

UiO : Faculty of Mathematics and Natural Sciences
University of Oslo

Department of Informatics
Networks and Distributed Systems (ND) group

IN3230/4230 - Nettverk

Wireless Communications - I



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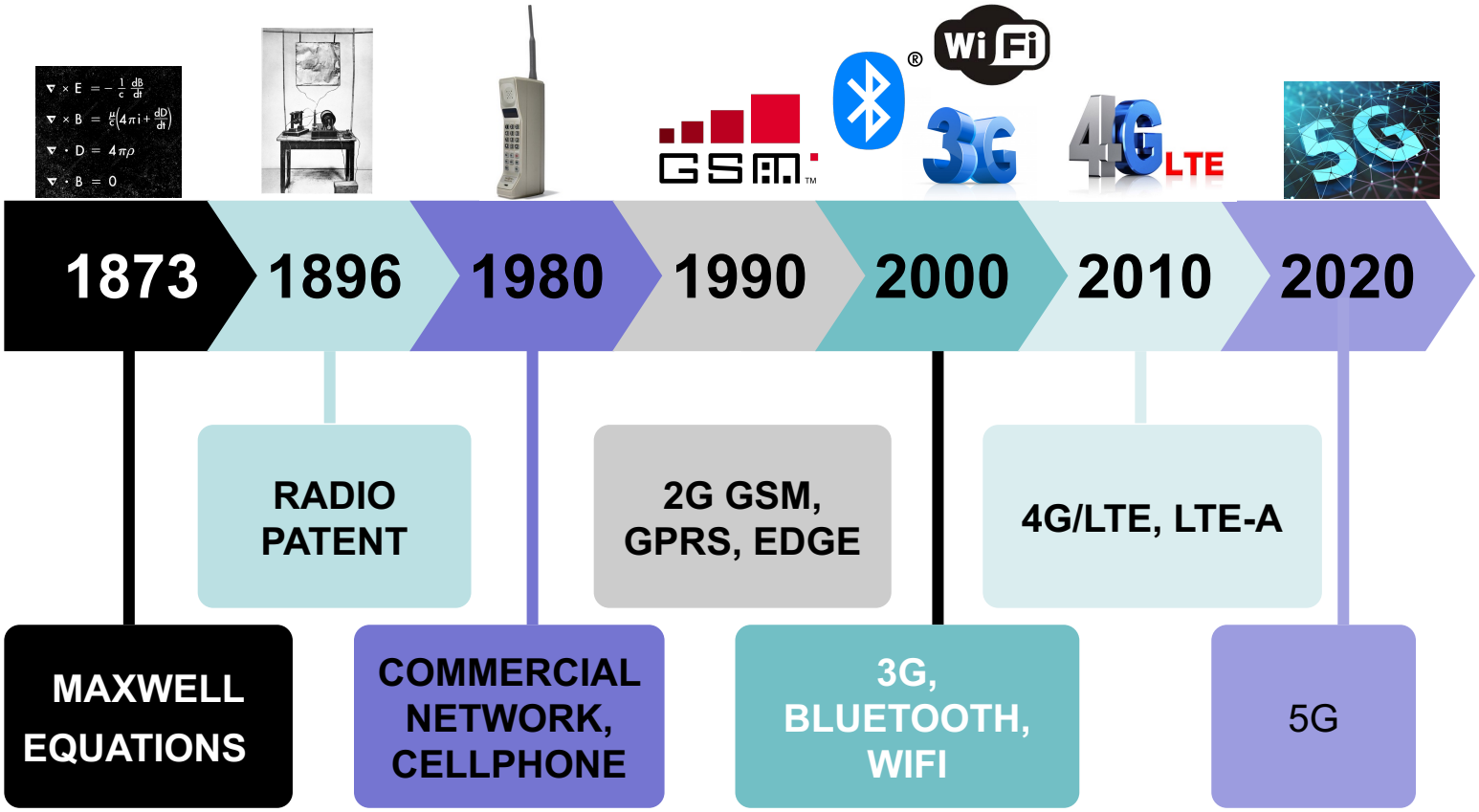
Wireless Communications Networks



Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach: Wireless basics
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- More advanced methods
  - MIMO
  - Beamforming
  - mmWave

Looking back in time to wireless



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Why Wireless?

- Freedom from wires
  - No cost of installing the wires
  - Not deal with bunches of wires running around
- Global coverage
  - where wired communication is not feasible or costly e.g. rural areas, battle field and outer space.
- Stay Connected
  - Any where any time, even under mobility
- Flexibility
  - Connect to multiple devices simultaneously

What is Wireless Communication?

- Transmitting voice and data using electromagnetic waves in open space
- Electromagnetic waves
  - Travel at speed of light ($c = 3x10^8$ m/s)
  - Has a frequency (f) and wavelength (λ)
    - » $c = f \times \lambda$

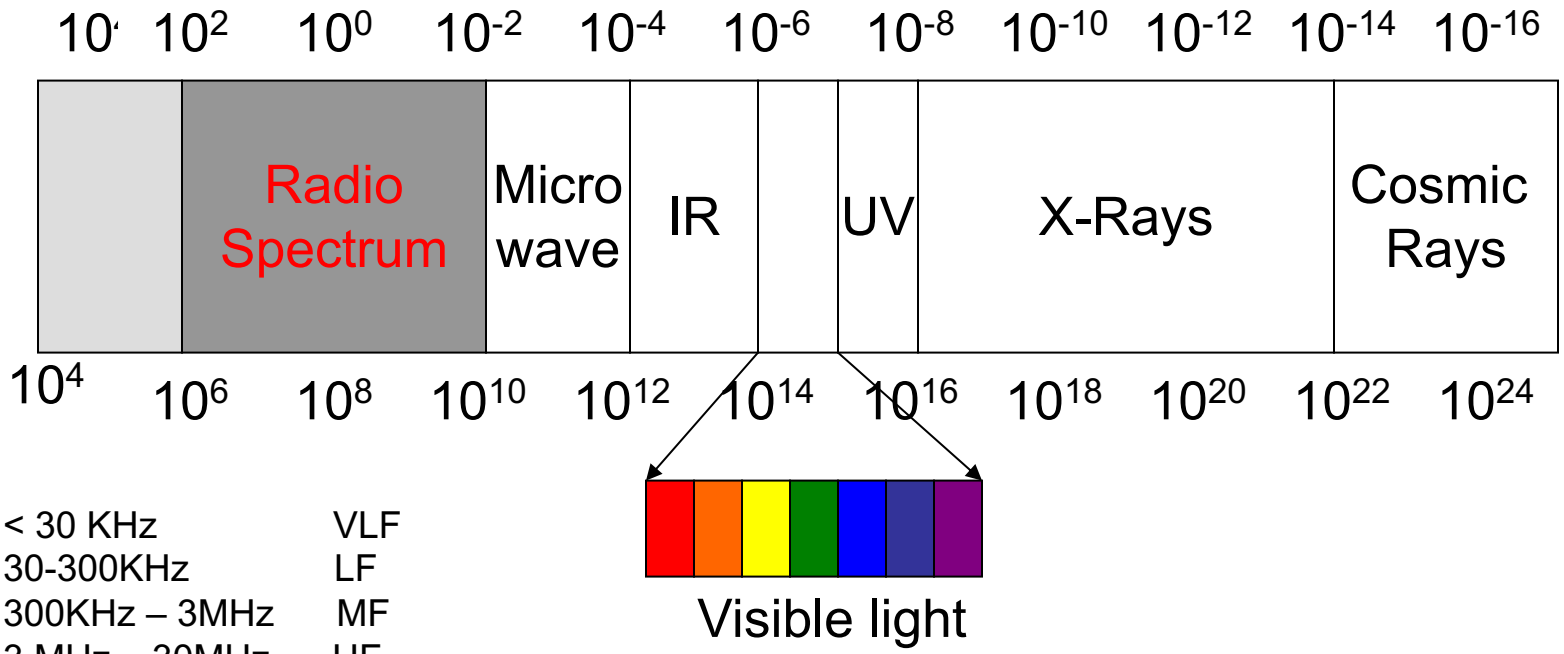
Wireless Link Characteristics

- *decreased signal strength:* radio signal attenuates (lose signal strength) as it propagates through matter (path loss)
    - Higher frequencies will attenuate FASTER
    - Higher frequencies also don't penetrate objects as well
- *interference from other sources:* standardized wireless frequencies shared by other devices (e.g., phone); devices (motors) interfere as well
- *multipath propagation:* radio signal reflects off objects/ground, reaching destination at slightly different times

…. make communication across (even a point to point) wireless link much more "difficult"

Electromagnetic Spectrum

3MHz ==100m
300MHz ==1m
30GHz ==1cm



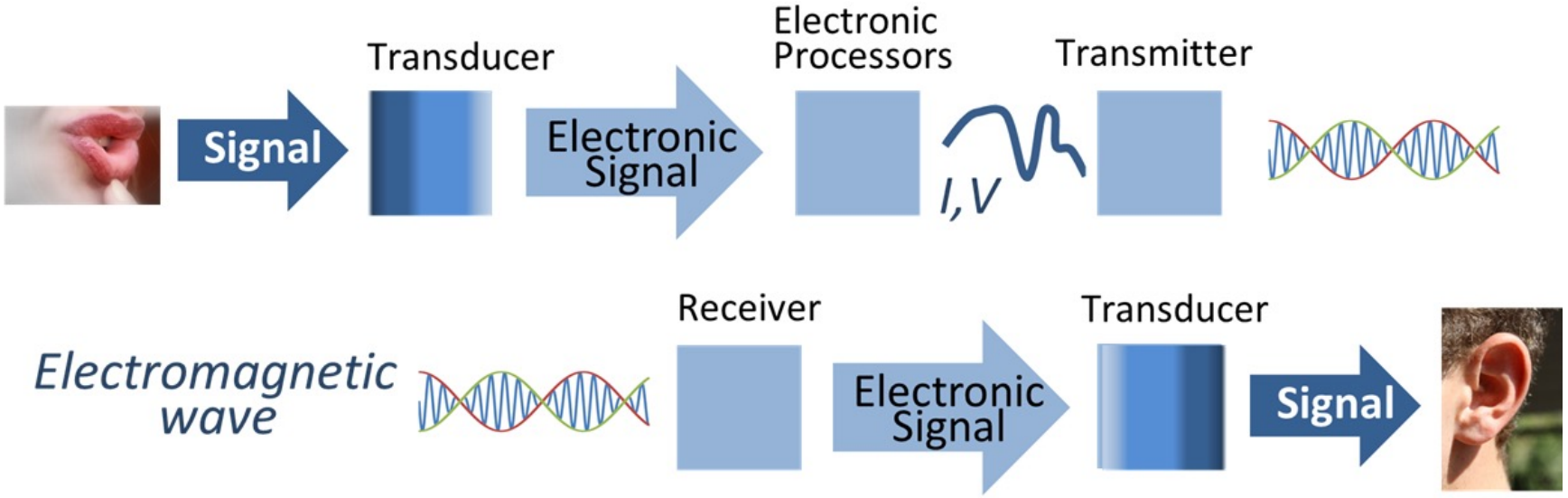
< 30 KHz	VLF
30-300KHz	LF
300KHz – 3MHz	MF
3 MHz – 30MHz	HF
30MHz – 300MHz	VHF
300 MHz – 3GHz	UHF
3-30GHz	SHF
> 30 GHz	EHF

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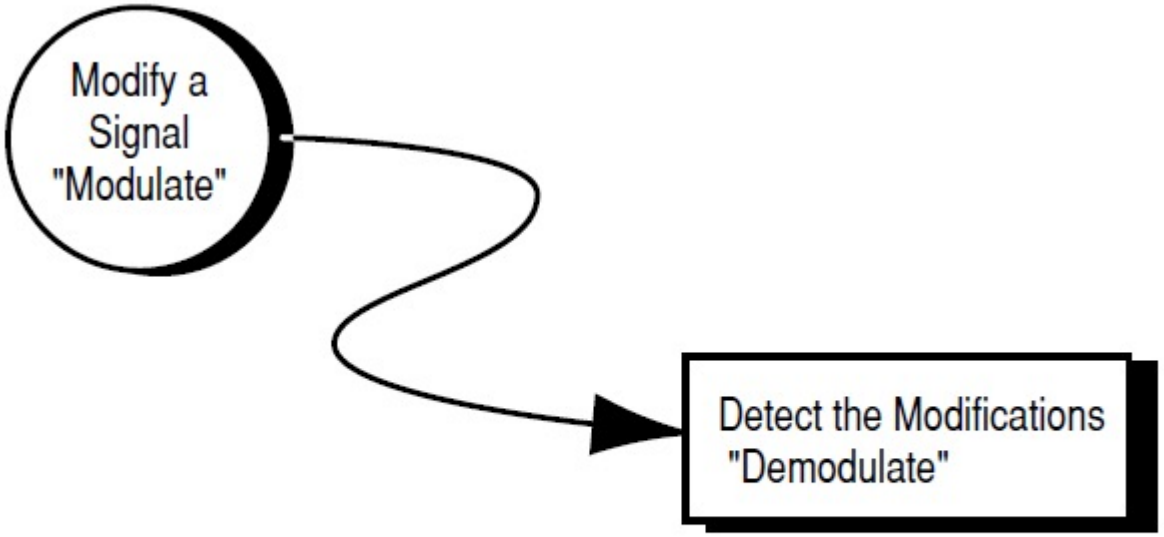
Block diagram of radio transmission

- Information (e.g. sound) is converted by a transducer (e.g. a microphone) to an electrical signal
- This signal is used to modulate a radio wave sent from a transmitter.
- A receiver intercepts the radio wave and extracts the information-bearing electronic signal, which is converted back using another transducer such as a speaker.



What is modulation?

- Modulation = Adding information to a carrier signal



Modulation Process

$$f = f\left(a_1, a_2, a_3, \ldots a_n, t\right) \text{ (= carrier)}$$

$$a_1, a_2, a_3, \ldots a_n \text{ (= modulation parameters)}$$

$$t \text{ (= time)}$$

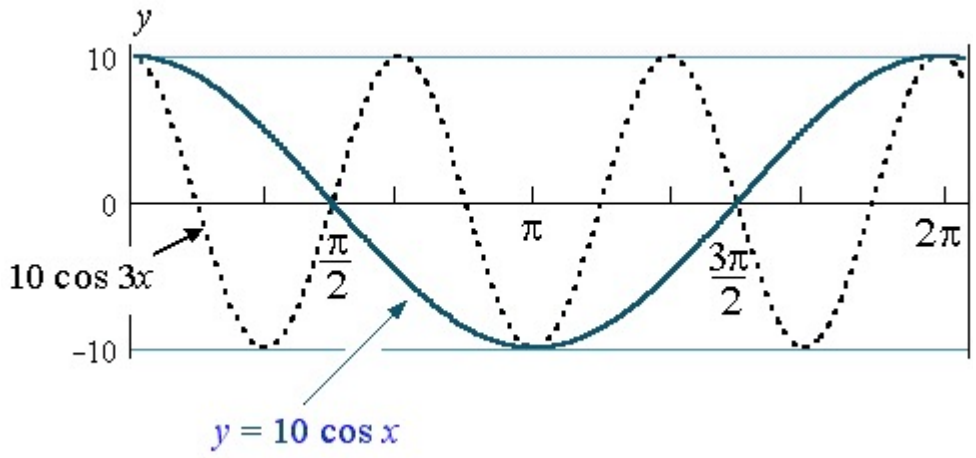
- Modulation implies varying one or more characteristics (modulation parameters a_1, a_2, … a_n) of a carrier *f* in accordance with the information-bearing (modulating) baseband signal.
- Sinusoidal waves, pulse train, square wave, etc. can be used as carriers

Carrier Signal

Carrier signal:

$$\bullet\ A\cos(2\pi f_C t + \varphi)$$

Amplitude — Frequency — Phase

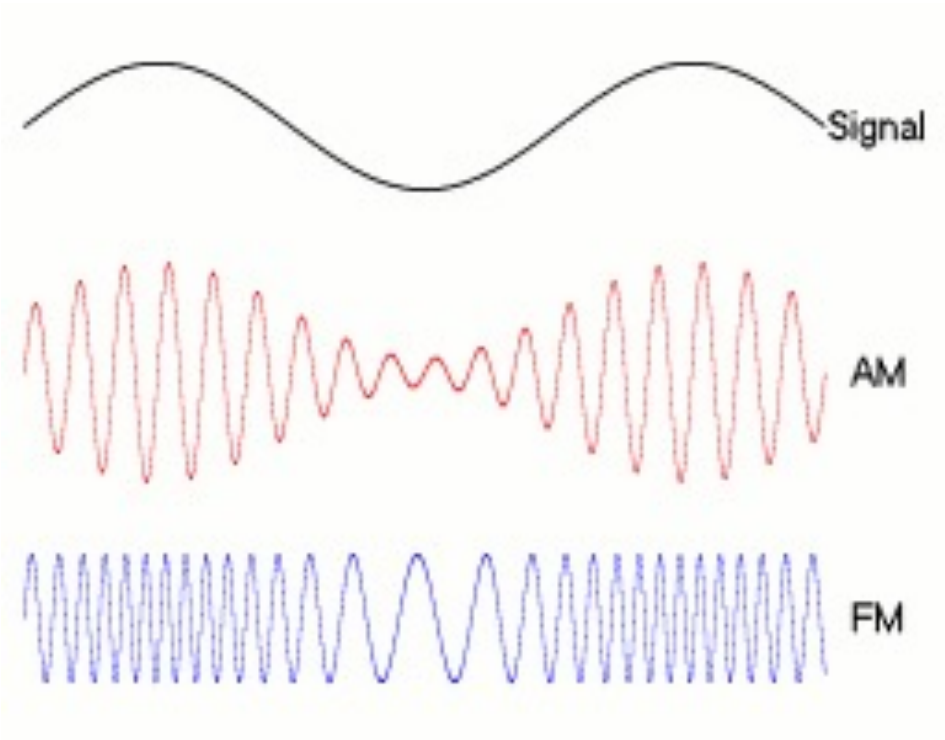


Types of Modulation

- ANALOG MODULATION: If the variation in the parameter of the carrier is continuous in accordance to the input analog signal the modulation technique is termed as analog modulation scheme

- DIGITAL MODULATION: If the variation in the parameter of the carrier is discrete then it is termed as digital modulation technique

ANALOG MODULATION



Amplitude Modulation:
Signal shapes the amplitude of the carrier

Frequency Modulation:
Signal shapes the frequency of the carrier

DIGITAL MODULATION TECHNIQUES

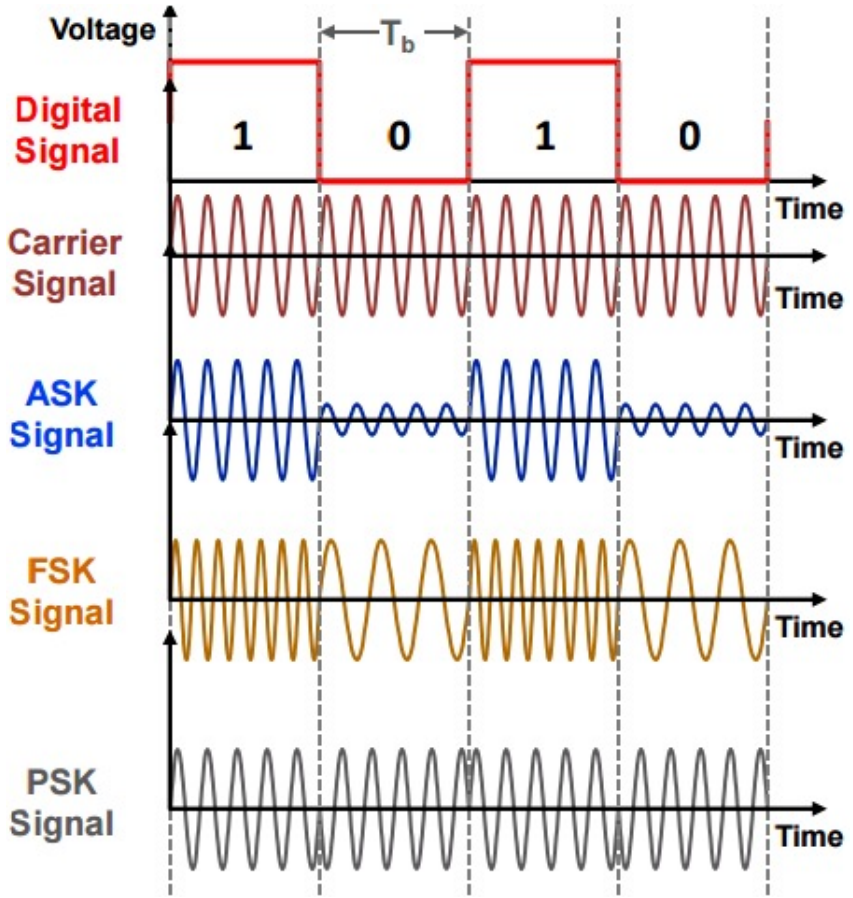
1. **Baseband digital message signal**: $m(t)$

2. **Analog sinusoidal carrier signal**:
   A. Carrier signal: $A_c \cos(2\pi f_c t + \phi_c)$

3. **ASK: Amplitude Shift Keying**.
   A. Message signal changes the carrier's **amplitude** : $A_i(t)$.

4. **FSK: Frequency Shift Keying**.
   A. Message signal changes the carrier's **frequency** : $f_i(t)$.

5. **PSK: Phase Shift Keying.**
   A. Message signal changes the carrier's **phase** : $\phi_i(t)$.



DIGITAL MODULATION TECHNIQUES

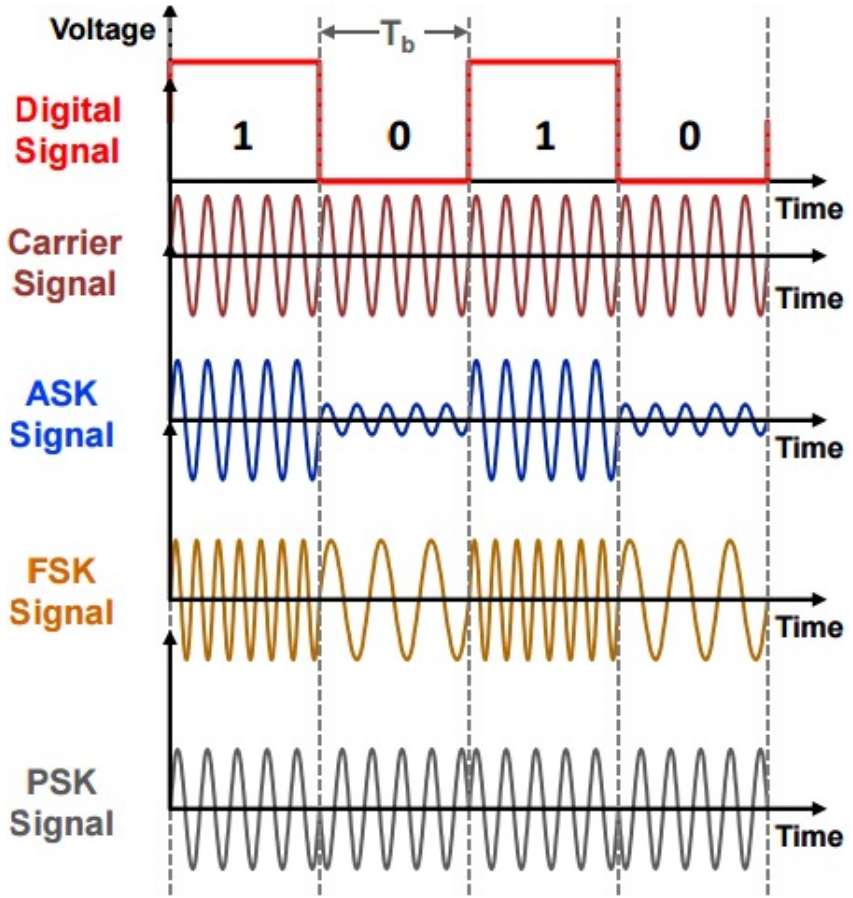
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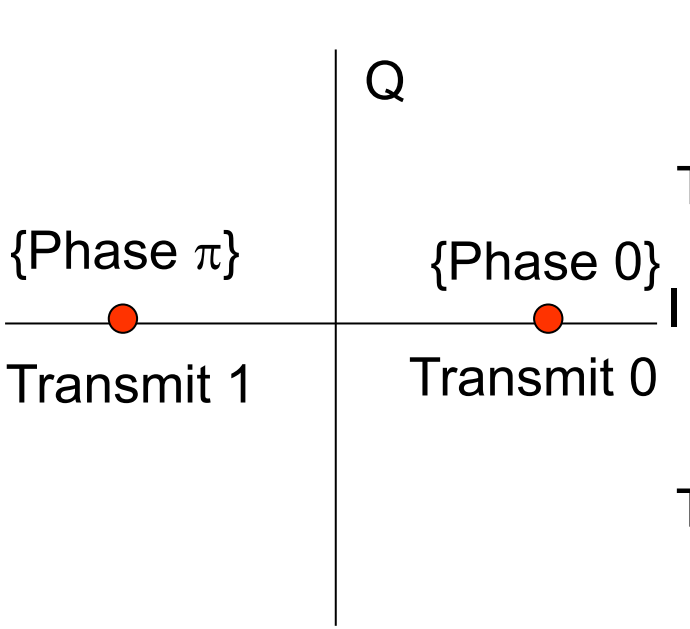
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   A. Message signal changes the carrier's **amplitude** : $A_i(t)$.

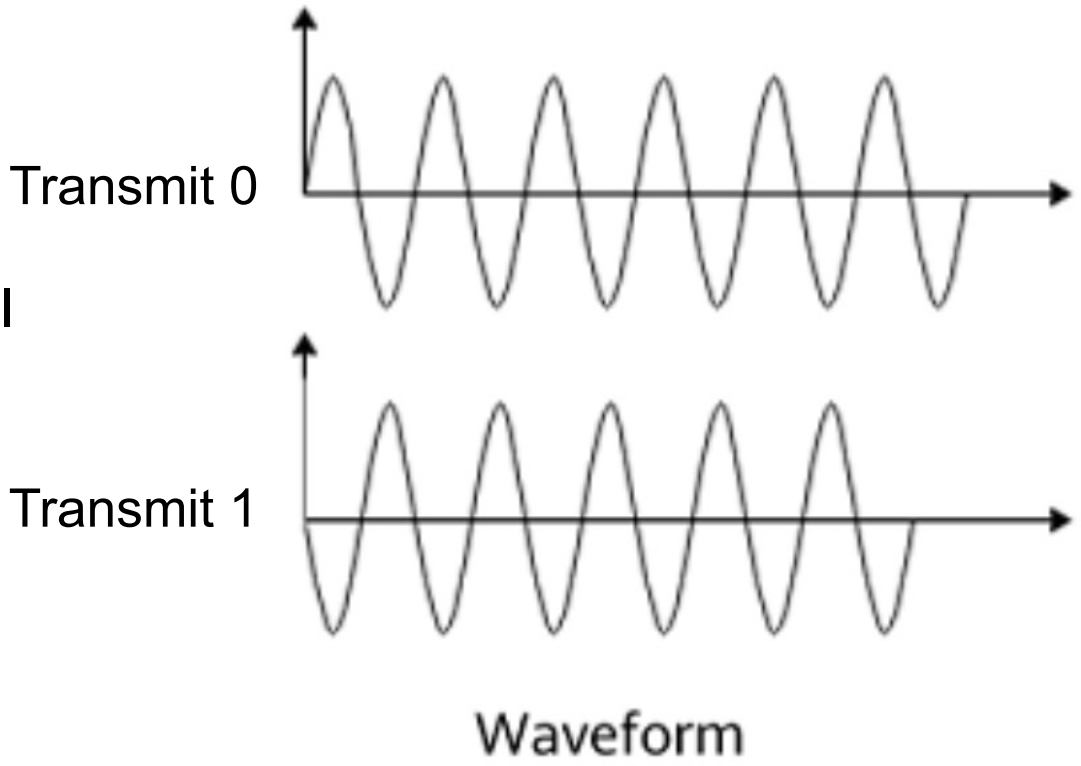
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   A. Message signal changes the carrier's **frequency** : $f_i(t)$.

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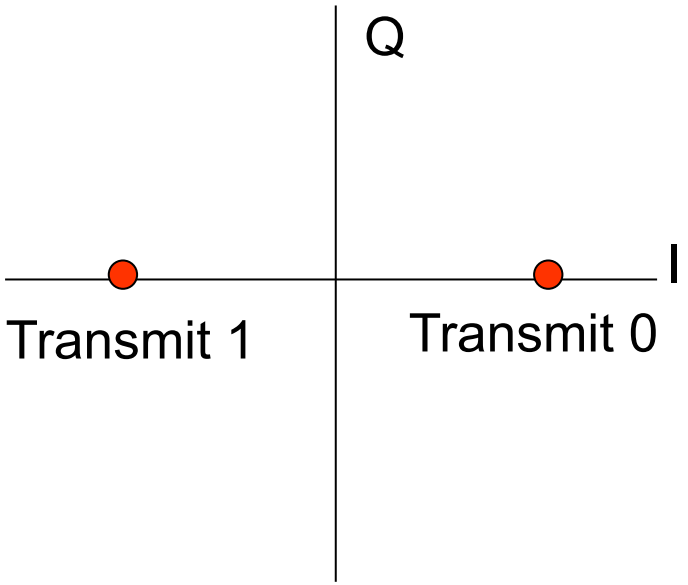


BPSK Representation





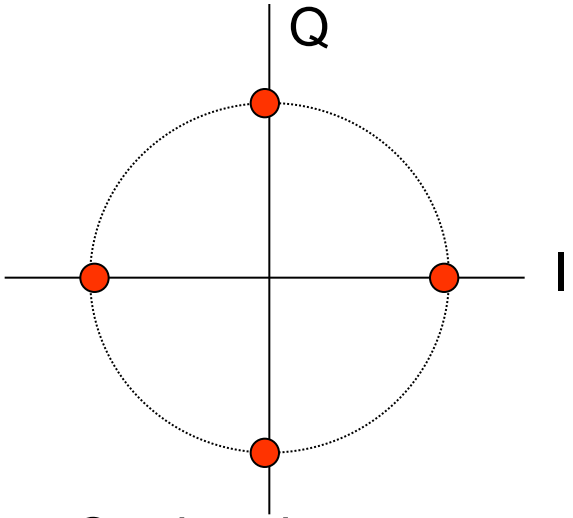
Constellation Diagram



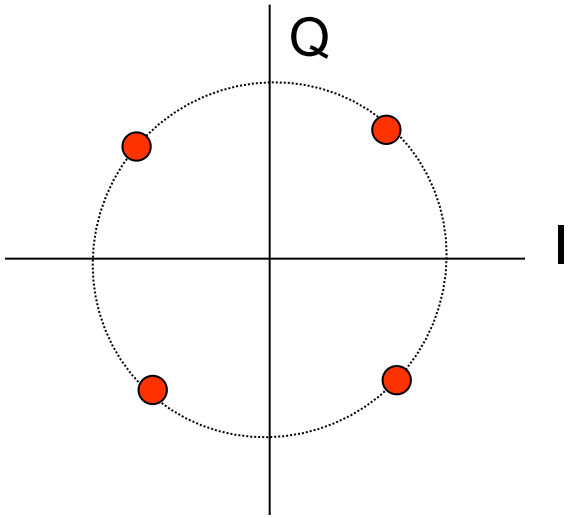
= graphical representation of the complex envelope of each possible symbol state

- The x-axis represents the in-phase component and the y-axis the quadrature component of the complex envelope
- The distance between signals on a constellation diagram relates to how different the modulation waveforms are and how easily a receiver can differentiate between them.

QPSK Constellation Diagram



Carrier phases
{0, π/2, π, 3π/2}

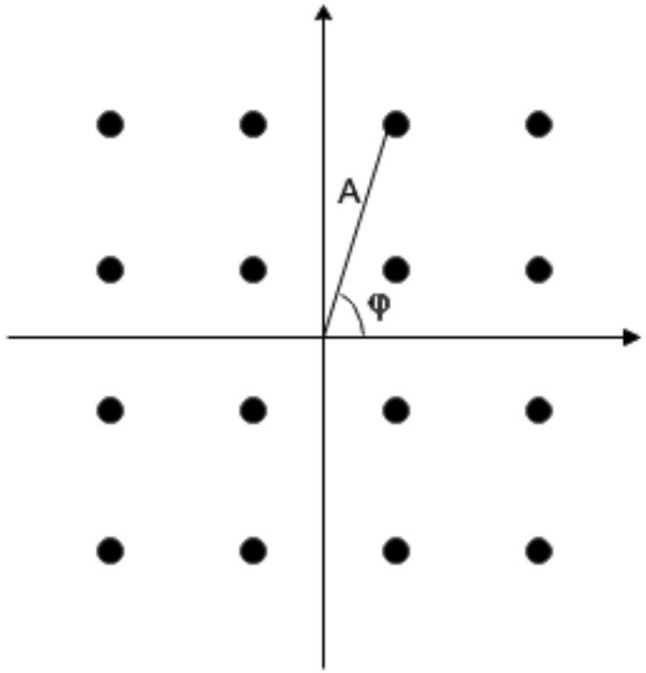


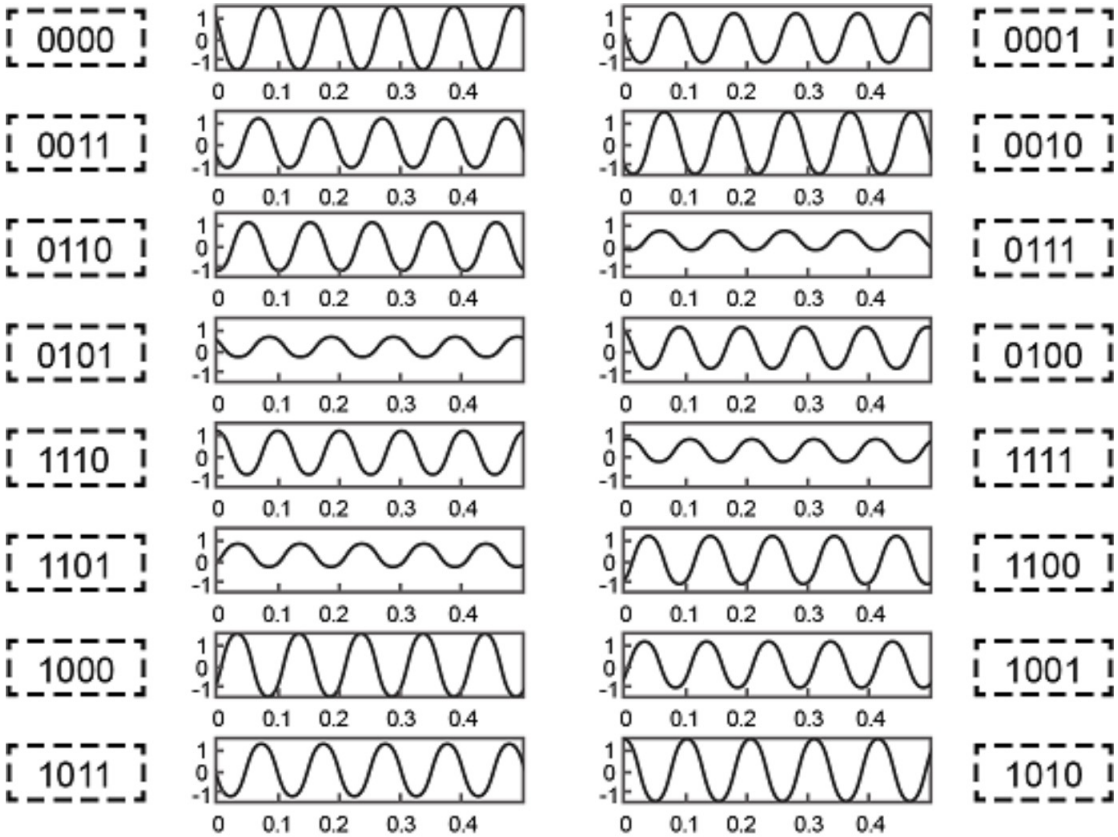
Carrier phases
{π/4, 3π/4, 5π/4, 7π/4}

- Quadrature Phase Shift Keying (QPSK) can be interpreted as two independent BPSK systems (one on the I-channel and one on Q)
- Quadrature Phase Shift Keying has twice the bandwidth efficiency of BPSK since 2 bits are transmitted in a single modulation symbol

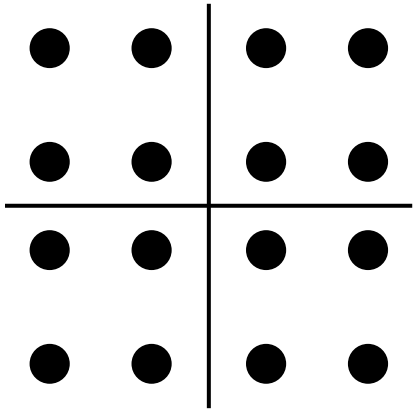
Quadrature Amplitude Modulation (QAM)

Both amplitude and phase modulation

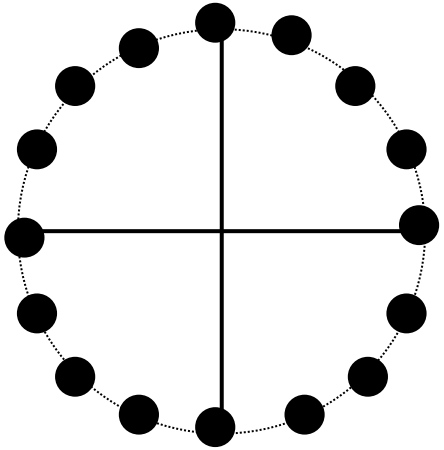




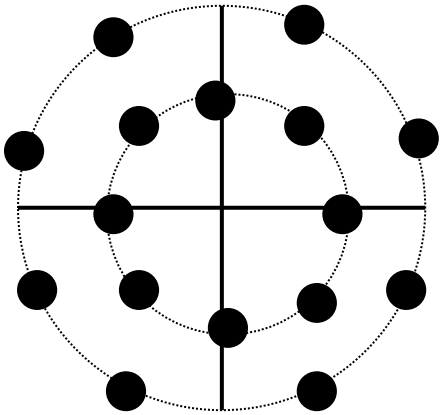
Multi-level (M-ary) Phase and Amplitude Modulation



16 QAM



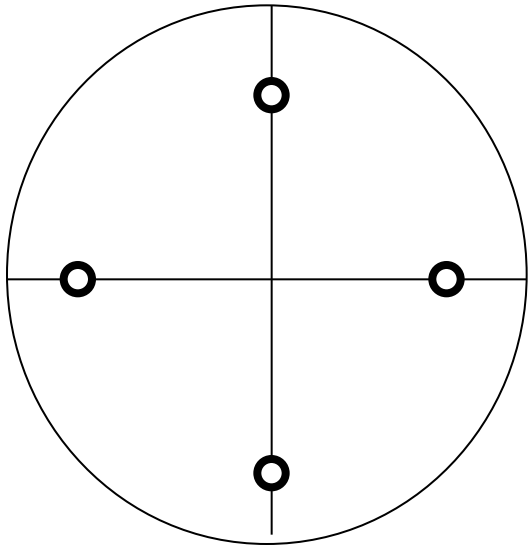
16 PSK



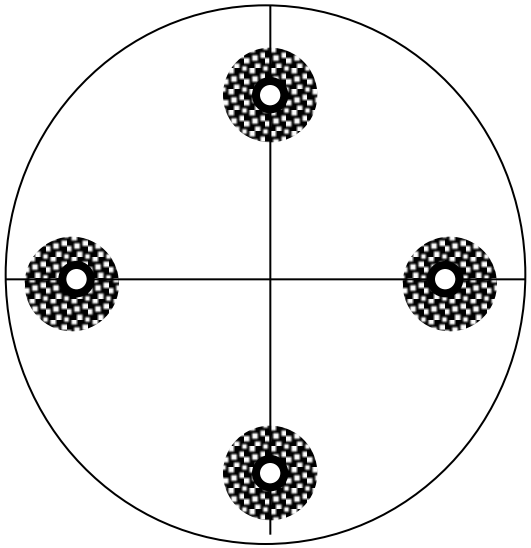
16 APSK

- There are different constellations having same number of logical states but different efficiency

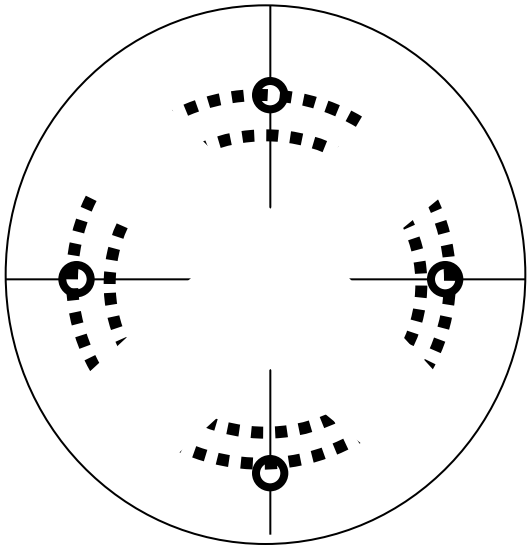
What is a good constellation?



Perfect channel



White noise



Phase jitter

Need to consider **Distortions** and the signal can be decoded!

Impact of Distortions

- Noise can change the amplitude easier than the phase. PSK is less susceptible to noise than ASK.
- Major drawback of PSK is the rapid amplitude change between symbols due to phase discontinuity
- PSK is superior to FSK because we do not need two carrier signals.
- Binary Phase Shift Keying (BPSK) demonstrates better performance than ASK and BFSK

Demodulation & Detection

- Demodulation
  - Is process of removing the carrier signal to obtain the original signal waveform
- Detection – extracts the symbols from the waveform
  - Coherent detection
  - Non-coherent detection

Coherent Detection (synchronous detection)

- An estimate of the channel phase and attenuation is recovered. It is then possible to reproduce the transmitted signal and demodulate.
- Requires a replica carrier wave of the same frequency and phase at the receiver.
- The received signal and replica carrier are cross-correlated using information contained in their amplitudes and phases.

Non-Coherent Detection

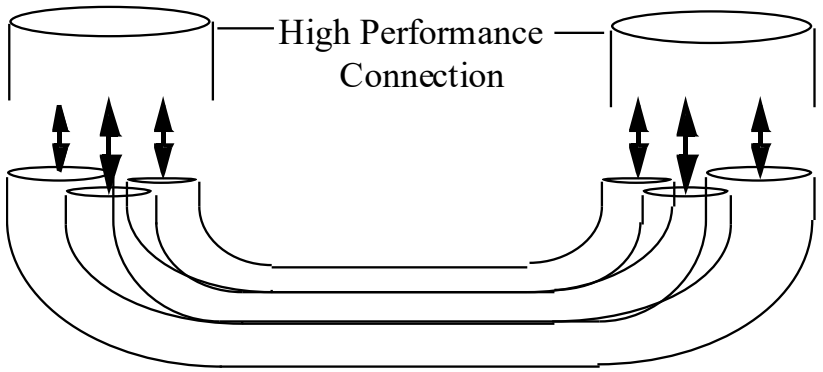
- Requires no reference wave; does not exploit phase reference information (envelope detection)
- Non-coherent detection is less complex than coherent detection (easier to implement), but has often worse performance.

Outline

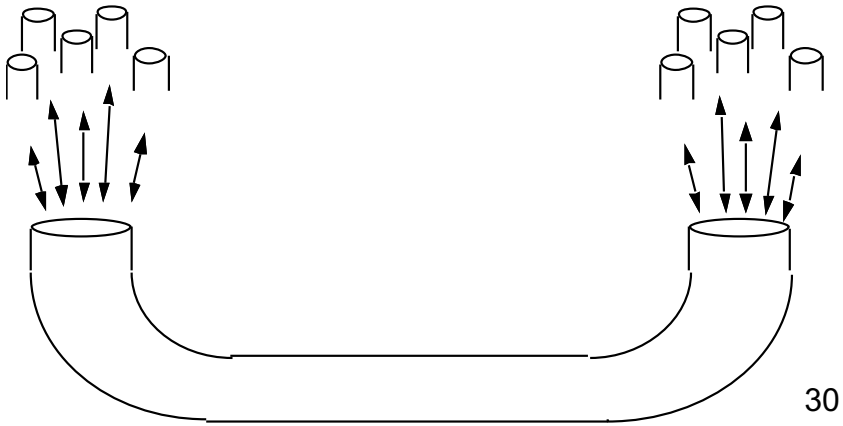
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- More advanced methods
  - MIMO
  - Beamforming
  - mmWave

Multiplexing (MUX) / Multiple Access (MA)

- Transmission of several data flows (logical connections) over one medium
  - Realize individual “connections“, *normally* with deterministic properties (throughput, delay)
  - Terminology: M (“.. Multiplexing“) or MA (“.. Multiple Access“)
- Also:
  Transmission of one data flow (logical connection) over several media
  - (increase performance and/or reliability)

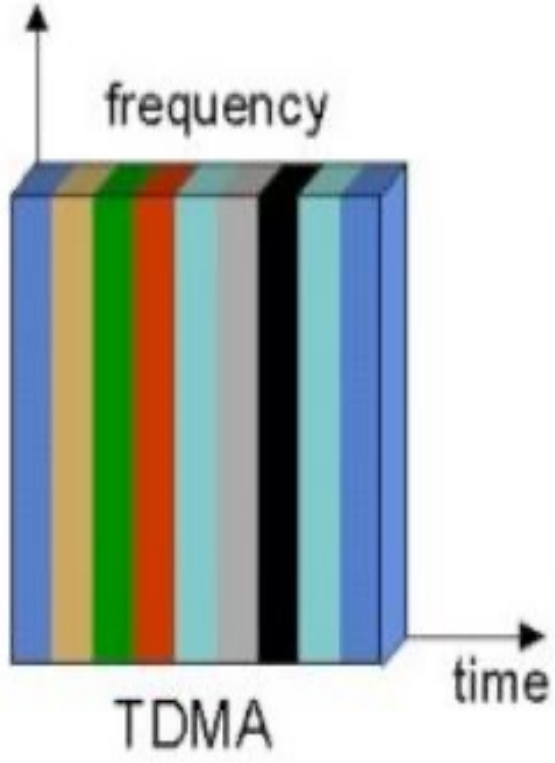


several connections with less performance / quality



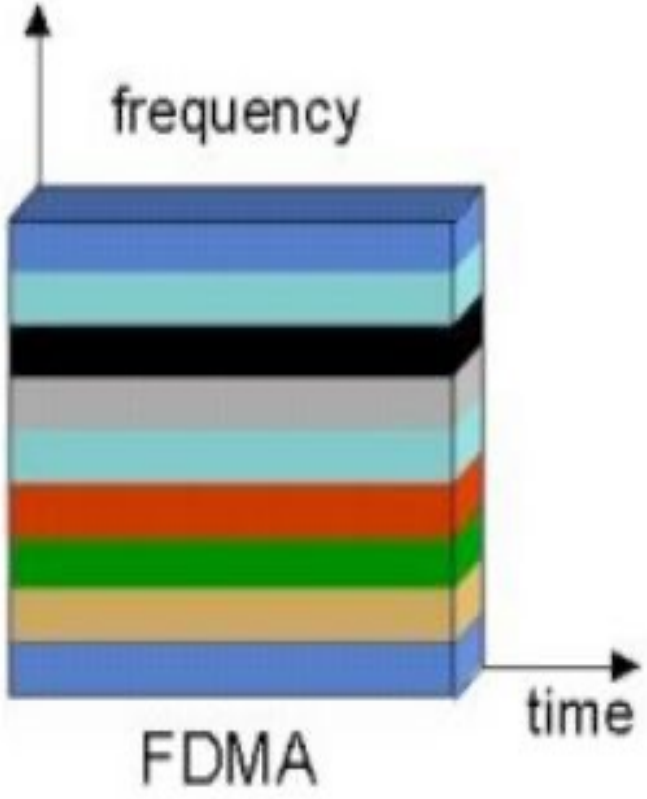
Time Division Multiple Access (TDMA)

- Each user is allowed to transmit only within specified time intervals (Time Slots). Different users transmit in different Time Slots.
- When users transmit, they occupy the whole frequency bandwidth (separation among users is performed in the time domain).
- Commonly used in GSM together with frequency hopping



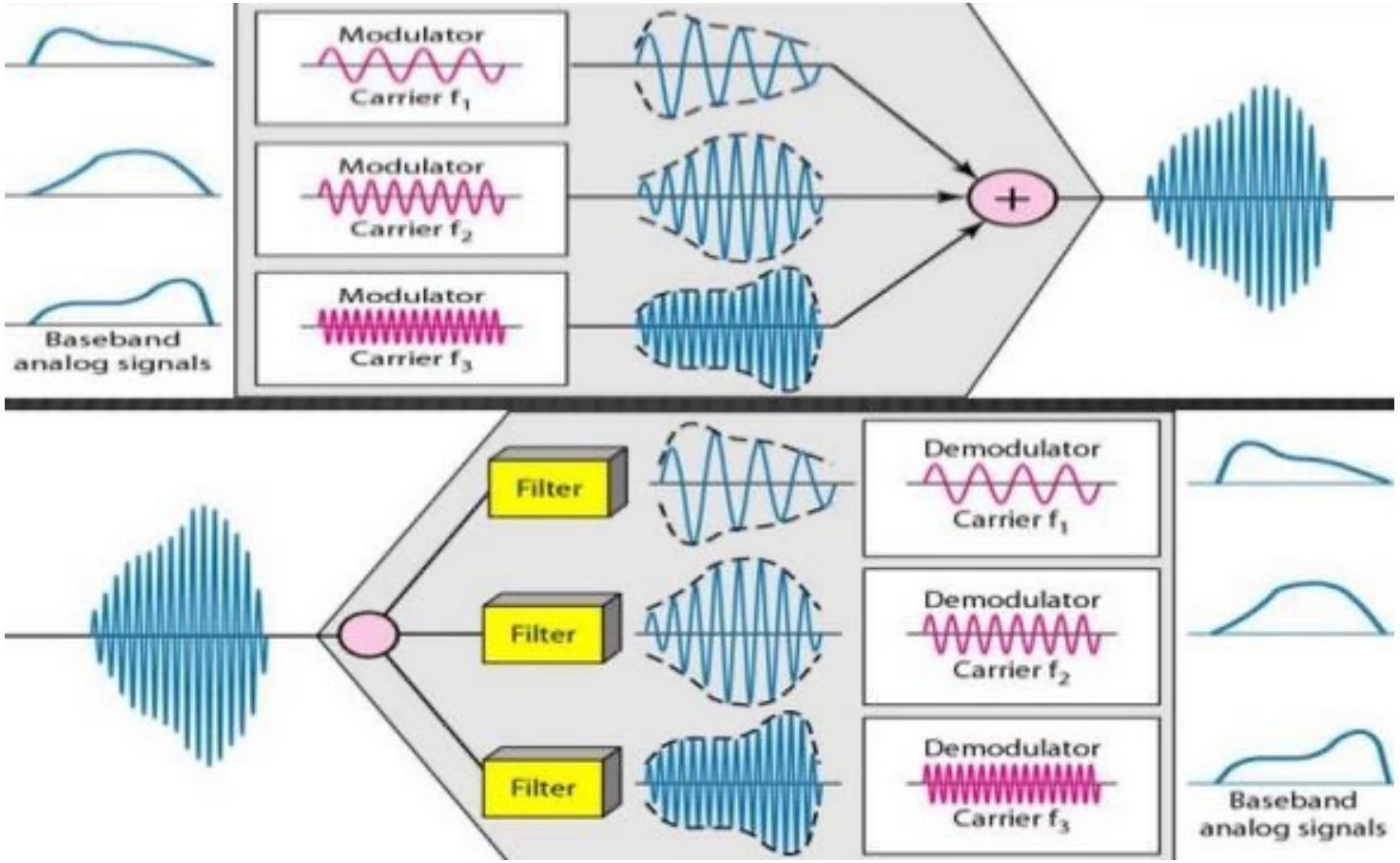
Frequency Division Multiple Access (FDMA)

- Each user transmits with no limitations in time, but using only a portion of the whole available frequency bandwidth
- Different users are separated in the frequency domain
- FDMA can be used for both digital and analog signals
- Very common in satellite communications



❑ The major disadvantage of FDMA is the relatively expensive and complicated bandpass filters required.

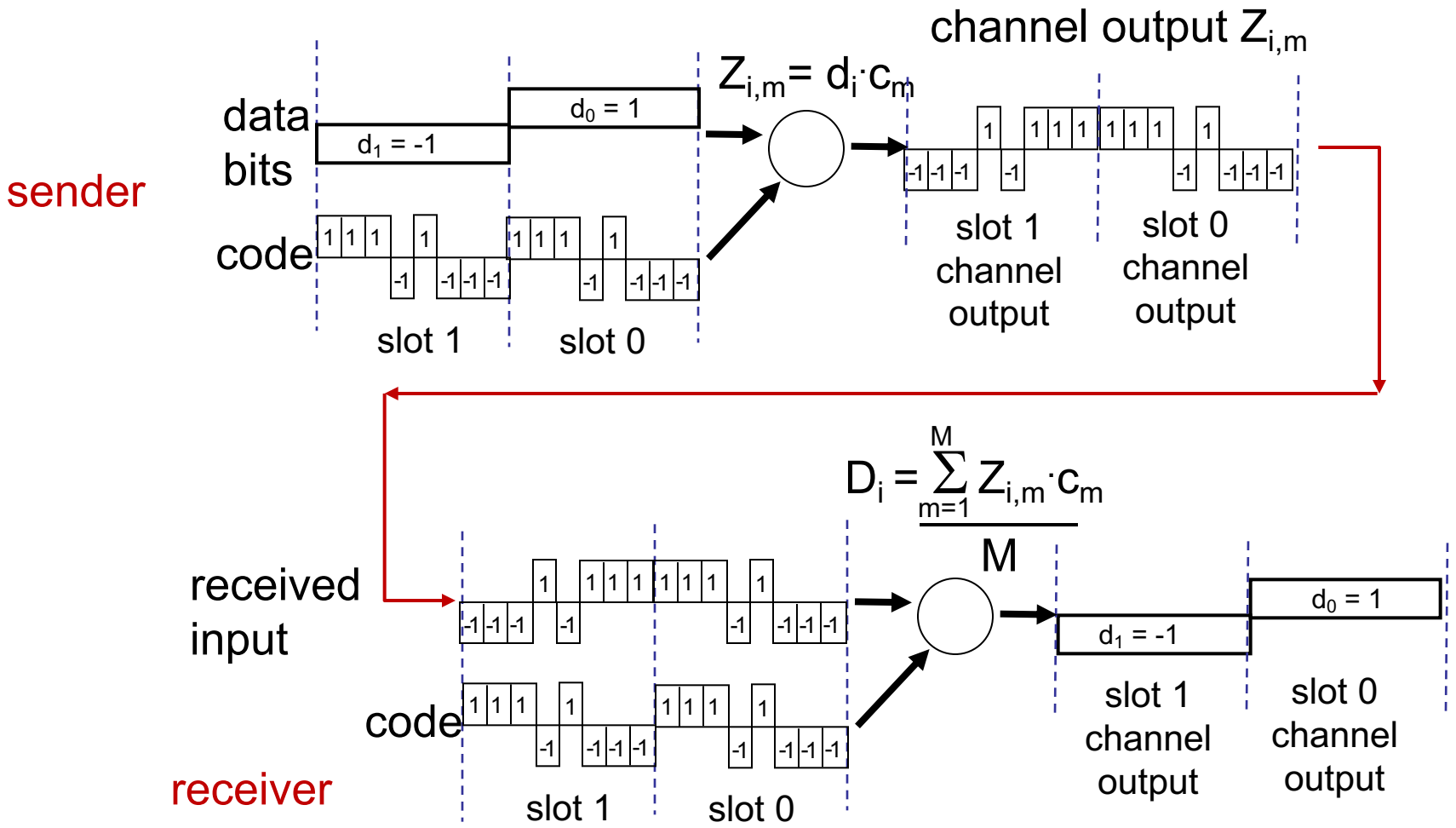
FDMA in time domain



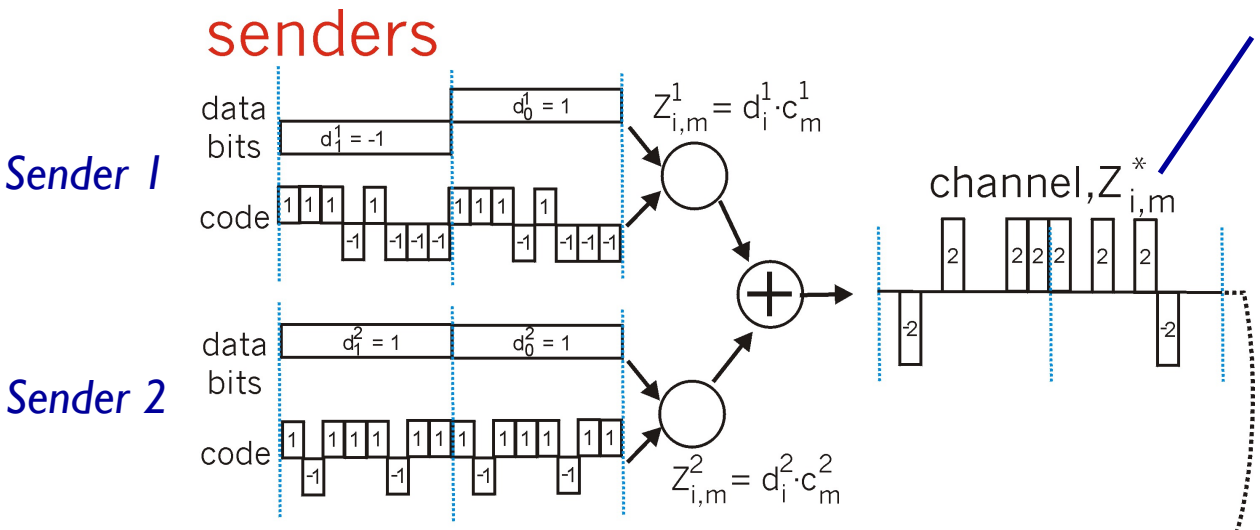
Code Division Multiple Access (CDMA)

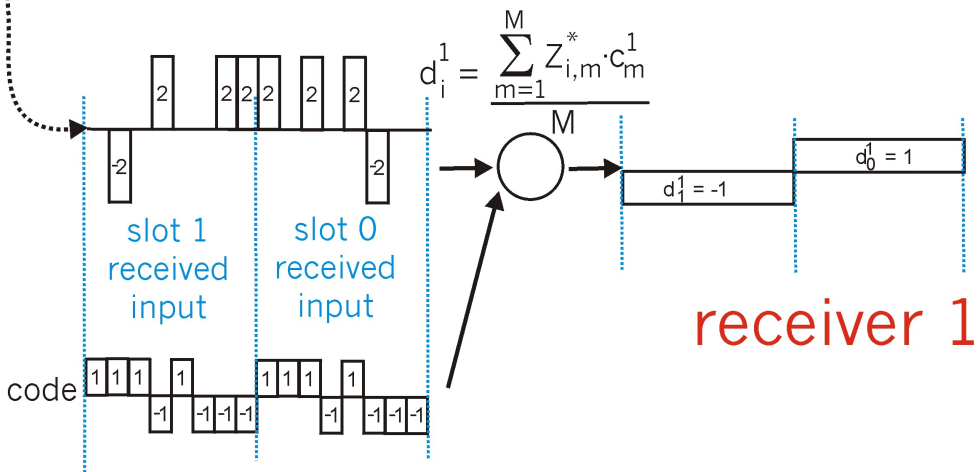
- unique "code" assigned to each user; i.e., code set partitioning
  - all users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data
  - allows multiple users to "coexist" and transmit simultaneously with minimal interference
- Chip sequences are orthogonal to ensure reconstructability:
  - seq. 1: $x = (x_1, .. x_n)$, seq. 2: $y = (y_1, .. y_n)$ $\sum x_i y_i = 0$
  - Common choice: Walsh sequence
- *encoded signal* = (original data) X (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence

CDMA encode/decode



CDMA: two-sender interference

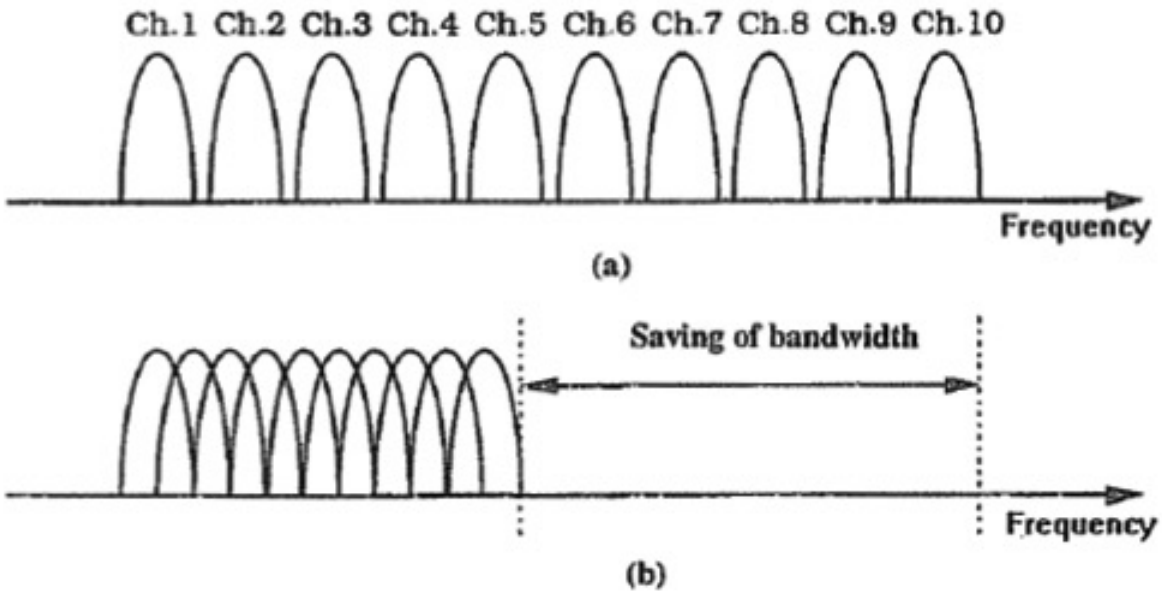




using same code as sender 1, receiver recovers sender 1's original data from summed channel data!

Orthogonal Frequency Division Multiple Access (OFDMA)

- The carriers are chosen such that they are orthogonal to one another
- It allocates in both the time domain and the frequency domain, allowing for multiple users—even those with widely varying use patterns or data loads



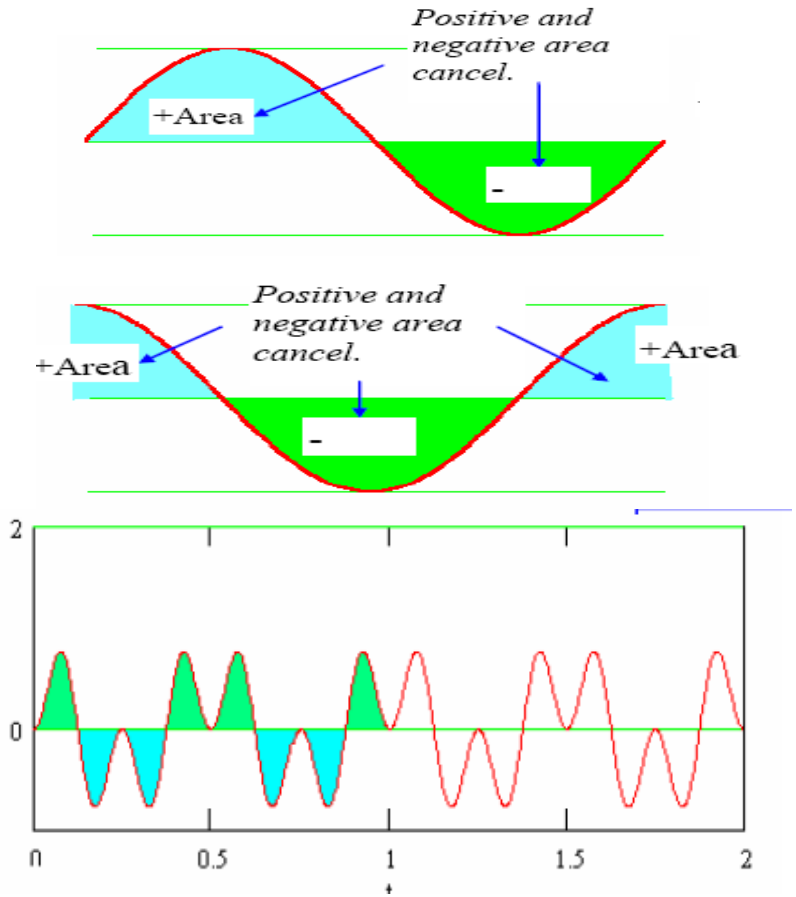
Conventional multicarrier

Orthogonal multicarrier

Orthogonality Principle

- Real Function space

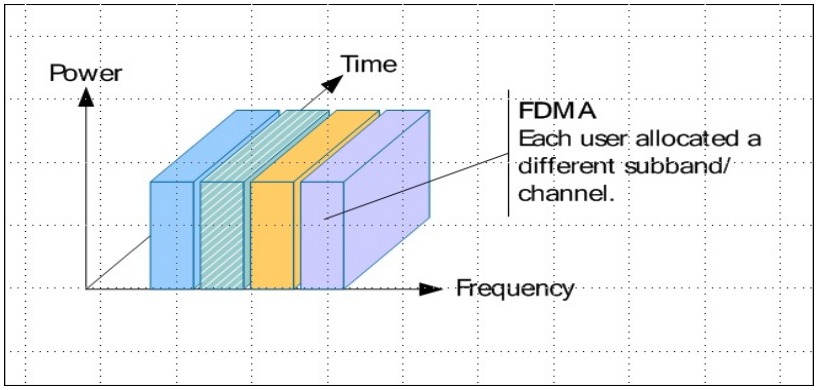
$$f_1(t) = A\sin(wt)$$
$$f_2(t) = B\cos(wt)$$
$$\int_{\tau}^{\tau+T} f_1(t) f_2(t) dt = 0$$
$$f_m(t) = M\sin(mwt)$$
$$f_n(t) = N\cos(nwt)$$
$$\int_{\tau}^{\tau+T} f_m(t) f_n(t) dt = 0$$



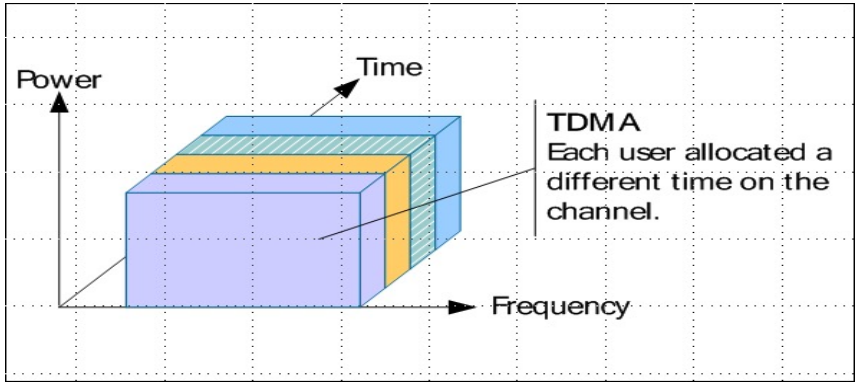
Here *mw* and *nw* are called *m-th* and *n-th* harmonics of *w respectively*

Summary: FDMA,TDMA, CDMA and OFDMA

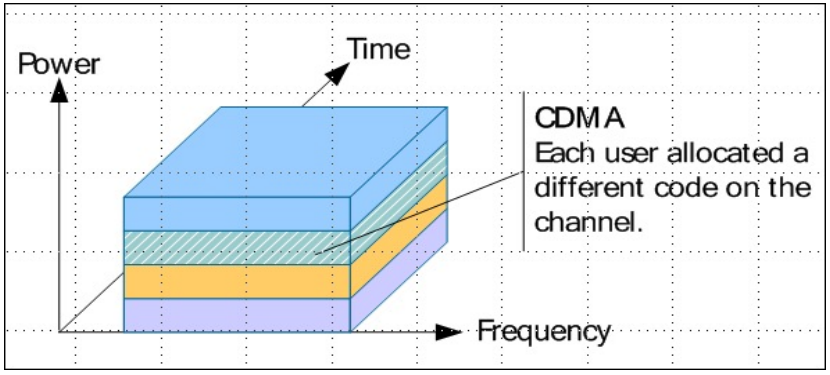
1G/TACS



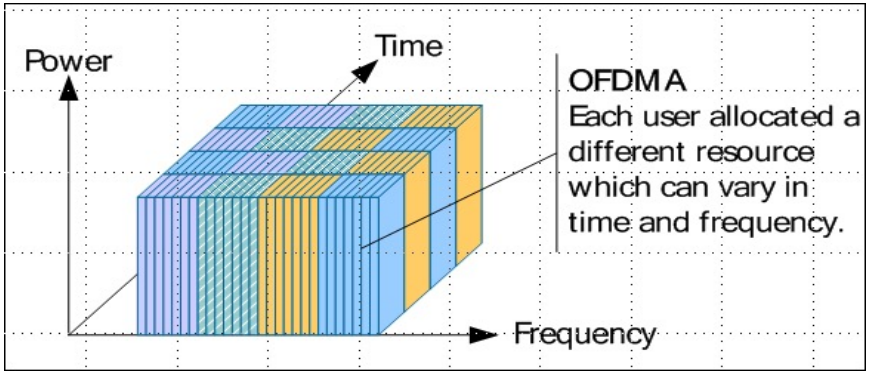
2G/GSM



3G



4G/LTE and Wimax



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Wireless: impact on higher layers

- logically, impact *should* be minimal …
  - best effort service model remains unchanged
  - TCP and UDP can (and do) run over wireless, mobile
- … but performance-wise:
  - packet loss/delay due to bit-errors (discarded packets, delays for link-layer retransmissions), and handoff
  - TCP interprets loss as congestion, will decrease congestion window un-necessarily
  - delay impairments for real-time traffic
  - limited bandwidth of wireless links

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What is MIMO?

- MIMO is an acronym that stands for **Multiple Input Multiple Output**
- Motivation: current wireless systems
  - Capacity constrained networks
  - Increasing interference, limited spectrum
- MIMO exploits the space dimension to improve wireless systems capacity, range and reliability

Wireless Capacity

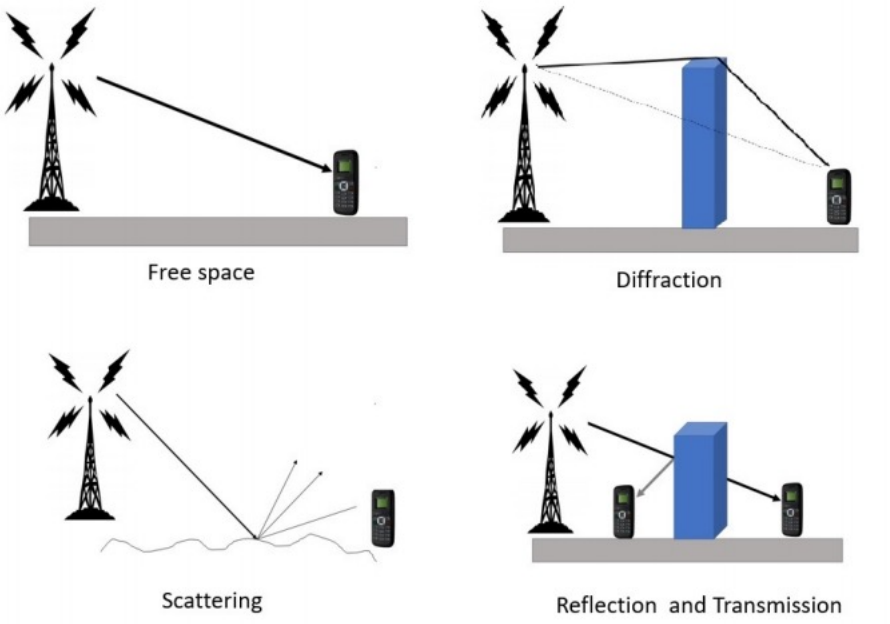
Shannon-Hartley Theorem

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

- C—channel capacity (bps),
- B—channel bandwidth (Hz),
- S—average signal power, and
- N— average noise and interference power.

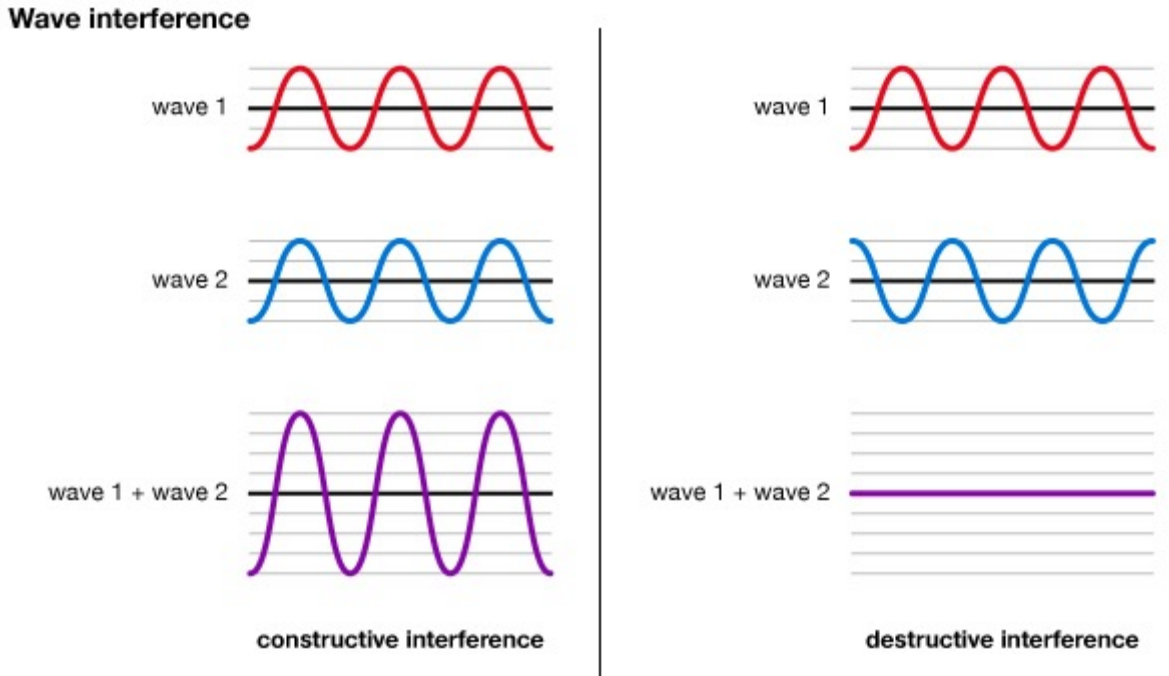
Multipath Interference

- Radio transmitter sends signals in all directions
- Signals bounce off various objects, arrive at destination through many alternate paths
- At object surfaces, reflection, diffraction or scattering can happen
- Different path lengths, net effect of multiple paths



Multipath Interference

- Radio waves at different freq: no interference
- Radio waves at same freq can **interfere,** result:
  - 2 signals enhance each other (constructive)
  - 2 signals cancel out each other (destructive)

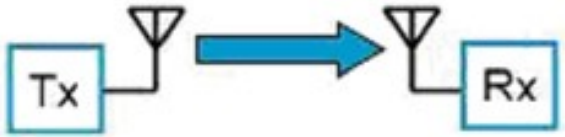


How does MIMO work?

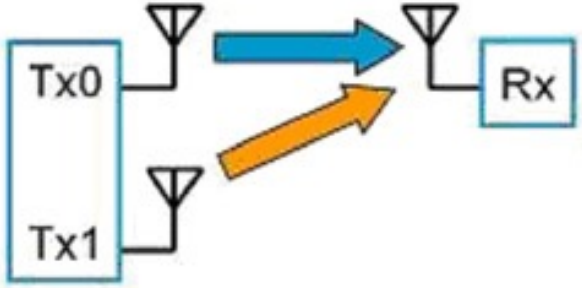
- MIMO takes advantage of multi-path
- MIMO uses multiple antennas to send multiple parallel signals (from transmitter). These parallel signals are intelligently coded
- When there is enough distance between the antennas, different signals experience different paths
- With MIMO, the receiving end uses an algorithm or special signal processing to sort out the multiple signals to produce one signal that has the originally transmitted data

Different types

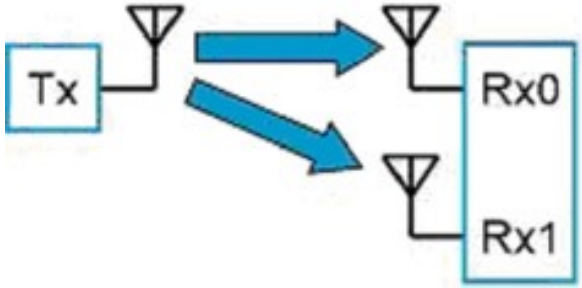
SISO



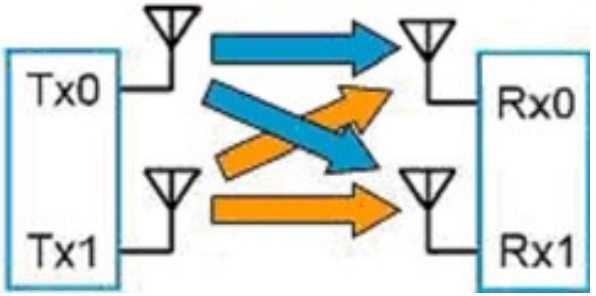
MISO



SIMO



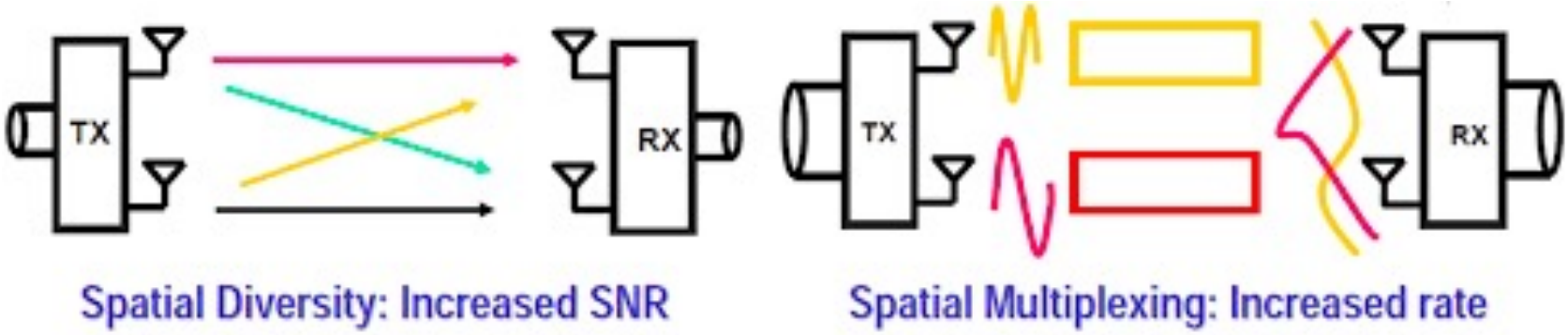
MIMO (2x2)



Main Types of MIMO

- **Space Time Transmit Diversity (STTD)** - The same data is coded and transmitted through different antennas, which effectively doubles the power in the channel. This improves Signal Noise Ratio (SNR) for cell edge performance.

- **Spatial Multiplexing (SM)** - SM delivers parallel streams of data by exploiting multi-path. It can double (2x2 MIMO) or quadruple (4x4) capacity and throughput. SM gives higher capacity when RF conditions are favorable and users are closer to the base station.

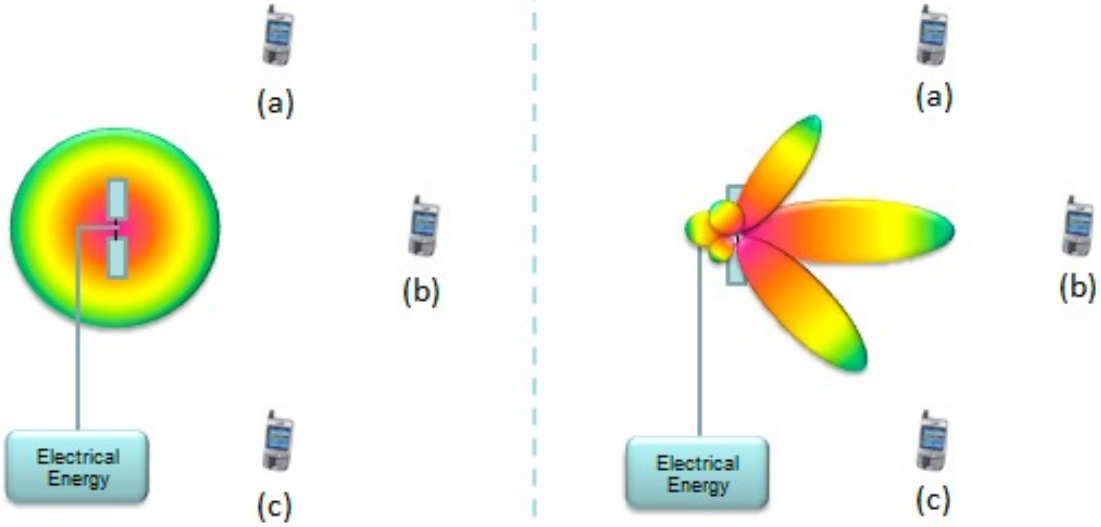


Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- More advanced methods
  - MIMO
  - Beamforming
  - mmWave

Beamforming

- **Beamforming** is a signal processing technique used for directional signal transmission or reception.
- Elements of an antenna array is combined in such a way that signals at particular angles experience constructive interference while others experience destructive interference.



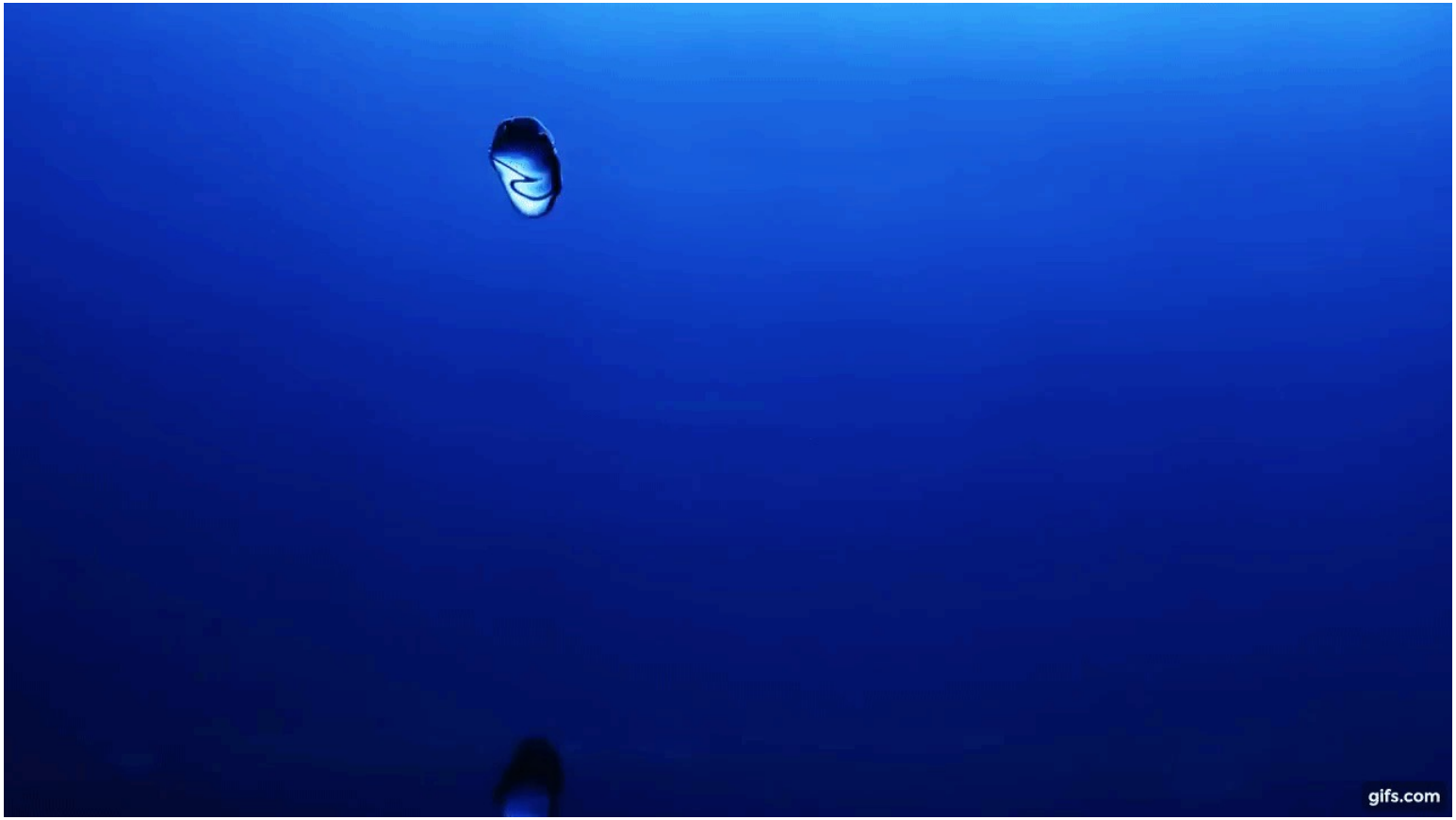
< Case 1 > < Case 2 >

An antenna radiates energy like....

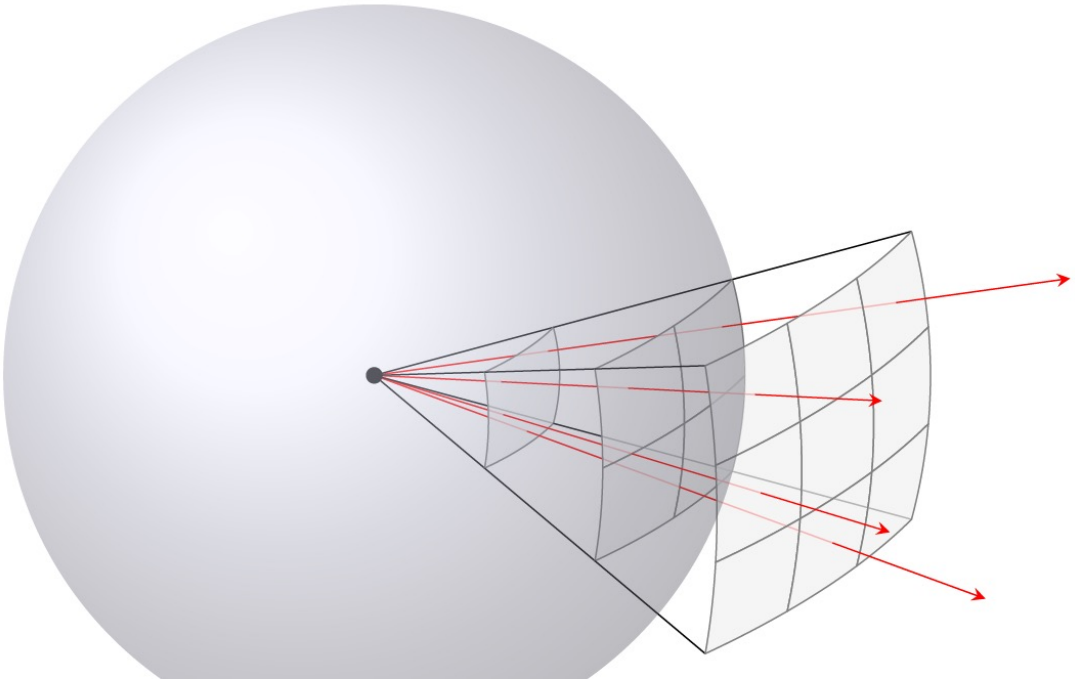


from Mark Hickle https://youtu.be/vtPPAnvJS6c

Forming a beam



Transmit beam and receive strength



All directions

$$P_r \propto \frac{P_{tx}}{4\pi r^2}$$

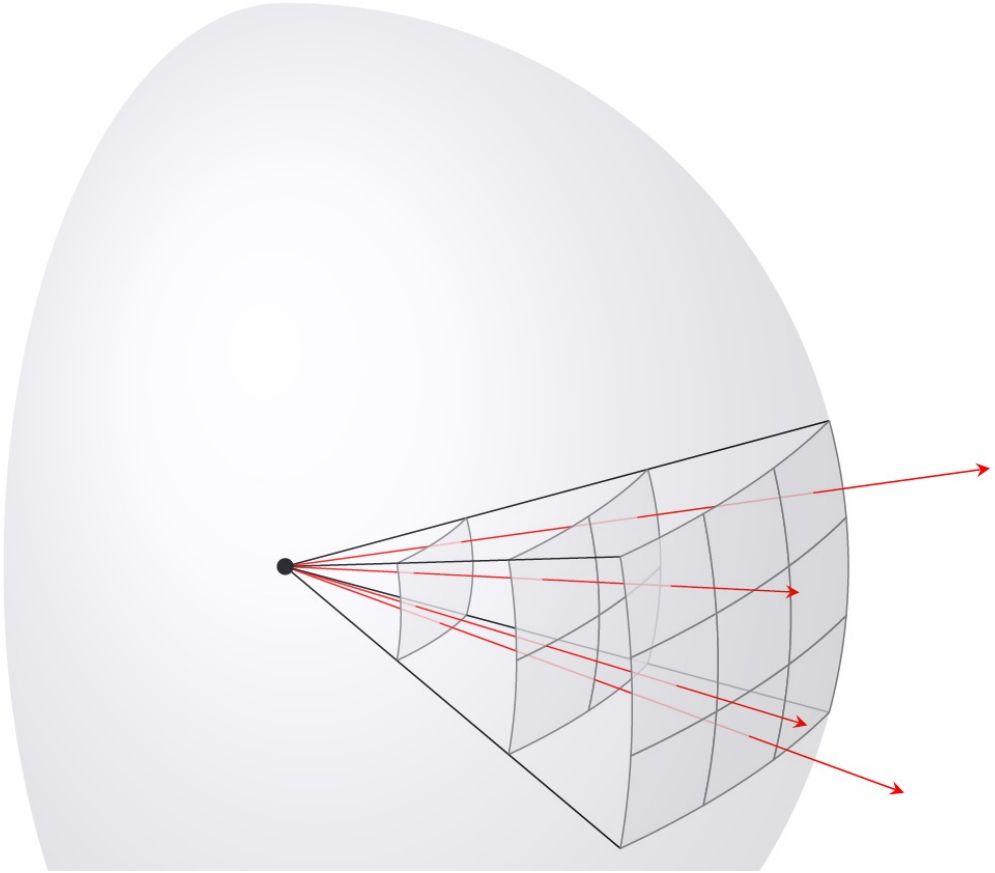
one side

$$P_r \propto \frac{2P_{tx}}{4\pi r^2}$$

2 deg conical beam

$$P_r \propto \frac{1300P_{tx}}{4\pi r^2}$$

Transmit beam and receive strength



All directions

$$P_r \propto \frac{P_{tx}}{4\pi r^2}$$

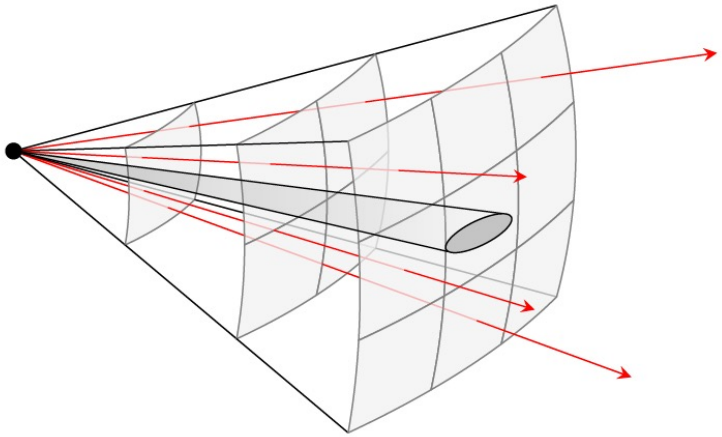
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Transmit beam and receive strength



All directions

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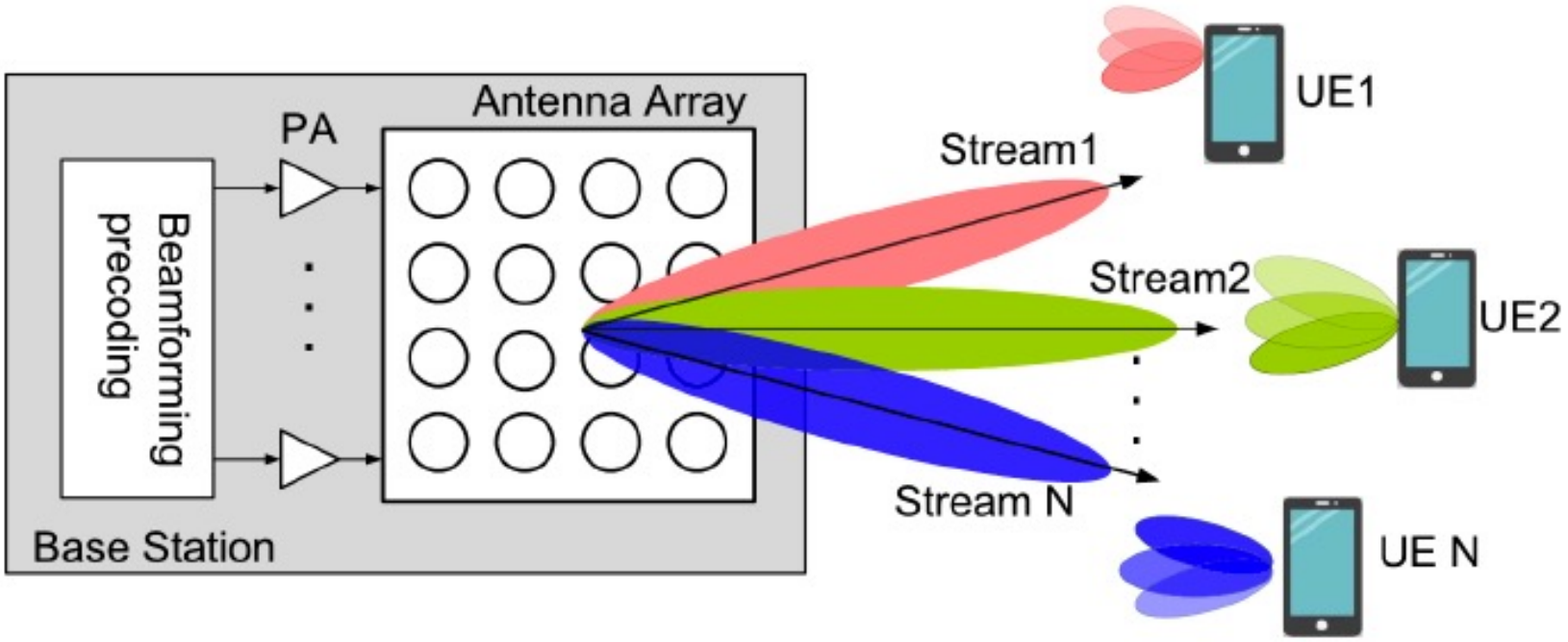
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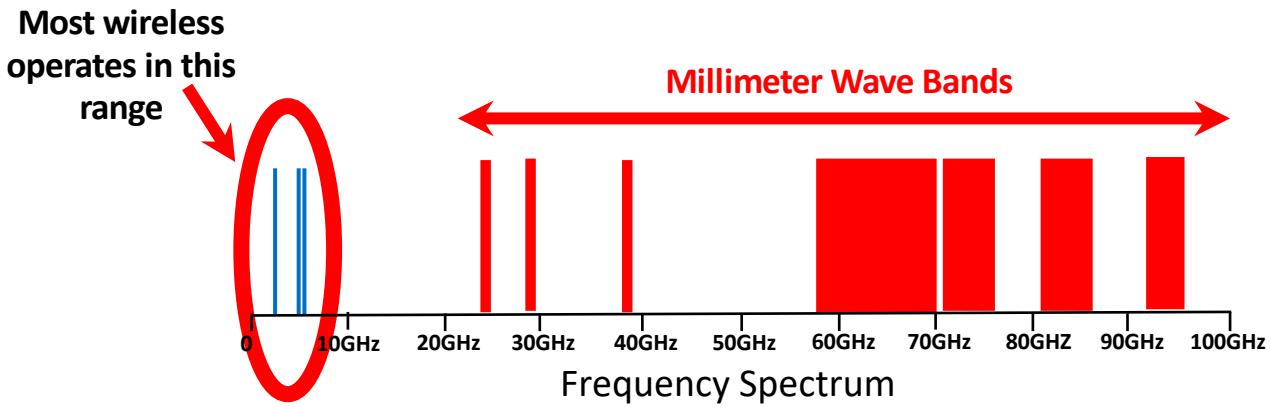
Beamforming and Steering



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What is mmWave?



Why mmWave?

Shannon-Hartley Theorem

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

- C—channel capacity (bps),
- B—channel bandwidth (Hz),
- S—average signal power, and
- N— average noise and interference power.

At higher carrier rates, larger B -> higher rates.

100-1000 times faster than existing wireless networks

How does mmWave work?

mmWave: High attenuation at high frequencies -> very short range



How does mmWave work?

To address high attenuation, beamforming is used!

Challenge: Beam alignment



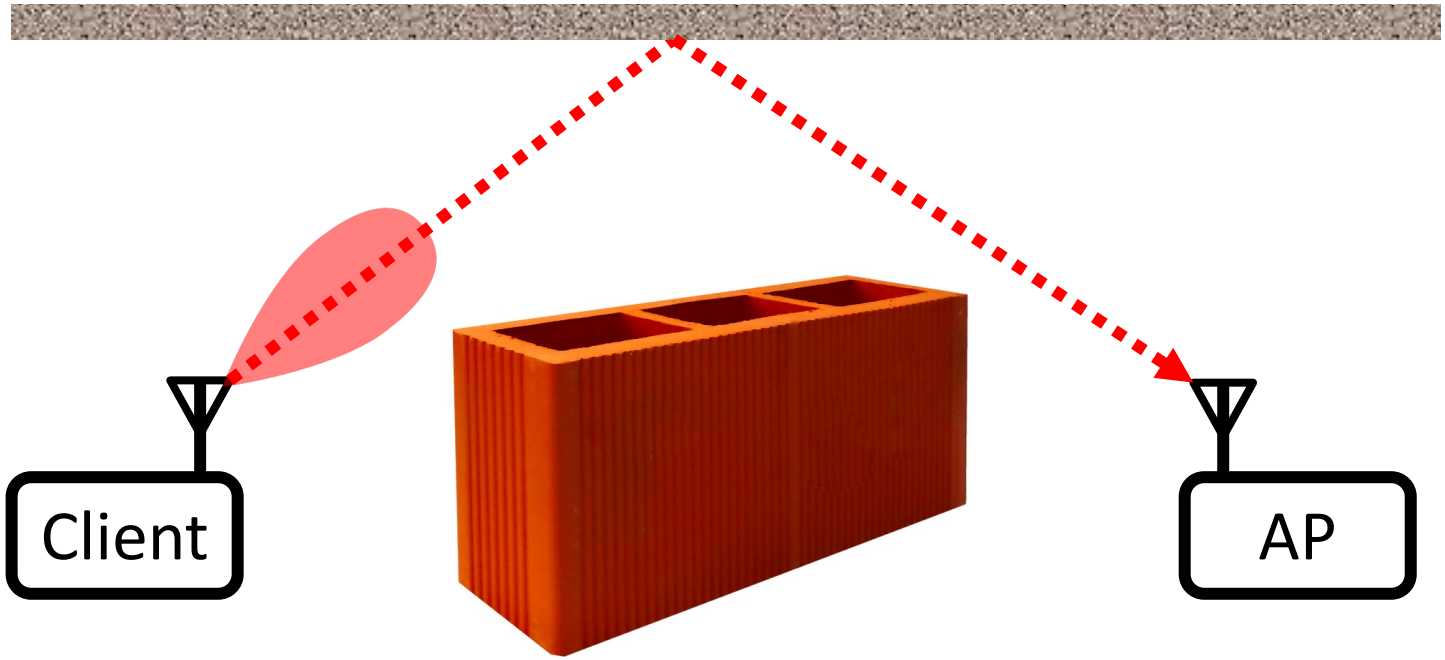
How does mmWave work?

Line of sight exists

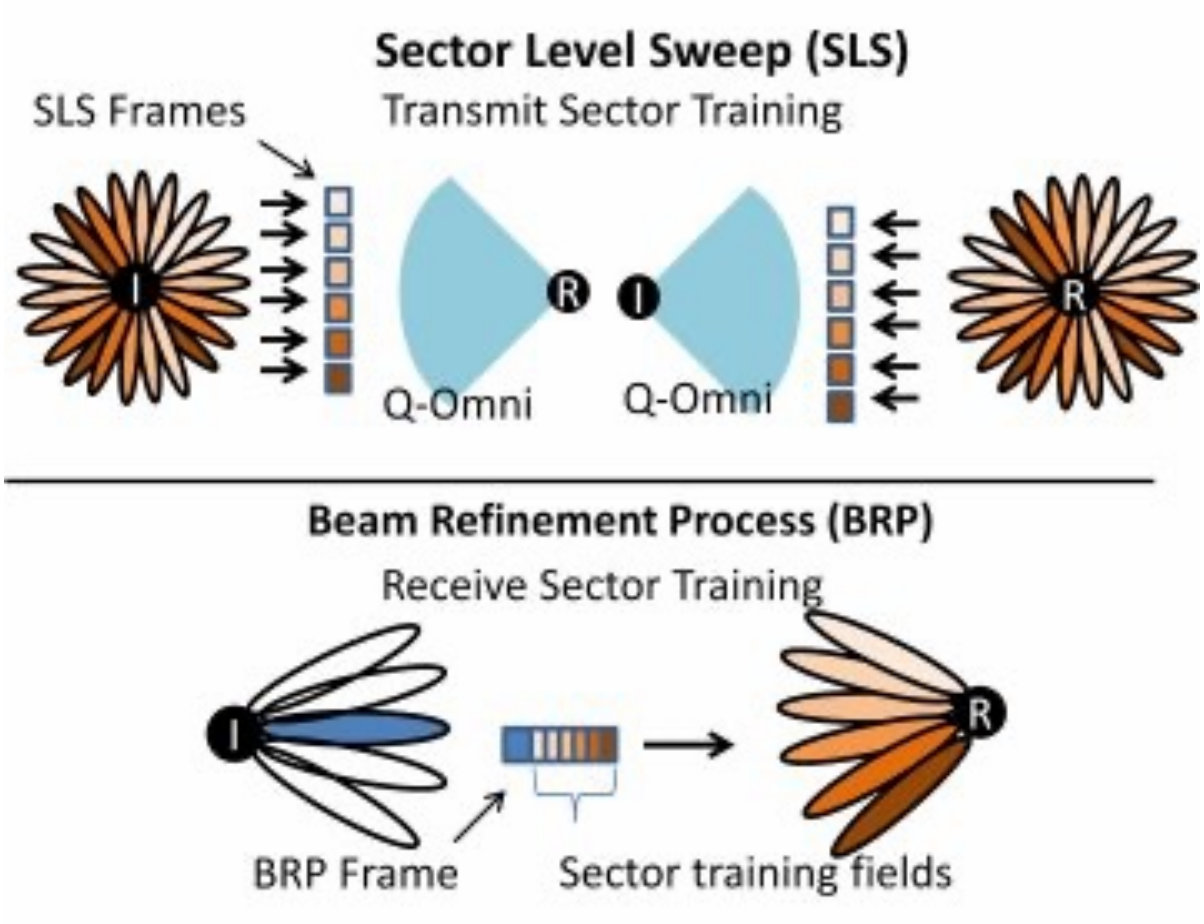


How does mmWave work?

Line of sight blocked



Beamforming Training



Beamforming Training in 802.11ad