Evolution of Telecommunications

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- Objectives revisited.
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Introduction

- Communication is the art (engineering) of conveying information from a source to destination.
- Early methods: smoke signals, drumbeats, lighthouses for sailors, messengers on horses.
- In the 1800s, electricity was used to transmit information e.g. telegraph, telephone.
- In the 1900s, radio and television used as broadcasting media.
- Email, internet services start in 1970s.
- Arrival of mobile (cellular) phones in 1980s.

1G
- Analog, voice
- NTT, Motorola

2G
- Voice, SMS, MMS
- GSM, EDGE-500kbps

3G
- Packet switching, internet
- VoIP-2 Mbps

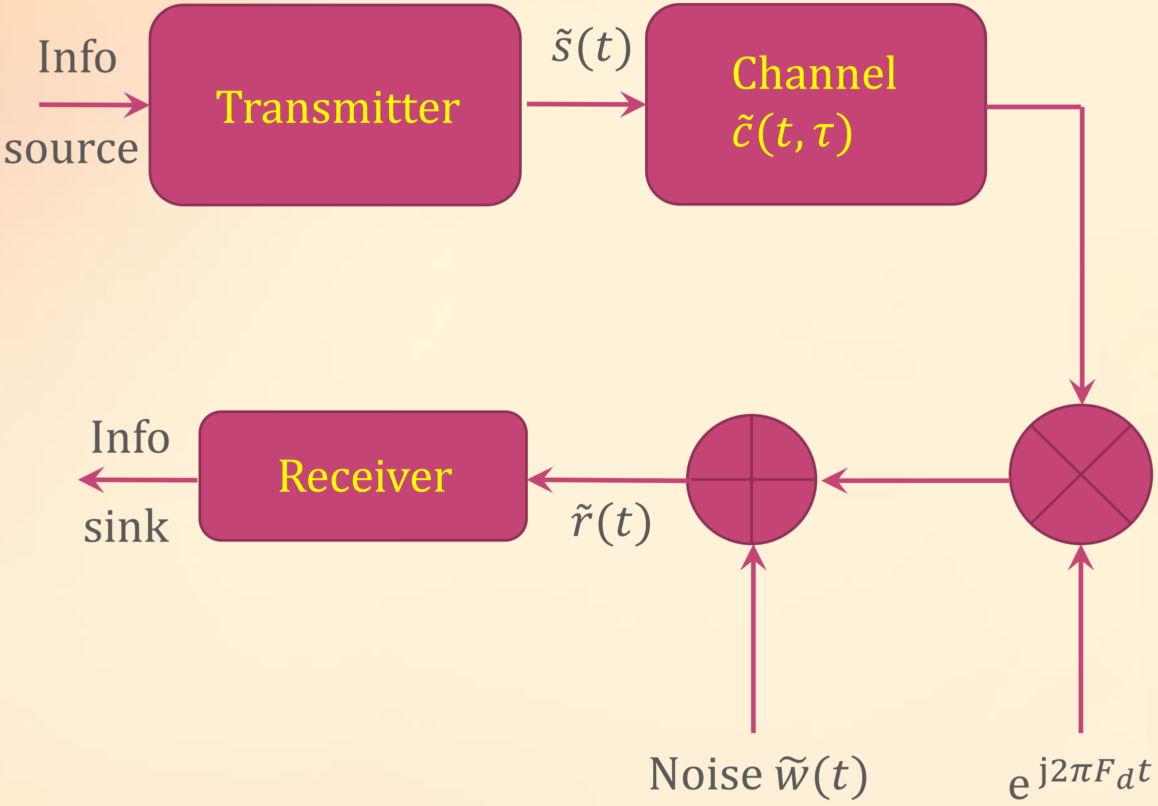
4G
- LTE, video conferencing
- Gaming-1 Gbps

5G
- Internet of things-fridge, TV over WiFi
- HD streaming-10 Gbps

6G
- Internet of senses
- Smell & taste over IP, UHD streaming-100 Gbps

Figure 1

Evolution from 1G to 6G and beyond



Info source

Transmitter

$\tilde{s}(t)$

Channel $\tilde{c}(t,\tau)$

Receiver

Info sink

$\tilde{r}(t)$

Noise $\widetilde{w}(t)$

$e^{j2\pi F_d t}$

Figure 2

Communication system model.

Analog vs Digital Communications

Analog	Digital
Hardwired, less flexible to changes.	Can be implemented in software - easily modified.
Errors cannot be detected and corrected.	Errors can be detected and corrected.
Difficult to encrypt information.	Information can be easily encrypted, for secrecy.
Difficult to “compress” information.	Digital information can be easily compressed - less storage.

A Caveat – The Fine Print

- Hardwired implementations are faster than software implementations.
- Many concepts in digital communications are borrowed from analog.

Analog	Digital Counterpart
FM	CPM
SSB, VSB	FBMC, UFMC, OFDM-OQAM
Amplitude modulation	Pulse amplitude modulation
Pre-emphasis/de-emphasis	Noise whitening
Frequency division multiplexing	Multicarrier communications
Quadrature carrier multiplexing	Quadrature amplitude modulation

Abbreviations

- FM – frequency modulation.
- CPM – continuous phase modulation.
- SSB, VSB – single sideband, vestigial sideband.
- FBMC, UFMC, OFDM-OQAM - filterbank multicarrier, universal filtered multicarrier, orthogonal frequency division multiplexing – offset quadrature amplitude modulation.

Linear Modulation

- If

$$
\begin{aligned}
m_1(t) &\xrightarrow{\text{yields}} s_1(t) \\
m_2(t) &\xrightarrow{\text{yields}} s_2(t) \\
am_1(t) + bm_2(t) &\xrightarrow{\text{yields}} as_1(t) + bs_2(t)
\end{aligned}
$$

where $m_1(t), m_2(t)$ are message signals, $s_1(t), s_2(t)$ are modulated signals, a, b are constants.

Signal Model

- The complex envelope of the received signal can be written as:

$$\tilde{r}(t) = \left(\tilde{s}(t) \star \tilde{c}(t,\tau)\right)\mathrm{e}^{\mathrm{j}\,2\pi F_d t} + \tilde{w}(t) \qquad (1)$$

  - $\tilde{s}(t)$ is the complex envelope of the transmitted signal.
  - $\tilde{c}(t,\tau)$ is the (possibly) time-varying complex envelope of the impulse response of the channel.
  - F_d is the Doppler frequency.
  - $\tilde{w}(t)$ is the complex envelope of additive noise.
- The received signal is (F_c is the carrier frequency)

$$r(t) = \mathrm{Re}\left\{\tilde{r}(t)e^{j2\pi F_c t}\right\} \qquad (1a)$$

Transmitted Signal

- Linear modulation:

$$\tilde{s}(t) = \sum_{k=-\infty}^{\infty} S_k \tilde{p}(t - kT) \qquad (2)$$

- S_k denotes symbols drawn from a 1D/2D/multi-D constellation.
- $\tilde{p}(t)$ denotes the complex valued pulse shaping filter, which determines the bandwidth of the transmitted signal.
- $1/T$ is the symbol-rate (T is the symbol duration).

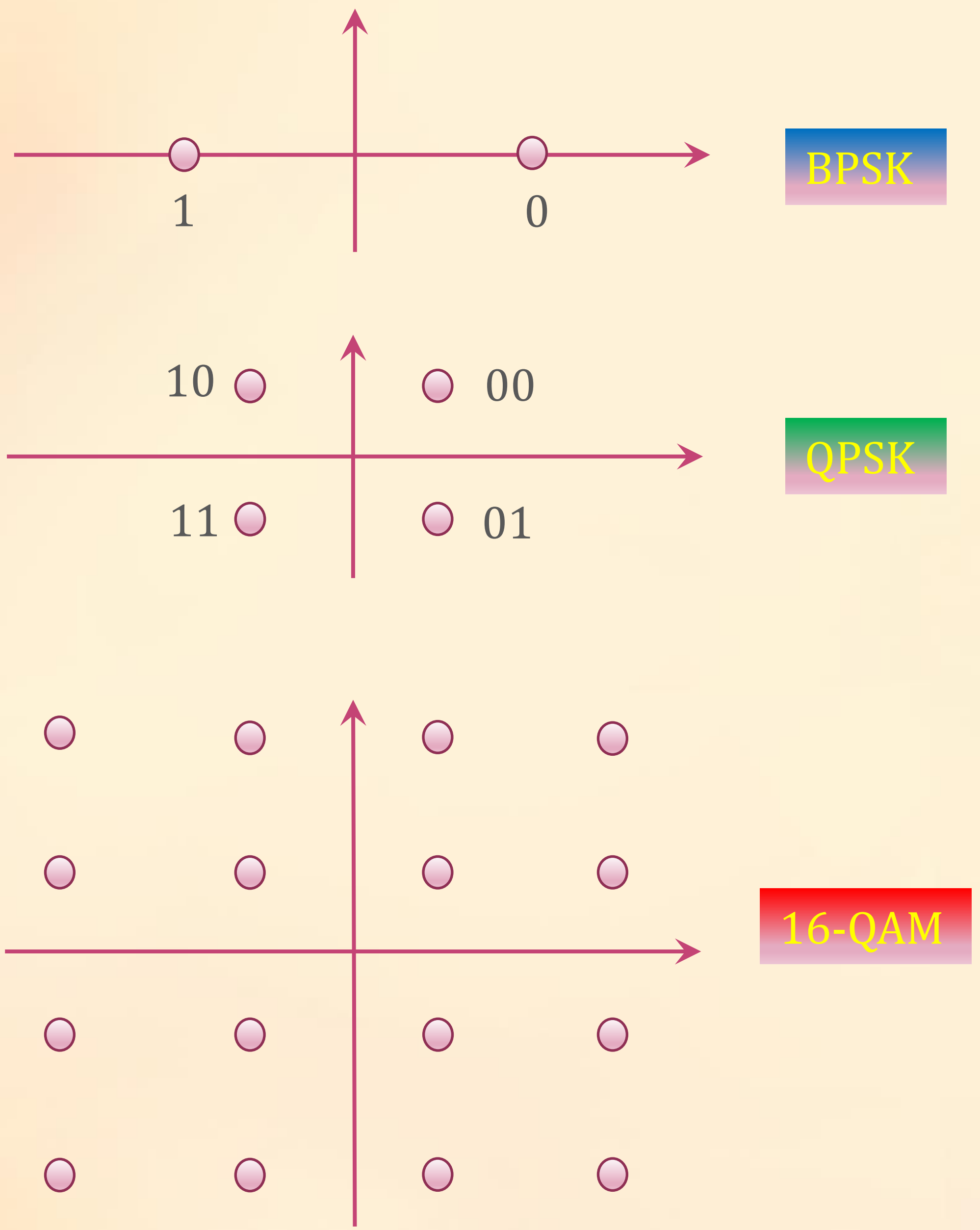


Figure 3

1D/2D symbol constellations.

Quantization: Analog-to-Digital Conversion

- Converts an analog signal to bits – quantizers.
  - Uniform quantizers – sensitive to input signal power.
    - Mid step.
    - Mid rise.
  - Robust quantizers – insensitive to large variations in input signal power.
    - $A -$ law.
    - $\mu -$ law.
  - Optimum (Lloyd-Max) quantizers – designed for signals with specific statistical properties.
  - Quantizers with memory – quantized output depends on the present as well as past inputs e.g. differential pulse code modulation (DPCM).

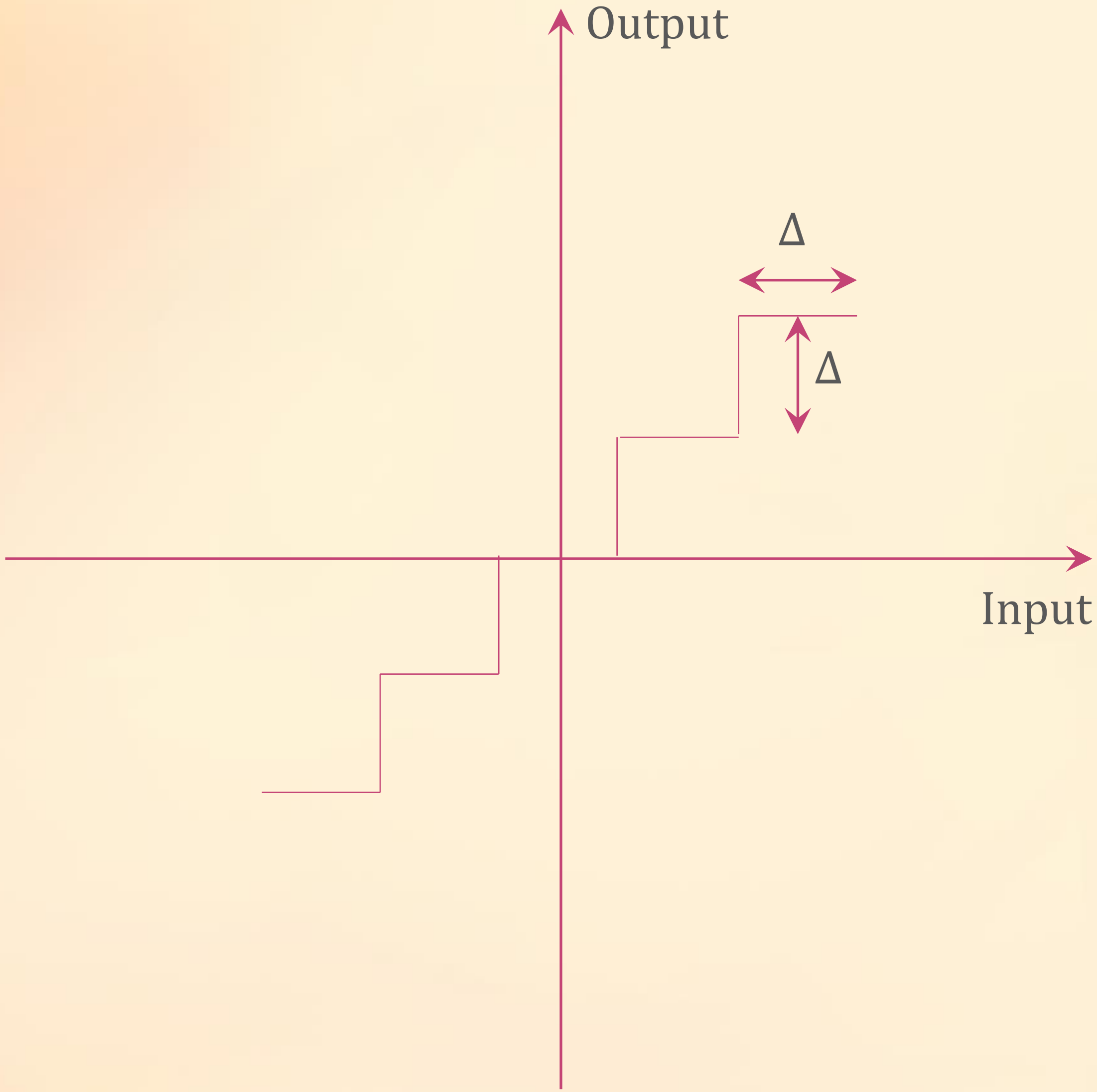


Figure 3a

Mid step quantizer.

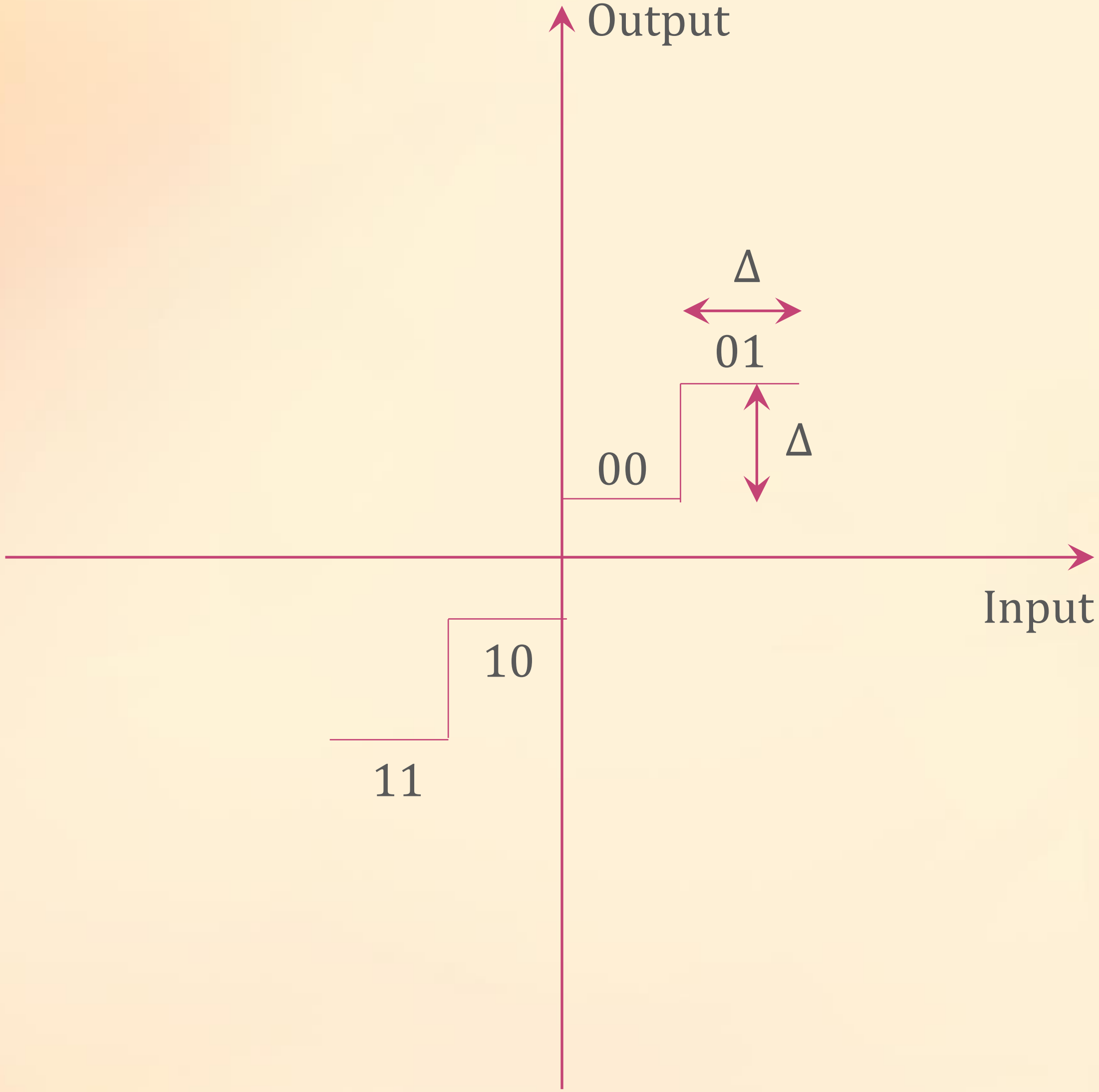
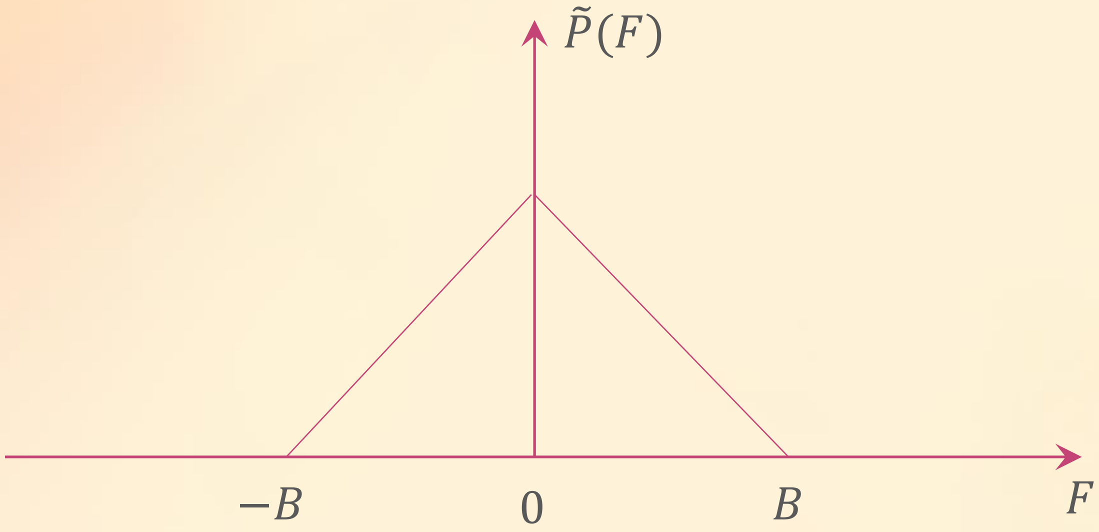


Figure 3b

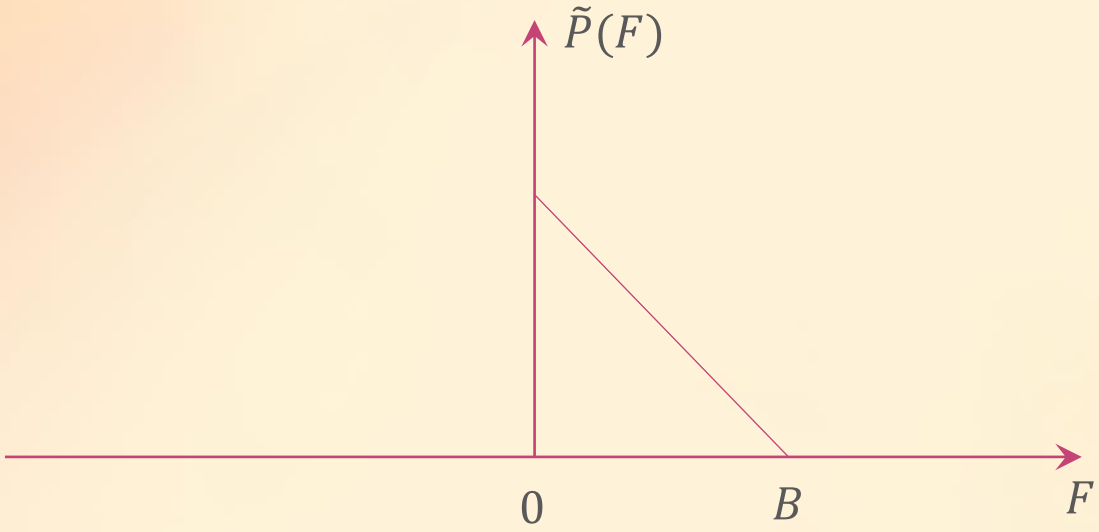
Mid rise quantizer.



$\tilde{P}(F)$ is the Fourier transform of $\tilde{p}(t)$

Figure 4

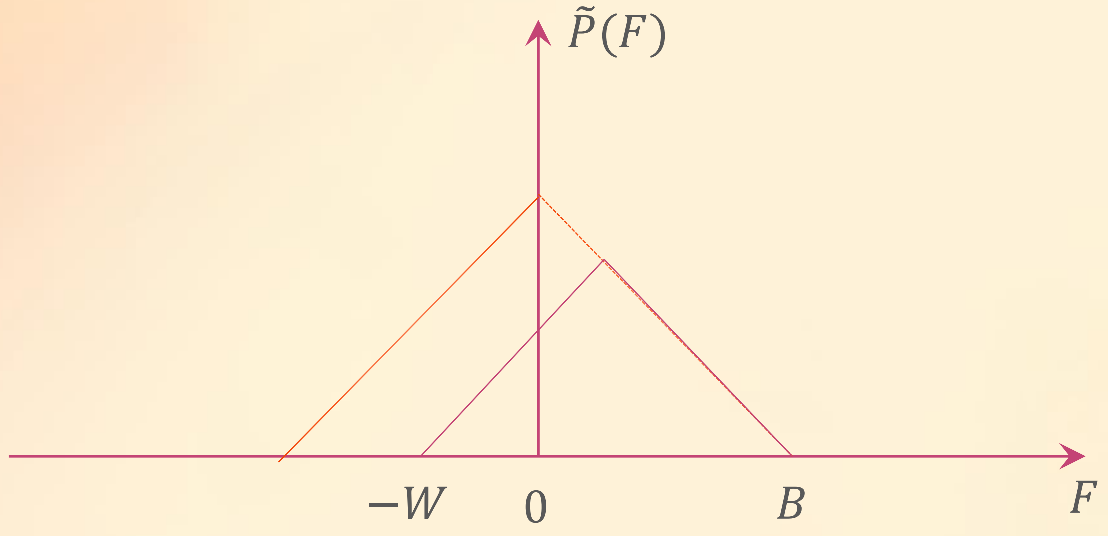
Double sideband suppressed carrier type modulation.



$\tilde{P}(F)$ is the Fourier transform of $\tilde{p}(t)$

Figure 5

Single sideband type modulation. Saves bandwidth. Used in filter bank multicarrier (FBMC), universal filtered multicarrier (UFMC) in 5G and beyond.



$\tilde{P}(F)$ is the Fourier transform of $\tilde{p}(t)$

Figure 6

Vestigial sideband type modulation. Saves bandwidth. Used in filter bank multicarrier (FBMC), universal filtered multicarrier (UFMC) in 5G and beyond.

Figure 7

Doppler frequency

- Due to relative motion between transmitter & receiver.
- $F_d = F_c \frac{v}{c}$.
  - F_c is the carrier frequency.
  - v is the relative velocity between tx and rx along line-of-sight.
  - c is the speed of light.

Communications between aircraft and air traffic control.

Channel

- Distorting vs distortionless.
- Time invariant vs fading.
- Four channel types:
    - Distortionless time invariant e.g. multicarrier communications
    - Distortionless fading (flat fading).
    - Distorting time invariant e.g. telephone lines.
    - Distorting fading (doubly dispersive or frequency selective fading).

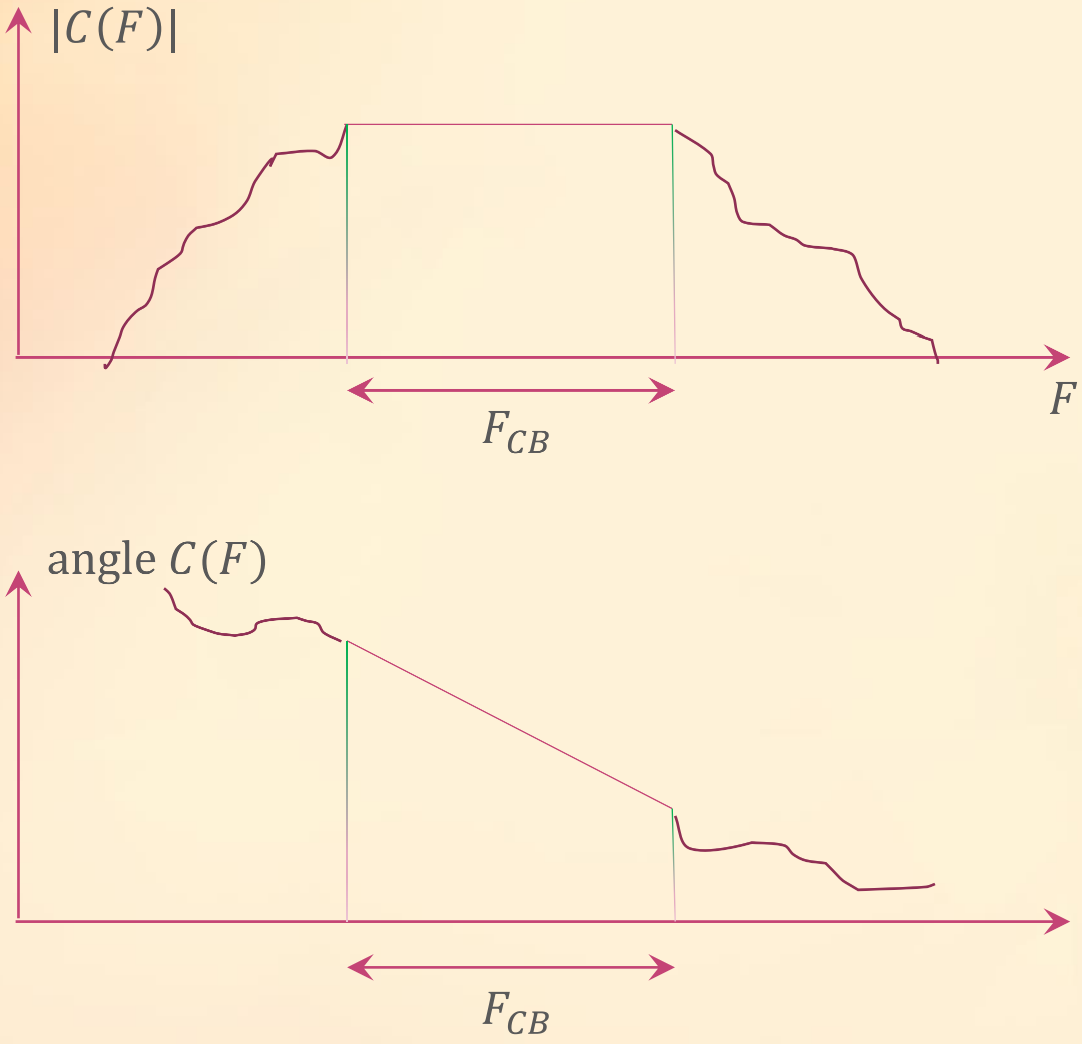


Figure 8

Channel coherence bandwidth F_{CB}. Magnitude response of the channel is constant and phase response is linear over the bandwidth of the transmitted signal. $C(F)$ is the Fourier transform of the time invariant channel $c(t)$.

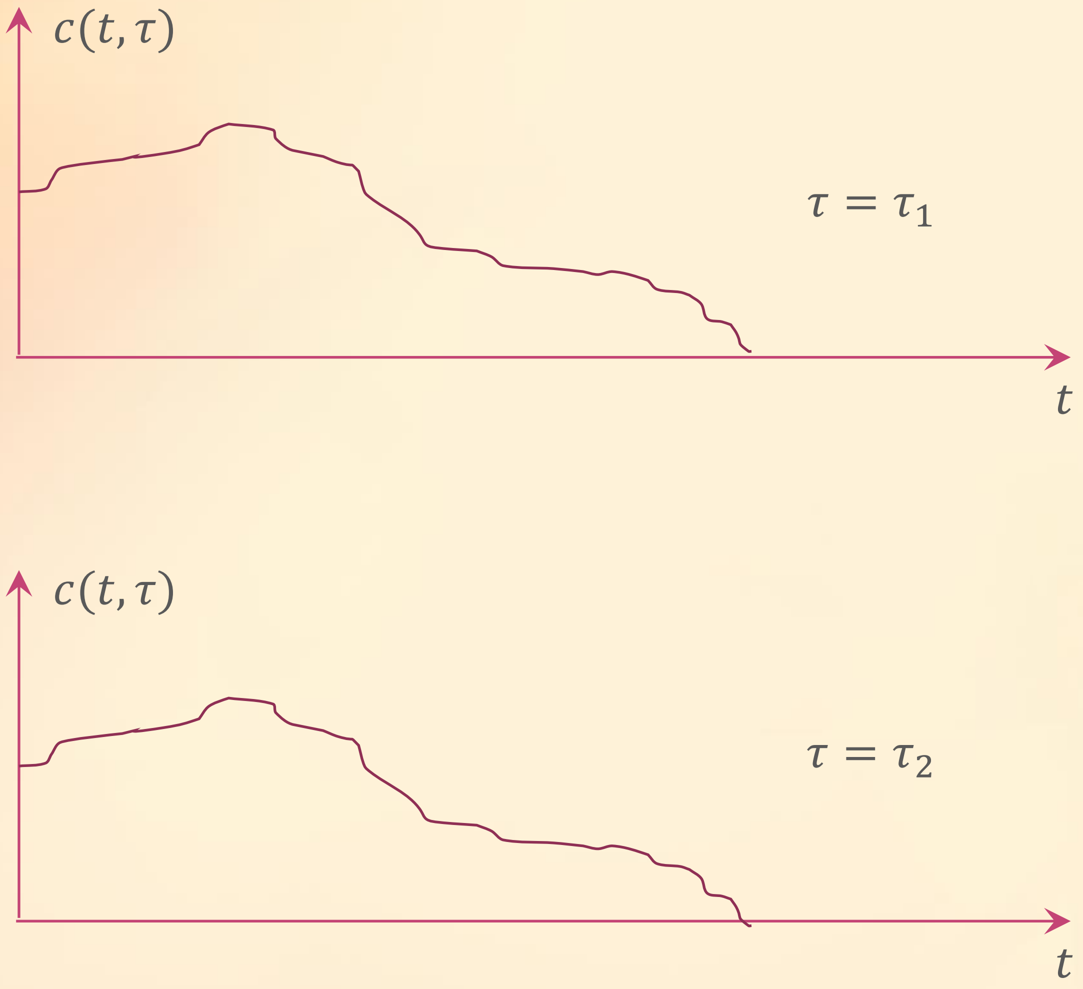


Figure 9

Channel coherence time $T_{CT} = \tau_2 - \tau_1$. Impulse response of the channel is invariant over T_{CT}.

Doppler Spread

- A time varying channel introduces Doppler spread.
- Let the transmitted signal be given by:

$$s(t) = A\cos(2\pi F_c t).$$

  - It has zero bandwidth.
- The received noise-free signal is:

$$r(t) = B(t)\cos(2\pi F_c t + \theta)$$

  - Similar to DSB-SC.
  - Has finite bandwidth – which is the Doppler spread.

Receiver

- For distortionless time invariant channel – matched filter receiver.
- For distorting time invariant channel:
    - Equalizer: low complexity, suboptimal error rate performance.
        - Linear: symbol-spaced, fractionally spaced.
        - Non-linear: decision feedback.
    - Maximum likelihood sequence estimation: complexity increases exponentially with channel memory.
    - Multicarrier communication: split up a wideband distorting channel into a large number of narrowband distortionless subchannels. Use matched filter receiver for each subchannel.
- Fading channels: exploit the coherence time of the channel e.g. OFDM.

Nonlinear Modulation

- The transmitted signal is given by

$$s(t) = A\cos(2\pi F_c t + \theta(t))$$

  - Frequency modulation: $\theta(t) = 2\pi k_f \int_{-\infty}^{t} m(\tau)\, d\tau$ where k_f is the frequency sensitivity.
  - Phase modulation: $\theta(t) = 2\pi k_p m(t)$ where k_p is the phase sensitivity.
- Transmitted signal has constant envelope: suitable for nonlinear amplification.
- Channel needs to be distortionless.
- Receiver:
  - Frequency discriminator.
  - Phase locked loop (PLL).

Objectives of Digital Communications

- Maximize the bit rate.
- Minimize the bit error rate – turbo, low density parity check codes.
- Minimize the transmission bandwidth – SSB, VSB type transmission.
- Minimize the transmit power – constellation shaping (shell mapping) – operate close to the minimum E_b/N_0 for error-free transmission.
- Ensure mobility:
  - Wireless communications – 5G and beyond.
  - Multiple input multiple output (MIMO) systems – spatial multiplexing, diversity, beamforming.

Objectives Revisited

- Spatial multiplexing – the process of transmitting independent signals through a large number of transmit antennas to increase the spectral efficiency – massive MIMO.
- Diversity – signals in all receive antennas do not simultaneously undergo deep fade.
- Beamforming – the process of transmitting the same signal (with delay) through a large number of transmit antennas to increase the received signal power, like a convex lens – massive MIMO
  - Spatial multiplexing and beamforming are conflicting operations.

Massive MIMO

- Multiuser massive MIMO
  - Base station has a large number of antennas, user has only one antenna.
  - Beamforming can be used in the downlink.
  - Spatial multiplexing cannot be used.
  - Low spectral efficiency.
- Single user massive MIMO
  - Both base station and user have a large number of antennas – possible in mmwave frequencies ($F_c > 100$ GHz) due to the small antenna size.
  - Beamforming & spatial multiplexing can be used in both uplink & downlink.
  - High spectral efficiency.

The Way Forward

- Quantum communications
  - Quantum teleportation.
- Quantum computing
  - Ability to perform large number of operations in parallel.