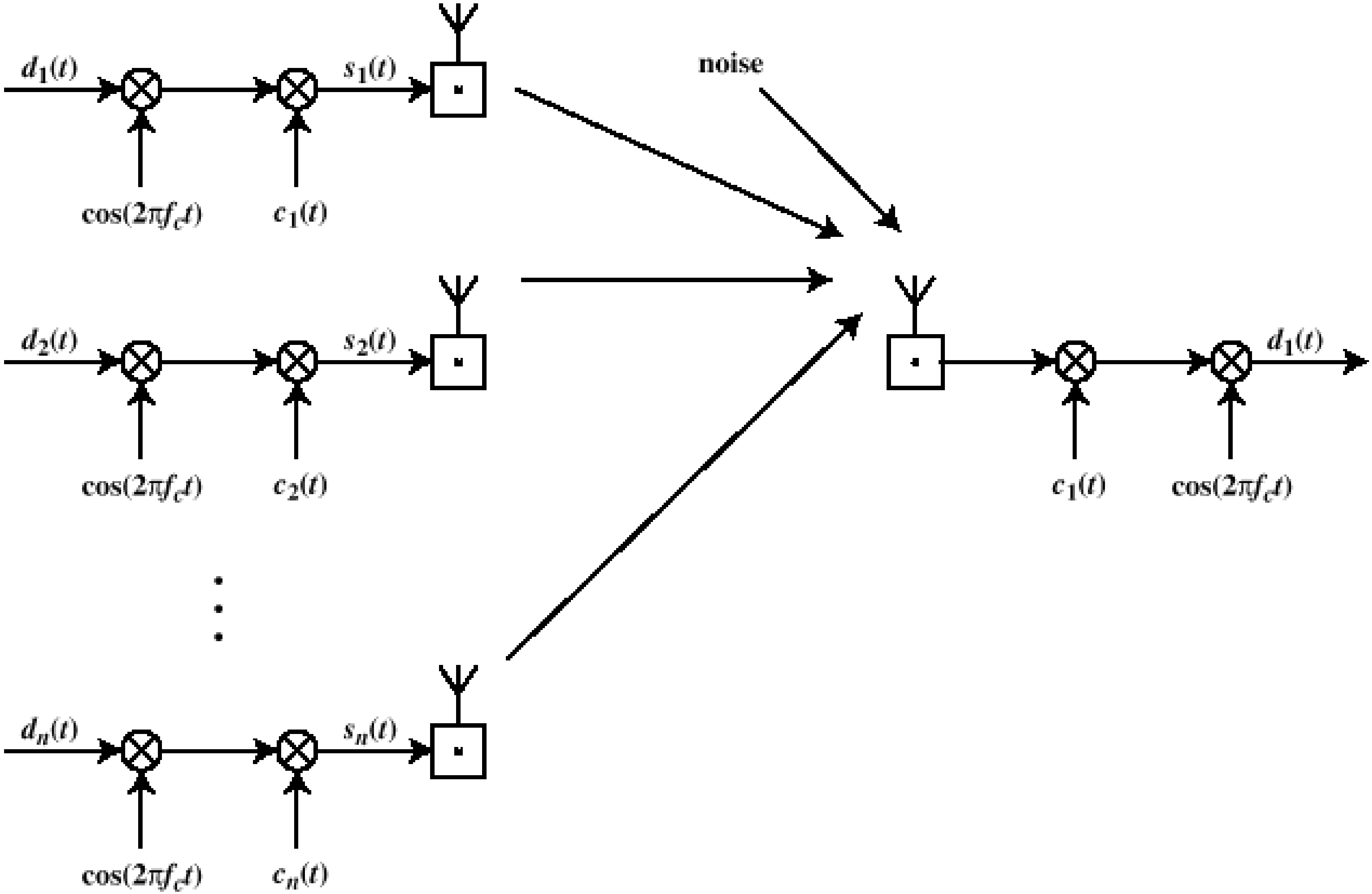
- If k=6 and code is a sequence of 1s and -1s
  - For a ‘1’ bit, A sends code as chip pattern
    - <c1, c2, c3, c4, c5, c6>
  - For a ‘0’ bit, A sends complement of code
    - <-c1, -c2, -c3, -c4, -c5, -c6>
- Receiver knows sender’s code and performs electronic decode function

$$S_u(d) = d1 \times c1 + d2 \times c2 + d3 \times c3 + d4 \times c4 + d5 \times c5 + d6 \times c6$$

  - <d1, d2, d3, d4, d5, d6> = received chip pattern
  - <c1, c2, c3, c4, c5, c6> = sender’s code

CDMA Example

- User A code = <1, –1, –1, 1, –1, 1>
  - To send a 1 bit = <1, –1, –1, 1, –1, 1>
  - To send a 0 bit = <–1, 1, 1, –1, 1, –1>
- User B code = <1, 1, –1, – 1, 1, 1>
  - To send a 1 bit = <1, 1, –1, –1, 1, 1>
- Receiver receiving with A’s code
  - (A’s code) x (received chip pattern)
    - User A ‘1’ bit: 6 -> 1
    - User A ‘0’ bit: -6 -> 0
    - User B ‘1’ bit: 0 -> unwanted signal ignored



$d_1(t)$
$s_1(t)$
$\cos(2\pi f_c t)$
$c_1(t)$
noise
$d_2(t)$
$s_2(t)$
$\cos(2\pi f_c t)$
$c_2(t)$
$d_1(t)$
$c_1(t)$
$\cos(2\pi f_c t)$
$d_n(t)$
$s_n(t)$
$\cos(2\pi f_c t)$
$c_n(t)$

Categories of Spreading Sequences

- Spreading Sequence Categories
  - PN sequences
  - Orthogonal codes
- For FHSS systems
  - PN sequences most common
- For DSSS systems not employing CDMA
  - PN sequences most common
- For DSSS CDMA systems
  - PN sequences
  - Orthogonal codes

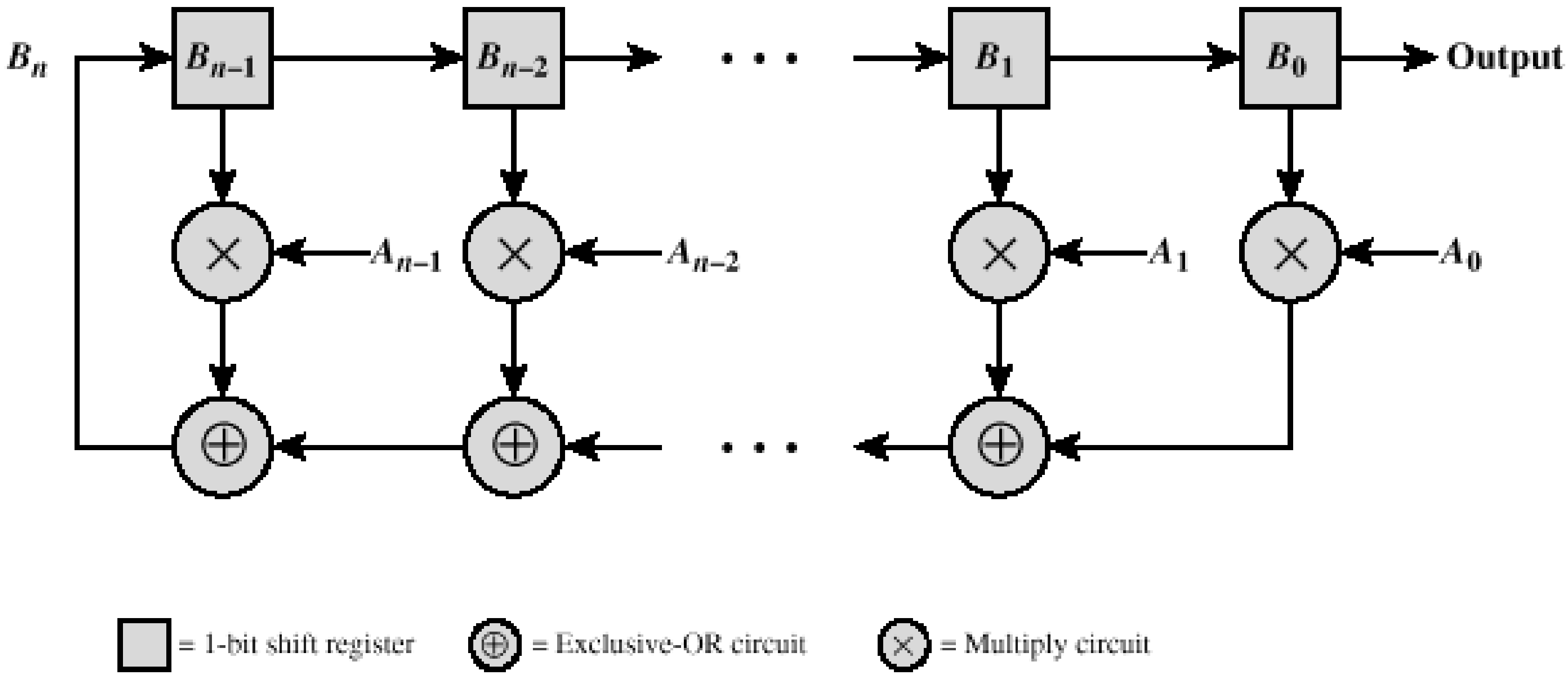
PN Sequences

- PN (Pseudonoise) generator produces periodic sequence that appears to be random
- PN Sequences
  - Generated by an algorithm using initial seed
  - Sequence isn't statistically random but will pass many test of randomness
  - Sequences referred to as pseudorandom numbers or pseudonoise sequences
  - Unless algorithm and seed are known, the sequence is impractical to predict

Important PN Properties

- Randomness
  - Uniform distribution
    - Balance property
    - Run property
  - Independence
  - Correlation property
- Unpredictability

Linear Feedback Shift Register Implementation



Binary Linear Feedback Shift Register Sequence Generator

Multiple Access Techniques

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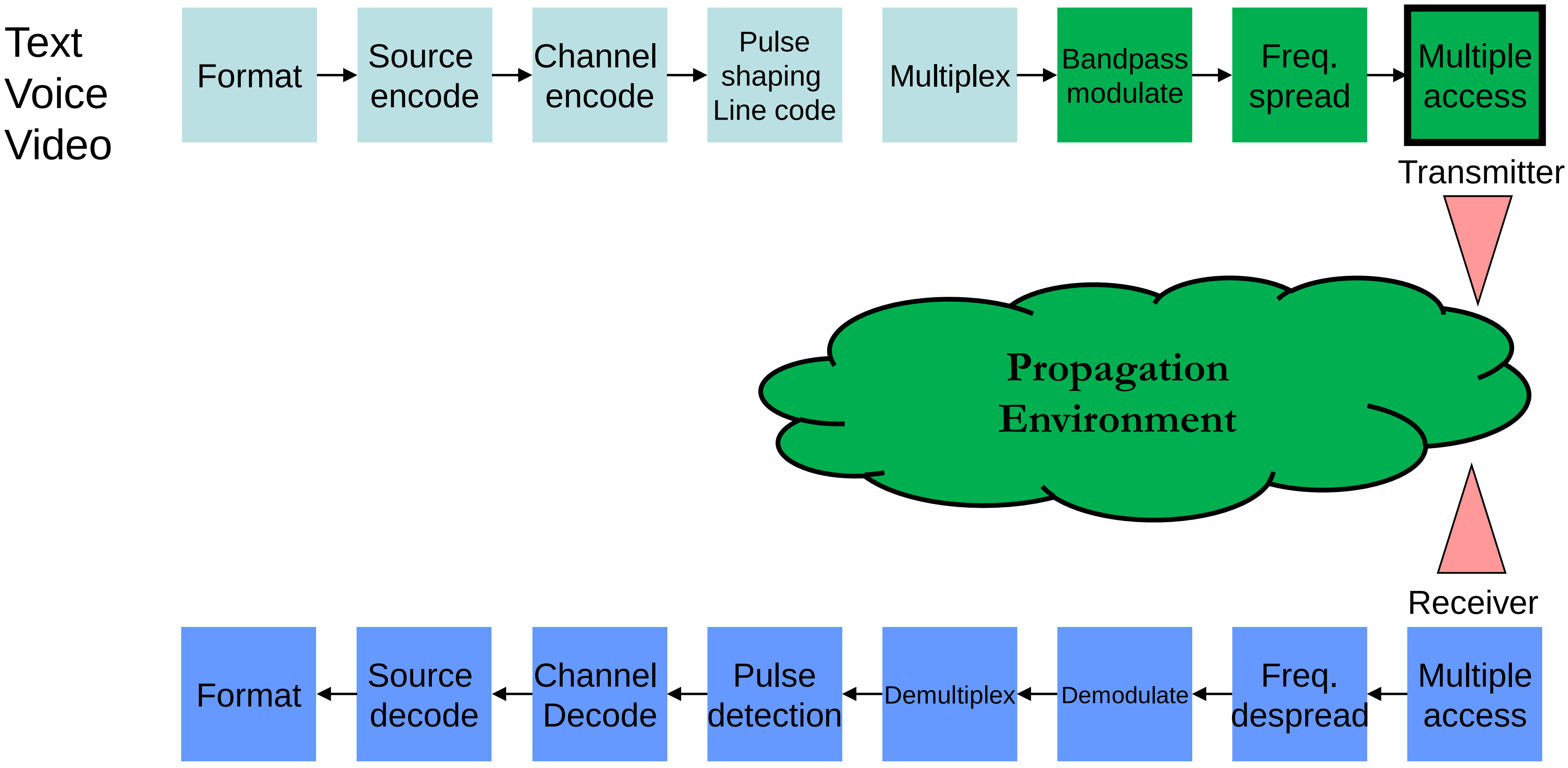
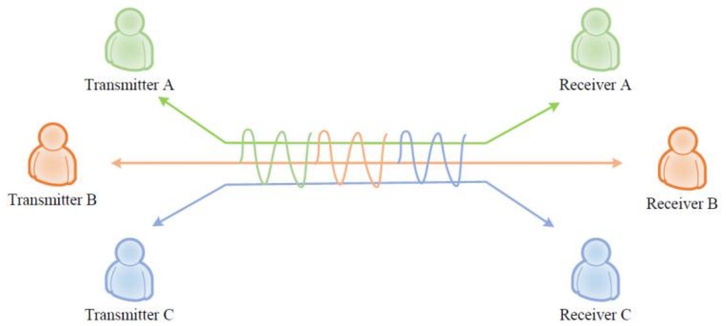
Overview of Wireless Communication System



Multiple access

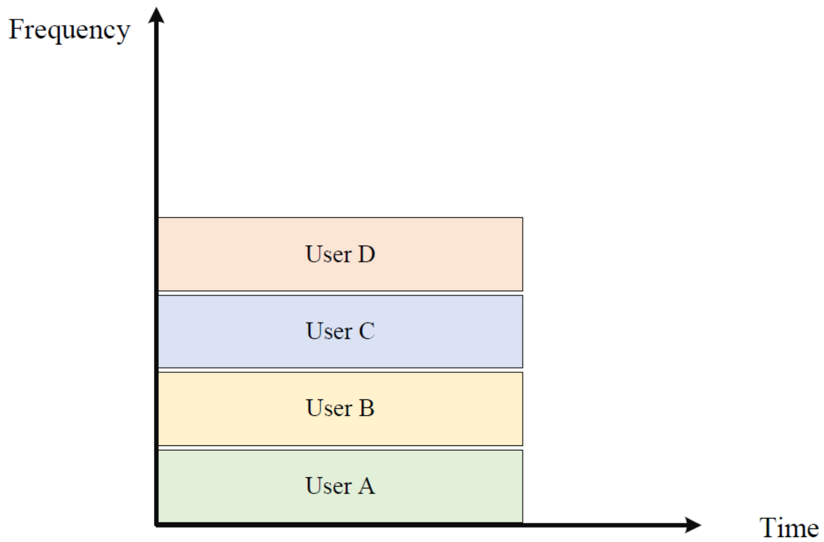
- **Multiple Access**: to enable multiple users to share the same channel simultaneously.



- Possible approaches for multiple access
  - Time.
  - Pitch.
  - Language.

Frequency Division Multiple Access (FDMA) - Pitch

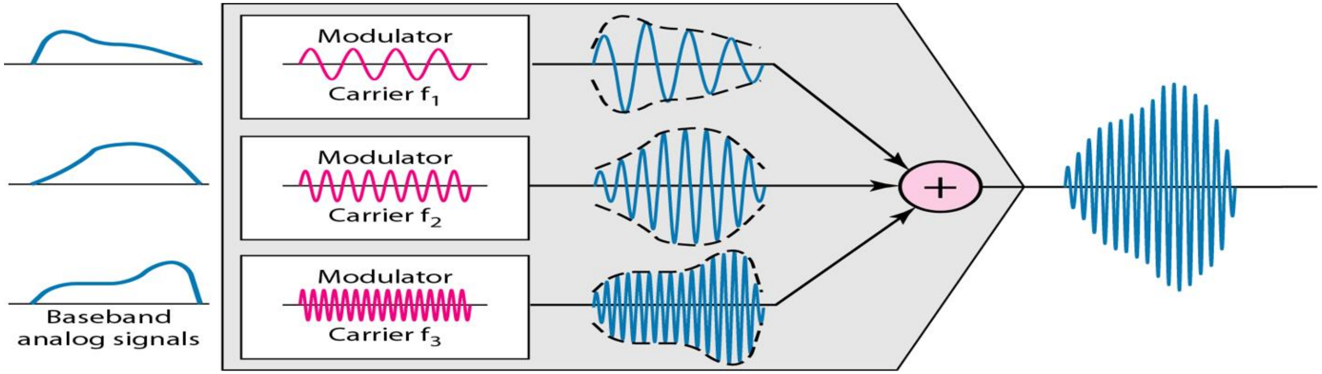
- **Key features**:
  - Assign each user to a particular channel.
  - Transmit signals simultaneously and continuously.to enable multiple users to share the same channel simultaneously.



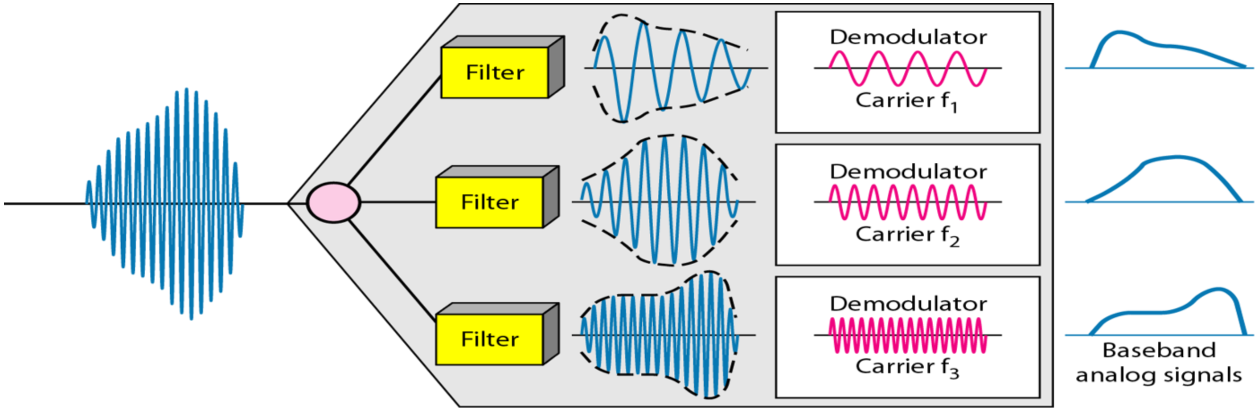
- **Application**: all 1G systems use FDMA.

Frequency Division Multiple Access (FDMA)

- **Transmitter:**



- **Receiver:**



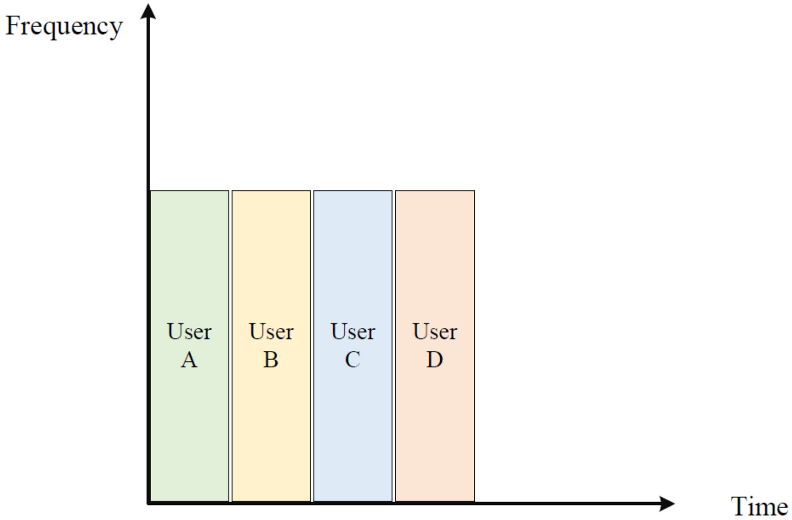
Frequency Division Multiple Access (FDMA)

- **Advantages**
  - Low overhead
  - Simple hardware at users and base stations

- **Disadvantages**
  - If no talking, a channel sits idle (resource waste)
  - Require tight radio frequency filters

Time Division Multiple Access (TDMA) - Time

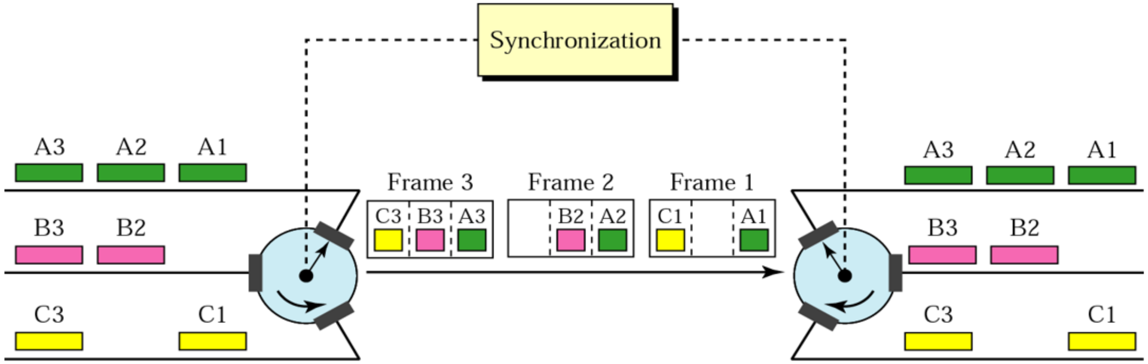
- **Key features**
  - Single carrier frequency with multiple users.
  - Non-continuous transmission.
  - Each user occupies a **cyclically repeating** time slot.



- **Application**: most 2G systems use TDMA.

Time Division Multiple Access

- **Advantages**
  - Interference-free technique.
  - Low battery consumption.
  - Slots can be assigned on demand.
- **Disadvantages:**
  - "CLOCK" is required.
  - Large synchronization overheads.



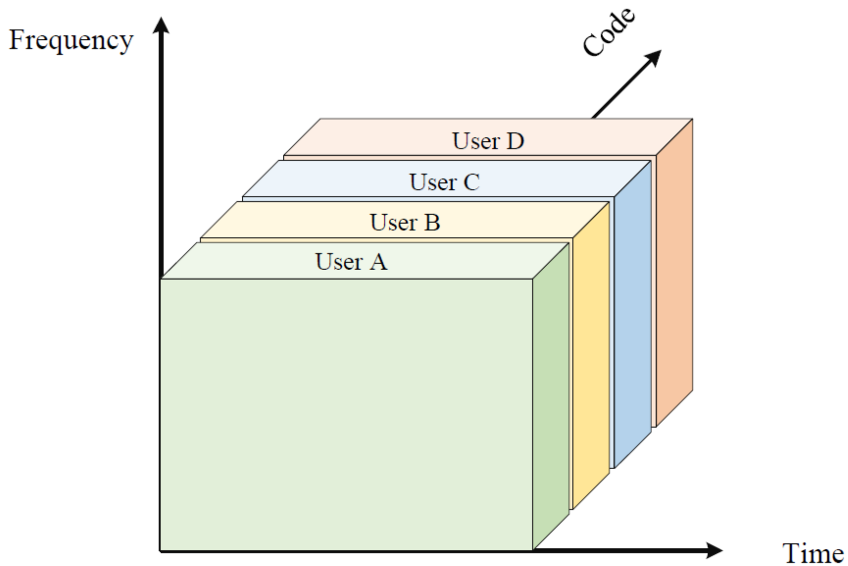
Application: most 2G systems use TDMA.

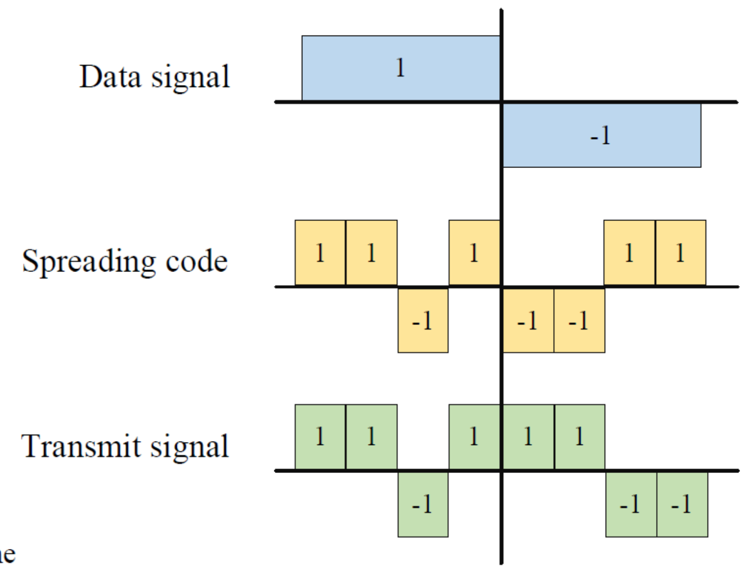
GSM Multiple access

- TDMA on each carrier
  - 8 time slots (channels) per carrier
- Multiple carriers (FDMA)
  - 200kHz spacing
  - Number of carriers per cell depends on network and radio planning
- So GSM uses combined TDMA/FDMA

Code Division Multiple Access (CDMA) - Language

- **Key features**
  - All users use same time and frequency.
  - Narrowband signals multiplied by wideband spreading codes.





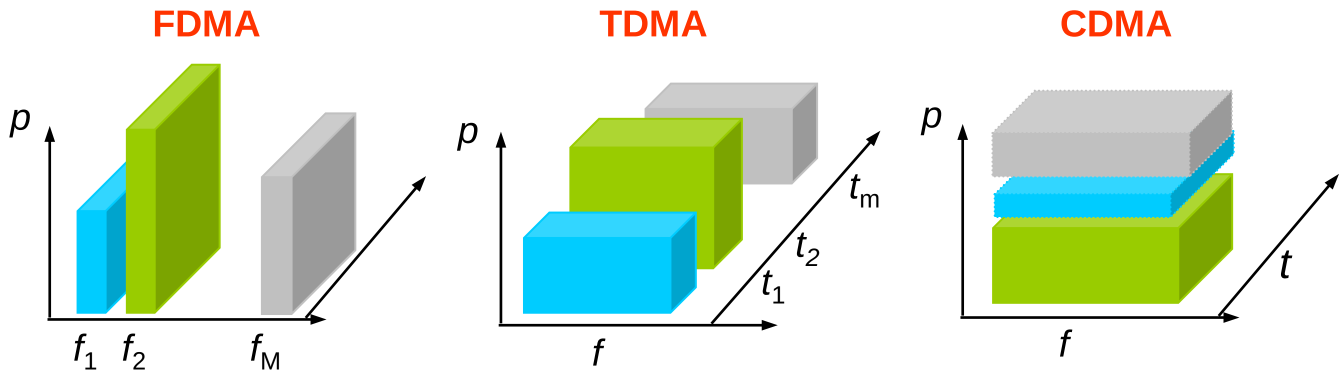
- **Application**: some 2G and most 3G systems.

Code Division Multiple Access (CDMA) - Language

- **Advantages**
  - Easy addition of more users.
  - No absolute limit on the number of users.

- **Disadvantages**
  - QoS decreases as the number of users increases.
  - Near-far problem exists (power control is required).

CDMA for 3G multiple access



- FDMA: different frequency bands are assigned to different users.
- TDMA: different time slots are assigned to different users.
- CDMA: different codes are assigned to different users.

OFDMA for 4G (3GPP LTE/LTE-A)

- **OFDM** =**O**rthogonal **F**requency **D**ivision **M**ultiplexing
- Many orthogonal sub-carriers are multiplexed in one symbol
  - What is the orthogonal?
  - How multiplexed?
  - What is the merit of OFDM?
  - What kinds of application?
  - What is the drawback of OFDM?

OFDMA for 4G (3GPP LTE/LTE-A)

- **OFDMA** =**O**rthogonal **F**requency **D**ivision **M**ultiple **A**ccess
- OFDMA is a multi-user version of the popular OFDM digital modulation scheme. Multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users.

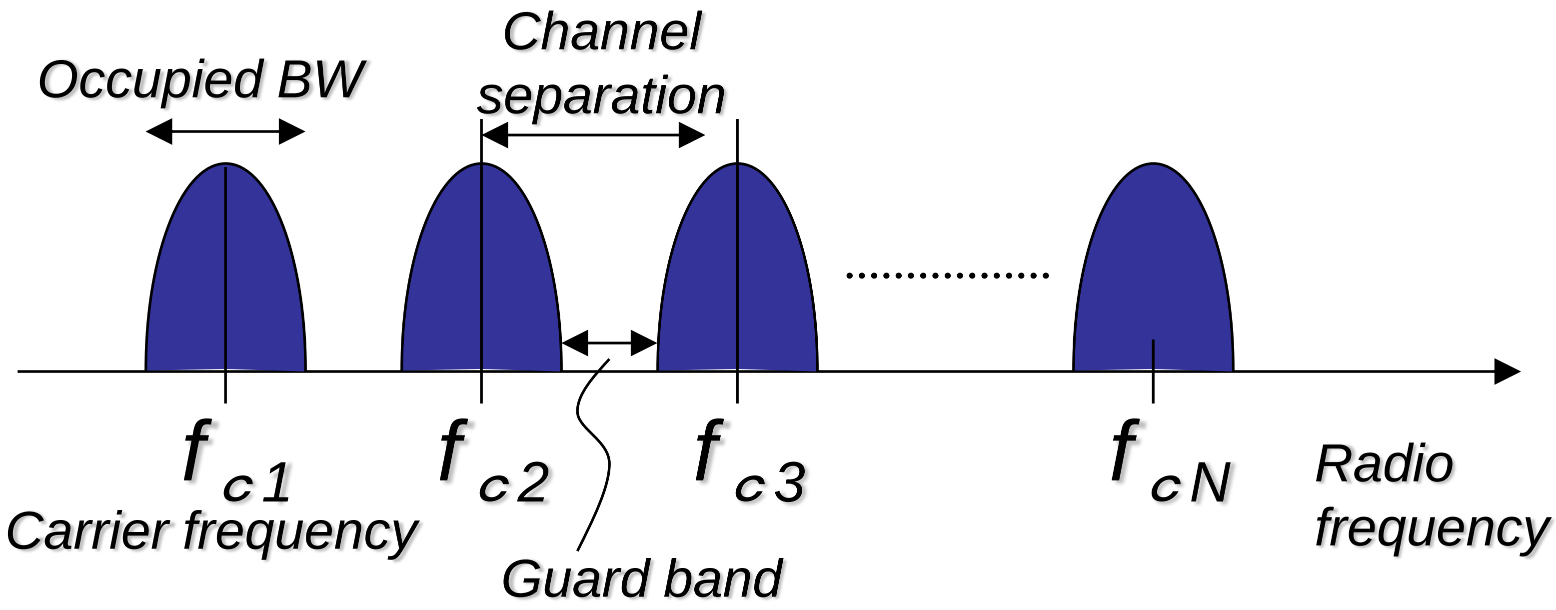
Why OFDM is getting popular？

- State-of-the-art high bandwidth digital communication start using OFDM
  - Terrestrial Video Broadcasting in Japan and Europe
  - ADSL High Speed Modem
  - WLAN such as IEEE 802.11a/g/n
  - 3GPP LTE downlink
  - WiMAX as IEEE 802.16d/e

- Economical OFDM implementation become possible because of advancement in the LSI technology

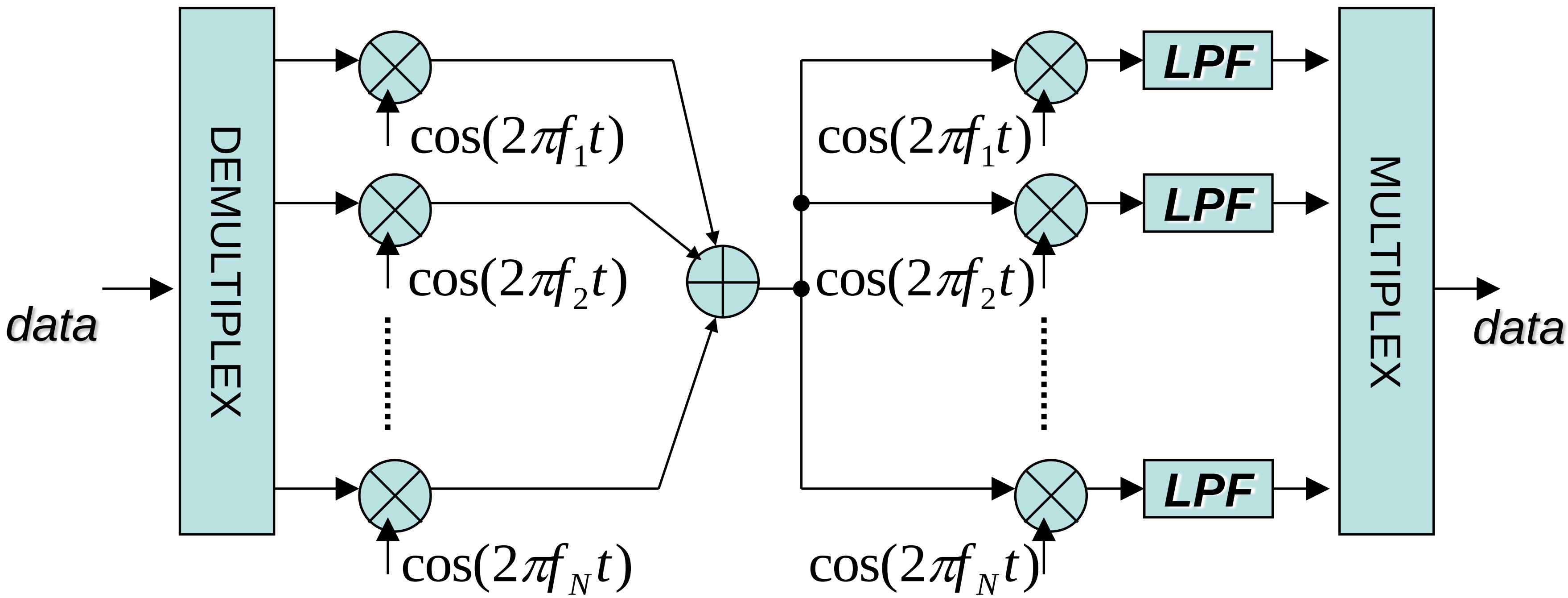
Frequency Division Multiple Access (FDMA)

- Old conventional method (Analog TV, Radio etc.)
- Use separate carrier frequency for individual transmission

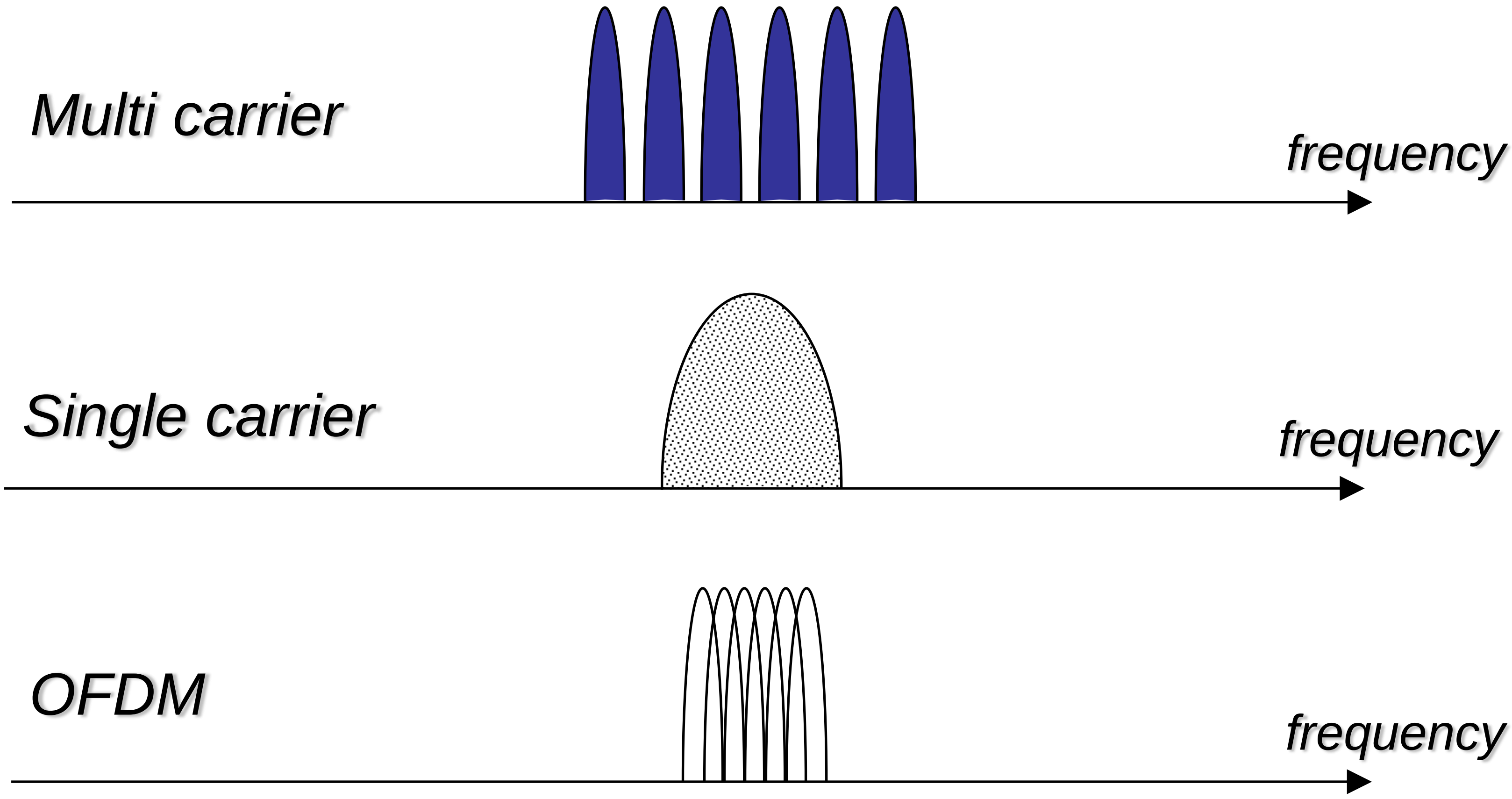


Multi-carrier modulation

- Use multiple channel (carrier frequency) for one data transmission



Spectrum comparison for same data rate transmission



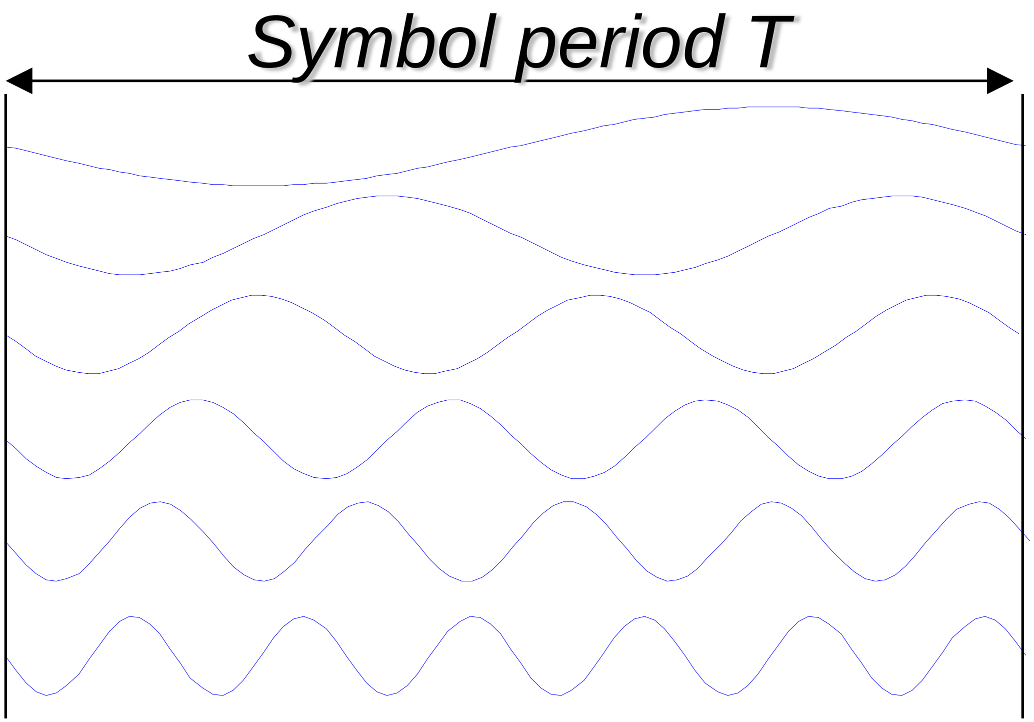
OFDM vs. Multi carrier

- OFDM is a multi-carrier modulation
- OFDM sub-carrier spectrum is overlapping
- In FDMA, band-pass filter separates each transmission
- In OFDM, each sub-carrier is separated by DFT because carriers are orthogonal
  - Condition of the orthogonality will be explained later
- Each sub-carrier is modulated by PSK, QAM

Thousands of PSK/QAM symbol can be simultaneously transmitted in one OFDM symbol

OFDM carriers

- OFDM carrier frequency is n ▪ 1/T



$$f_0 = \frac{1}{T}$$

$$\cos(2\pi \cdot 1 \cdot f_0 \cdot t + \theta_1)$$

$$\cos(2\pi \cdot 2 \cdot f_0 \cdot t + \theta_2)$$

$$\cos(2\pi \cdot 3 \cdot f_0 \cdot t + \theta_3)$$

$$\cos(2\pi \cdot 4 \cdot f_0 \cdot t + \theta_4)$$

$$\cos(2\pi \cdot 5 \cdot f_0 \cdot t + \theta_5)$$

$$\cos(2\pi \cdot 6 \cdot f_0 \cdot t + \theta_6)$$

Sinusoidal Orthogonality

- m,n: integer, $T=1/f_0$

$$\int_0^T \cos(2\pi m f_0 t)\cdot\cos(2\pi n f_0 t)\,dt = \begin{cases} \dfrac{T}{2} & (m=n) \\ 0 & (m\neq n) \end{cases} \longrightarrow \text{Orthogonal}$$

$$\int_0^T \sin(2\pi m f_0 t)\cdot\sin(2\pi n f_0 t)\,dt = \begin{cases} \dfrac{T}{2} & (m=n) \\ 0 & (m\neq n) \end{cases} \longrightarrow \text{Orthogonal}$$

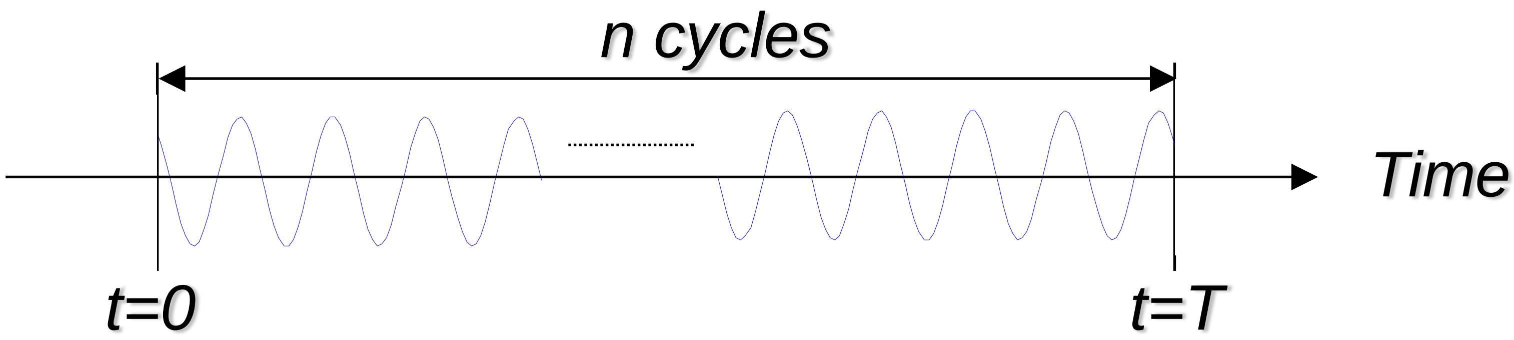
$$\int_0^T \cos(2\pi m f_0 t)\cdot\sin(2\pi n f_0 t)\,dt = 0$$

A sub-carrier of $f=nf_0$

$$a_n \cdot \cos(2\pi n f_0 t) - b_n \cdot \sin(2\pi n f_0 t)$$

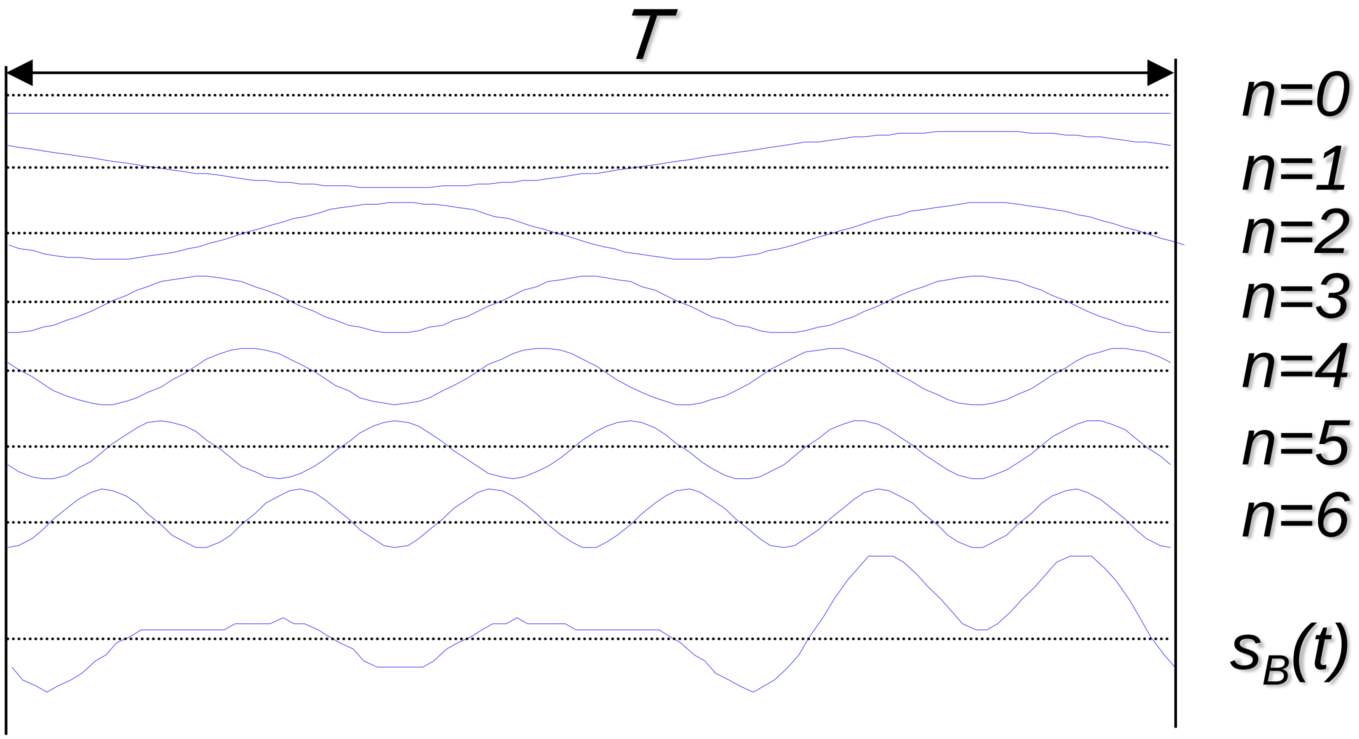
$$= \sqrt{{a_n}^2 + {b_n}^2} \cos(2\pi n f_0 t + \phi_n), \qquad \phi_n = \tan^{-1} \frac{b_n}{a_n}$$

- Amplitude and Phase will be digitally modulated



Base-band OFDM signal

$$s_B(t) = \sum_{n=0}^{N-1} \left\{ a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t) \right\}$$



How a_n,b_n are calculated from $s_B(t)$ - Demodulation Procedure -

$$\int_0^T s_B(t)\cdot\cos(2\pi k f_0 t)dt$$

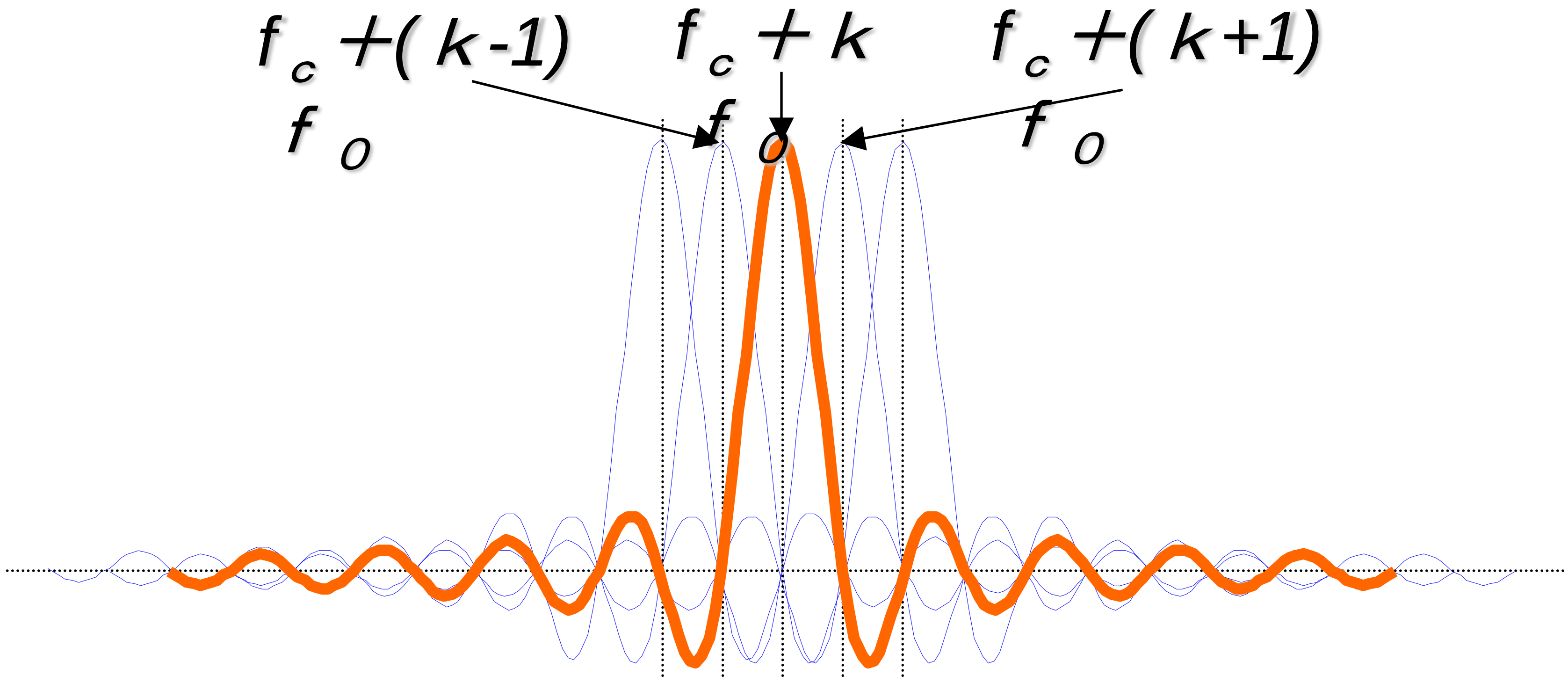
$$=\sum_{n=0}^{N-1}\left\{a_n\int_0^T \cos(2\pi n f_0 t)\cos(2\pi k f_0 t)dt - b_n\int_0^T \sin(2\pi n f_0 t)\cos(2\pi k f_0 t)dt\right\}$$

$$=\frac{T}{2}a_k$$

$$\int_0^T s_B(t)\{-\sin(2\pi k f_0 t)\}dt=\frac{T}{2}b_k$$

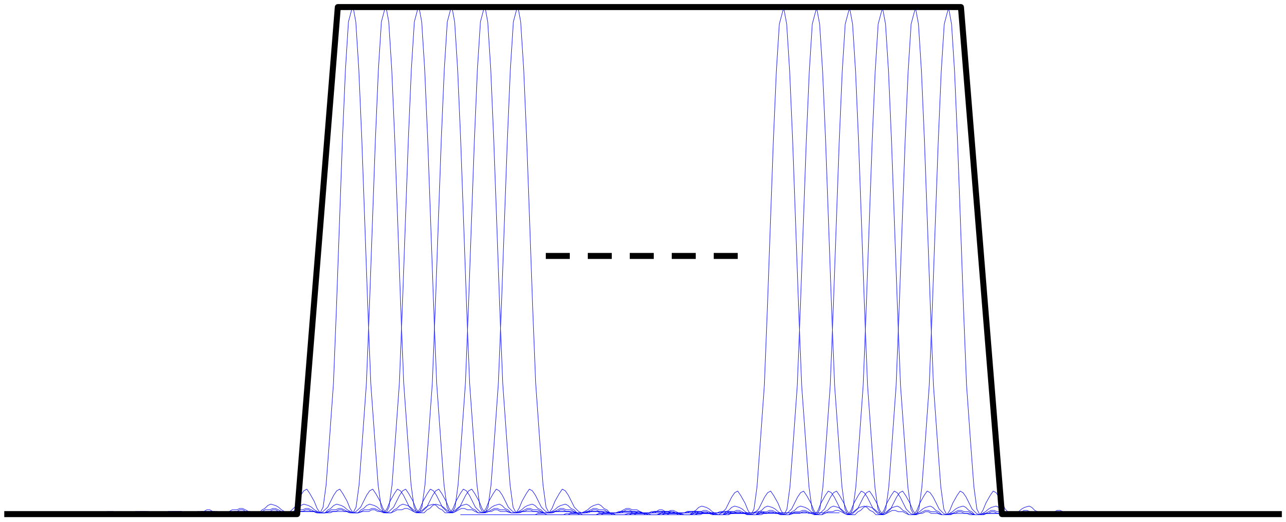
- According to the sinusoidal orthogonality, a_n,b_n can be extracted.
- In actual implementation, DFT(FFT) is used
- N is roughly 64 for WLAN, thousand for Terrestrial Video Broadcasting

Actual OFDM spectrum



OFDM power spectrum

- Total Power spectrum is almost square shape



OFDM signal generation

$$s(t) = \sum_{n=0}^{N-1} \left[a_n \cos\{2\pi(f_c + nf_0)t\} - b_n \sin\{2\pi(f_c + nf_0)t\} \right]$$

- Direct method needs

  N digital modulators

  N carrier frequency generator

  ➔ Not practical

- In 1971, method using DFT is proposed to OFDM signal generation

OFDM signal generation in digital domain

- Define complex base-band signal u(t) as follows

$$s_B(t) = \mathrm{Re}\left[u(t)\right]$$

$$u(t) = \sum_{n=0}^{N-1} d_n \cdot e^{j2\pi n f_0 t}, \qquad d_n = a_n + jb_n$$

- Perform N times sampling in period T

$$u\left(\frac{k}{Nf_0}\right) = \sum_{n=0}^{N-1} d_n \cdot e^{j2\pi n f_0 \frac{k}{Nf_0}} = \sum_{n=0}^{N-1} d_n \cdot e^{j\frac{2\pi nk}{N}}$$

$$= \sum_{n=0}^{N-1} d_n \cdot \left(e^{j\frac{2\pi}{N}}\right)^{nk} \qquad (k = 0,1,2,\cdots, N-1)$$

$$u(k) = IFFT\,(d_n) = IFFT(a_n + jb_n)$$

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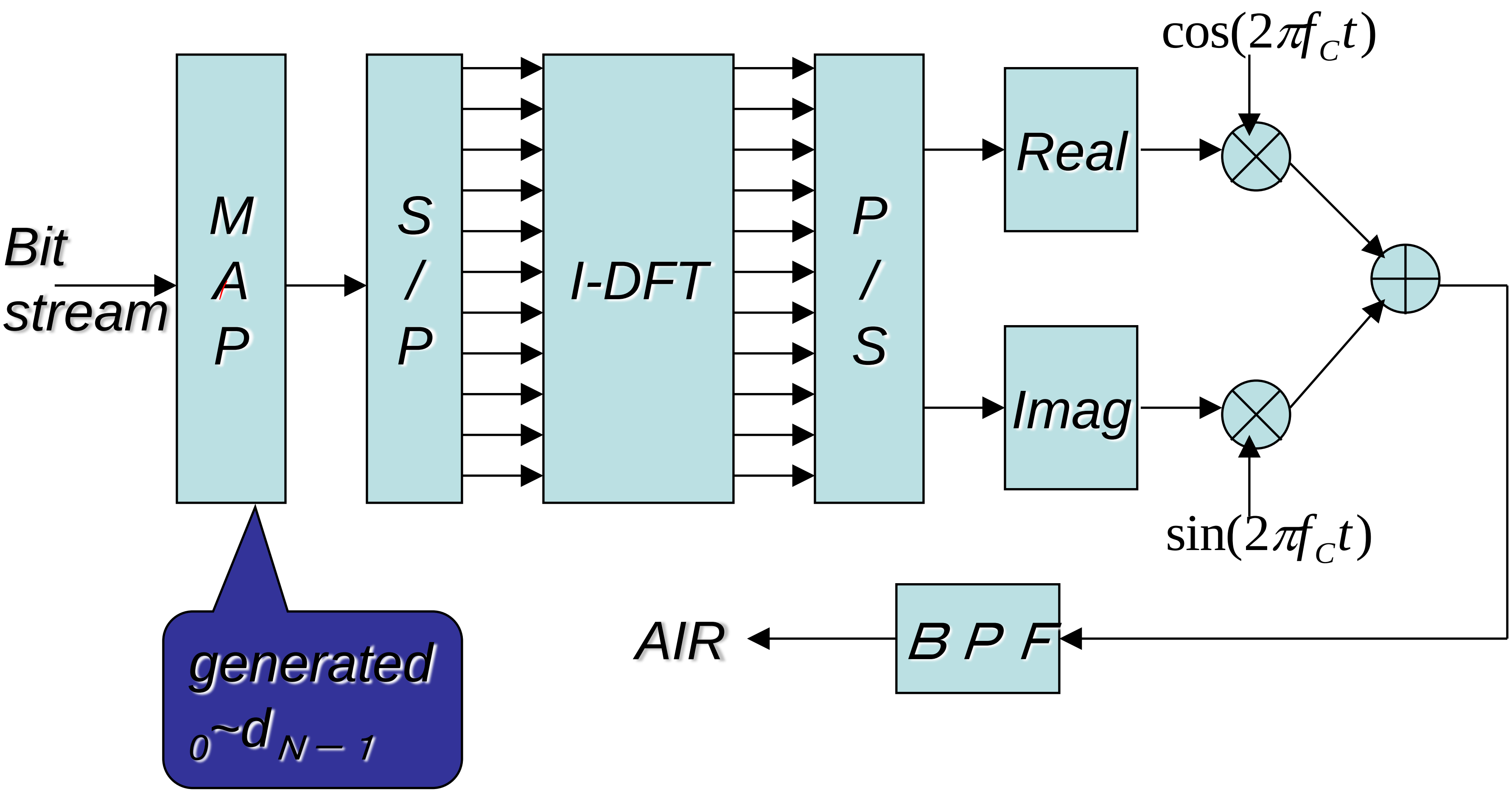
OFDM modulator



OFDM demodulation

$$s(t) = \sum_{n=0}^{N-1} \left[a_n \cos\{2\pi(f_c + nf_0)t\} - b_n \sin\{2\pi(f_c + nf_0)t\} \right]$$

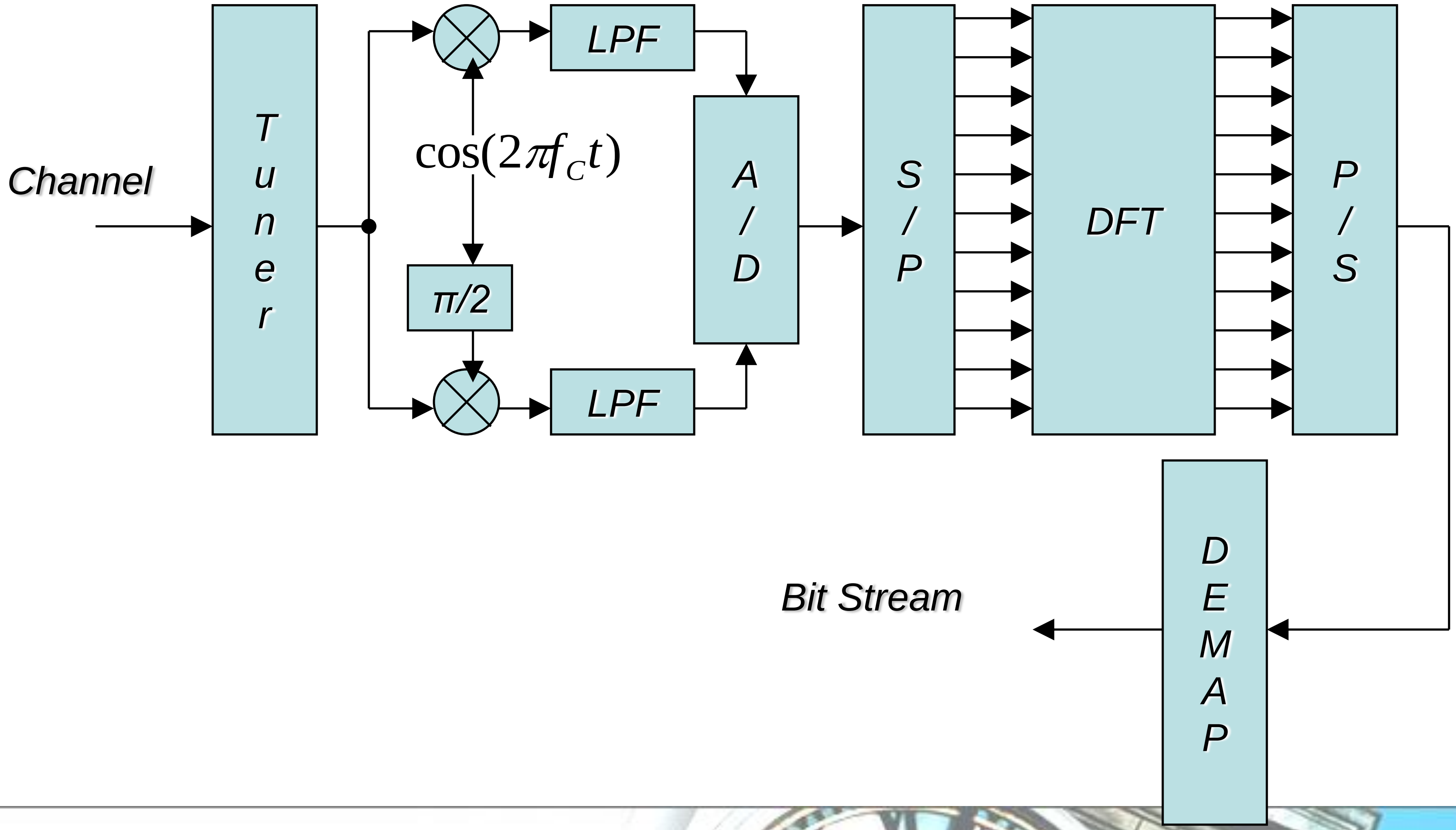
$$LPF[s(t) \cdot \cos(2\pi f_C t)] = \frac{1}{2} \sum_{n=0}^{N-1} \{ a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t) \} = \frac{1}{2} s_I(t)$$

$$LPF[s(t) \cdot \{-\sin(2\pi f_C t)\}] = \frac{1}{2} \sum_{n=0}^{N-1} \{ a_n \sin(2\pi n f_0 t) + b_n \cos(2\pi n f_0 t) \} = \frac{1}{2} s_Q(t)$$

$$u(t) = s_I(t) + j s_Q(t) = \sum_{n=0}^{N-1} d_n \cdot e^{j 2\pi n f_0 t}$$

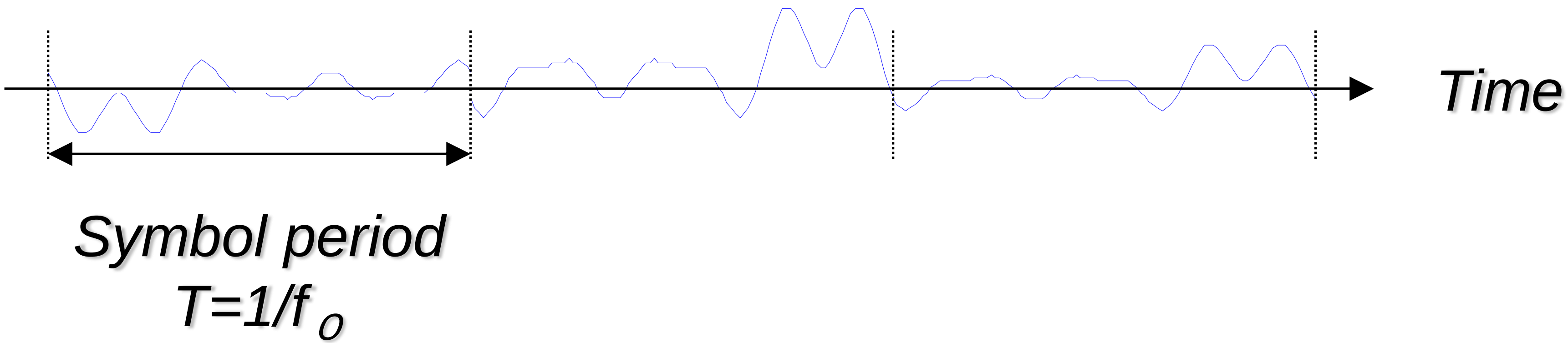
d_n = FFT(u(k))

OFDM demodulator



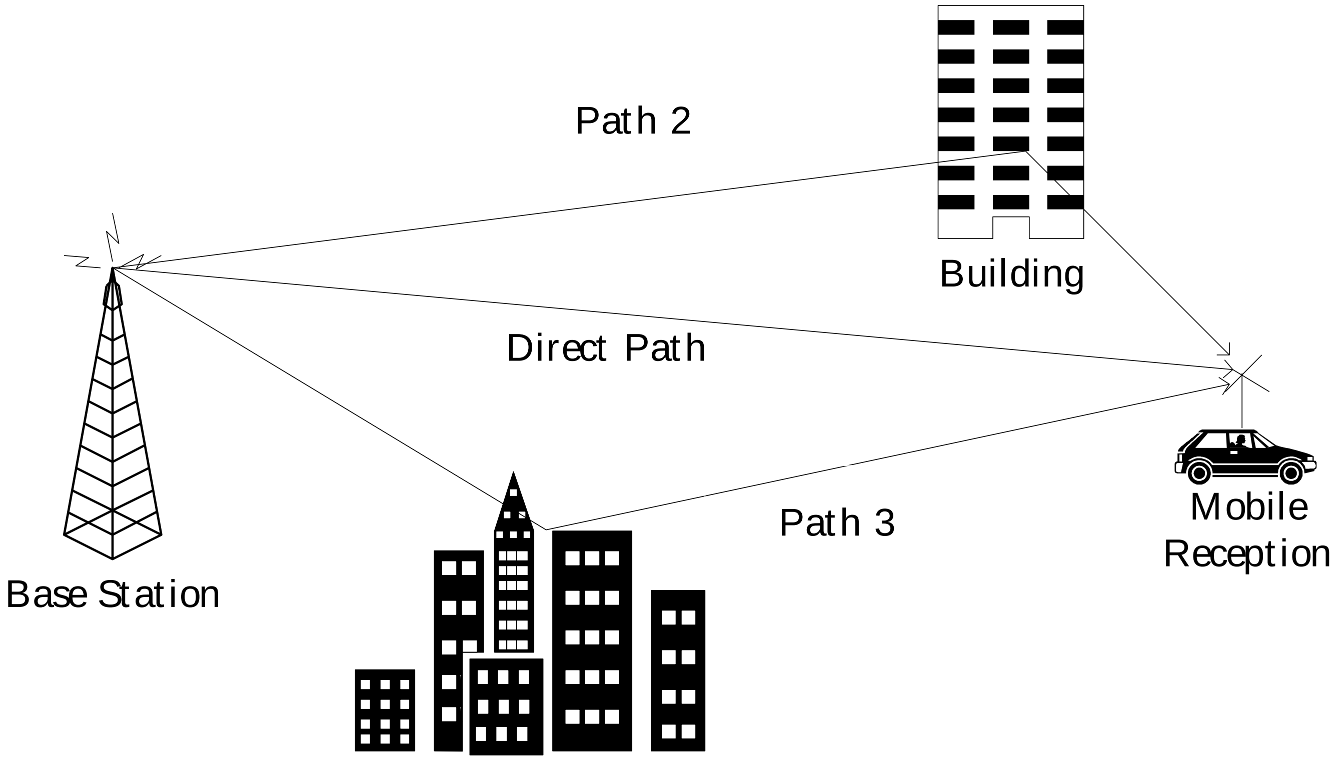
Summary of OFDM signal

- Each symbol carries information
- Each symbol wave is sum of many sinusoidal
- Each sinusoidal wave can be PSK, QAM modulated
- Using IDFT and DFT, OFDM implementation became practical

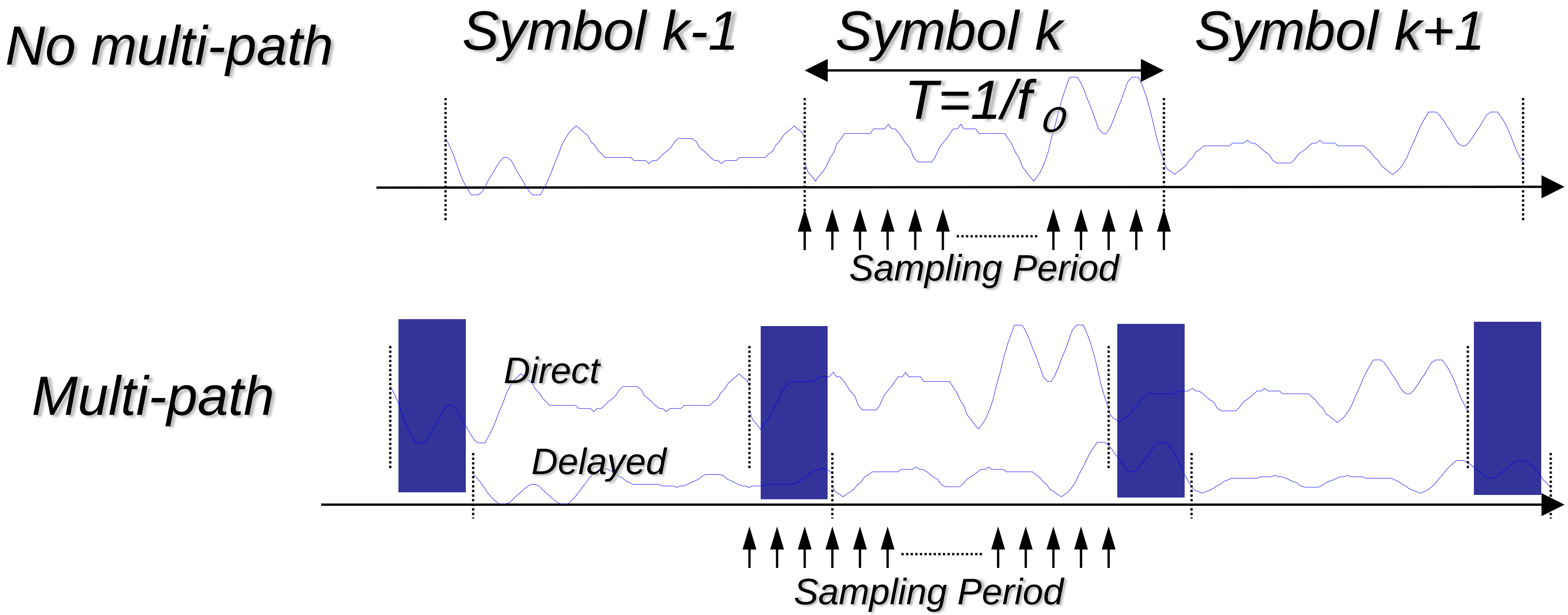


Multi-path

Delayed wave causes interference

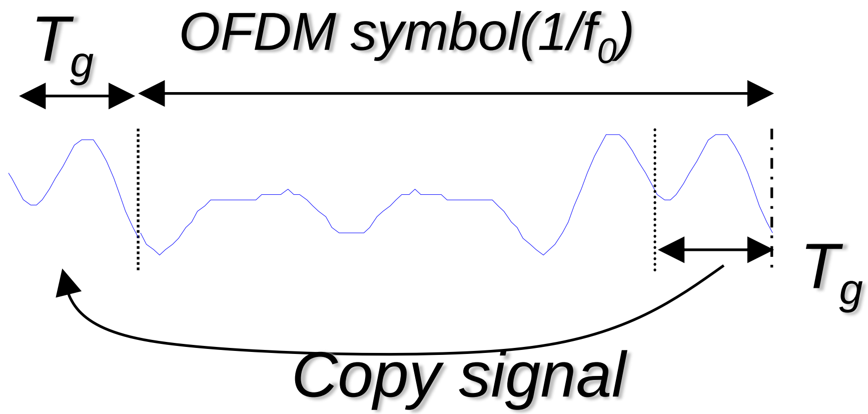


Multi-path effect

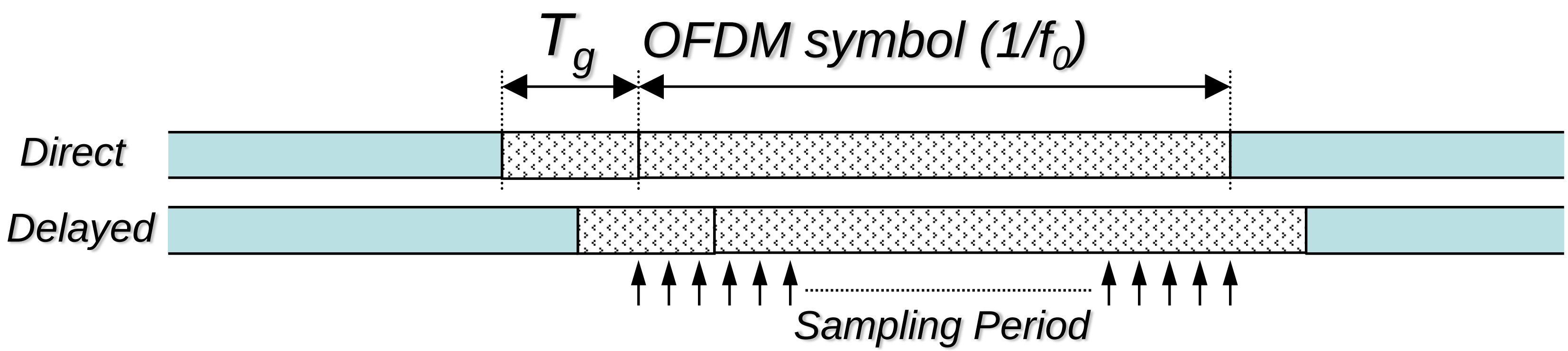


- Inter symbol interference (ISI) happens in Multi-path condition

Cyclic Prefix (Guard Interval) T_g



- By adding the Gurard Interval Period, ISI can be avoided



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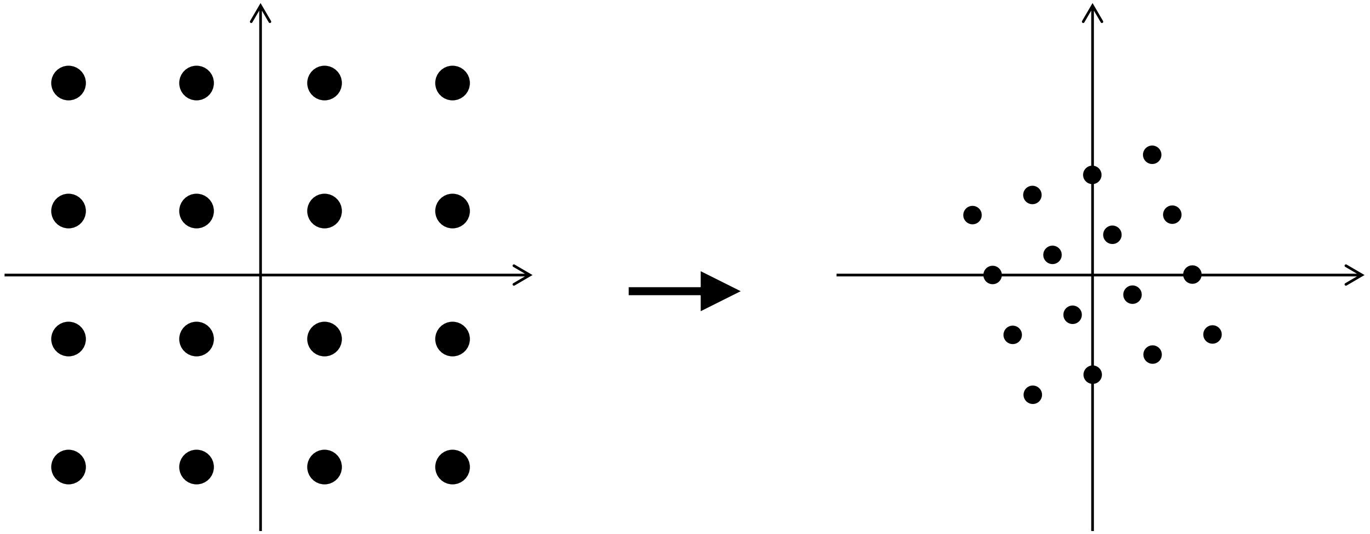
Multi-path

- By adding Cyclic Prefix, orthogonality can be maintained
- However, multi-path causes Amplitude and Phase distortion for each sub-carrier
- The distortion has to be compensated by Equalizer



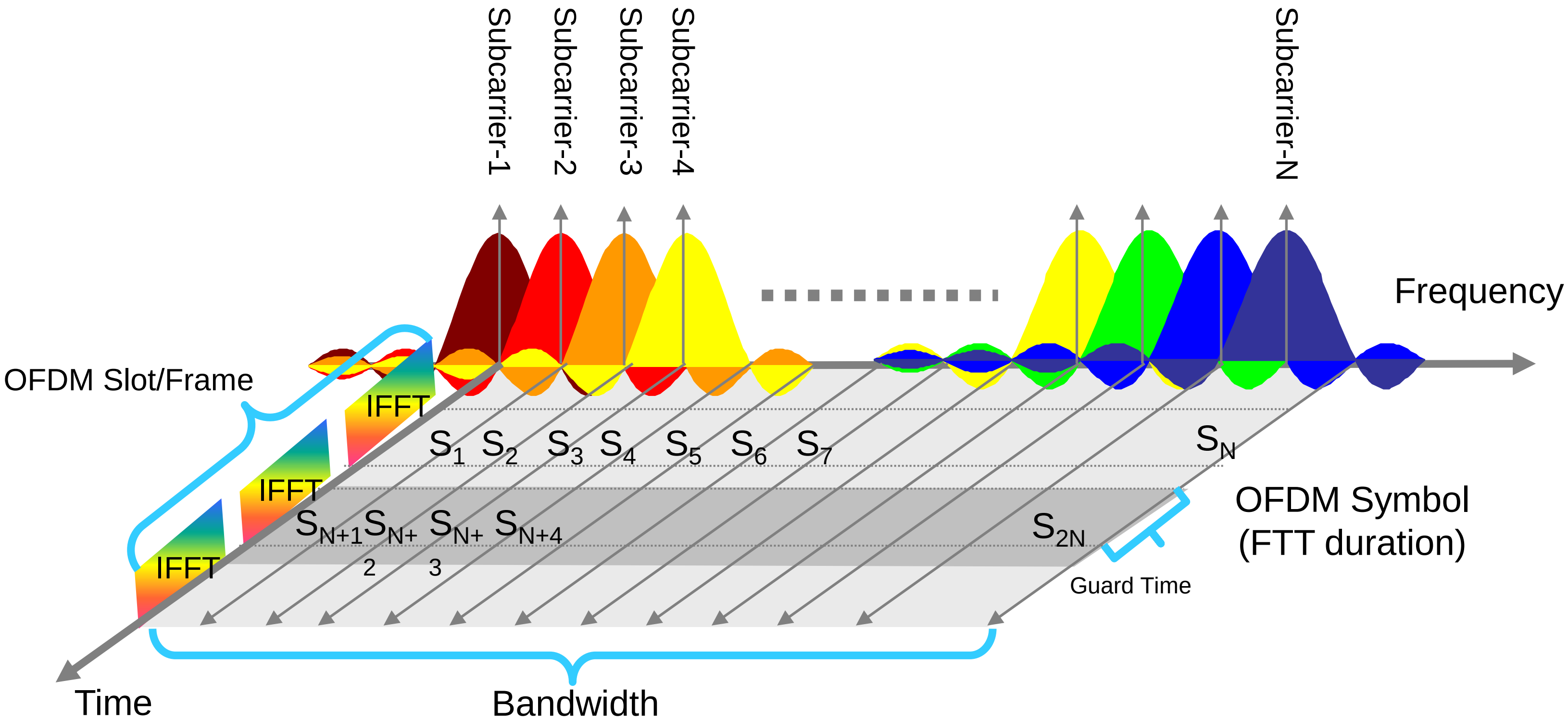
Summary for OFDM

- Feature of OFDM
  1. High Frequency utilization by the square spectrum shape
  2. Multi-path problem is solved by Cyclic Prefix
  3. Multiple services in one OFDM by sharing sub-carriers
  4. Implementation was complicated but NOW possible because of LSI technology progress

Is OFDM robust?

- The advantage of separating the transmission into multiple narrowband subchannels cannot itself translate into robustness against time variant channels if no channel coding is employed.
- The LTE downlink combines OFDM with channel coding and Hybrid Automatic Repeat reQuest (HARQ) to overcome the deep fading which may be encountered on the individual subchannels.

OFDMA Time-Frequency Domain

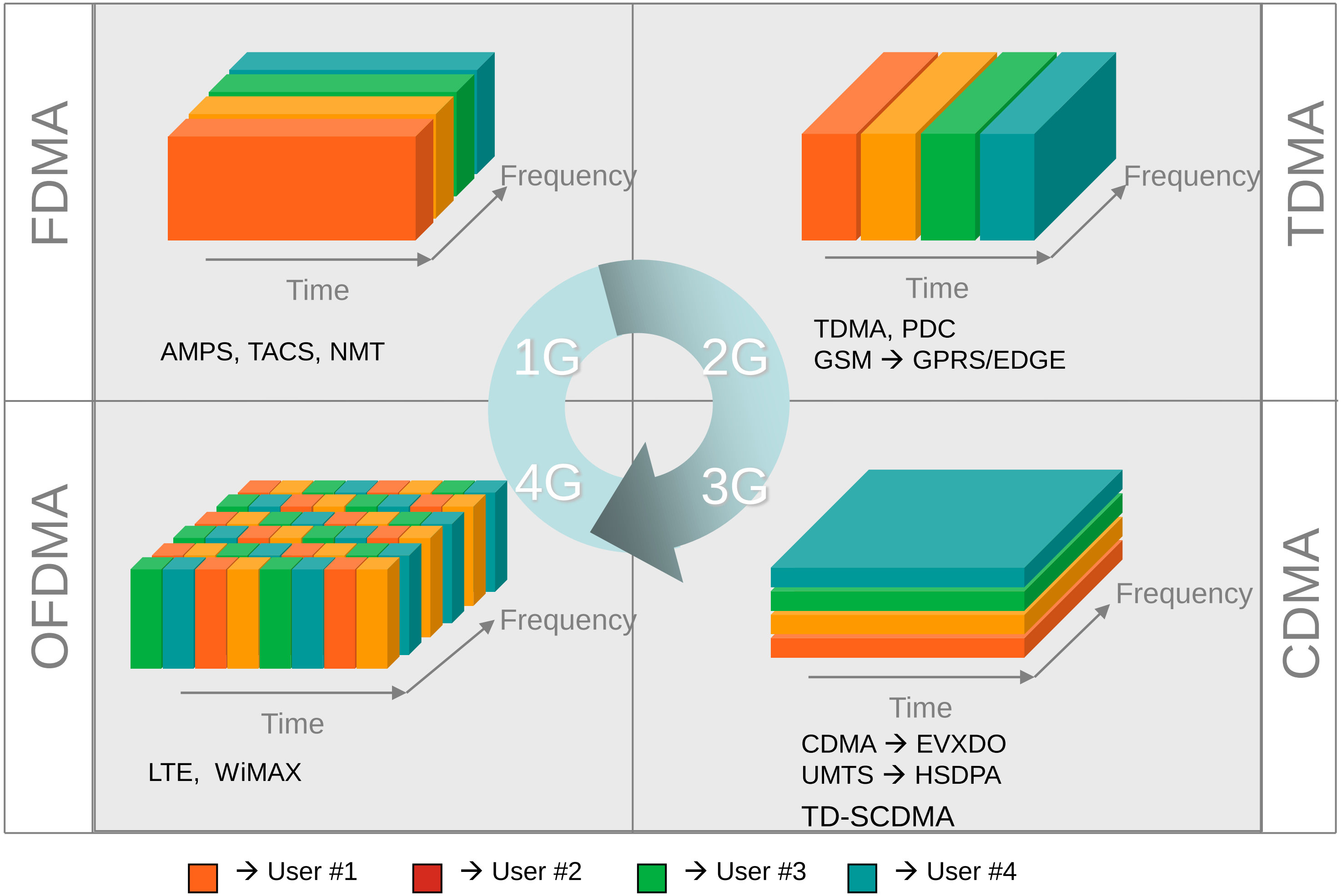


Advantages of OFDM technologies

- Higher spectral efficiency in real-life time dispersive channels
- More robust – less multi-path interference
- Easy to integrate MIMO technologies
- Simpler receiver to cope with real-life time dispersive channels → lower cost

OFDM Improves Radio Access Efficiency

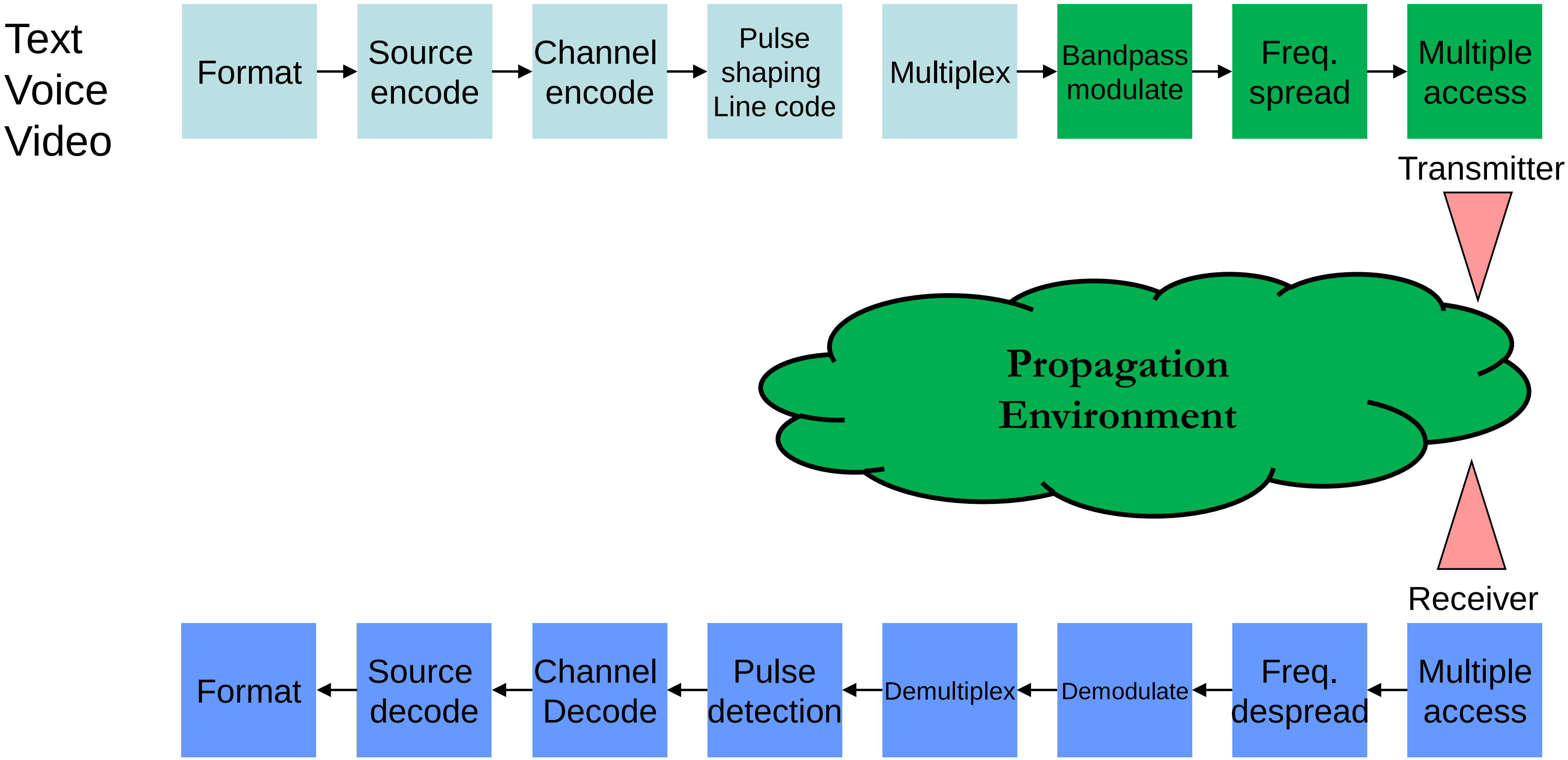
Moving from Voice to Broadband with VoIP



OFDM - scalable and most cost effective broadband solution

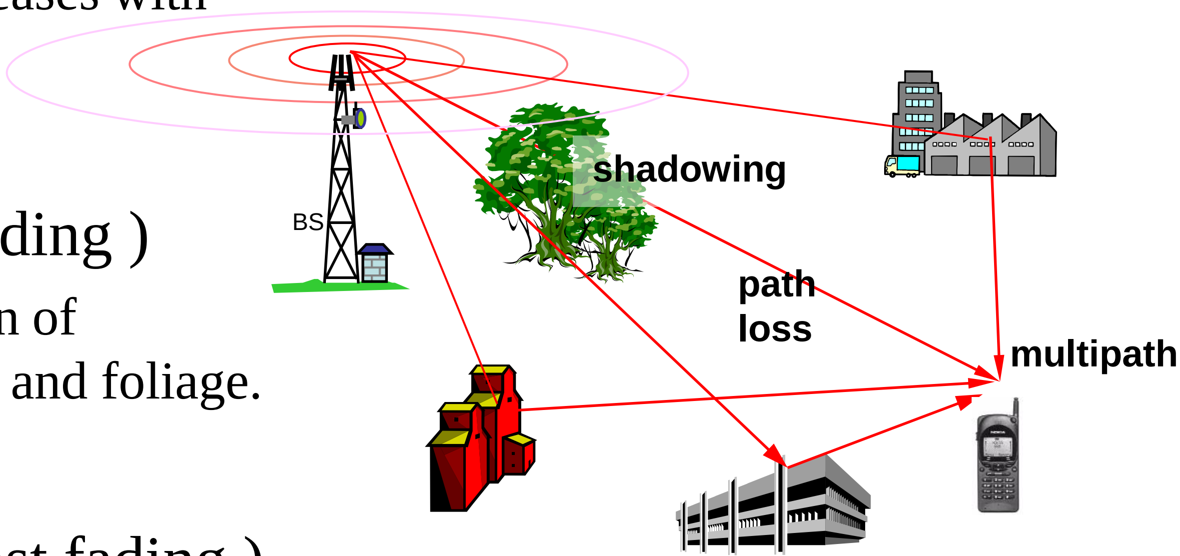
Radio Propagations & Network Architecture

Overview of Wireless Communication System



Radio transmission impairments

- Path loss
  - received power decreases with distance.
- Shadowing (slow fading)
  - caused by obstruction of buildings, hills, trees and foliage.
- Multipath fading (fast fading)
  - caused by multipath reflection of a transmitted wave by objects



Introduction

- An antenna is an electrical conductor or system of conductors
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception

- Radiation pattern
  - Graphical representation of radiation properties of an antenna
  - Depicted as two-dimensional cross section
- Beam width (or half-power beam width)
  - Measure of directivity of antenna
- Reception pattern
  - Receiving antenna's equivalent to radiation pattern

Antenna Gain

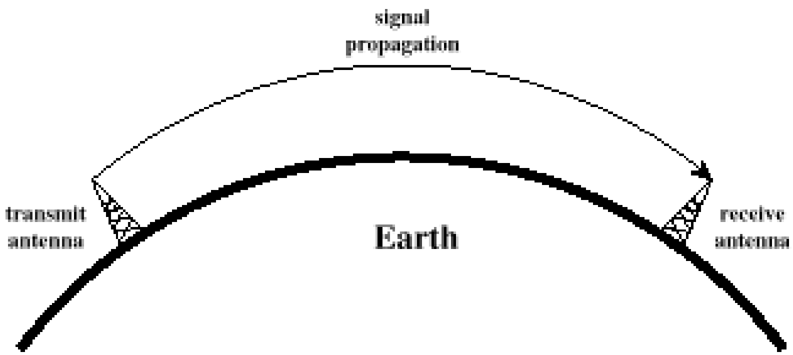
- Antenna gain
  - Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)
- Effective area
  - Related to physical size and shape of antenna

- Relationship between antenna gain and effective area

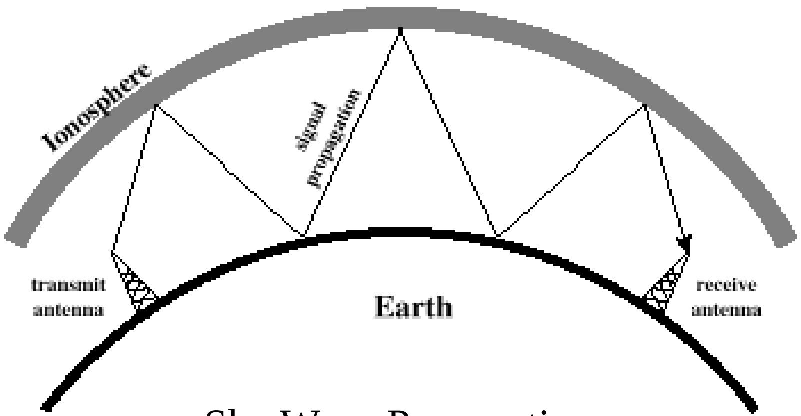
$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

- G = antenna gain
- A_e = effective area
- f = carrier frequency
- c = speed of light ($\approx 3\times10^8$ m/s)
- λ = carrier wavelength

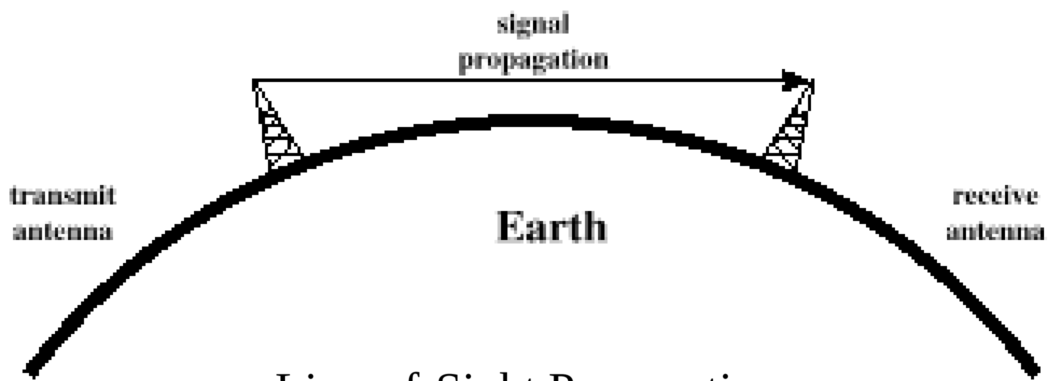
Propagation Modes



Ground Wave Propagation



Sky Wave Propagation



Line-of-Sight Propagation

LOS Wireless Transmission Impairments

- Attenuation and distortion
- Free space loss
- Noise
- Atmospheric absorption
- Multipath
- Refraction
- Thermal noise

Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors for unguided media:
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
  - Signal must maintain a level sufficiently higher than noise to be received without error
  - Attenuation is greater at higher frequencies, causing distortion

Free Space Loss

- Free space loss, ideal isotropic antenna

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

  - P_t = signal power at transmitting antenna
  - P_r = signal power at receiving antenna
  - λ = carrier wavelength
  - d = propagation distance between antennas
  - c = speed of light (≈ 3 ××10 8 m/s)

  where d and λ are in the same units (e.g., meters)

Categories of Noise

- Thermal Noise
- Intermodulation noise
- Crosstalk
- Impulse Noise

Thermal Noise

- Amount of thermal noise to be found in a bandwidth of 1Hz in any device or conductor is:

$$N_0 = \mathrm{k}T\left(\mathrm{W/Hz}\right)$$

  - N_0 = noise power density in watts per 1 Hz of bandwidth
  - k = Boltzmann's constant = 1.3803×10^{-23} J/K
  - T = temperature, in kelvins (absolute temperature)

Thermal Noise

- Noise is assumed to be independent of frequency
- Thermal noise present in a bandwidth of B Hertz (in watts):

$$N = \mathrm{k}TB$$

or, in decibel-watts

$$\begin{aligned} N &= 10\log \mathrm{k} + 10\log T + 10\log B \\ &= -228.6\,\mathrm{dBW} + 10\log T + 10\log B \end{aligned}$$

Noise Terminology

- Intermodulation noise – occurs if signals with different frequencies share the same medium
  - Interference caused by a signal produced at a frequency that is the sum or difference of original frequencies
- Crosstalk – unwanted coupling between signal paths
- Impulse noise – irregular pulses or noise spikes
  - Short duration and of relatively high amplitude
  - Caused by external electromagnetic disturbances, or faults and flaws in the communications system

Expression E_b/N_0

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

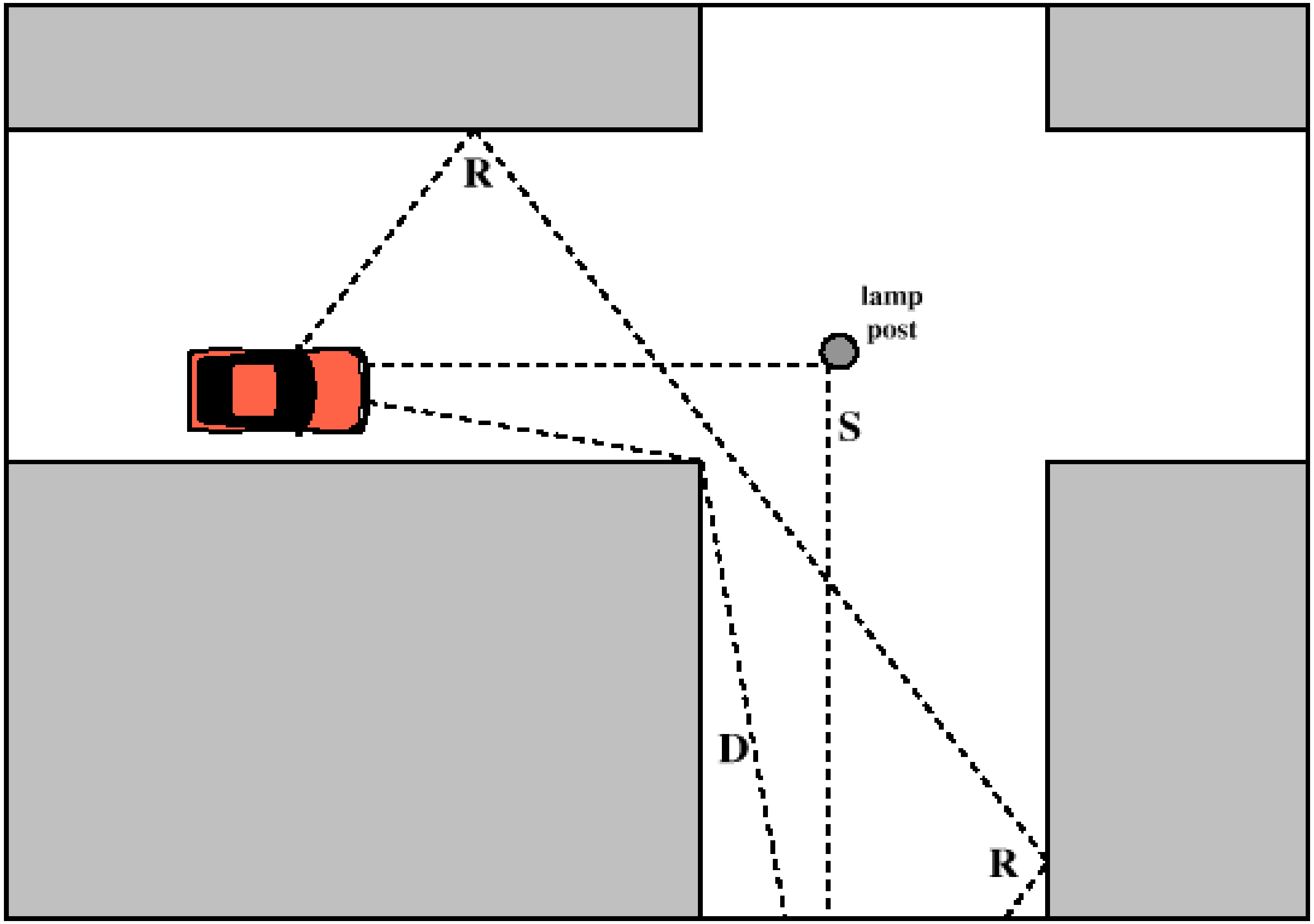
$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{\mathrm{k}TR}$$

- The bit error rate for digital data is a function of E_b/N_0
  - Given a value for E_b/N_0 to achieve a desired error rate, parameters of this formula can be selected
  - As bit rate R increases, transmitted signal power must increase to maintain required E_b/N_0

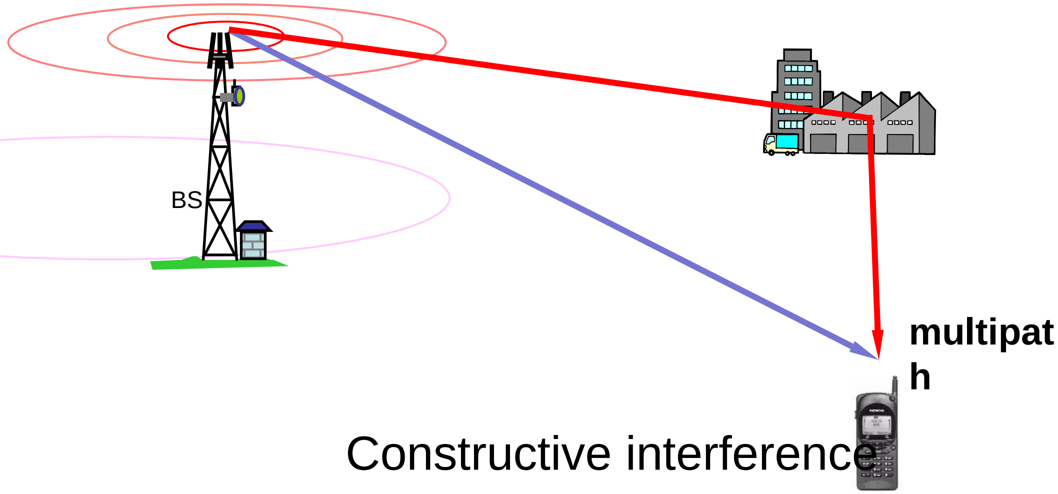
Other Impairments

- Atmospheric absorption – water vapor and oxygen contribute to attenuation
- Multipath – obstacles reflect signals so that multiple copies with varying delays are received
- Refraction – bending of radio waves as they propagate through the atmosphere

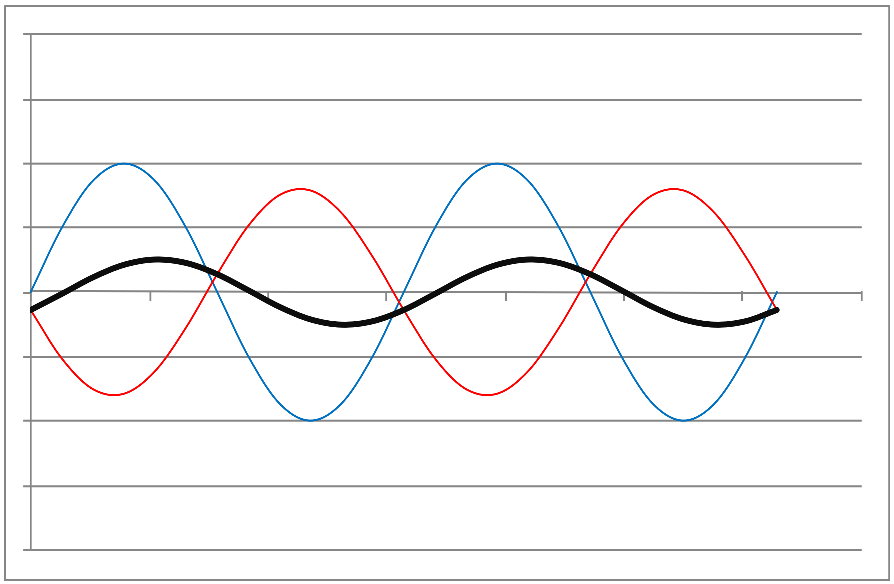
Multipath Propagation



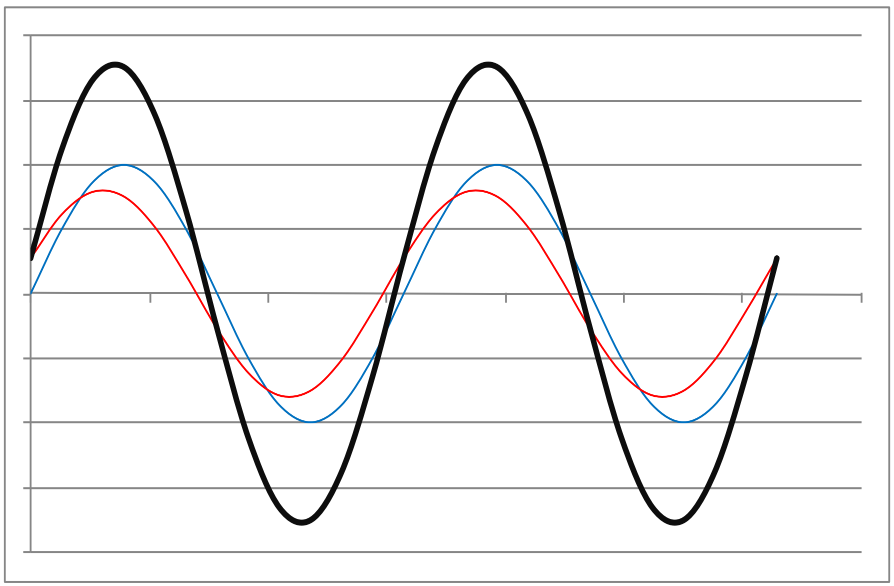
Multi-path



Destructive interference



Constructive interference



As mobile moves the relative phase changes and fading occurs

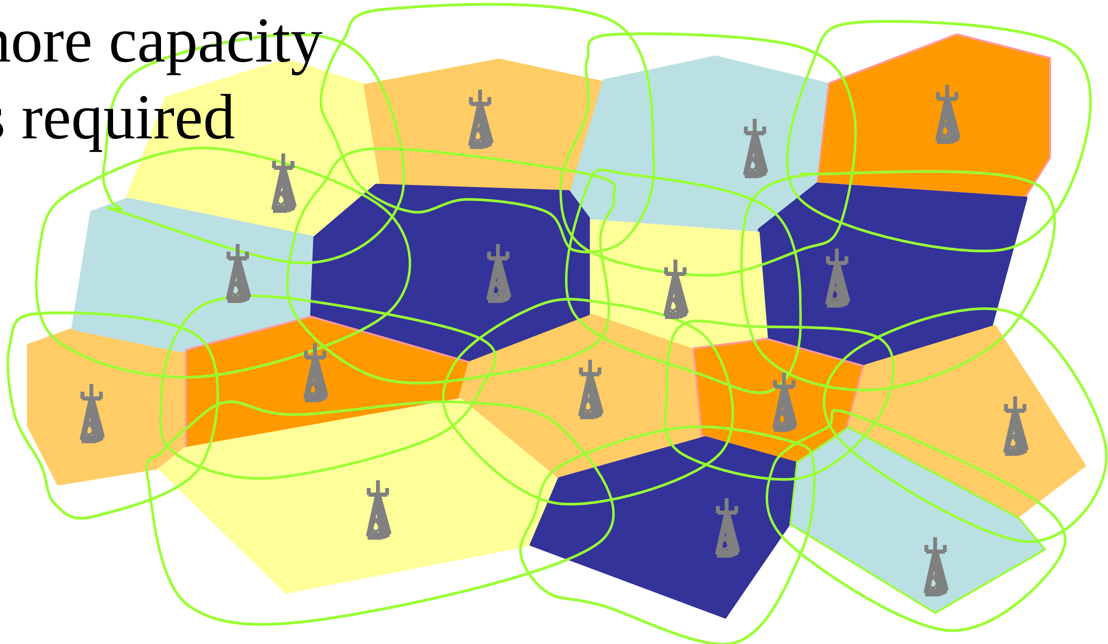
Types of Fading

- Fast fading, Slow fading, Flat fading, Selective fading
- Rayleigh fading, Nakagami-m and Rician fading

Radio Propagations & Network Architecture

Cellular concept

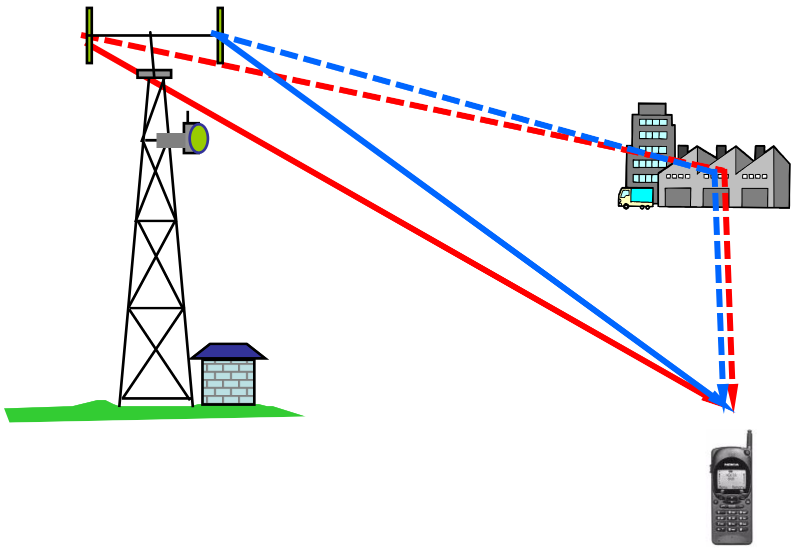
- Late 40s: AT&T developed cellular concept for frequency re-use
- Break the service area into cells
- Shrink the cell size; adopt intensive frequency re-use
- Add more cells to add more capacity
- Mobility management is required



Radio access

- This base station has 3 sectors each equipped with independent TRXs (transmitter/receivers)
- It has spaced pairs of antennas in each sector to provide diversity reception
- Microwave link antenna to the network
- LNAs on the antennas (LNA=low noise amplifiers)

Diversity



Different phase relations will exist between the multipath rays from each antenna – so the interference will be different.

Diversity: used in 2G, 3G, WLAN and 4G

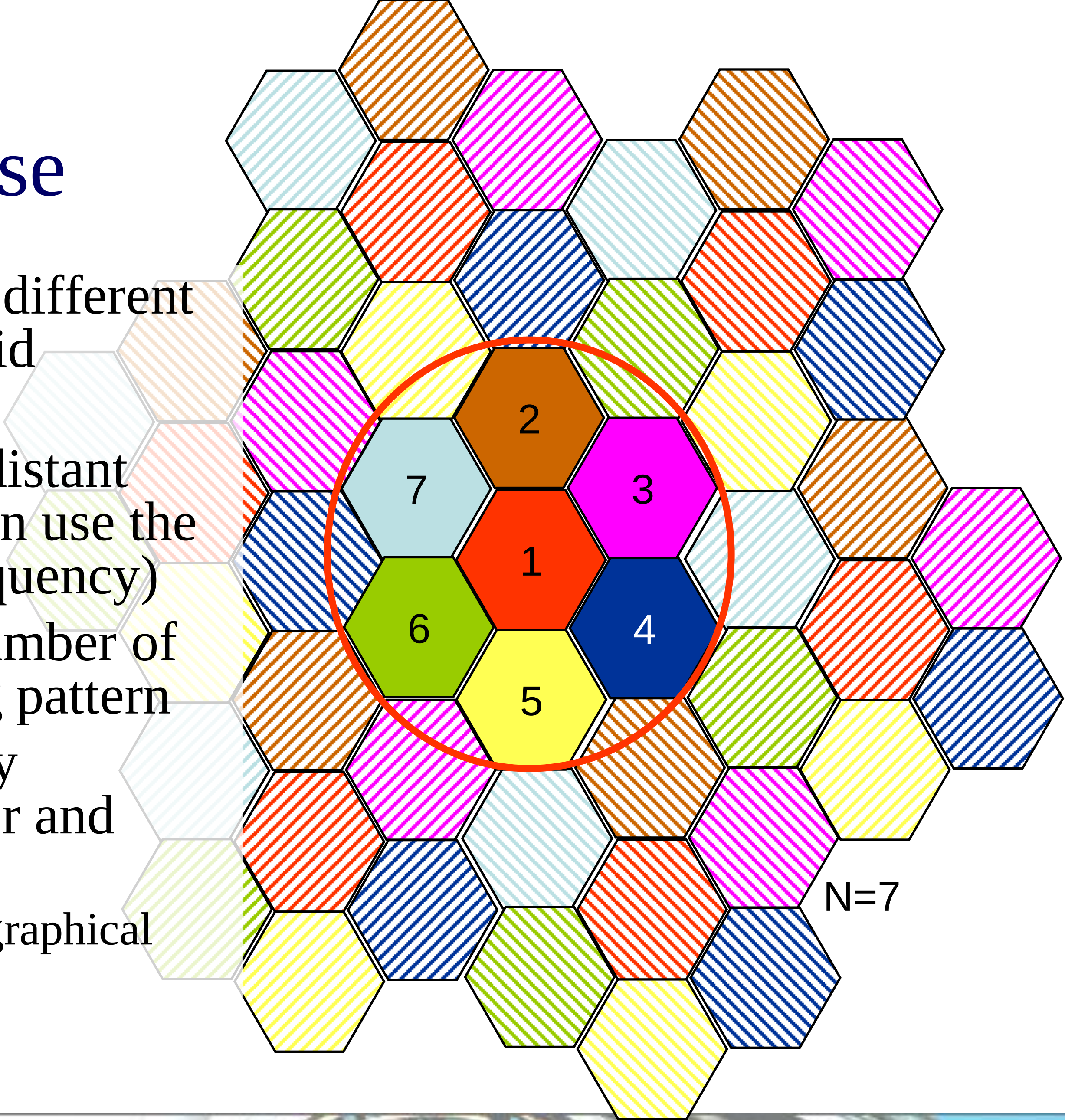
- Obtain two or more copies of the received signal
- Copies can be separated by:
  - **Time**: Convolutional coding 'smears' short errors
  - **Frequency**: Frequency hopping is used for GSM;
  - **Distance**: Spatial diversity (2G/3G/WLAN)
  - **Polarization**: Polarization diversity ±45º (2G/3G)

Diversity: Combining the signals

- Combine the signal from each branch and obtain a signal that is more reliable than any single branch
  - Switch diversity – when one is too low, try another
  - Selection diversity – choose the largest signal
  - Equal gain – signals equally weighted and added in phase
  - Maximal ratio – weight the power in the branches in proportion to their signal amplitude and add in phase
- Diversity gain = effective increase in signal power for some stated reliability. Typically 4–6dB depending on the environment.

Frequency reuse

- Adjacent cells use different frequencies to avoid interference
- Cells sufficiently distant from each other can use the same channel (frequency)
- Reuse factor N: number of cells in a repeating pattern
- Control cell size by choosing BS power and antennas
  - Make use of topographical screening



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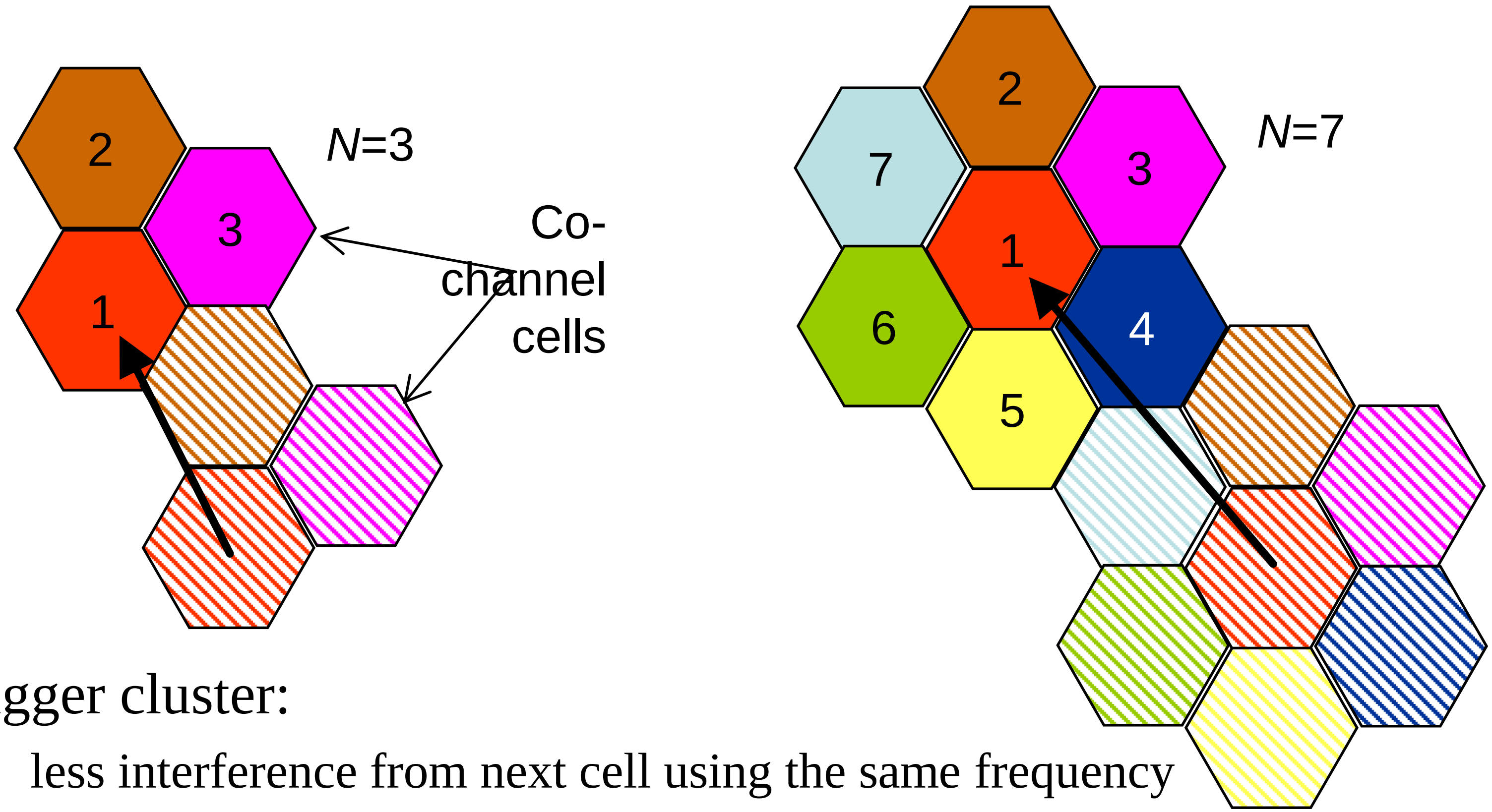
Effect of cluster size

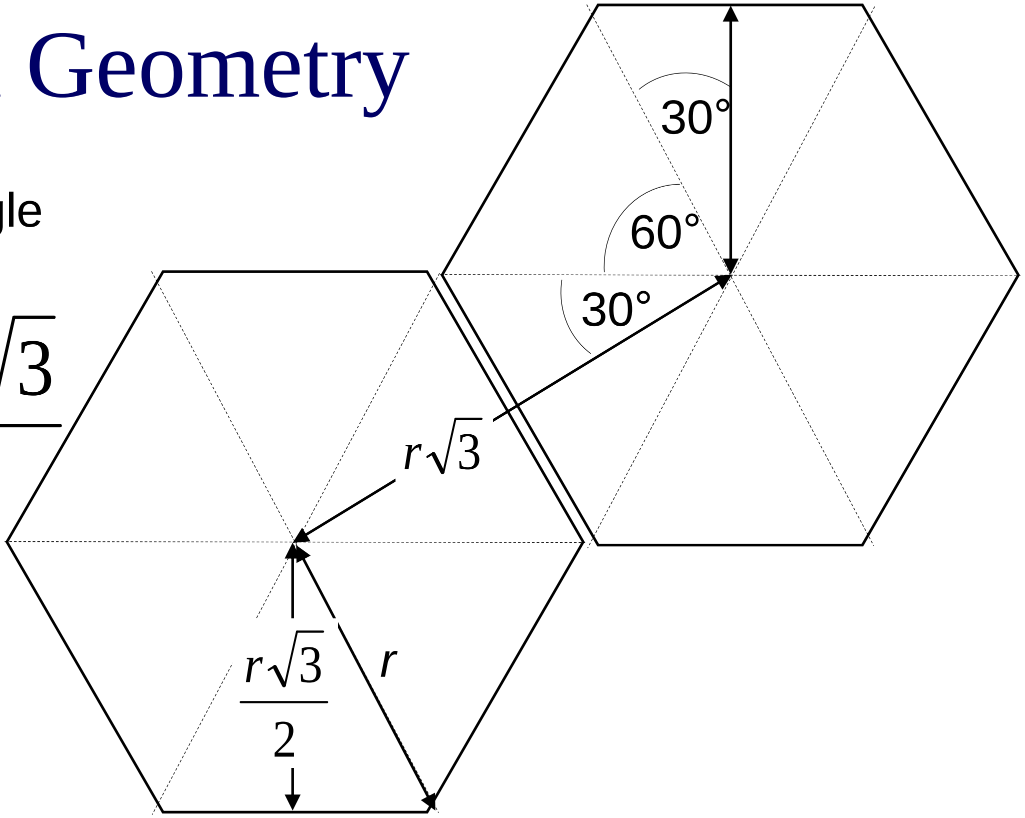


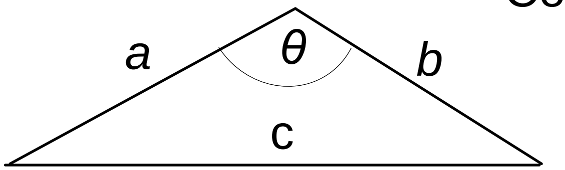
- Bigger cluster:
  - less interference from next cell using the same frequency
  - lower capacity – bandwidth available in cell is F_A/N (F_A is frequency spectrum allocated)

Reminders on Geometry

Surface area of a hexagon
=6*area of equilateral triangle

$$s = 6 \times r^2 \frac{\sqrt{3}}{4} = \frac{r^2 3\sqrt{3}}{2}$$

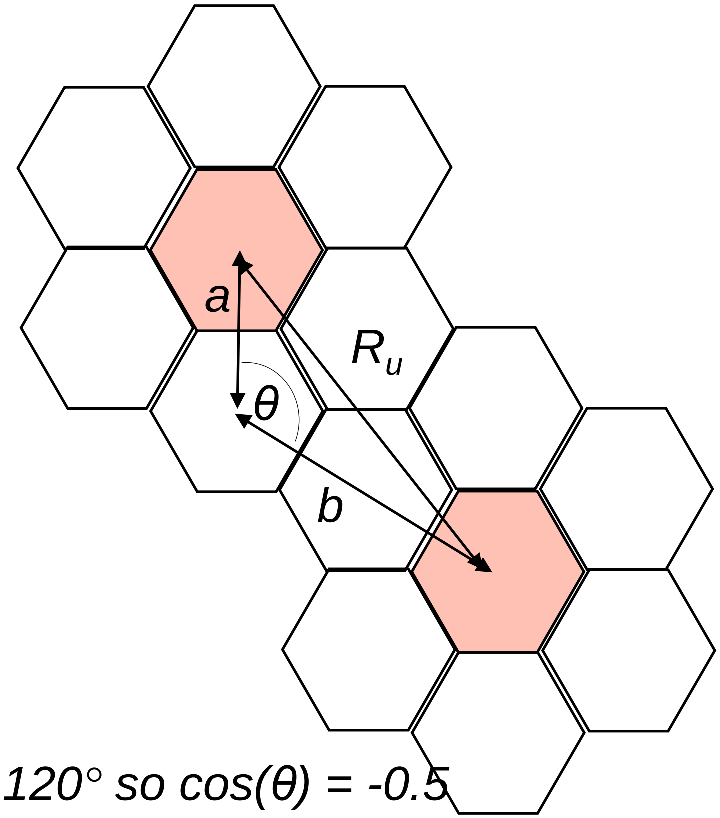




Cosine rule:

$$c^2 = a^2 + b^2 - 2ab\cos(\theta)$$

Derivation example (N=7 in pictures)



θ = 120° so cos(θ) = -0.5

In general

a is distance between *i* cells

$$a = ir\sqrt{3}$$

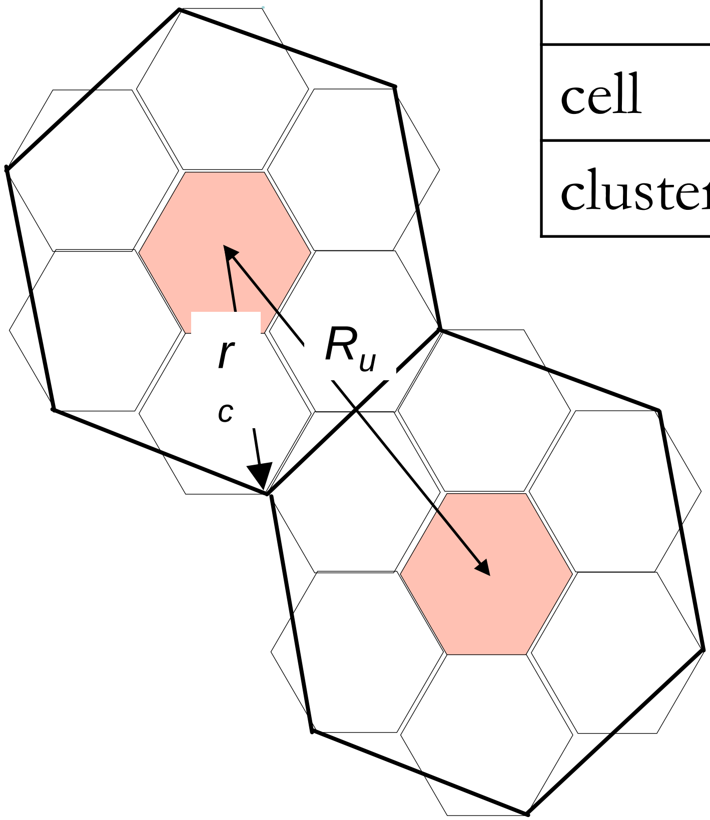
b is distance between *j* cells

$$b = jr\sqrt{3}$$

$$R_u^2 = i^2r^2 3 + j^2r^2 3 + 2\times 0.5ijr^2 3$$

$$R_u = \left(\sqrt{i^2 + j^2 + ij}\right)\left(r\sqrt{3}\right)$$

Cluster radius



	radius	area
cell	r	s
cluster	r_c	s_c

$$s_c = Ns$$

$$\frac{r_c^2 3\sqrt{3}}{2} = N\frac{r^2 3\sqrt{3}}{2}$$

$$r_c = r\sqrt{N}$$

$$R_u = r_c\sqrt{3}$$

$$R_u = r\sqrt{3N}$$

Thick lines define a cluster hexagon of same area as N cells

Possible values of N

$$R_u = \left(\sqrt{i^2 + j^2 + ij}\right)\left(r\sqrt{3}\right) \quad \text{and} \quad R_u = r\sqrt{3N}$$

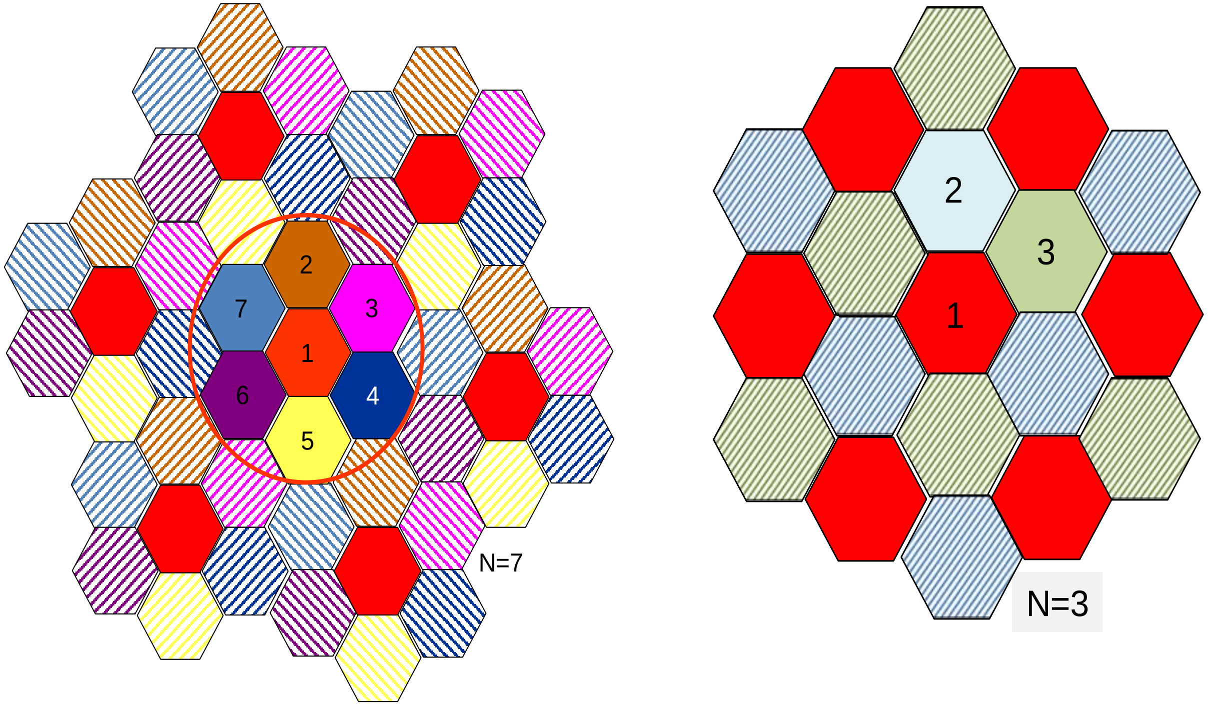
$$\left(\sqrt{i^2 + j^2 + ij}\right)\left(r\sqrt{3}\right) = r\sqrt{3N} \quad \text{or} \quad \sqrt{i^2 + j^2 + ij} = \sqrt{N}$$

$$i^2 + j^2 + ij = N$$

These means that only certain values of N are possible

i	j	N
1	1	3
1	2	7
2	2	12
1	3	13
2	3	19
1	4	21
3	3	27
2	4	28

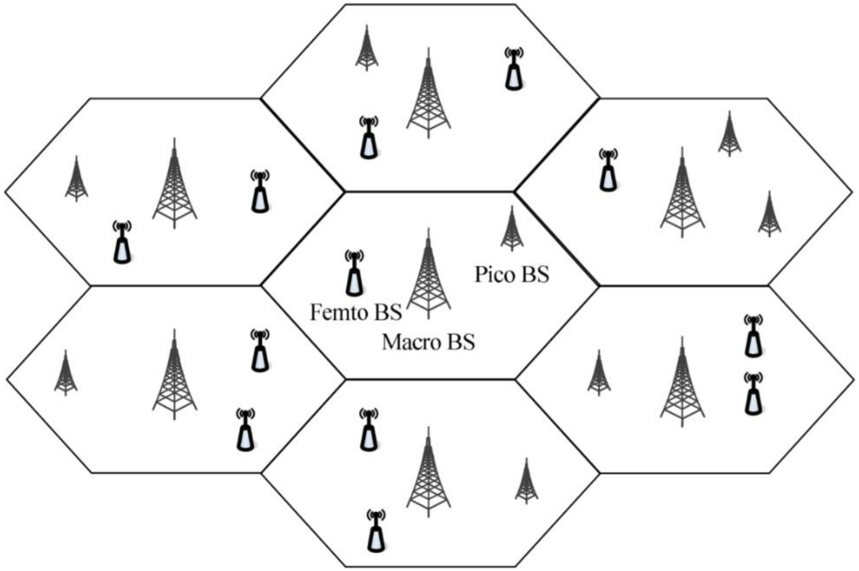
Different cluster size



6 surrounding cells of same frequency for both cluster size

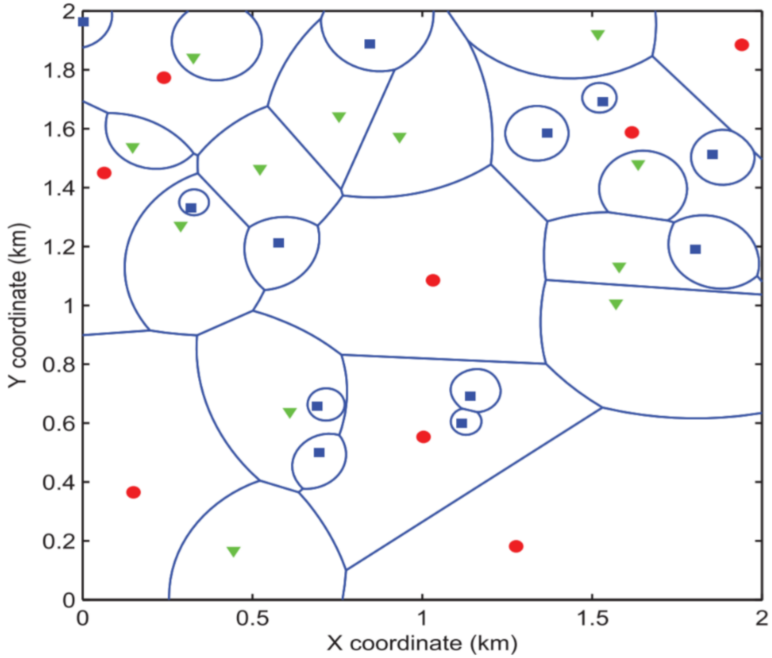
What is in practice?

- **Conventional Networks**
  - 3-tier Heterogenous Networks topology for the grid model



What is in practice?

- **Stochastic Geometry**
  - 3-tier Heterogenous Networks following the random spatial model



Class exercise

In a simple free-space radio propagation model, the received signal power is proportional to $1/d^4$, where d is distance.

Calculate the interfering power from the co-channel cells in a 7-cell cluster (P_{i7}) and compare it with the interfering power in a 3-cell cluster – i.e. evaluate P_{i7}/P_{i3} in dB

Assume the cell radius is the same in each case.