Telecom Systems (Week 4)

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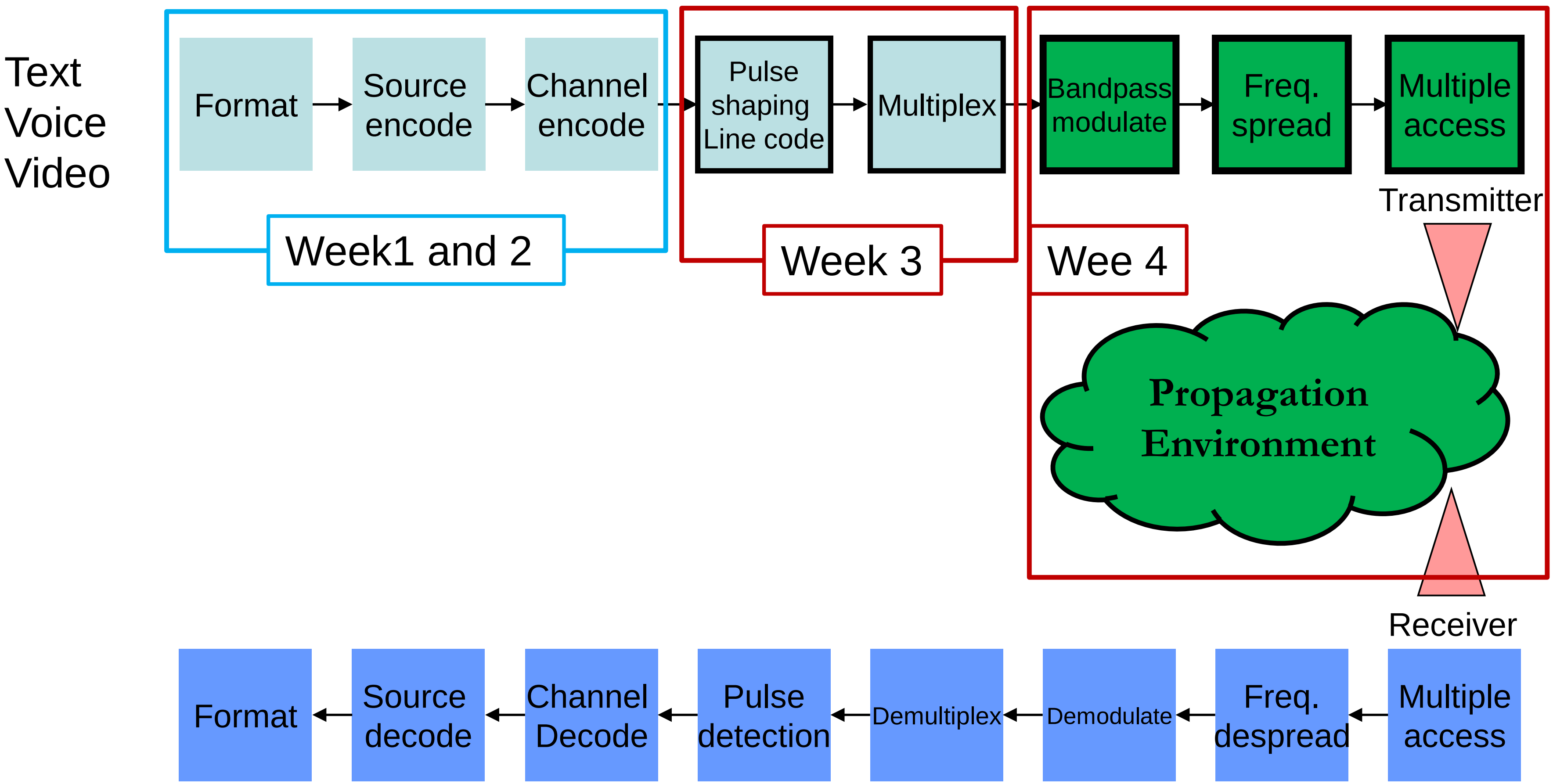
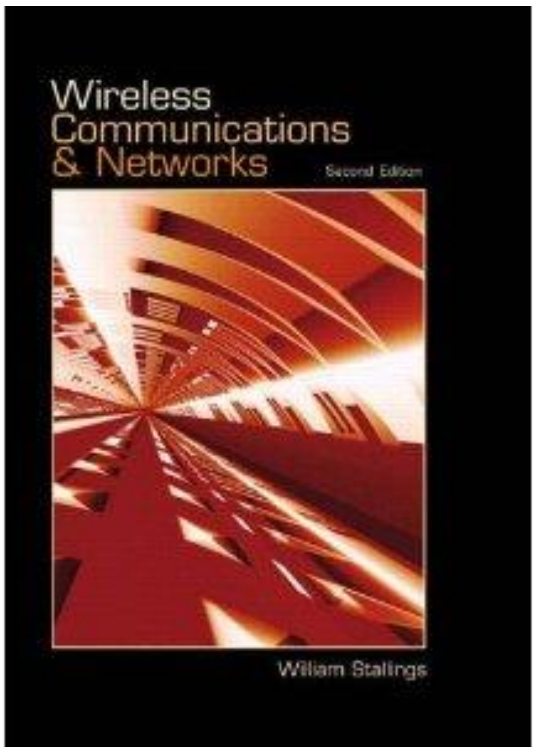
Overview of Wireless Communication System

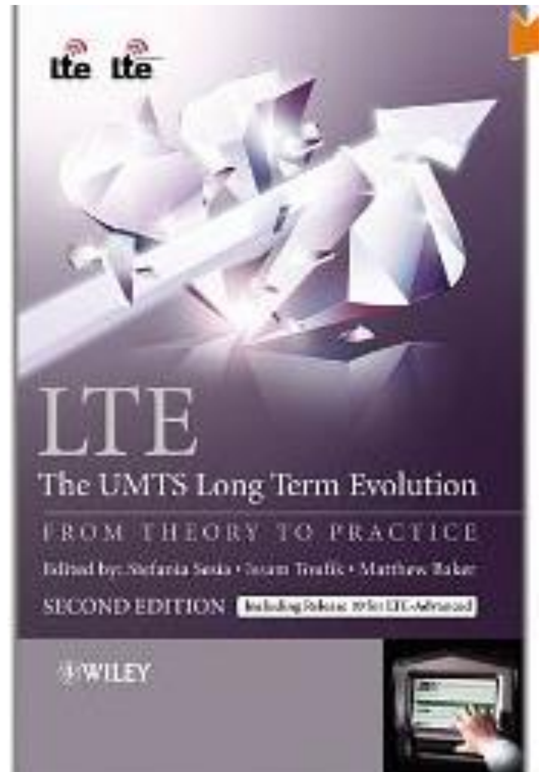


Reference books for week 4

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***



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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

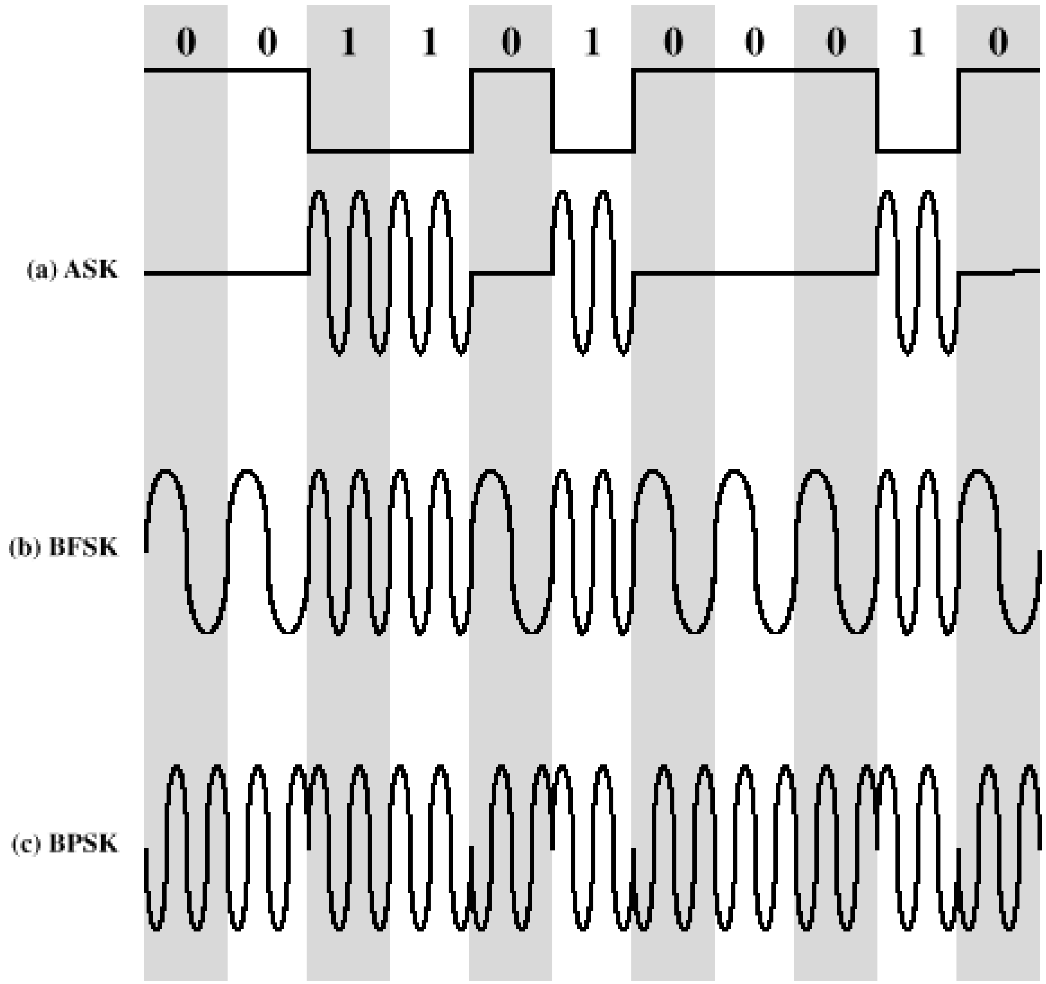
Signal Encoding Criteria

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

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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 and less 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 $= 1/T$)
- One signal element encodes L bits.
- The total bandwidth required is

$$2Mf_d$$

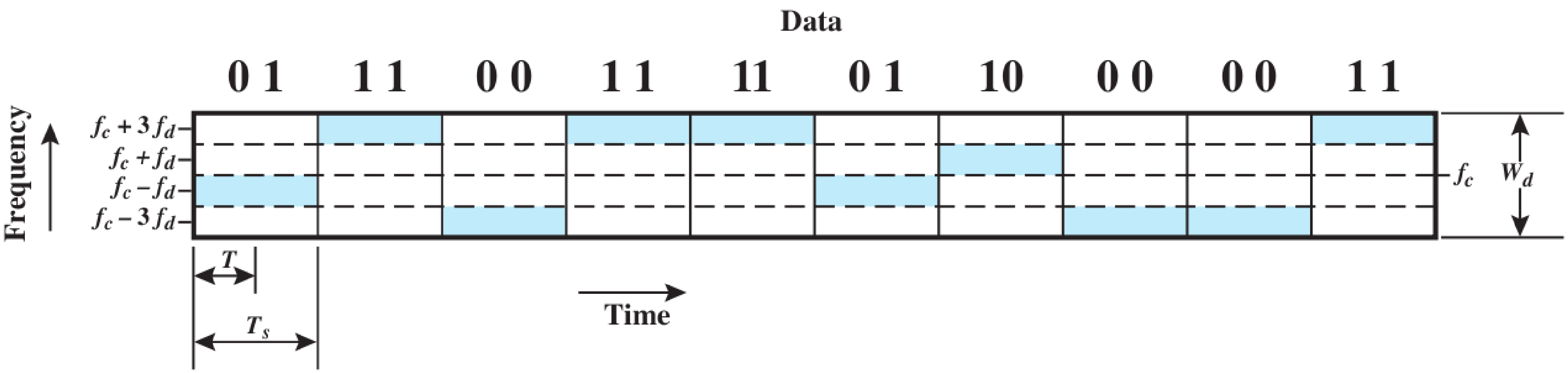
- Minimum frequency separation required

$$2f_d = 1/T_s$$

- 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

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

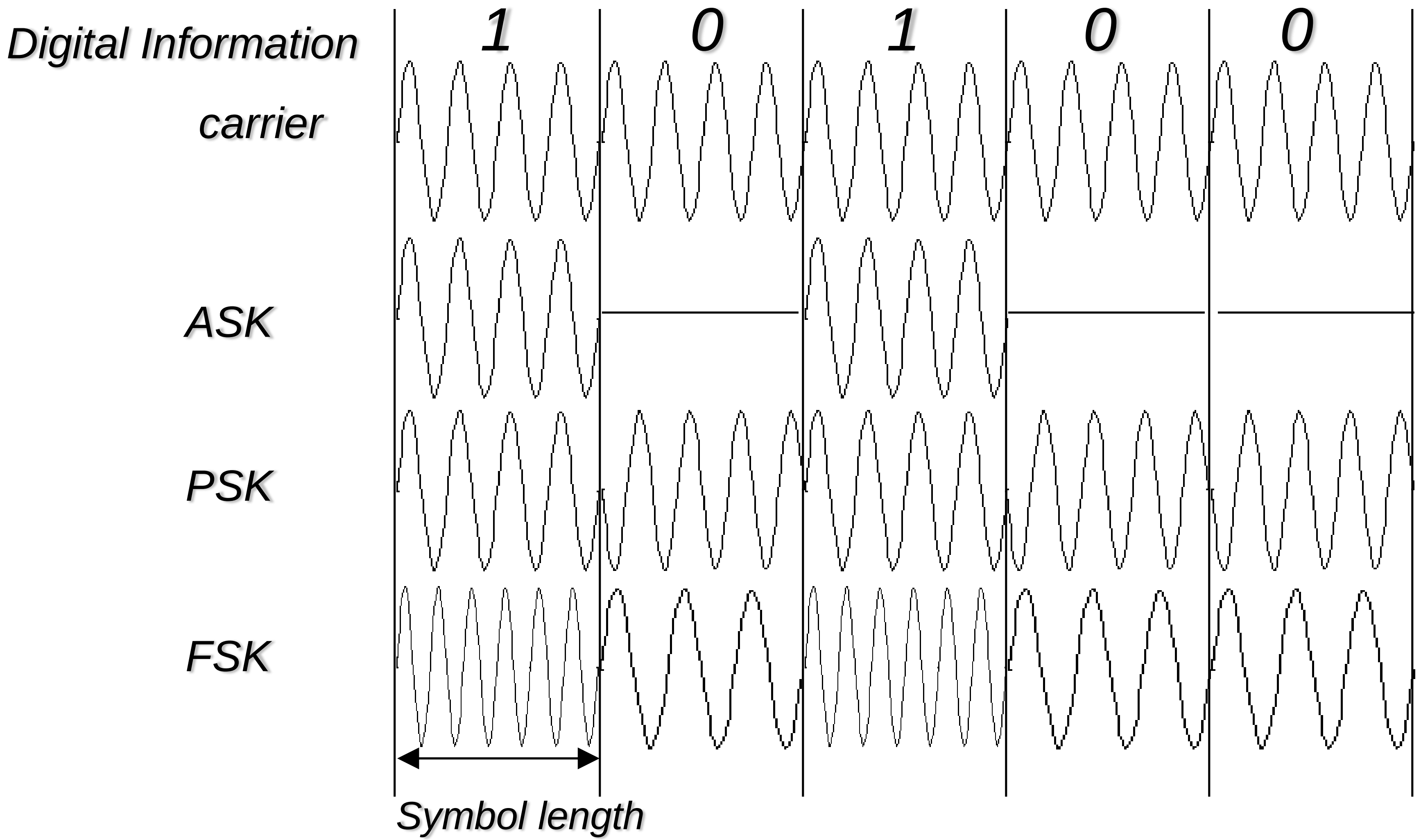
$$= \begin{cases} A\cos(2\pi f_c t) & \text{binary 1} \\ -A\cos(2\pi f_c t) & \text{binary 0} \end{cases}$$

Phase-Shift Keying (PSK)

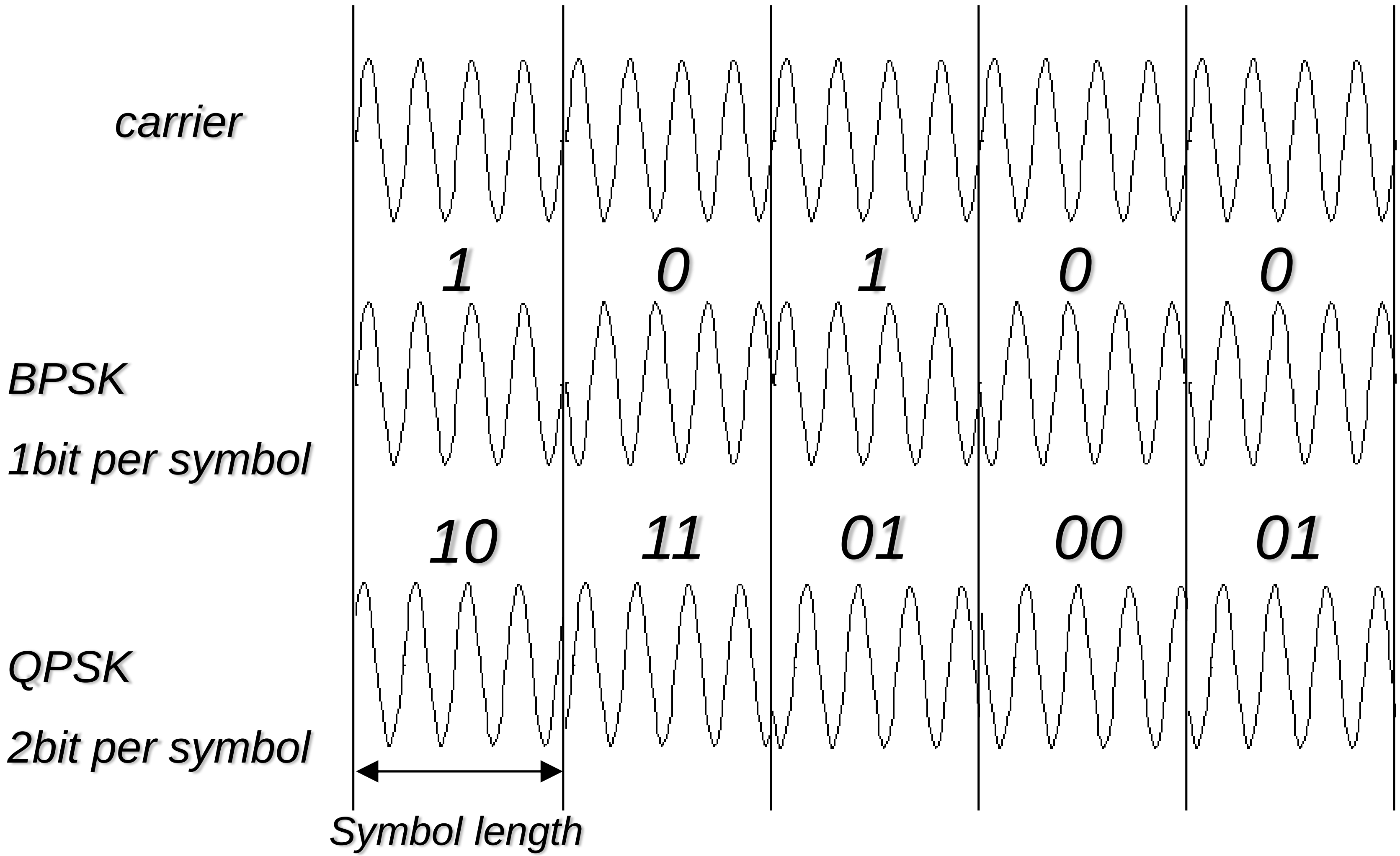
- Four-level PSK (QPSK)
  - Each element represents more than one bit

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

Symbol Waveform



Multi bit modulation



Mathematical expression of digital modulation

- Transmission signal can be expressed as follows

$$s(t) = \cos(2\pi \cdot f_c \cdot t + \theta_k)$$
$$= \cos\theta_k \cdot \cos(2\pi \cdot f_c \cdot t) - \sin\theta_k \cdot \sin(2\pi \cdot f_c \cdot t)$$
$$Let, \quad a_k = \cos\theta_k, \quad b_k = \sin\theta_k$$
$$s(t) = \mathrm{Re}[(a_k + jb_k)e^{j2\pi fc \cdot t}]$$ [Euler's formula: $\cos\theta_k = \mathrm{Re}(e^{j\Theta_k})$]

- 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*

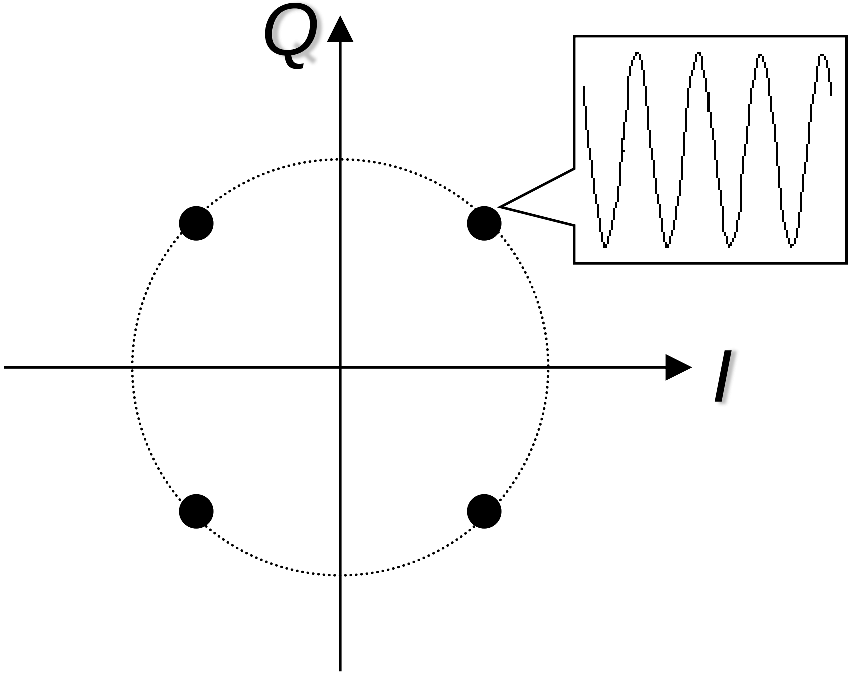
Digital modulation can be expressed by the complex number

Constellation map

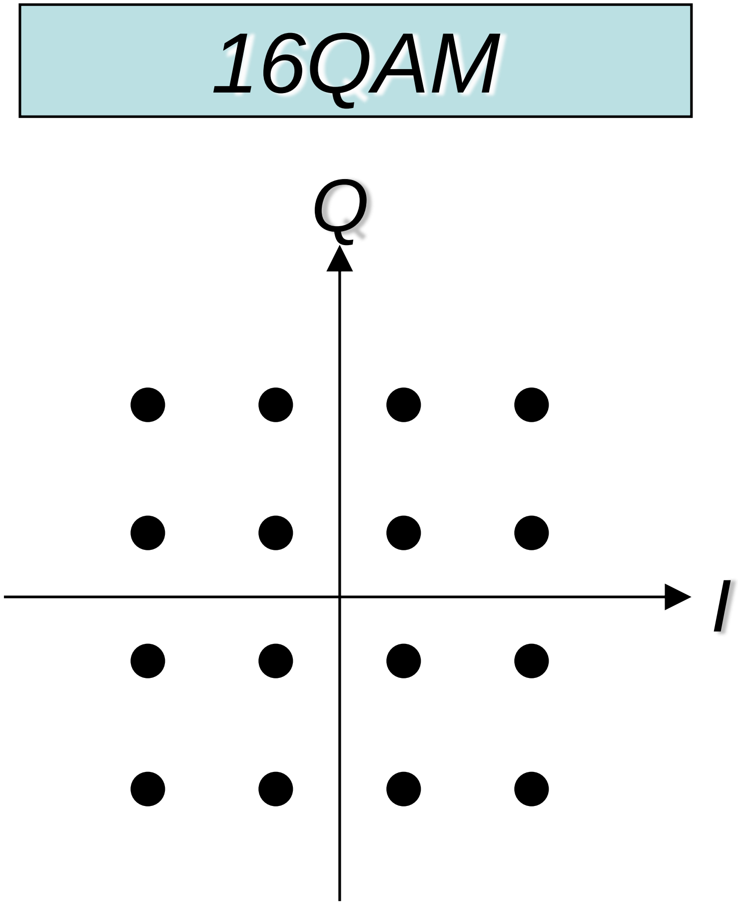
- $(a_k + jb_k)$ is plotted on I(real)-Q(imaginary) plane

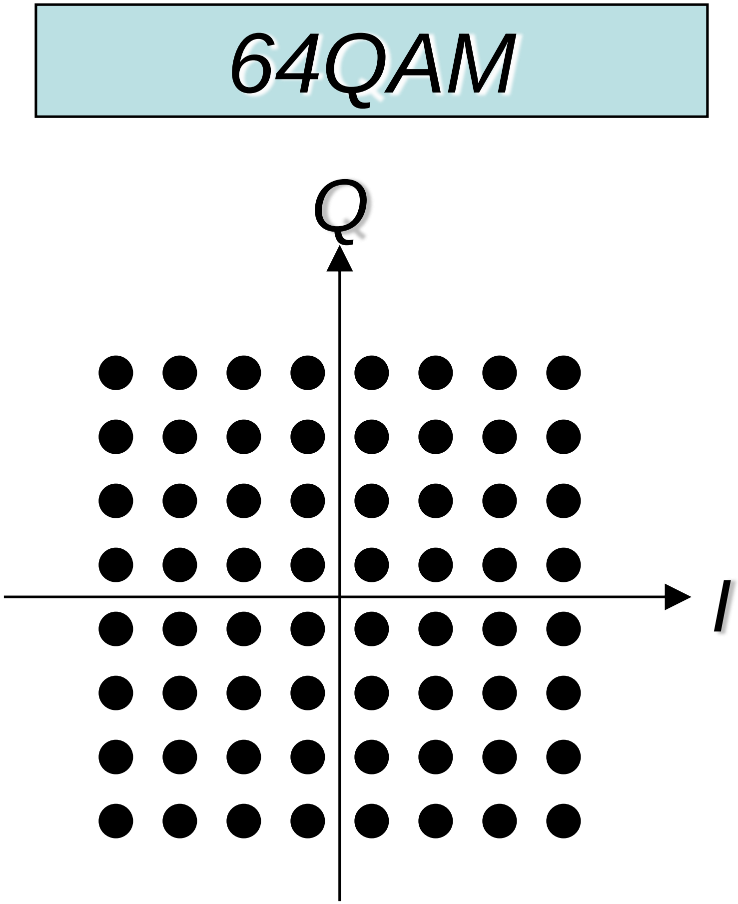
data	Phase	a_k	b_k
00	π/4	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
01	3π /4	$-\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
11	5π /4	$-\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$
10	7π /4	$\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$

QPSK

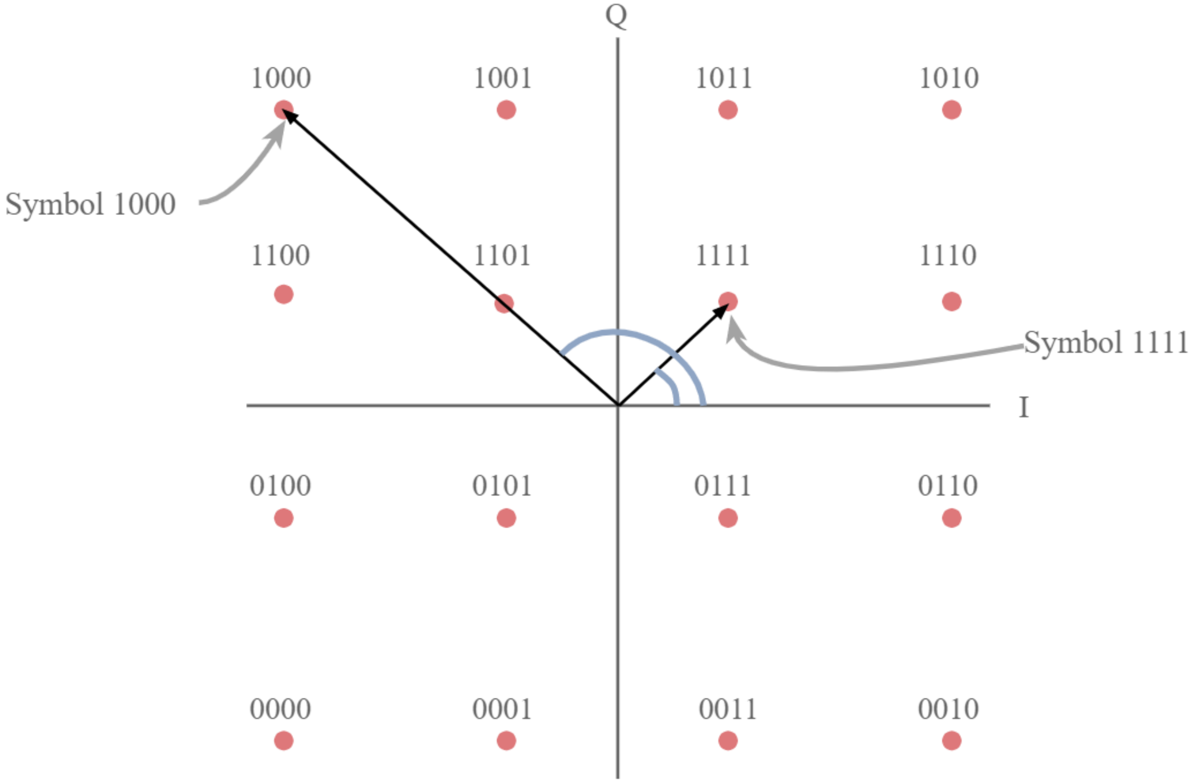


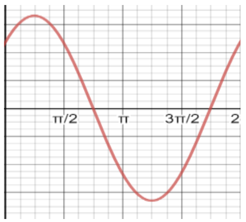
Quadrature Amplitude Modulation (QAM)





Quadrature Amplitude Modulation (QAM)





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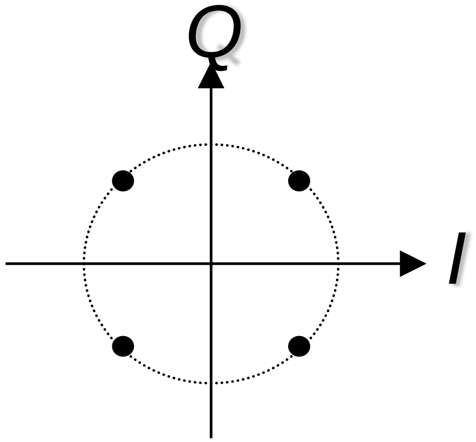
Summary of digital modulation

- 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



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Spread Spectrum (Freq. Spread)

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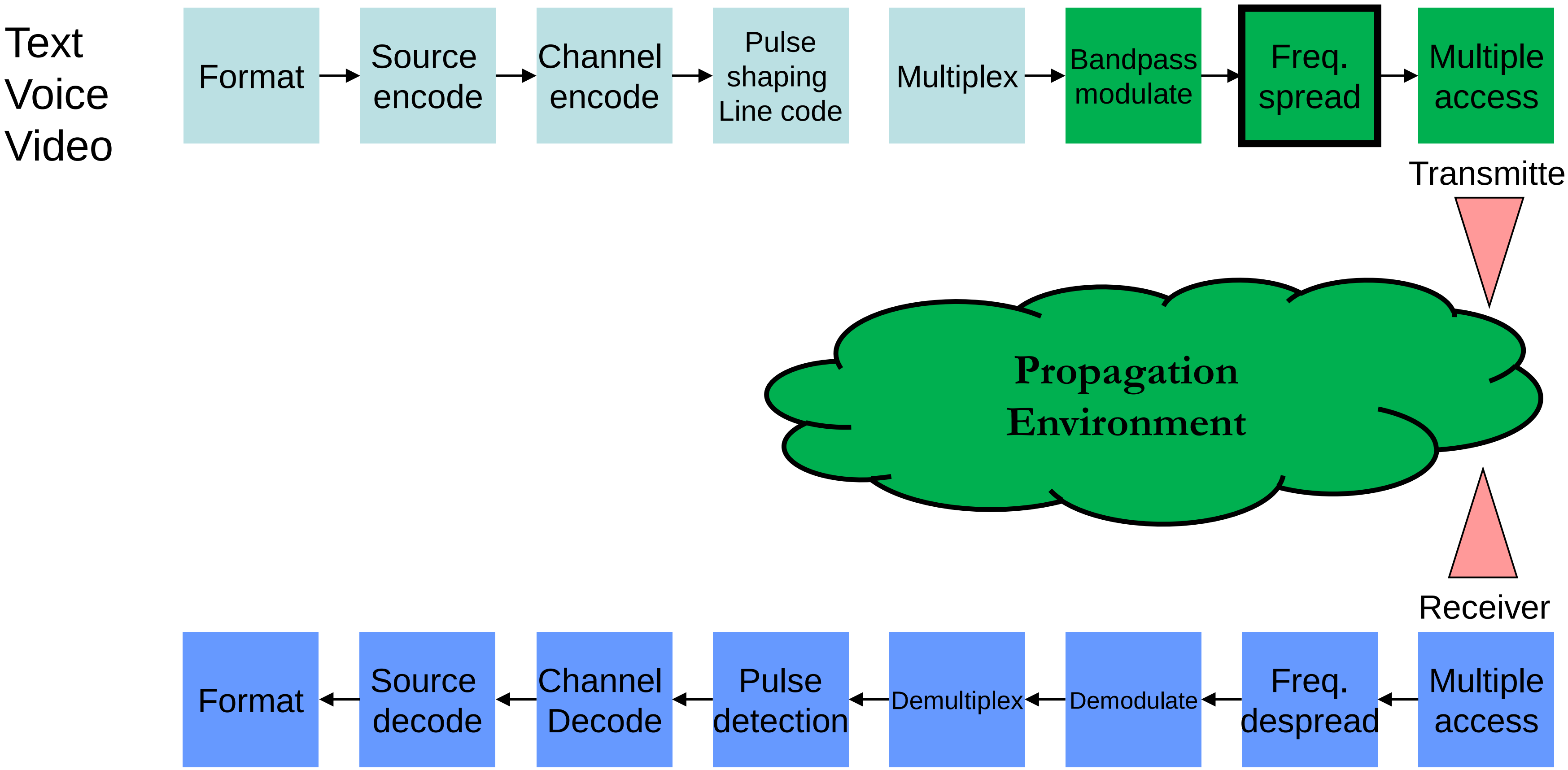
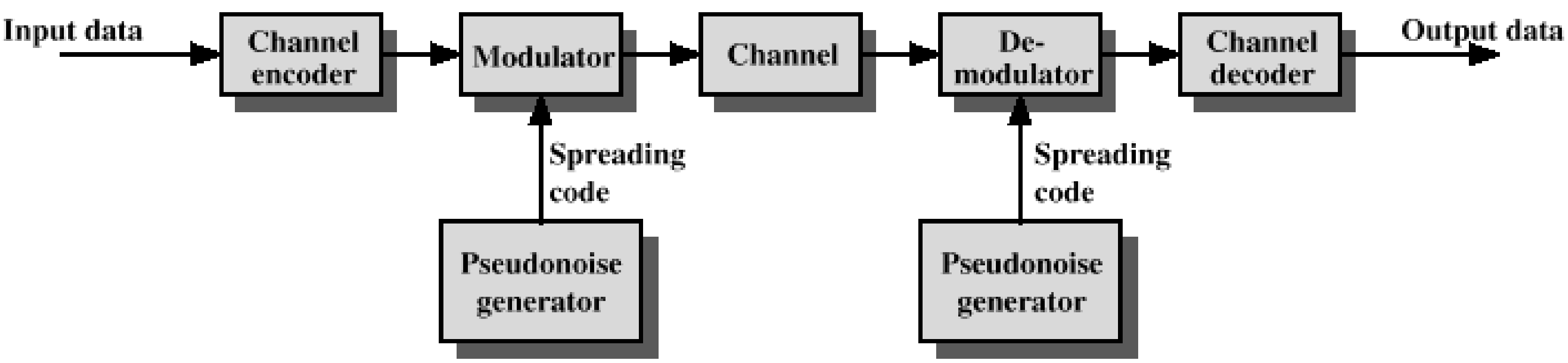
Overview of Wireless Communication System



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



Spread Spectrum

- Idea of this modulation is to increase bandwidth of signal to be transmitted and to make jamming and interception more difficult.

- General Techniques of Spread Spectrum in Digital Communication System:

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

Frequency Hoping Spread Spectrum (FHSS)

- Signal is broadcasted 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

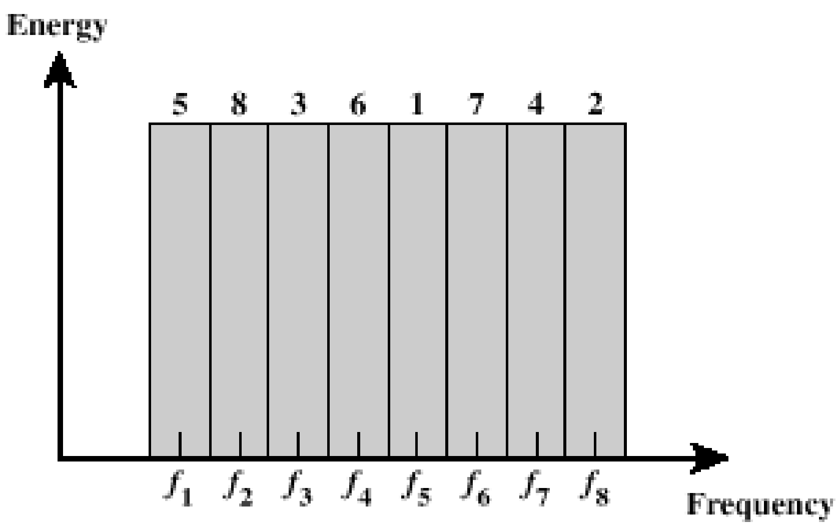
- Signal hops from frequency to frequency at fixed intervals
  - Transmitter operates in one channel at a time
  - Bits are transmitted using some encoding scheme
  - At each successive interval, a new carrier frequency is selected

Frequency Hoping Spread Spectrum

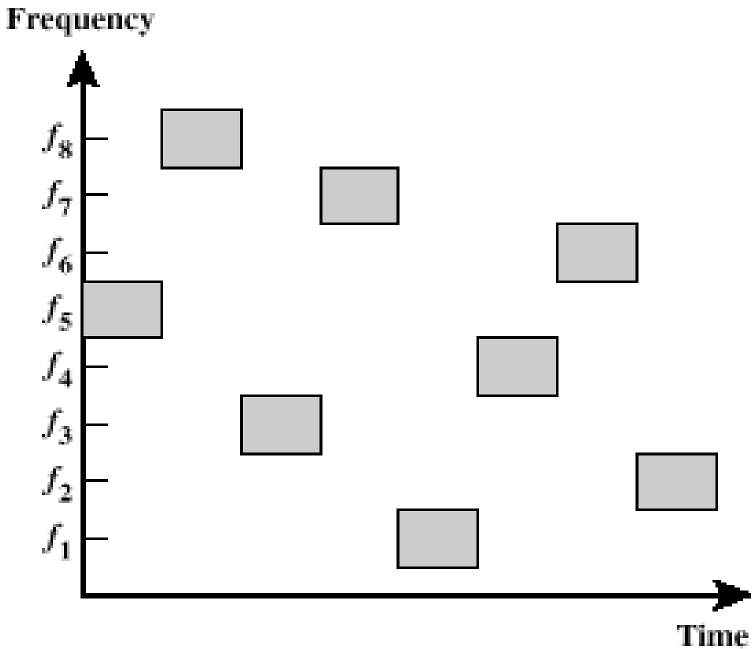
- Channel sequence dictated by spreading code
- Receiver, hopping between frequencies in synchronization with transmitter, picks up message
- Both transmitter and receiver use the same code to tune into a sequence of channels in synchronization. On reception, the spread spectrum signal is demodulated using the same sequence

- **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



(a) Channel assignment



(b) Channel use

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
- Th e effect is to translate the MFSK signal into the appropriate FHSS channel.
- For data rate of R:
  - duration of a bit: $T = 1/R$ seconds
  - duration of signal element: $T_s = LT$ seconds
- $T_c \geq T_s$ - slow-frequency-hop spread spectrum
- $T_c < T_s$ - fast-frequency-hop spread spectrum

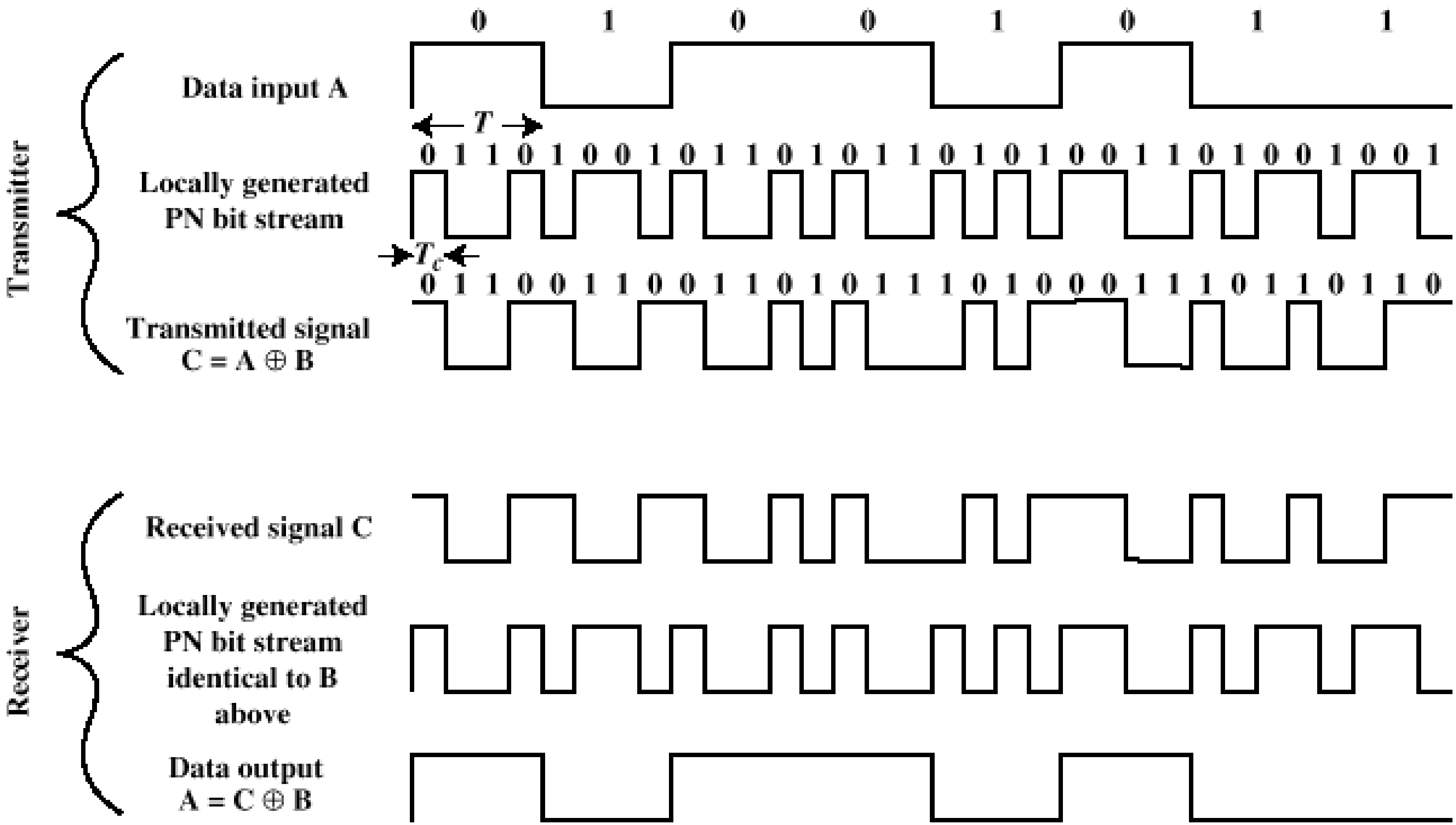
FHSS Performance Considerations

- Large number of frequencies are 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,

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

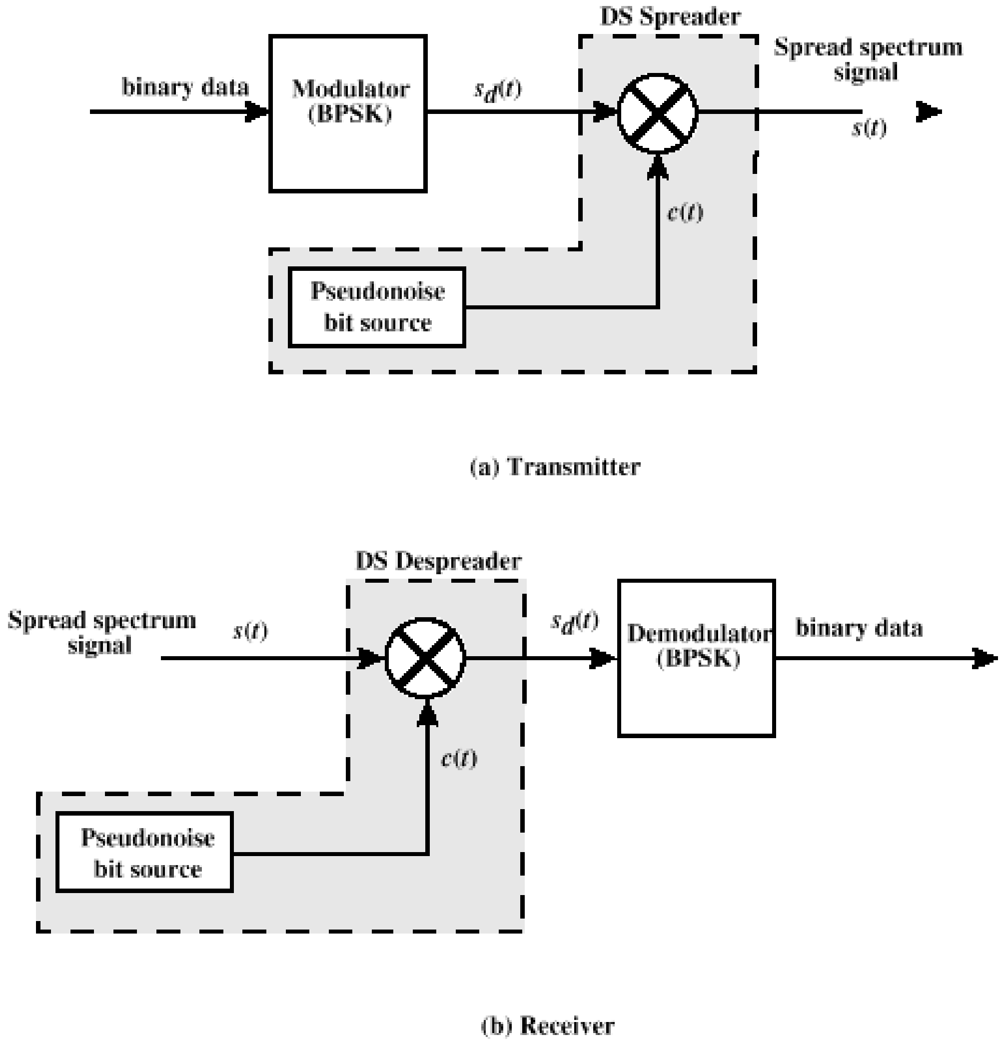
by $c(t)$ [PN sequence taking values +1, -1] to get

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

  - A = amplitude of signal
  - f_c = carrier frequency
  - $d(\mathrm{t})$ = discrete function [+1, -1]

- At receiver, incoming signal is multiplied by $c(t)$
  - Since, $c(t)$ x $c(t)$ = 1, incoming signal is recovered

DSSS Using BPSK



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

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

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

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

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

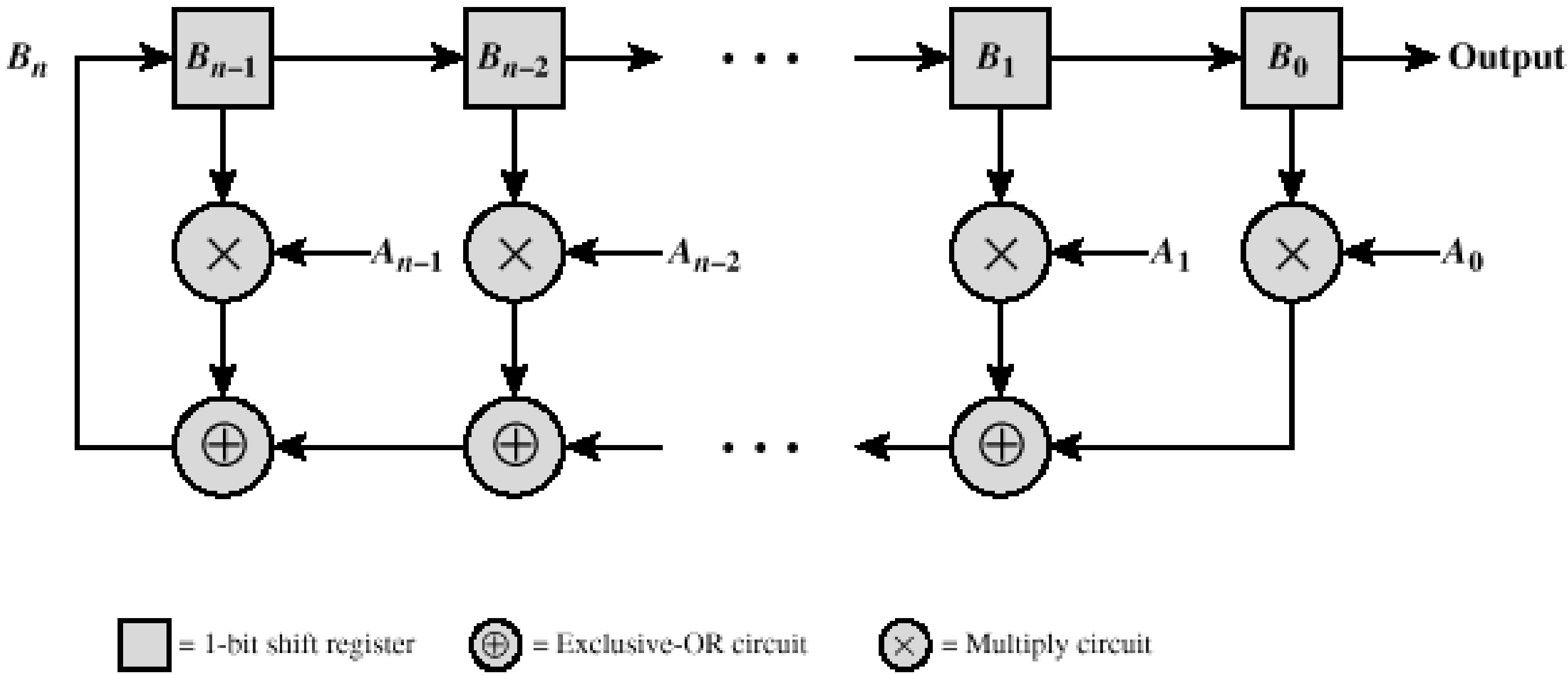
PN Sequences

- PN 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

Properties of M-Sequences

- Property 1:
  - Has 2^{n-1} ones and 2^{n-1}-1 zeros
- Property 2:
  - For a window of length n slide along output for N ($=2^n-1$) shifts, each n-tuple appears once, except for the all zeros sequence
- Property 3:
  - Sequence contains one run of ones, length n
  - One run of zeros, length n-1
  - One run of ones and one run of zeros, length n-2
  - Two runs of ones and two runs of zeros, length n-3
  - 2^{n-3} runs of ones and 2^{n-3} runs of zeros, length 1

Properties of M-Sequences

- Property 4:
  - The periodic autocorrelation of a m-sequence is

$$R(\tau)=\begin{cases} 1 & \tau = 0, \mathrm{N}, 2\mathrm{N}, \ldots \\ -\dfrac{1}{N} & \text{otherwise} \end{cases}$$

Multiple Access Techniques

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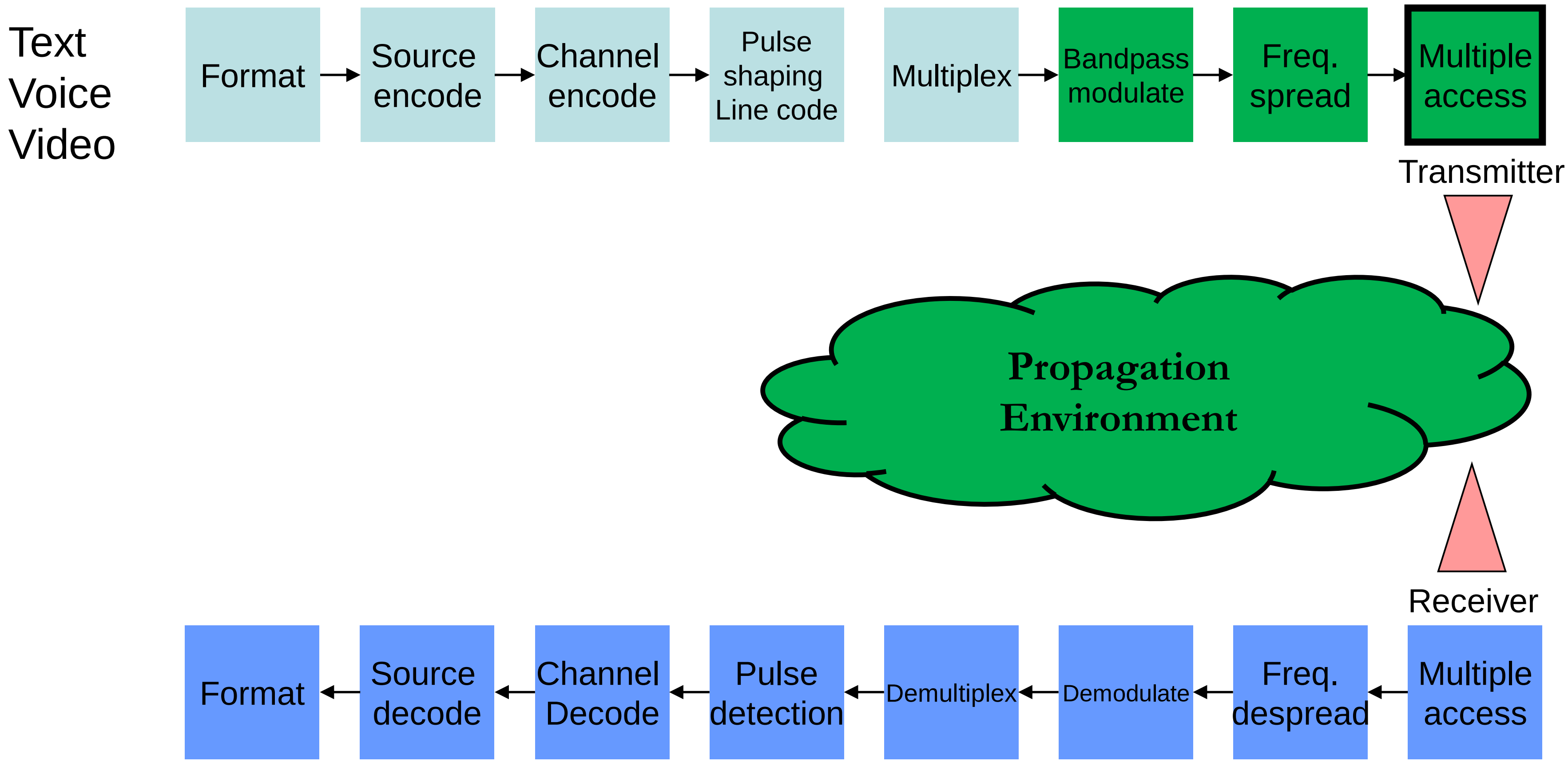
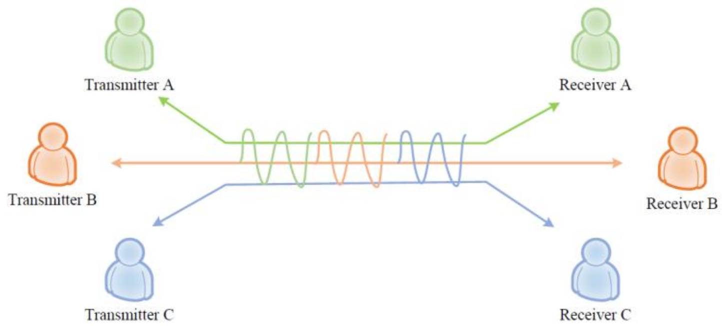
Overview of Wireless Communication System



Multiple access

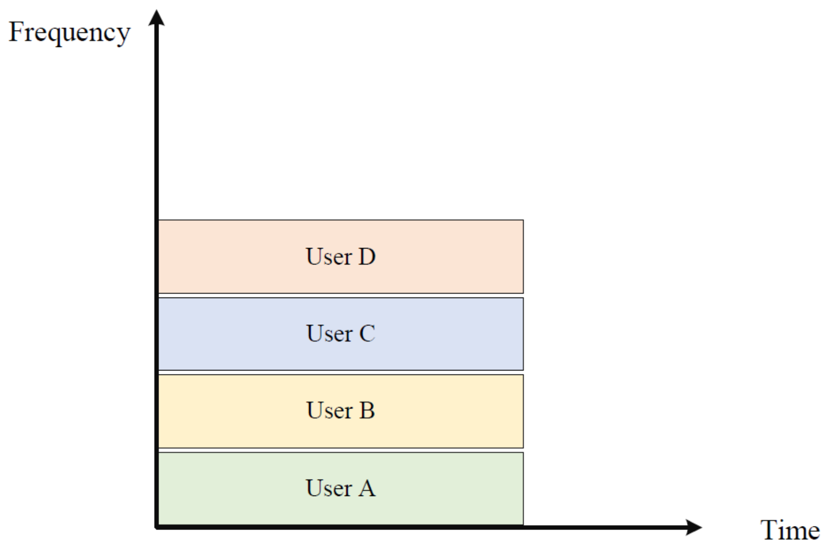
- **Multiple Access**: to enable multiple users to share the same channel simultaneously.



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

Frequency Division Multiple Access (FDMA) - Pitch

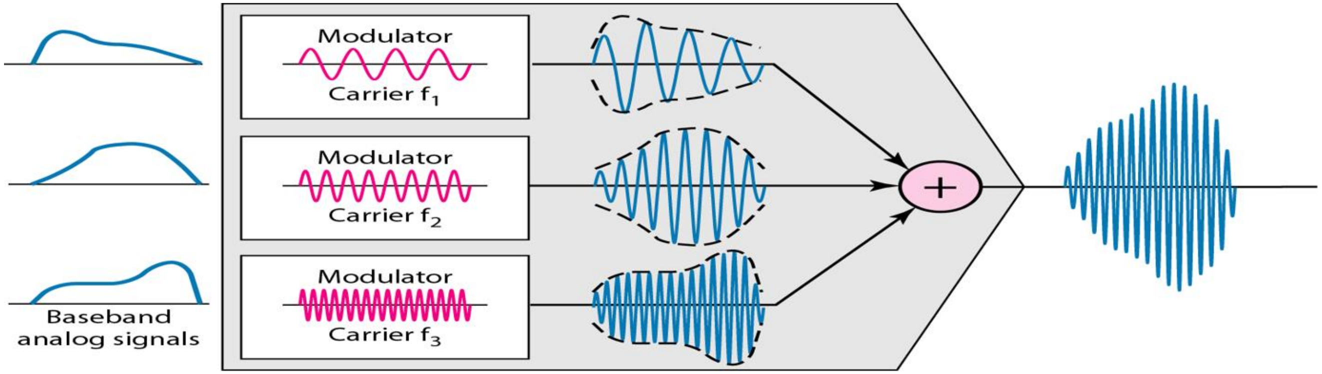
- **Key features**:
  - Assign each user to a particular channel.
  - Transmit signals simultaneously and continuously.to enable multiple users to share the same channel simultaneously.



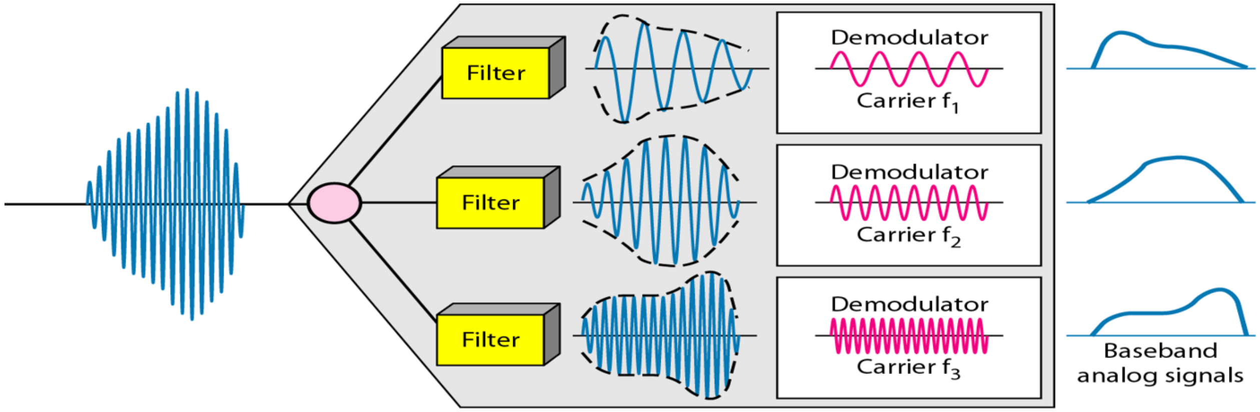
- **Application**: all 1G systems use FDMA.

Frequency Division Multiple Access (FDMA)

- **Transmitter:**



- **Receiver:**



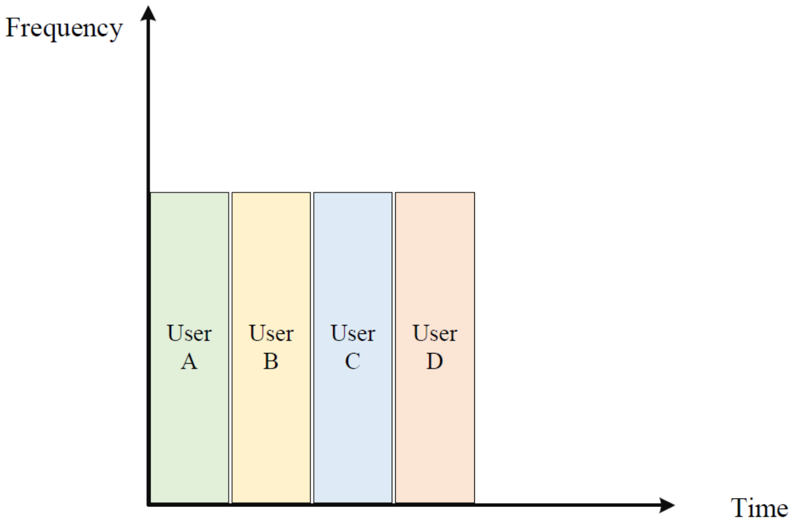
Frequency Division Multiple Access (FDMA)

- **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.

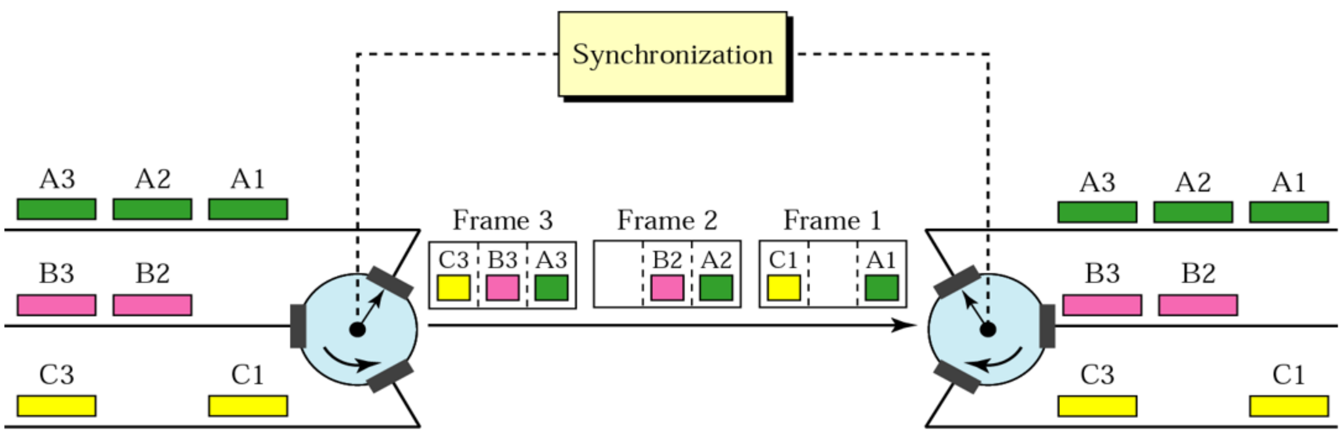


- **Application**: most 2G systems use TDMA.

Time Division Multiple Access

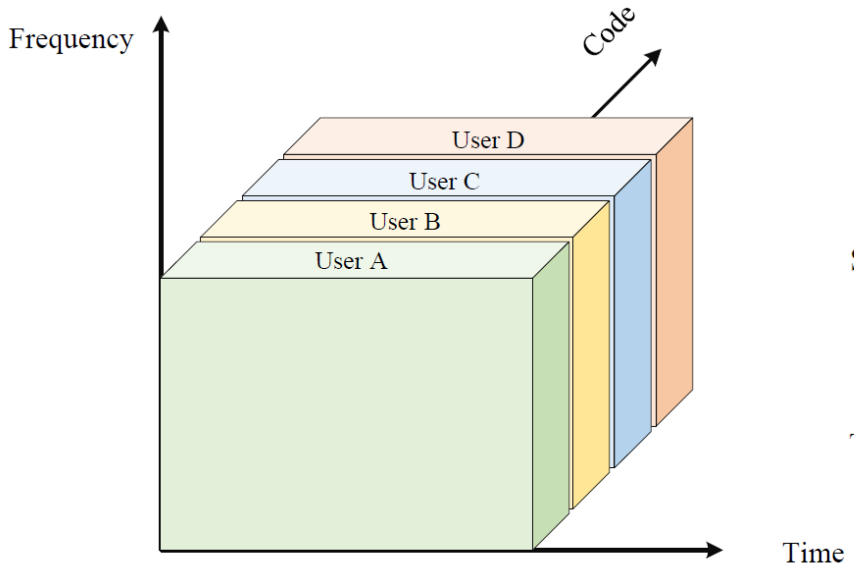
- **Advantages**
  - Interference-free technique.
  - Low battery consumption.
  - Slots can be assigned on demand.

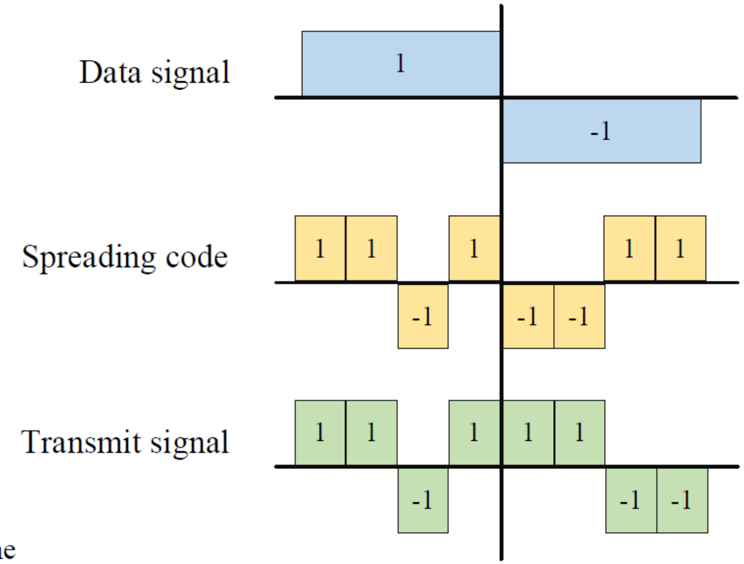
- **Disadvantages:**.
  - "CLOCK" is required.
  - Large synchronization overheads.
  - Most 2G systems use TDMA



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

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

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.
- **Application**: 4G systems.

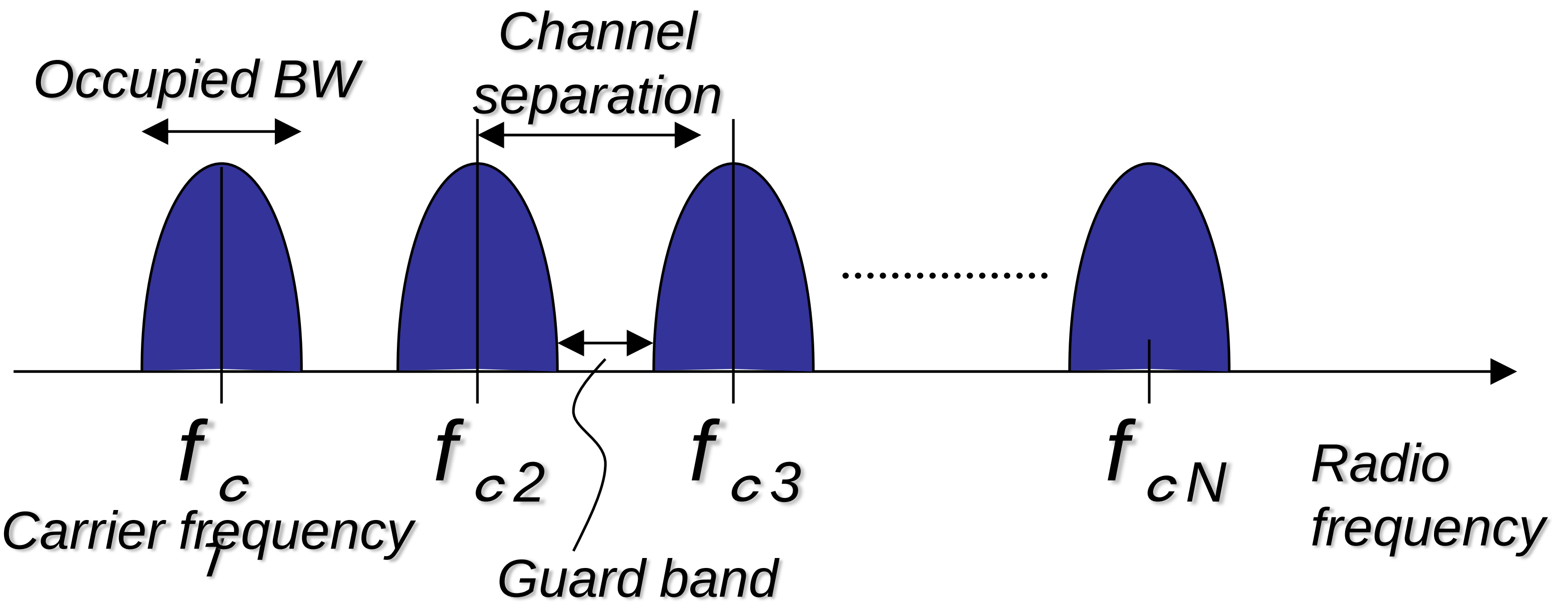
Why OFDM is getting popular？

- 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

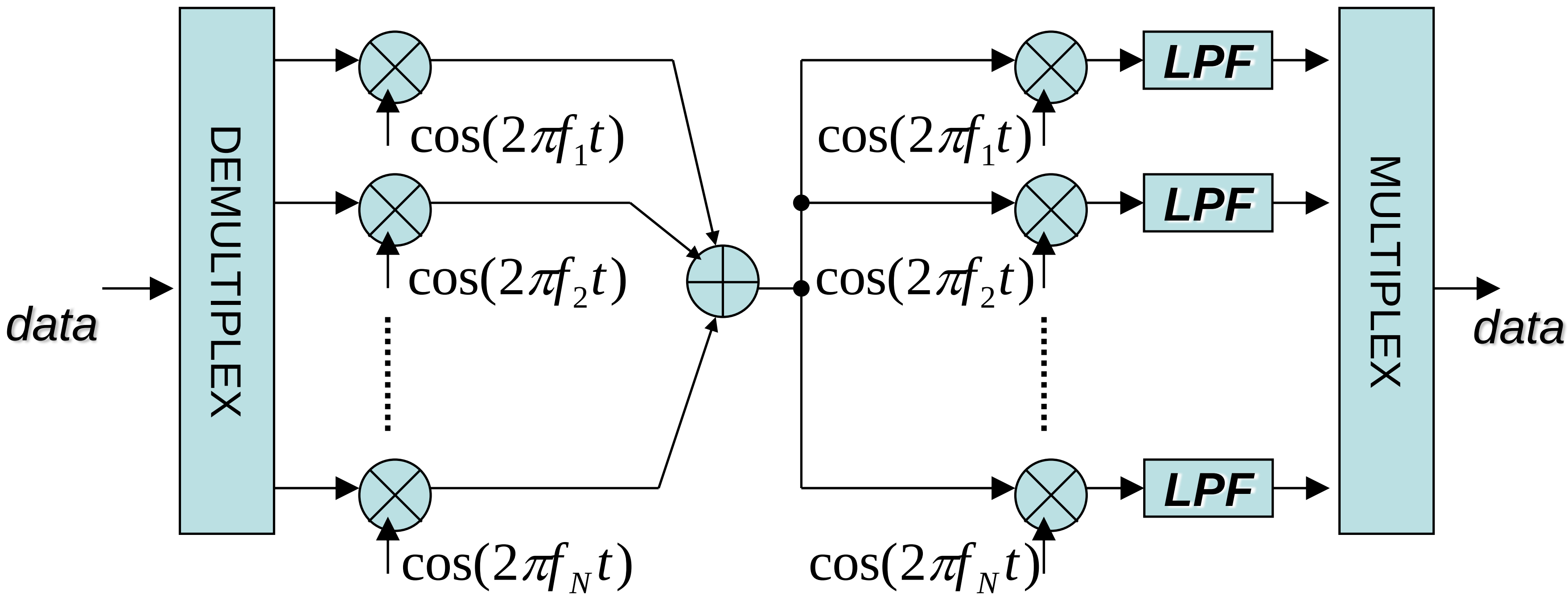
Frequency Division Multiple Access (FDMA)

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

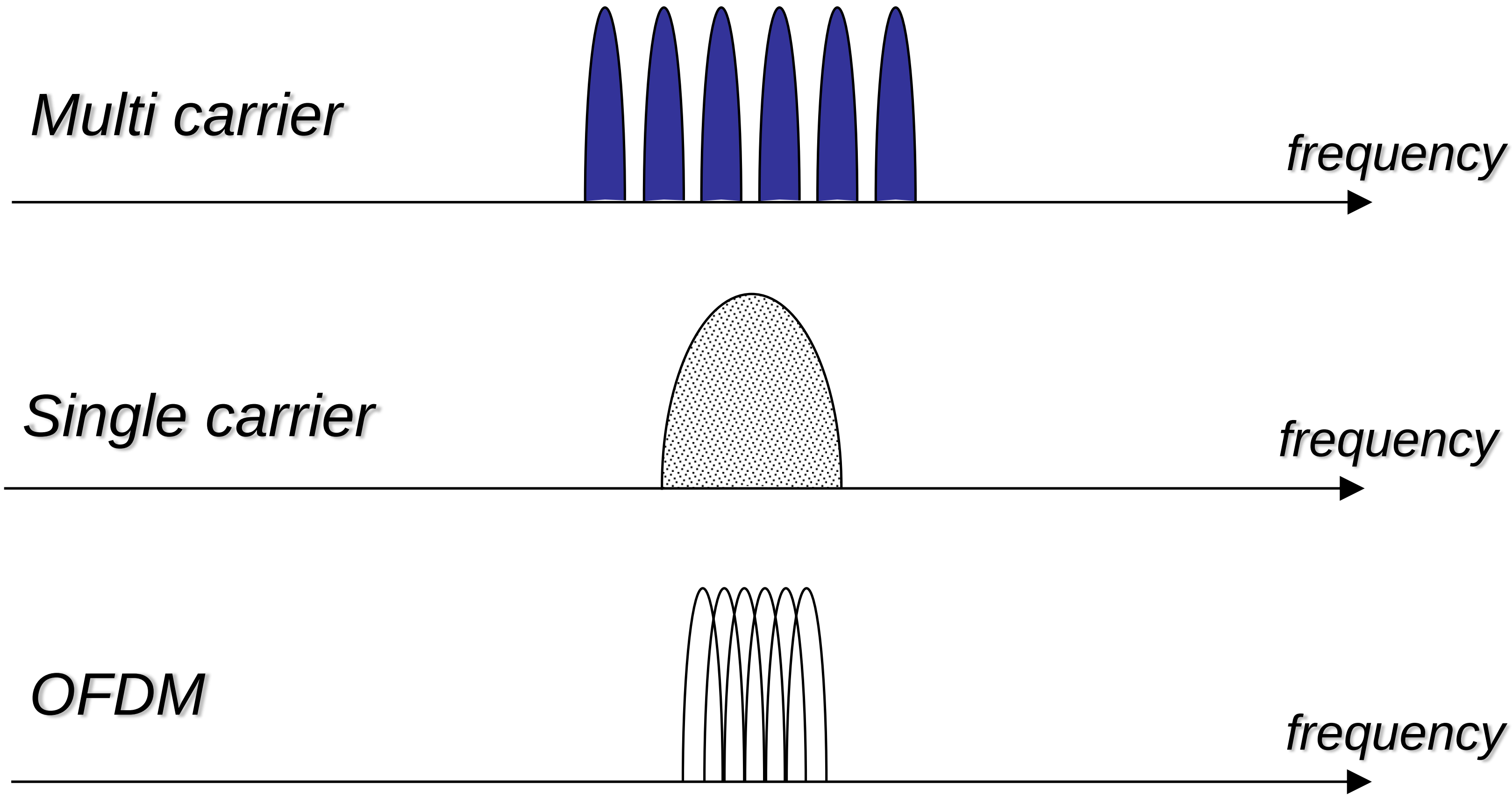


Multi-carrier modulation

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



Spectrum comparison for same data rate transmission



OFDM vs. Multi carrier

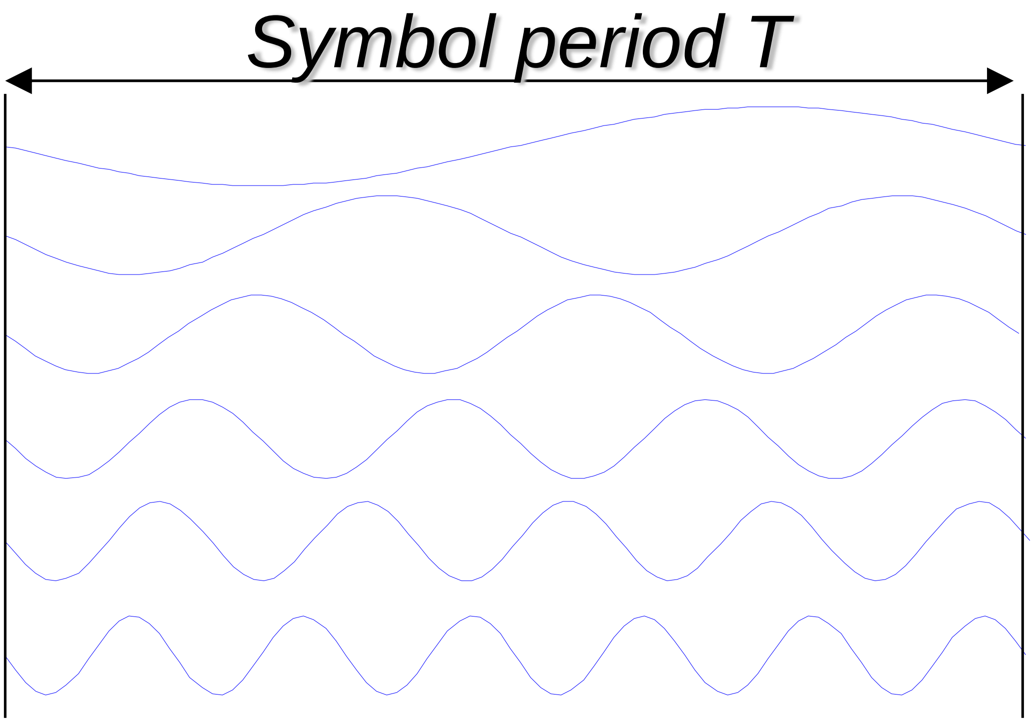
- OFDM is a multi-carrier modulation
- OFDM sub-carrier spectrum is overlapping
- In FDMA, band-pass filter separates each transmission
- In OFDM, each sub-carrier is separated by DFT because carriers are orthogonal
  - Condition of the orthogonality will be explained later
- Each sub-carrier is modulated 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, $T=1/f_0$

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

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

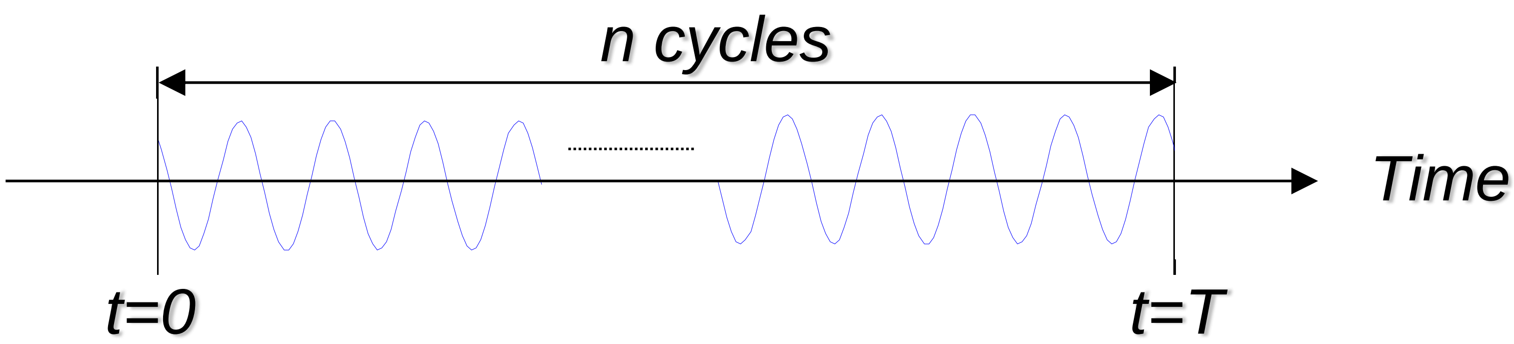
$$\int_0^T \cos(2\pi m f_0 t)\cdot\sin(2\pi n f_0 t)dt = 0$$

A sub-carrier of $f=nf_0$

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

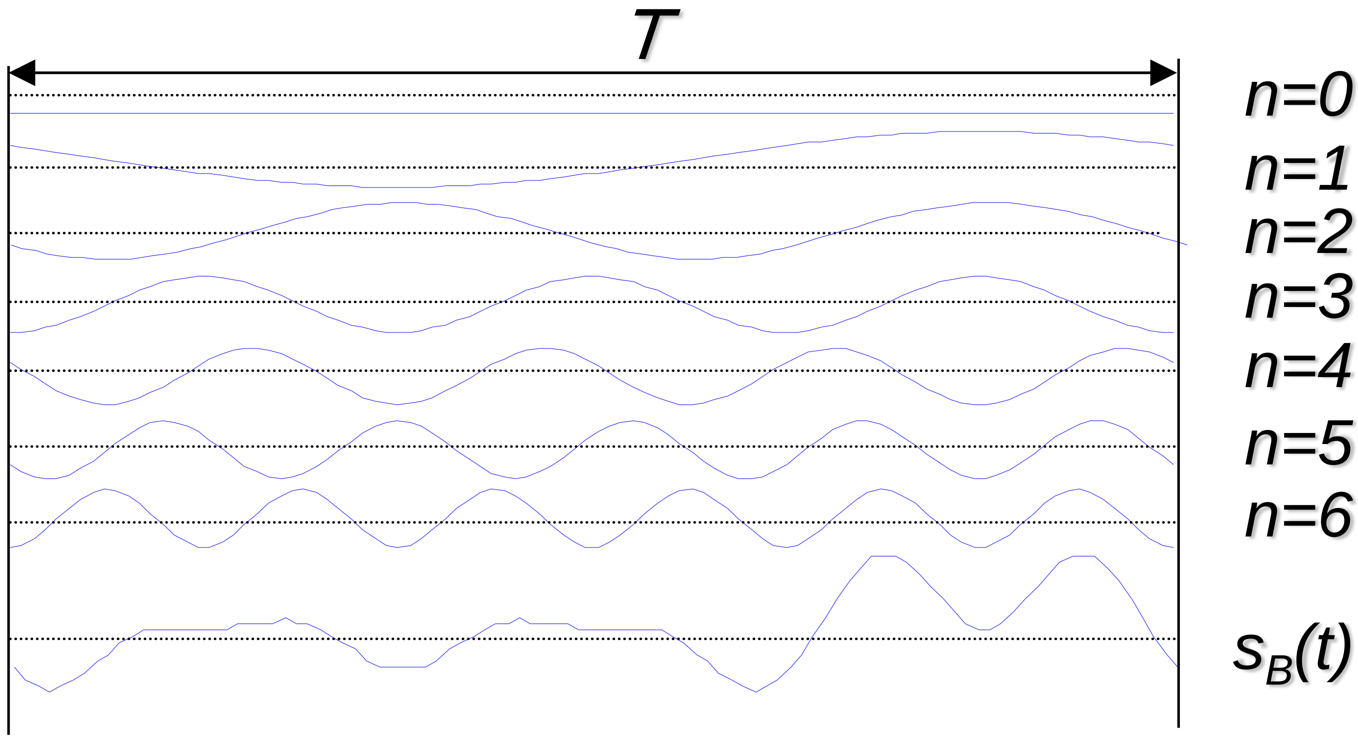
$$= \sqrt{a_n{}^2 + b_n{}^2}\cos(2\pi n f_0 t + \phi_n), \qquad \phi_n = \tan^{-1}\frac{b_n}{a_n}$$

- 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 caluculated from $s_B(t)$ - Demodulation Procedure -

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

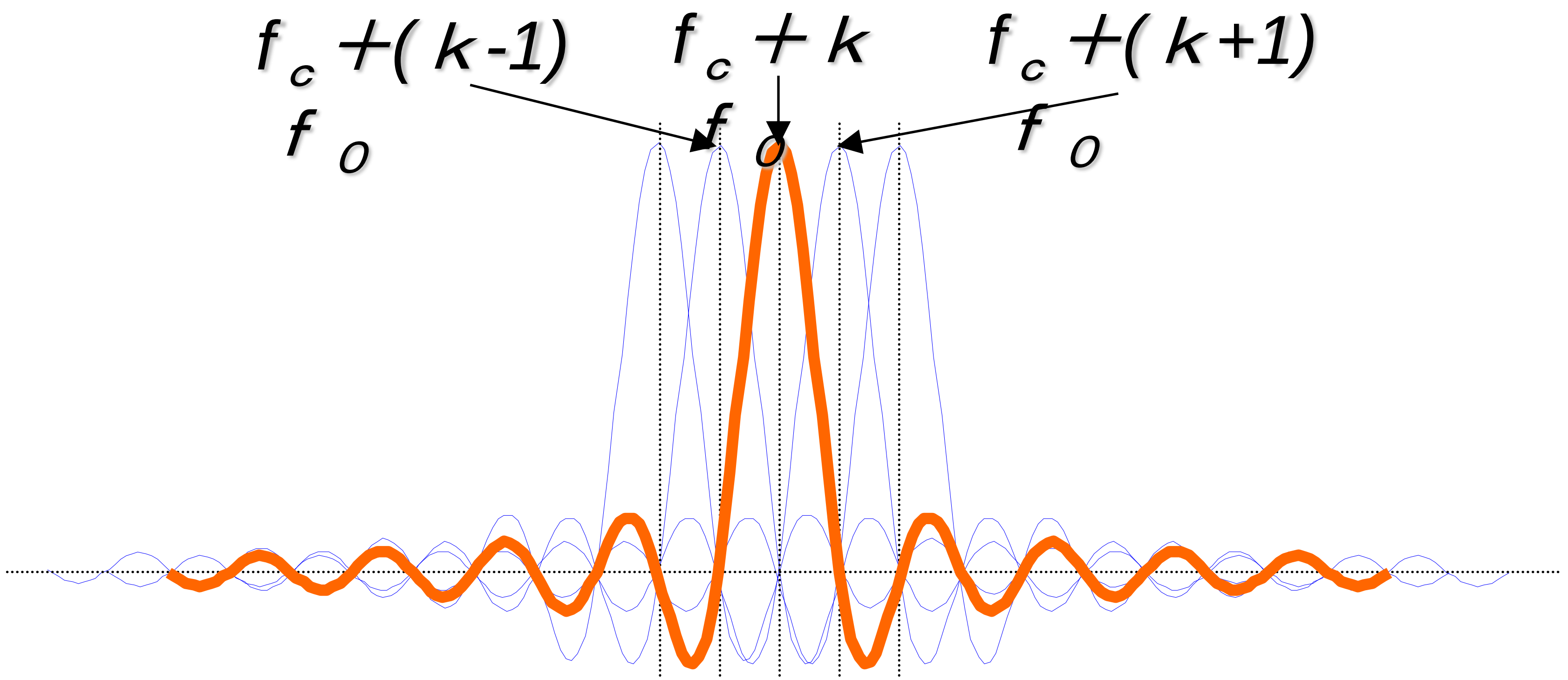
$$=\sum_{n=0}^{N-1}\left\{a_n\int_0^T\cos(2\pi n f_0 t)\cos(2\pi k f_0 t)dt - b_n\int_0^T\sin(2\pi n f_0 t)\cos(2\pi k f_0 t)dt\right\}$$

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

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

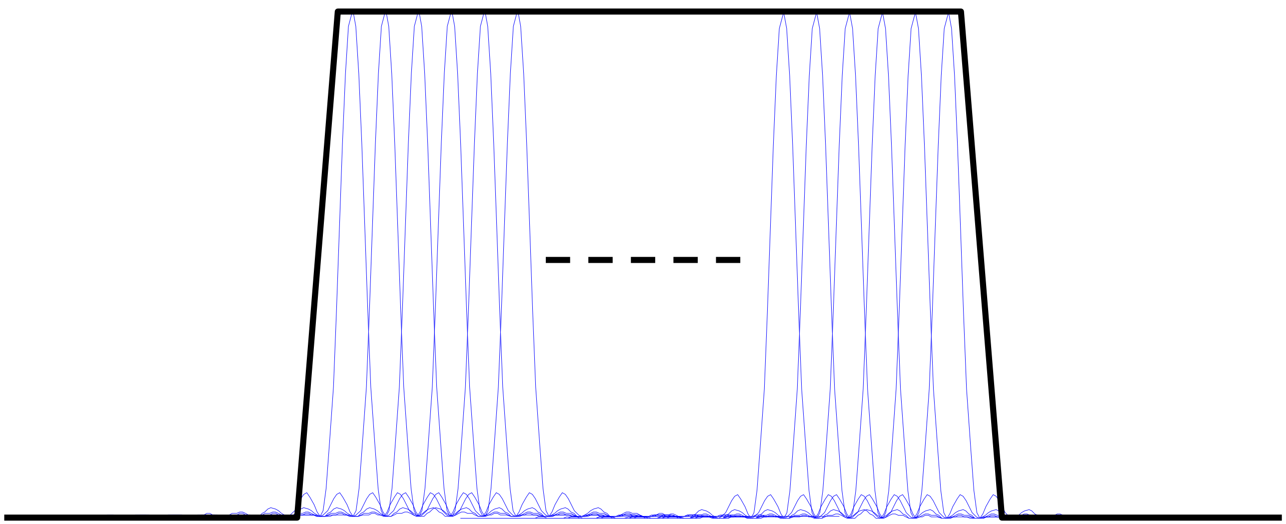
- According to the sinusoidal orthogonality, a_n,b_n can be extracted.
- In actual implementation, DFT(FFT) is used
- N is roughly 64 for WLAN, thousand for Terrestrial Video Broadcasting

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 siganal generation

OFDM signal generation in digital domain

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

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

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

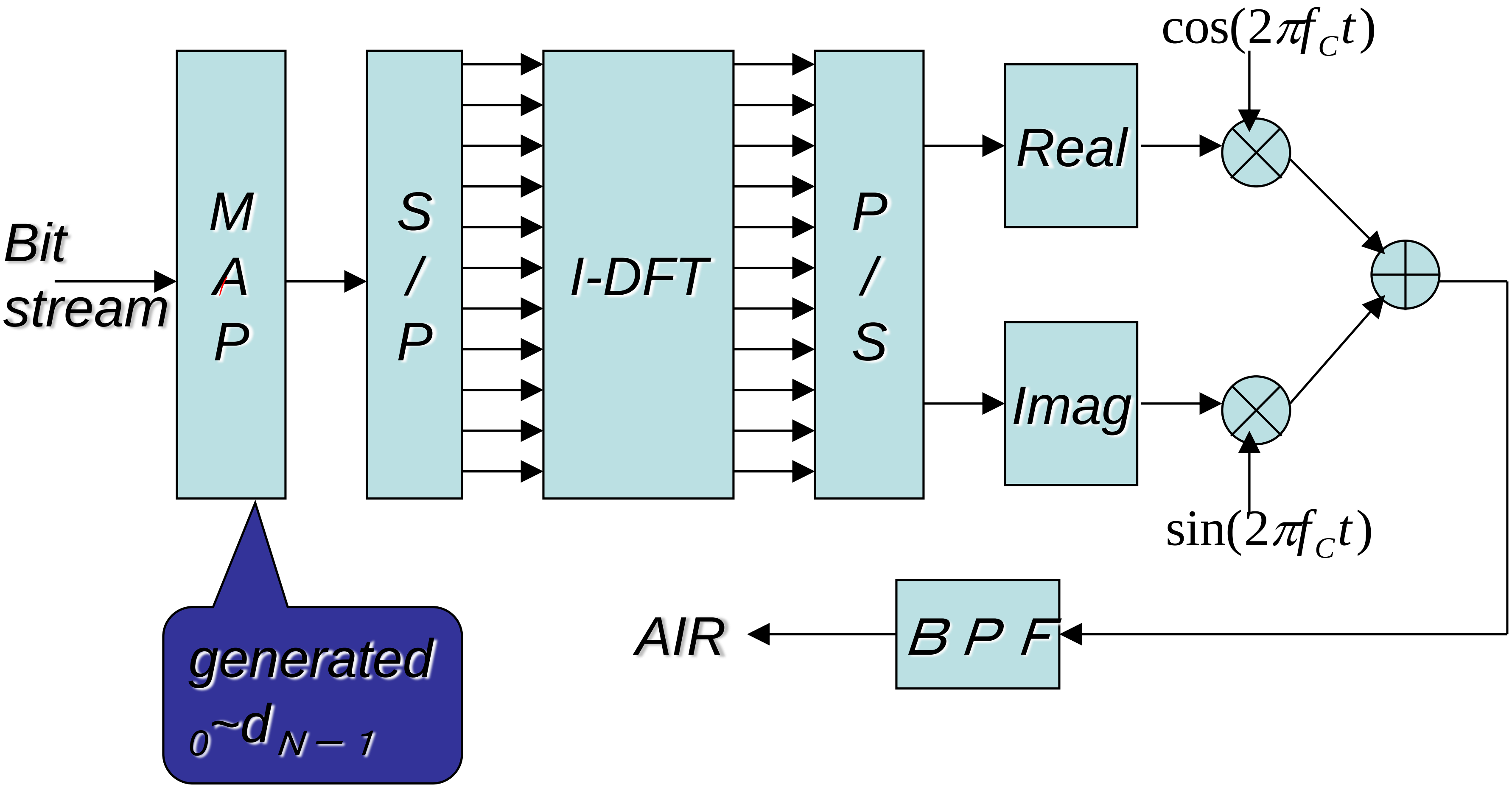
- Perform N times sampling in period T

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

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

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

OFDM modulator



OFDM demodulation

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

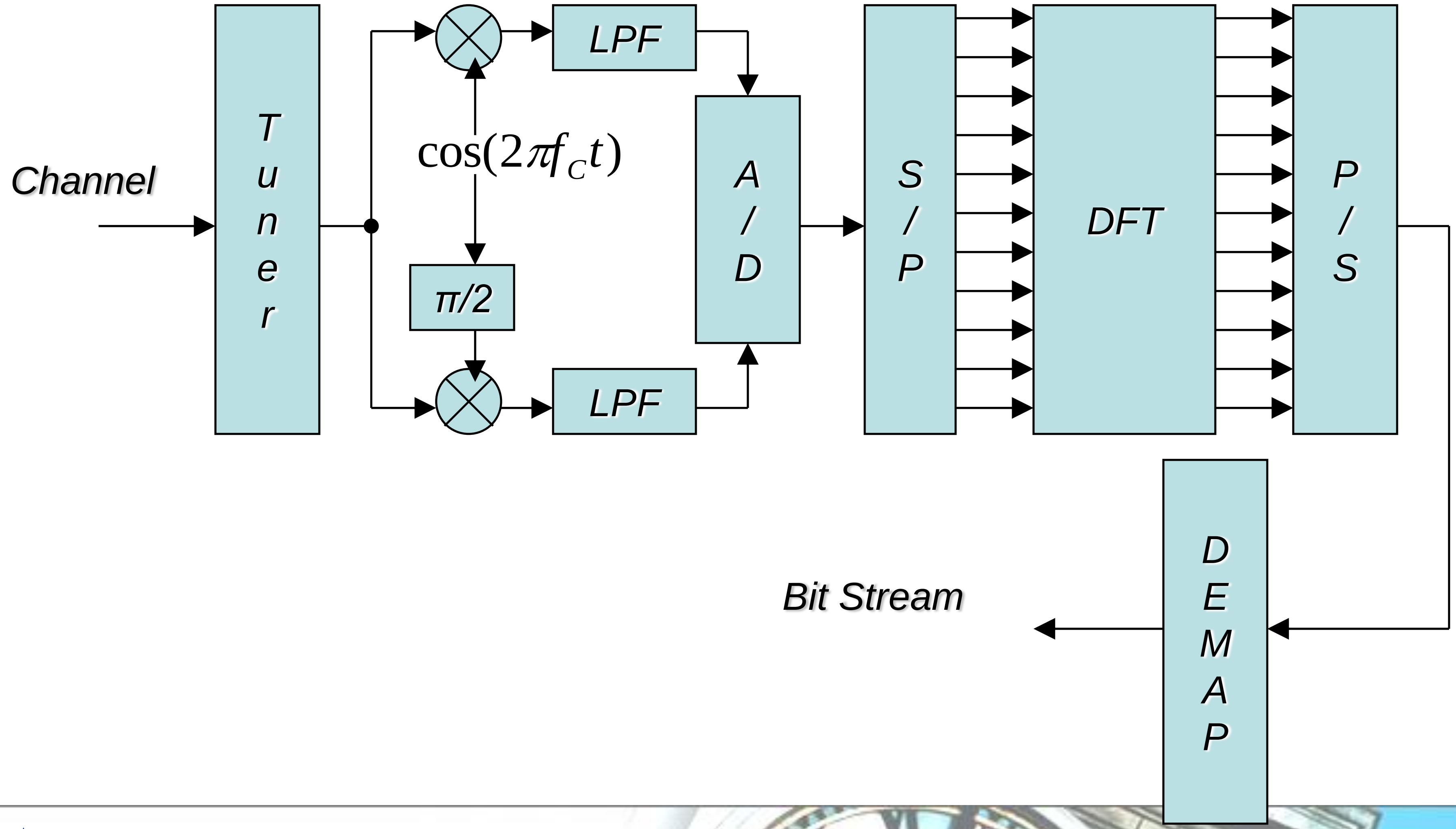
$$LPF[s(t)\cdot\cos(2\pi f_C t)] = \frac{1}{2}\sum_{n=0}^{N-1}\{a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t)\} = \frac{1}{2}s_I(t)$$

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

$$u(t) = s_I(t) + js_Q(t) = \sum_{n=0}^{N-1} d_n \cdot e^{j2\pi n f_0 t}$$

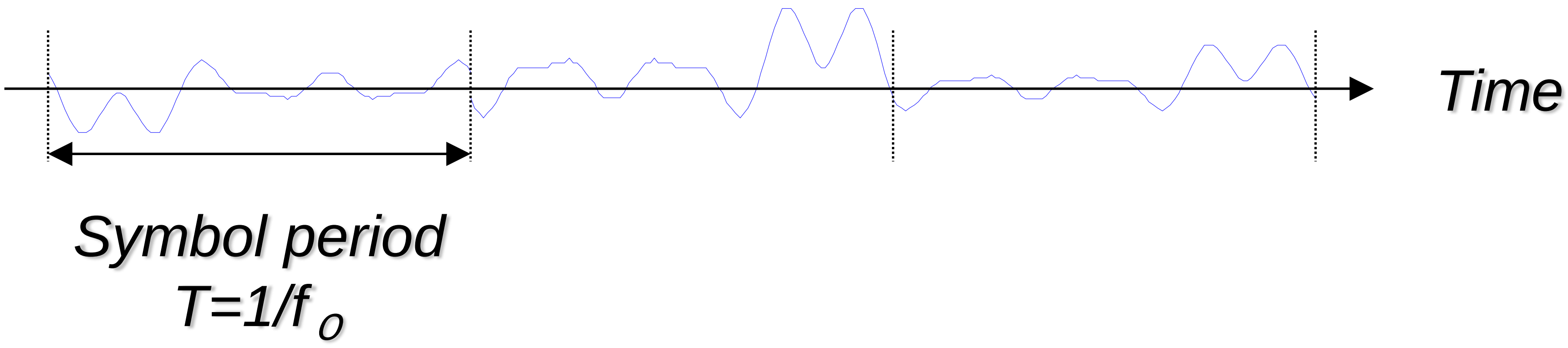
d_n = FFT(u(k))

OFDM demodulator



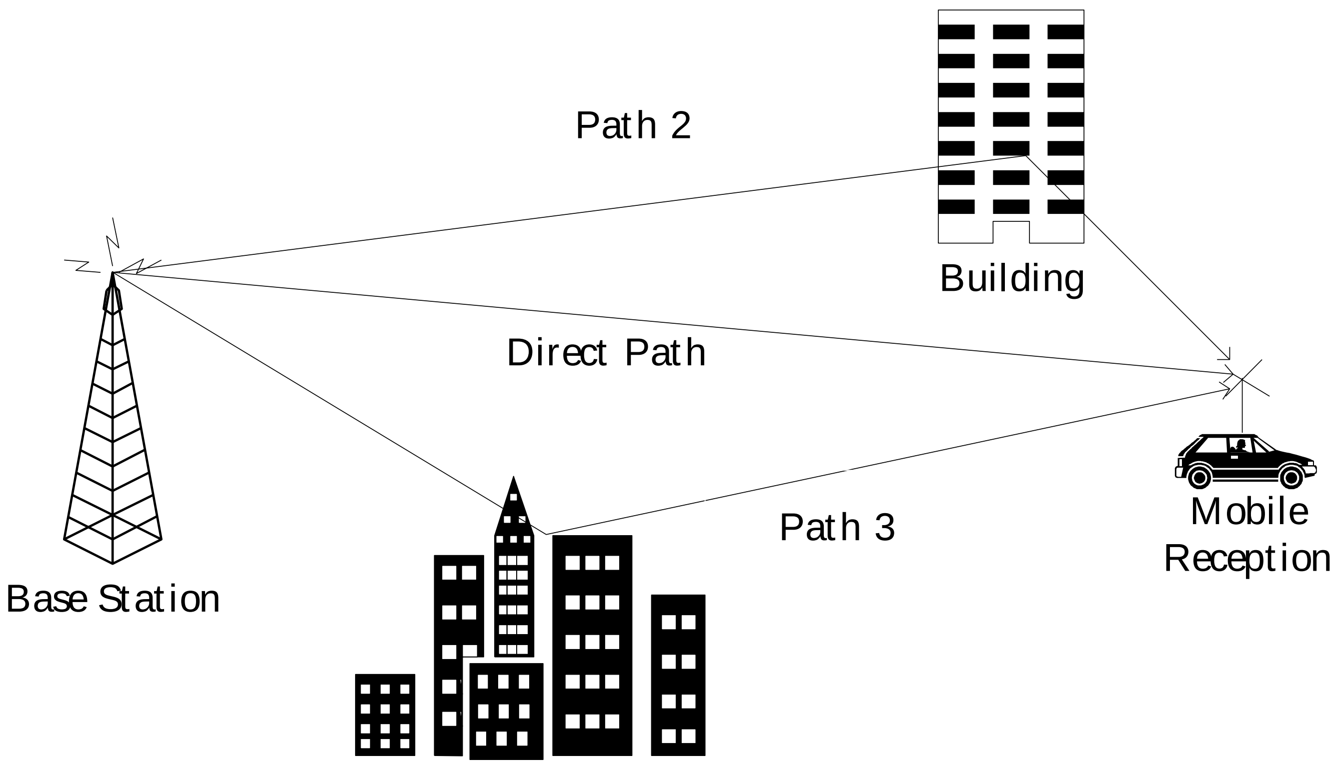
Summary of OFDM signal

- 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

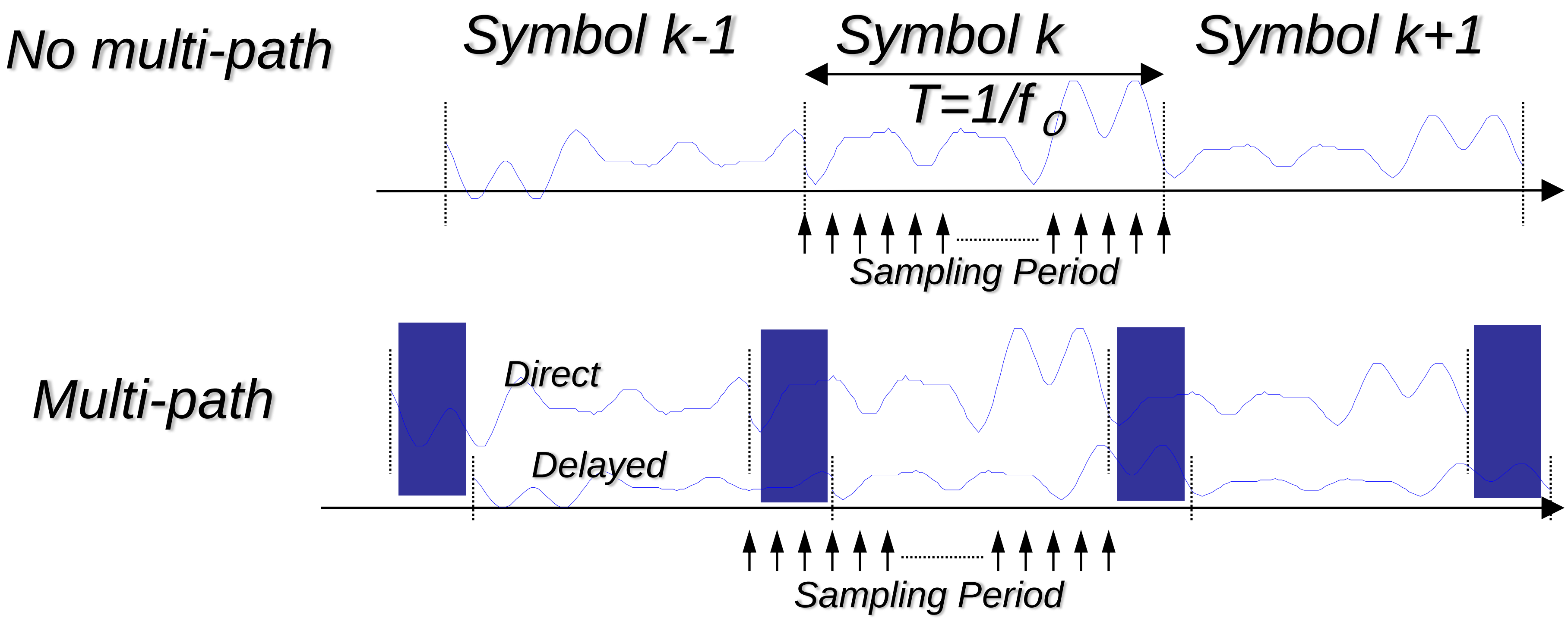


Multi-path

Delayed wave causes interference

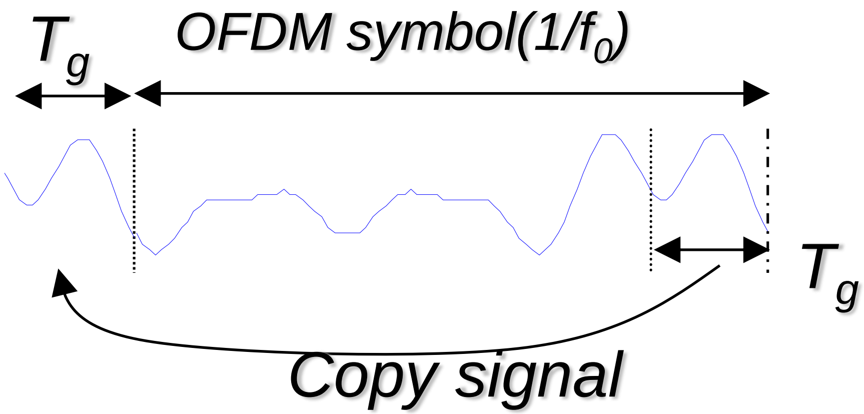


Multi-path effect

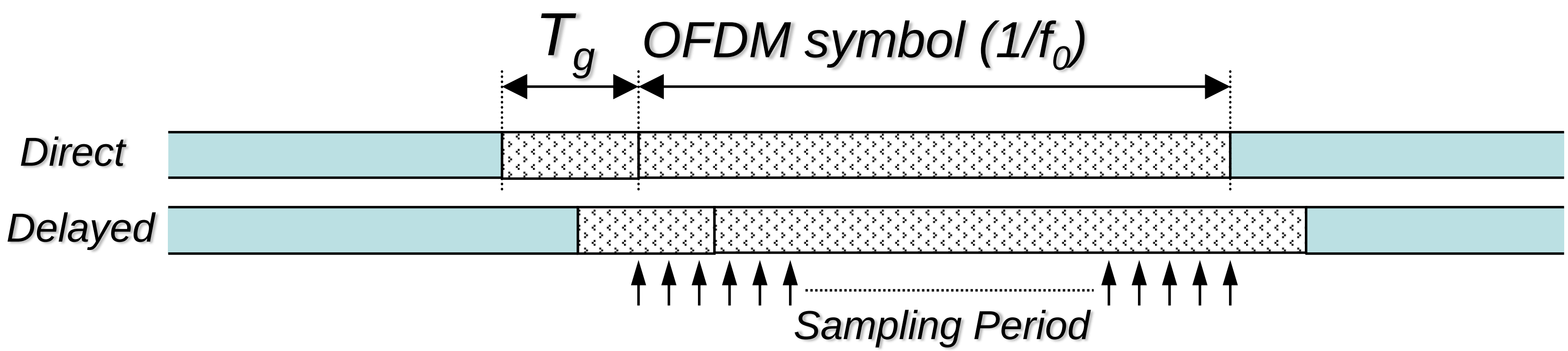


- Inter symbol interference (ISI) happens in Multi-path condition

Cyclic Prefix (Guard Interval) T_g

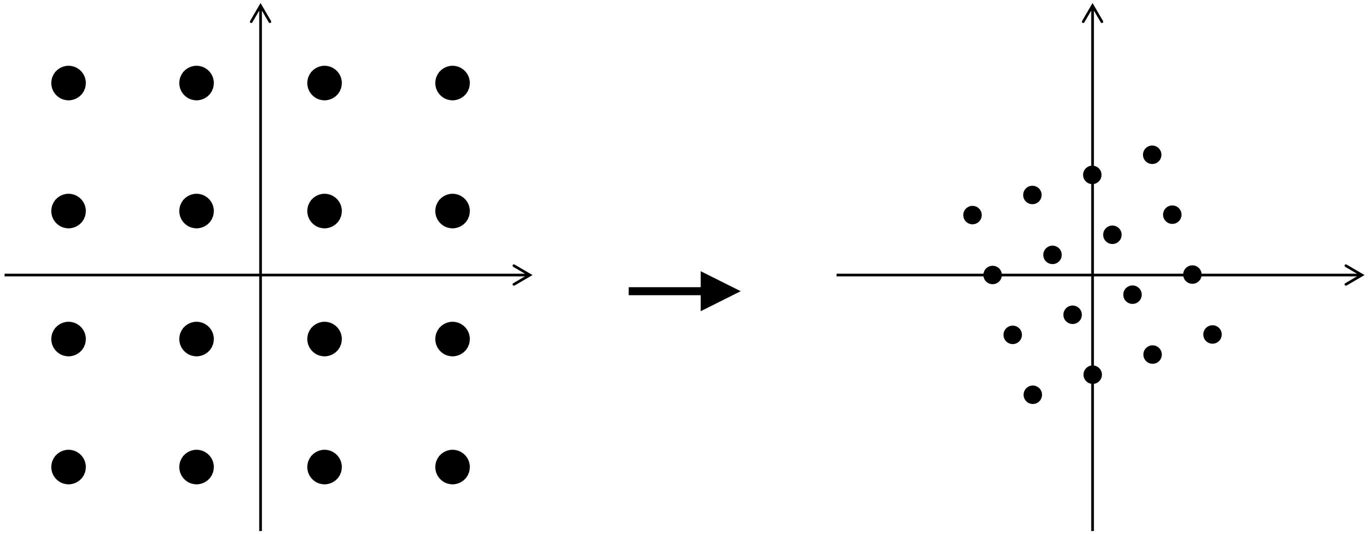


- By adding the Gurard Interval Period, ISI can be avoided



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

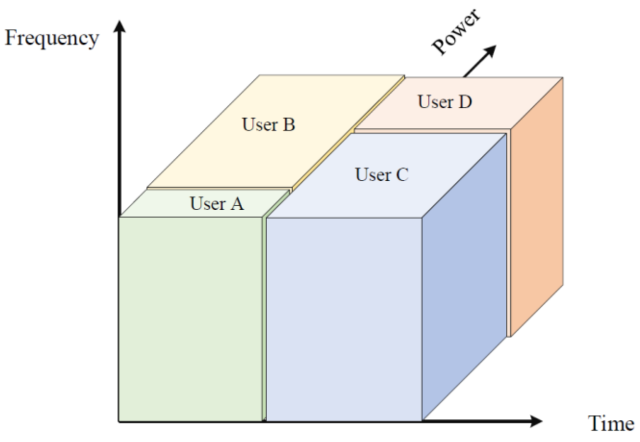
- Feature of OFDM
  1. High Frequency utilization by the square spectrum shape
  2. Multi-path problem is solved by Cyclic Prefix
  3. Multiple services in one OFDM by sharing sub-carriers
  4. Implementation was complicated but NOW possible because of LSI technology progress

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.

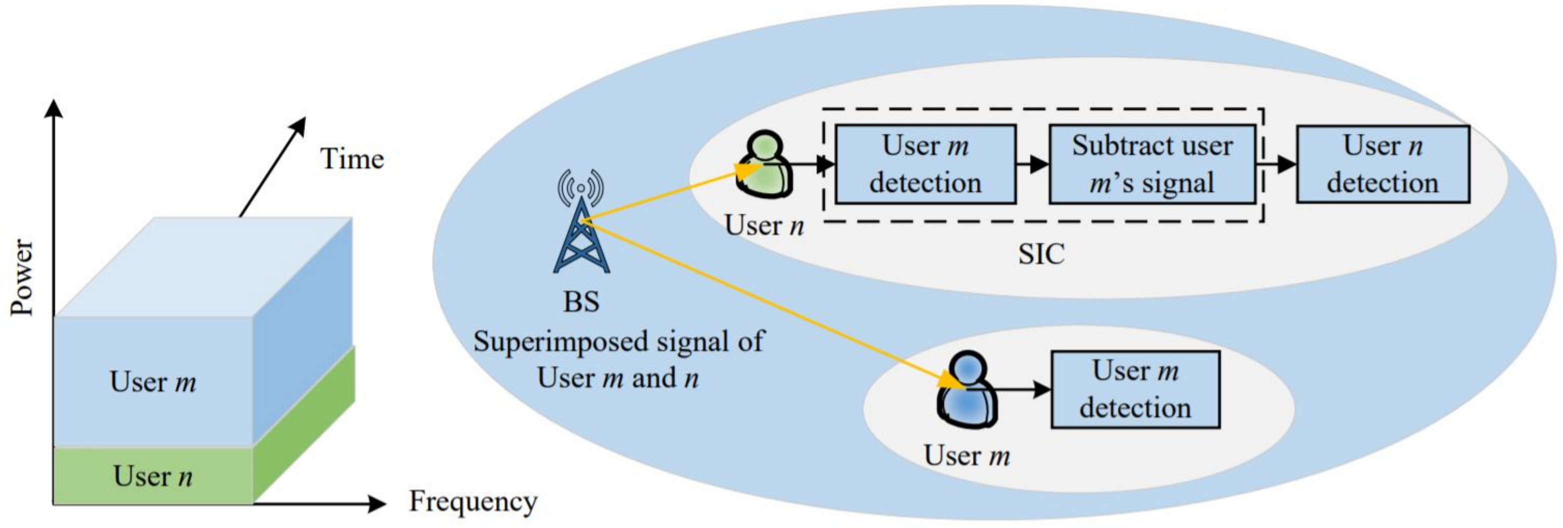
What's next - Non-orthogonal multiple access for 5G



- **Question**: What is multiple access?
- **Orthogonal multiple access (OMA)**:
  - e.g., FDMA, TDMA, CDMA, OFDMA.
- **New requirements** in 5G
  - High spectrum efficiency.
  - Massive connectivity.
- **Non-orthogonal multiple access (NOMA)**
  - Power Domain.
  - to break orthogonality.

- Standard and industry developments on NOMA
  - **Whitepapers for 5G**: DOCOMO, METIS, NGMN, ZTE, SK Telecom, etc.
  - **LTE Release 13**: a two-user downlink special case of NOMA.
  - **Next generation digital TV standard ATSC 3.0**: a variation of NOMA, termed Layer Division Multiplexing (LDM).

Non-orthogonal multiple access for 5G

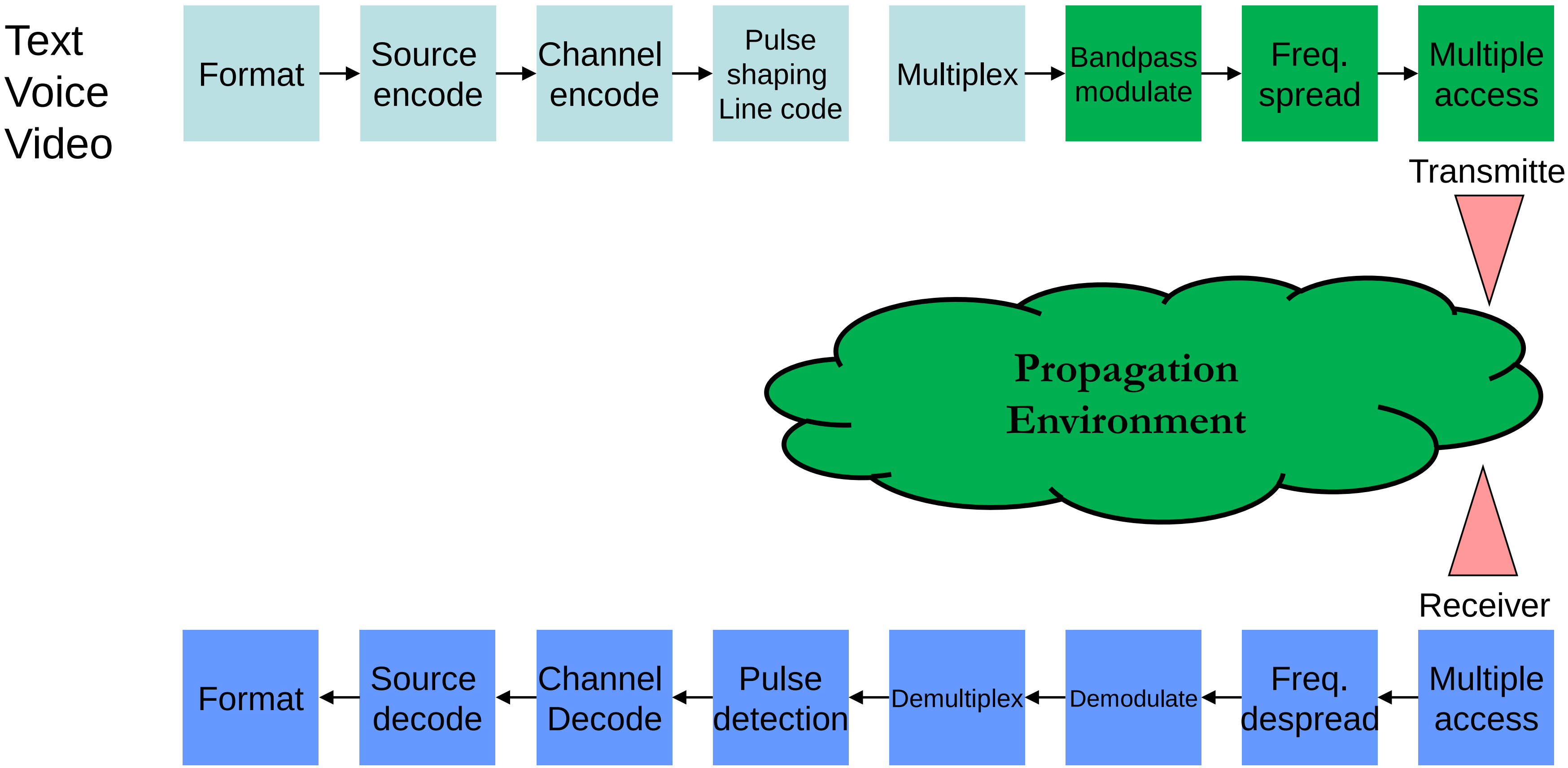


- Realize the multiple access in the same resource block (time/frequecy/code), but with **different power levels** [R1].
- Apply successive interference cancellation (SIC) at the receiver [R1].

[R1] Y. Liu et al., "Non-Orthogonal Multiple Access for 5G and Beyond", Proceedings of the IEEE; vol. 105, no. 12, pp. 2347-2381, Dec. 2017.

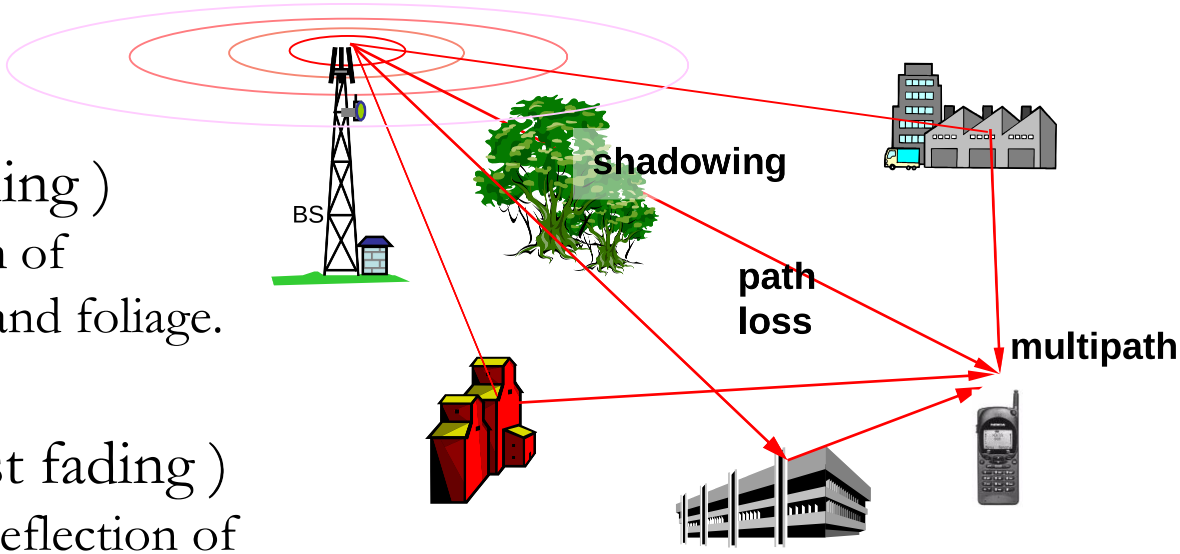
Radio Propagations & Network Architecture

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



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

Line-of-Sight (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)

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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

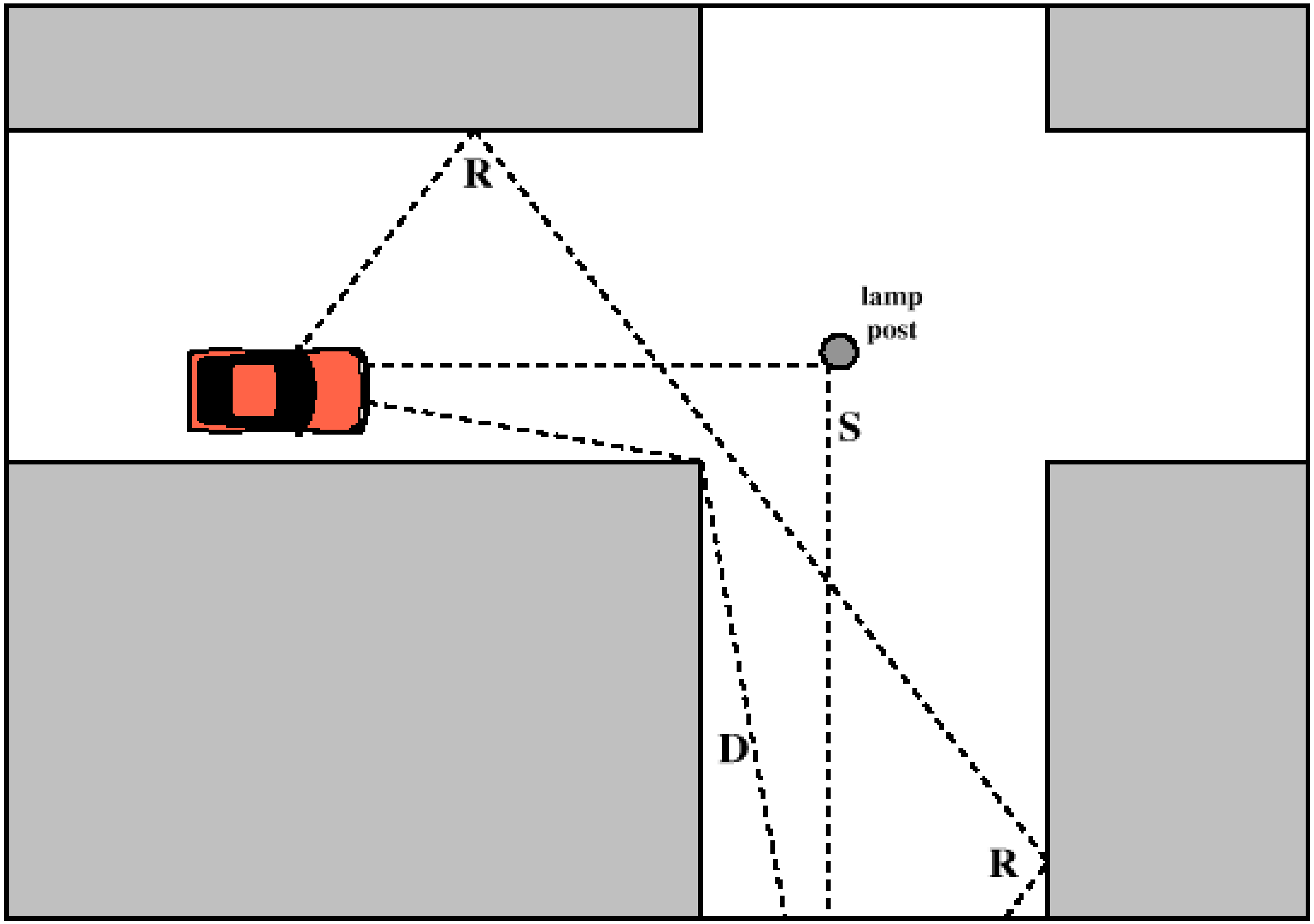
$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{\mathrm{k}TR}$$

- 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

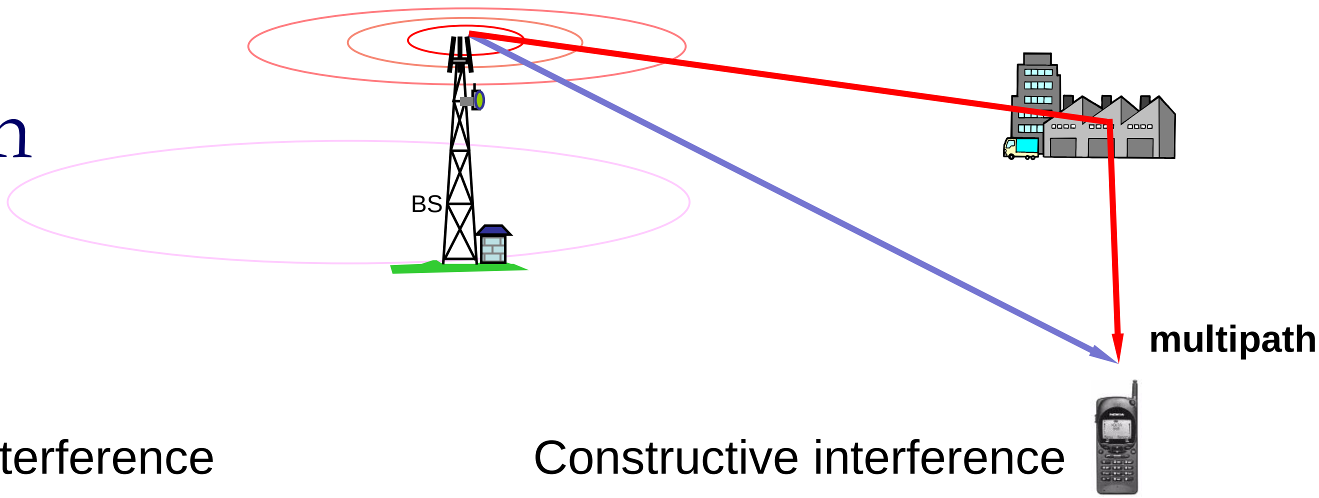
Other Impairments

- **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

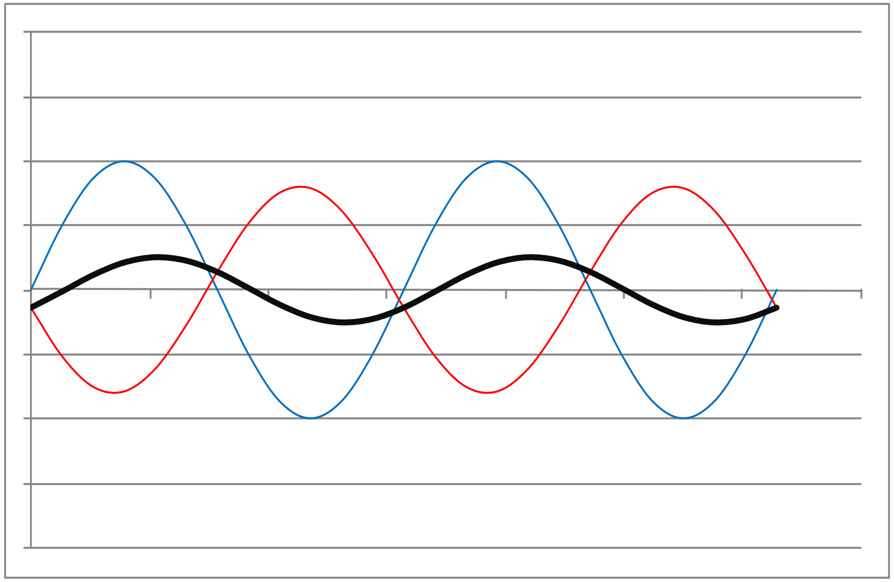
Multipath Propagation



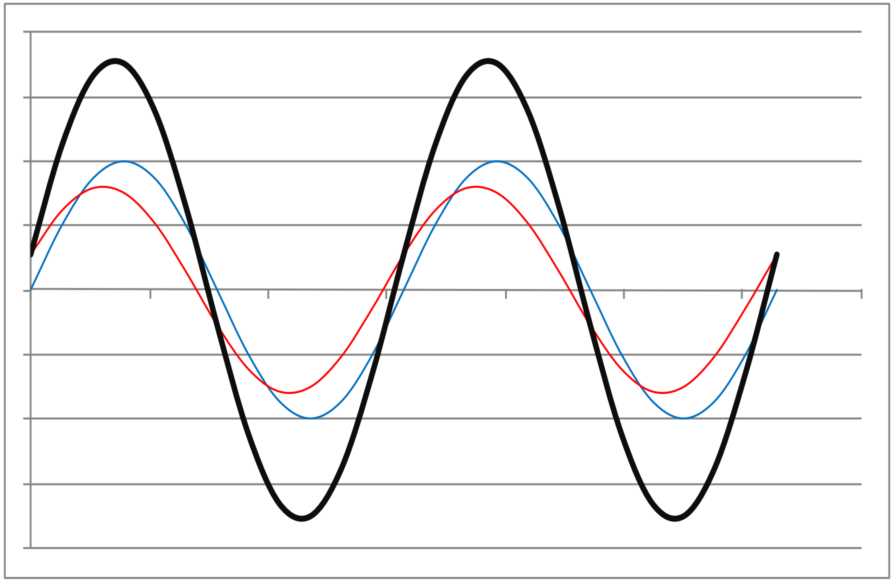
Multi-path



Destructive interference



Constructive interference



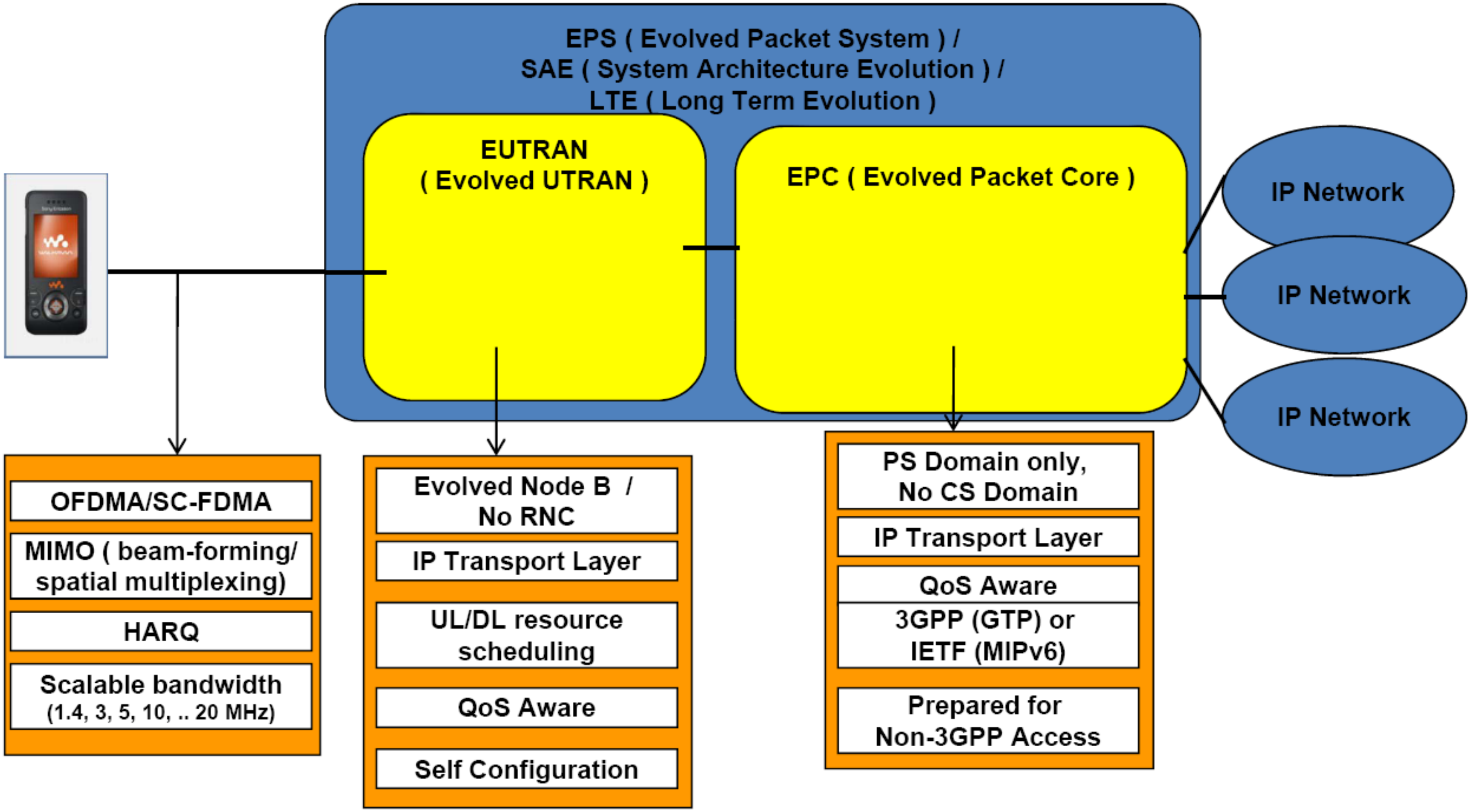
As mobile moves the relative phase changes and fading occurs

Types of Fading

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

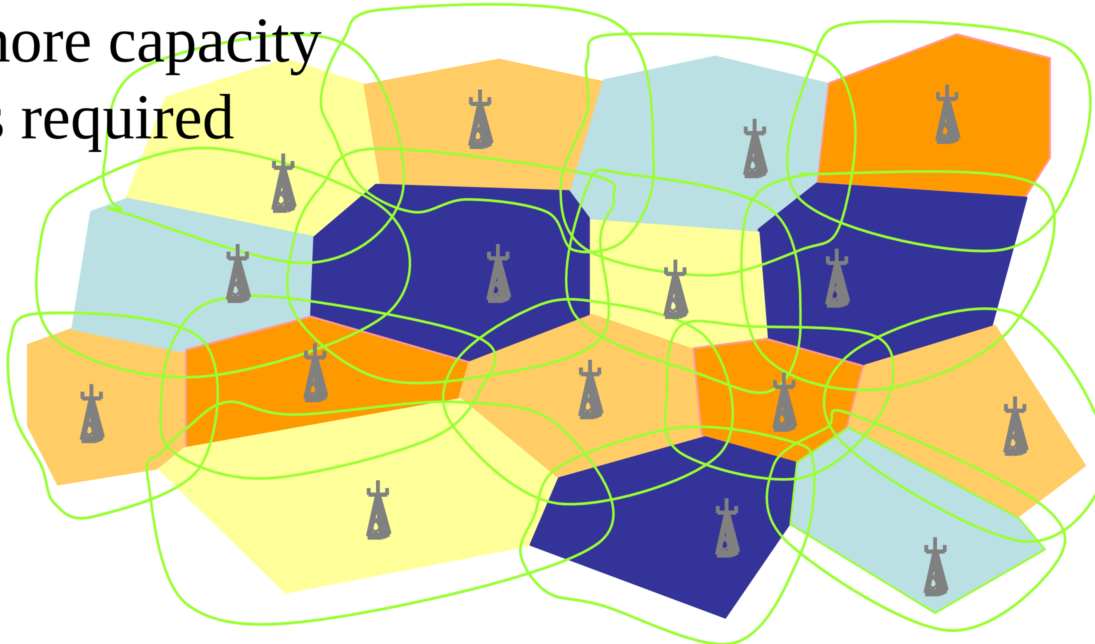
Radio Propagations & Network Architecture

LTE/SAE Key Features – Overview



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)

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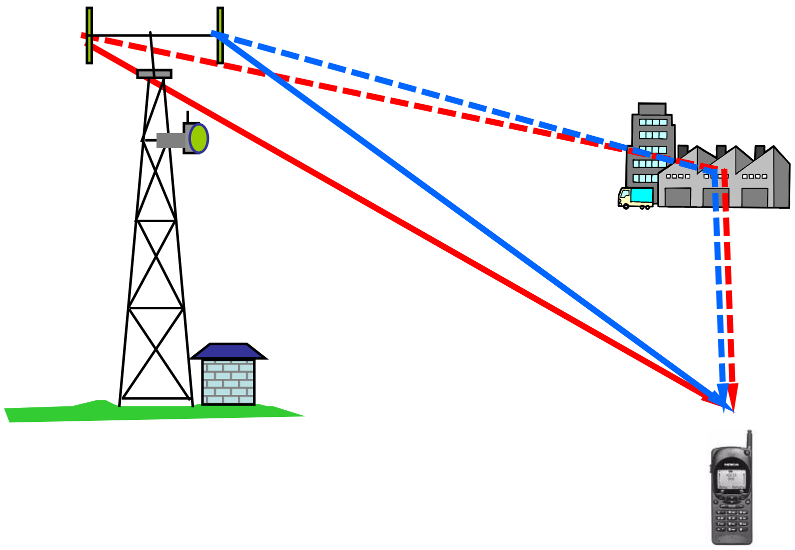
Diversity



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

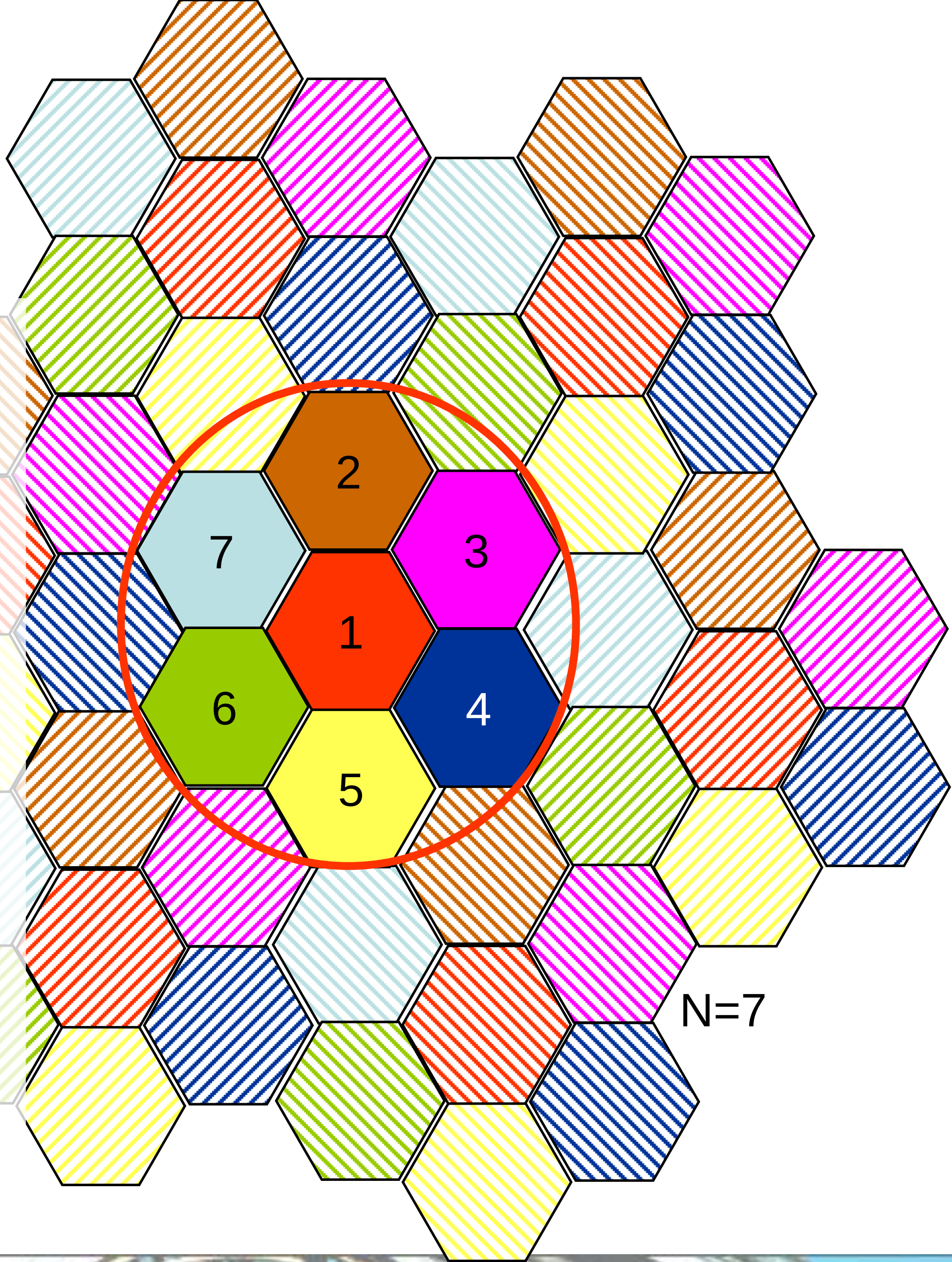
- Obtain two or more copies of the received signal
- Copies can be separated by:
  - **Time**: Convolutional coding ‘smears’ short errors
  - **Frequency**: Frequency hopping is used for GSM;
  - **Distance**: Spatial diversity (2G/3G/WLAN)
  - **Polarization**: Polarization diversity ±45° (2G/3G)

Diversity: Combining the signals

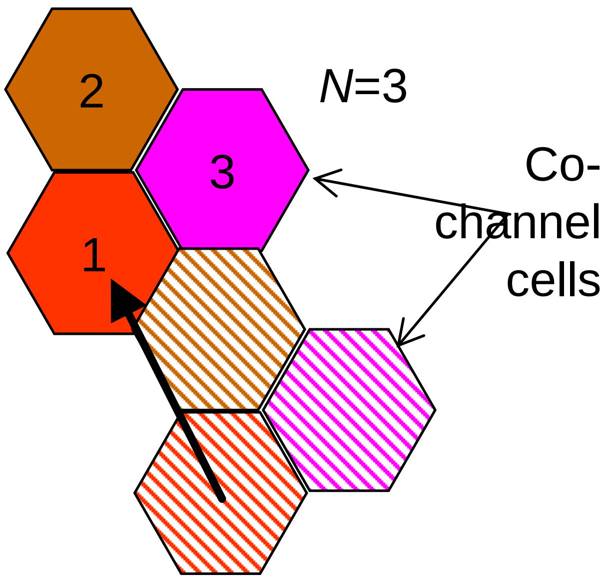
- Combine the signal from each branch and obtain a signal that is more reliable than any single branch
  - Switch diversity – when one is too low, try another
  - Selection diversity – choose the largest signal
  - Equal gain – signals equally weighted and added in phase
  - Maximal ratio – weight the 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.

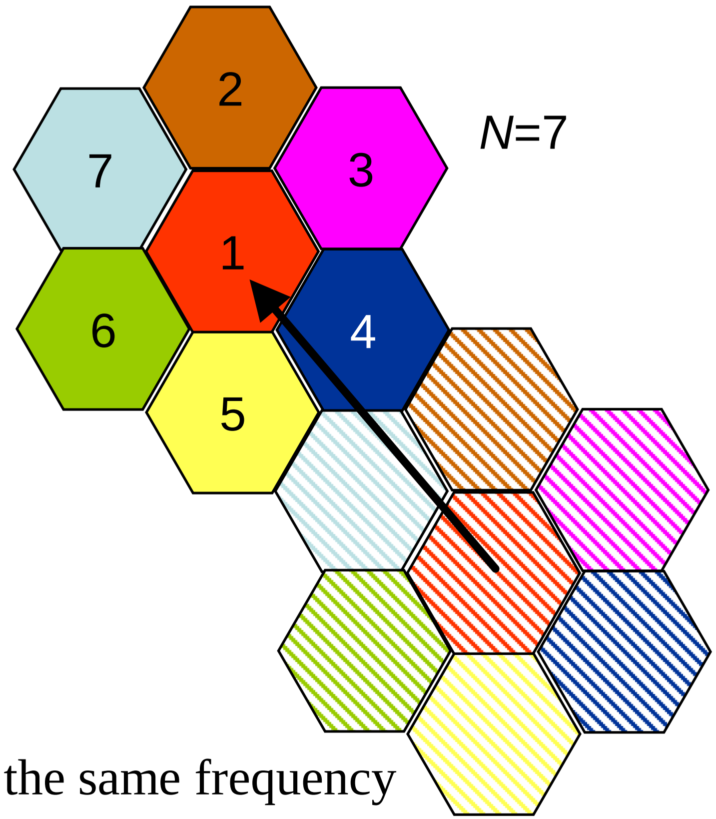
Frequency Reuse

- 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



Effect of cluster size



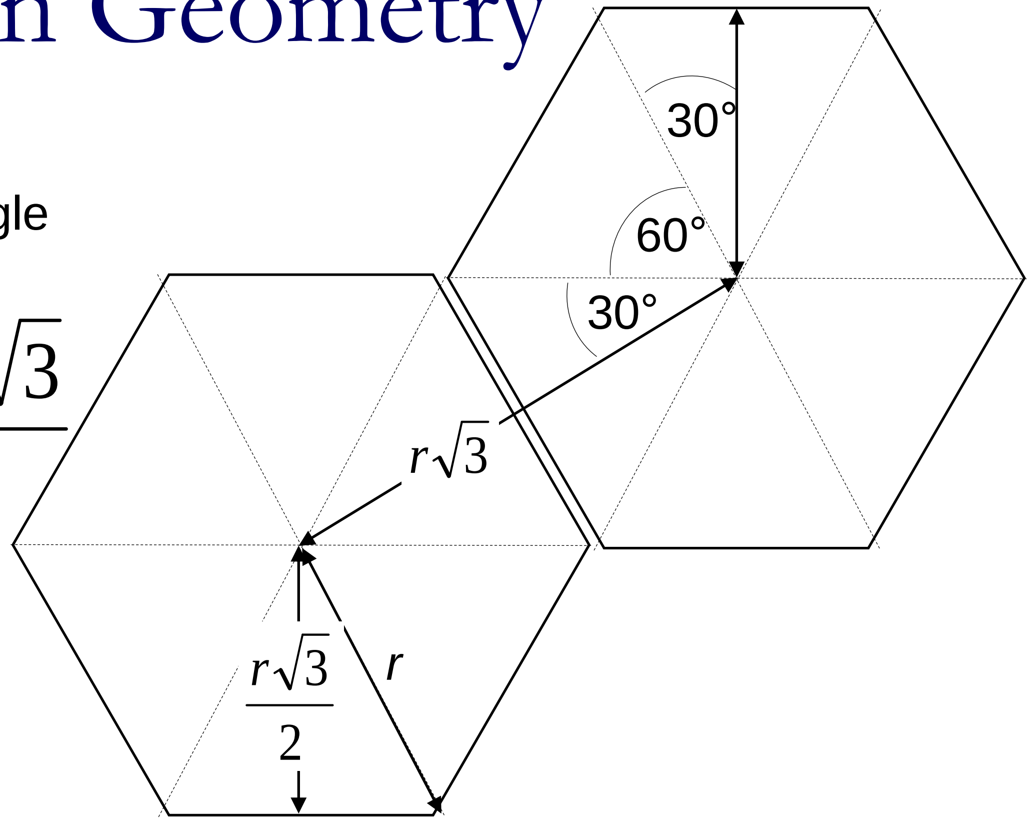


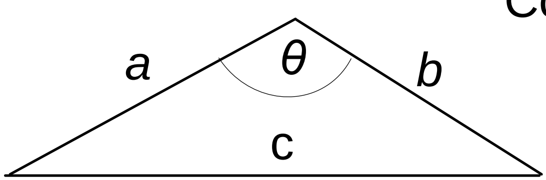
- Bigger cluster:
  - less interference from next cell using the same frequency
  - lower capacity – bandwidth available in cell is F_A/N (F_A is frequency spectrum allocated)

Reminders on Geometry

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

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

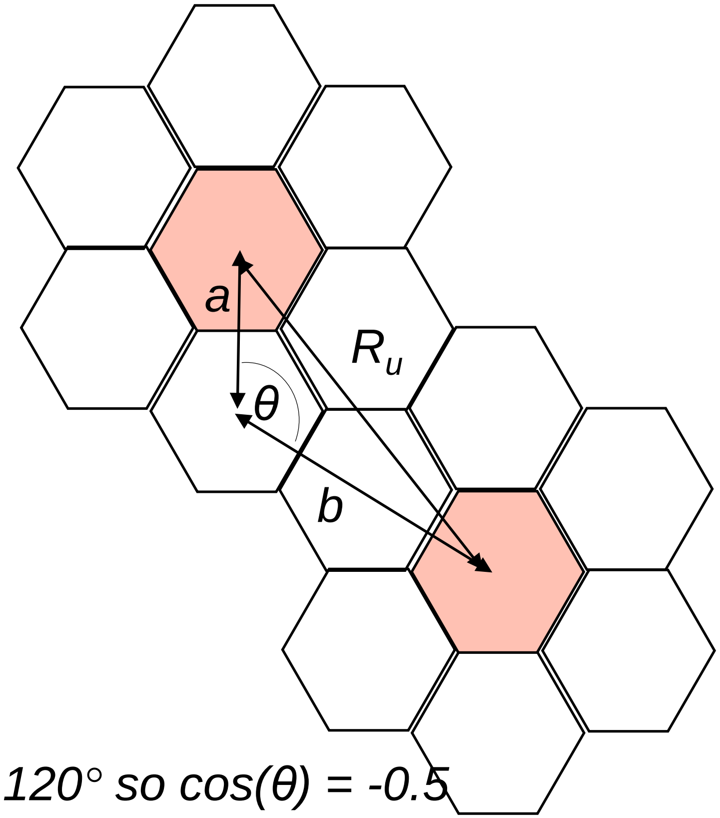




Cosine rule:

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

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

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

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

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

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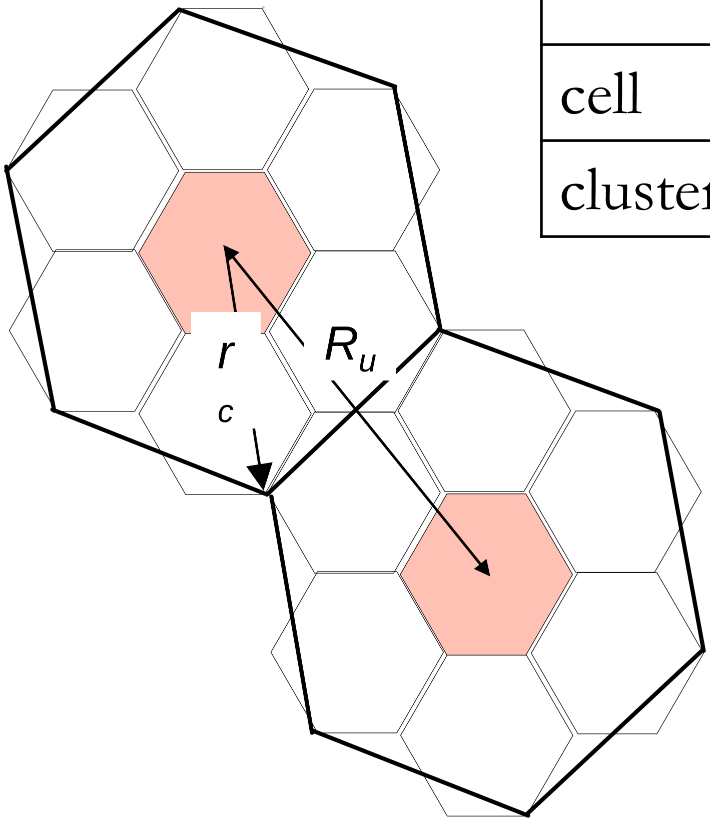
Cluster radius



	radius	area
cell	r	s
cluster	r_c	s_c

$$s_c = Ns$$

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

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

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

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

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

Possible values of N

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

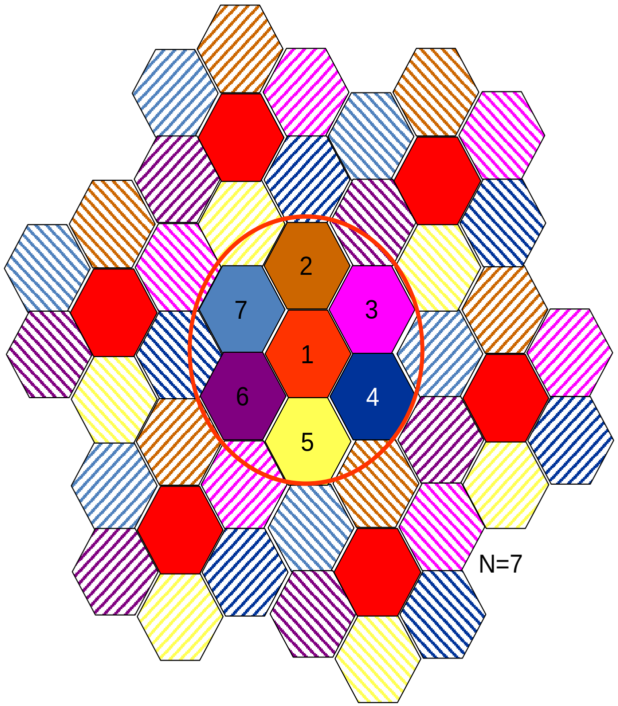
$$\left(\sqrt{i^2 + j^2 + ij}\right)\left(r\sqrt{3}\right) = r\sqrt{3N} \quad \text{or} \quad \sqrt{i^2 + j^2 + ij} = \sqrt{N}$$

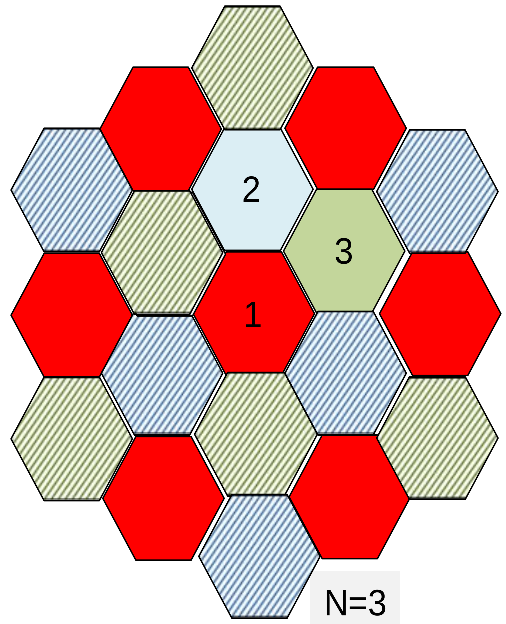
$$i^2 + j^2 + ij = N$$

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

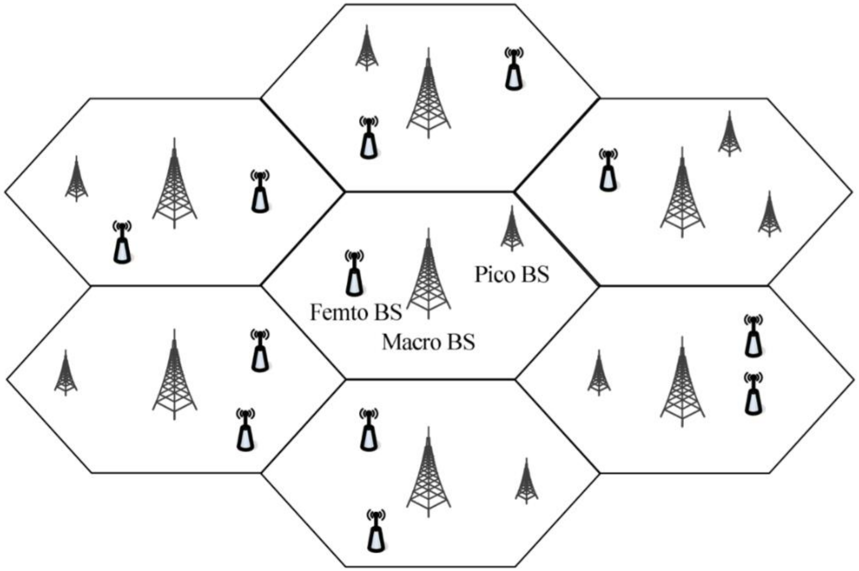




6 surrounding cells of same frequency for both cluster size

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