# ELG5375: Digital Communications

## Lecture 2: Introduction

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January 9, 2026

# What is a communication system?

- Any means for transmission of information (in space and time).
- Types of electronic communication systems:
  - wireline & wireless (RF)
  - digital & analog
  - point-to-point & broadcasting
  - single-user/multi-user (networks)
  - low /high/very high frequency

# What is a communication system?

- Examples:
  - cell phone, WiFi
  - Internet
  - optical fiber systems
  - TV, radio broadcast
  - GPS
  - remote control, wireless key, bluetooth
  - hard disk, USB memory stick, CD/DVD
- Active current R&D: 5/6G, optical, quantum

# Historical Review (milestones)

- 1807-1822: Fourier discovers Fourier Series/Transform
- 1833: Morse invents telegraph (operational in 1844).
- 1876: Bell invents telephone (Bell Telephone Company in 1877).
- 1895-96: A. Popov & G. Marconi invent radio (wireless)
- 1901: Marconi performs 1st transcontinental wireless transmission
- 1904(06): Fleming & De Foster invent vacuum diode & triode
- 1915: transcontinental telephone transmission (operational)
- 1918: Armstrong invents superheterodyne receiver (during WWI)
- 1920: 1st AM broadcast

# Historical Review

- 1924: Nyquist discovers zero-ISI criterion (for telegraph transmission)
- 1929: Zworykin invents TV (broadcasting in London, 1936)
- 1933: Armstrong invents FM communication system
- 1933: Kotelnikov discovers the sampling theorem
- 1945: 1st digital computer ENIAC built at the University of Penn.
- 1945: von Neumann invents modern computer architecture
- 1947: Brattain, Bardeen & Shockley invent transistor
- 1948: Shannon discovers information theory
- 1953: transatlantic cable/telephone service (Europe–USA)
- 1957: 1st Earth satellite is launched by USSR

# Historical Review

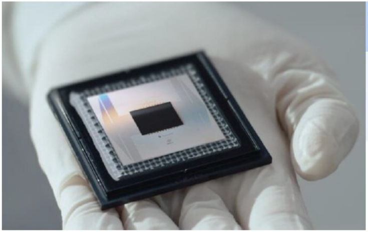
- 1958: Kilby invents IC
- 1965: 1st commercial communication satellite
- 1971: single-chip microprocessor by Intel
- 1973: 1st cell phone call (by Martin Cooper of Motorola to his rival at AT&T; the phone weighted 1kg and cost approximately $4000)
- 1976: Apple launches PC.
- 1981: IBM launches PC.
- 1984: Apple launches Macintosh (paved the way for modern PC).

# Historical Review

- 1990s: launch of Internet.
- 2000s: launch of WiFi
- 2007: launch of iPhone
- 2010: launch of iPad
- 1998-2008: Google, Youtube, Facebook, Twitter, etc.
- ChatGPT (?)
- quantum computers (IBM, Google, Amazon, etc.)
- quantum communications

# Historical Review: Quantum Computers

- Google's quantum chip 'Willow' (Dec. 2024): $10^{30}$ faster than the fastest supercomputer



| Willow System Metrics | |
|---|---|
| Number of qubits | 105 |
| Estimated time on Willow vs classical supercomputer | 5 minutes vs. $10^{25}$ years |

- *"…Willow performed a standard benchmark computation in under five minutes that would take one of today's fastest supercomputers 10 septillion (that is, $10^{25}$) years — a number that vastly exceeds the age of the Universe."* H. Neven, Founder and Lead, Google Quantum AI.

# Block Diagram of a Communication System

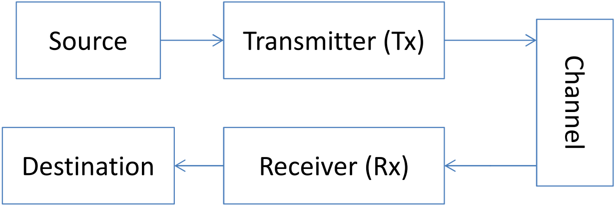



Figure: A high-level view of a communication system

# Block Diagram of a Communication System

- **Source**: a source of information (e.g. voice, data file, YouTube video)
- **Tx**: a transmitter
- **Channel**: a path (link) from the Tx to the Rx (e.g. cable, wireless medium, etc.)
- **Rx**: a receiver
- **Destination**: a location where the information has to be delivered/consumed

# A Wireless Communication System[1][2]

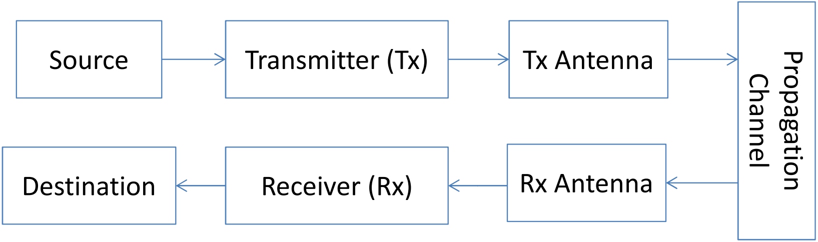



Figure: Block diagram of a wireless communication system

[1] T.S. Rappaport, Wireless Communications: Principles and Practice, Cambridge University Press, 2024

[2] D. Tse, P. Viswanath, Fundamentals of Wireless Communications, Cambridge University Press, 2005

# A Digital Communication System

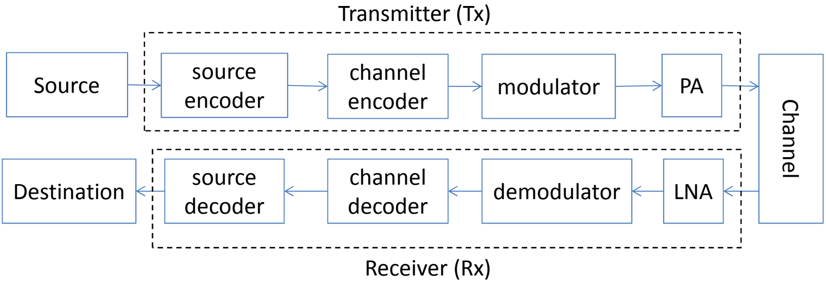
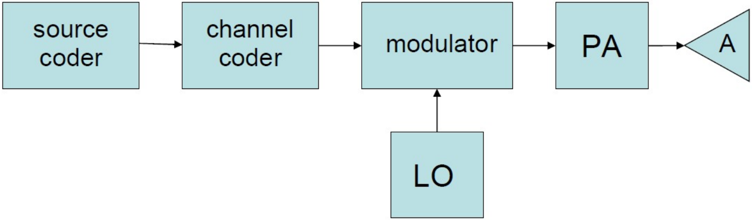



Figure: A high-level view of a digital communication system

# Transmitter

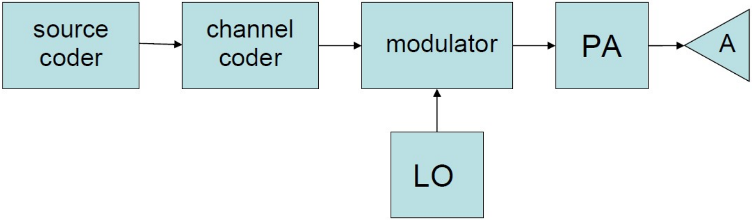
- Converts source signal into a form suitable for transmission through the channel (physical medium)
- This is needed because the source signal cannot be transmitted directly (doesn't match the channel)
- Conversion is made through source/channel coding and modulation
- Other functions: filtering, amplification, radiation (if wireless)

# Transmitter (RF/wireless/bandpass)




- **Source encoder**: encodes the message to remove redundancy
- **Channel encoder**: encodes the input to protect against errors introduced by the channel
- **Local oscillator (LO)**: generates the carrier (if bandpass/RF)
- **Modulator:** performs baseband and bandpass (carrier) modulation using the encoded message

# Transmitter (RF/wireless/bandpass)

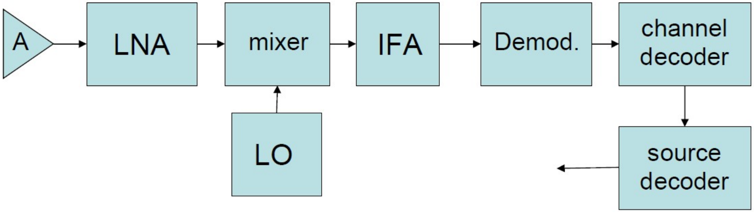



- **Power amplifier (PA):** amplifies the modulated signal to required power level
- **Antenna (A):** radiates the modulated signal as an electromagnetic wave (if RF/wireless)

# Receiver (Rx)

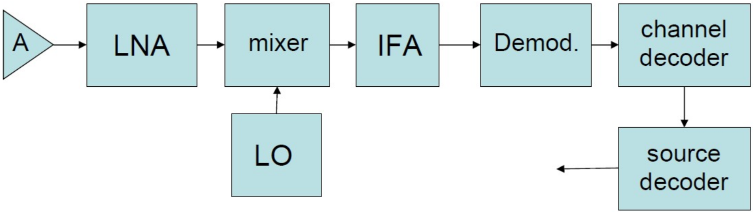
- Main function: to recover the message from the received signal
- Somewhat inverse of the transmitter function
- Demodulation: inverse of the modulation
- Operates in the presence of noise & interference. Hence, some distortions/errors are unavoidable.
- Other functions: filtering, suppression of noise & interference

# Receiver (RF/wireless/bandpass)




- **Antenna (A):** receives an incoming electromagnetic wave carrying the message, transforms it into voltage/current signal
- **Low-noise amplifier (LNA):** amplifies a weak RF signal coming out of the antenna. Rejects the image frequency. Bandwidth: much wider than the signal bandwidth.
- **Mixer:** down-converts the RF signal to intermediate frequency (IF)
- **Local oscillator (LO)**: generates the carrier

# Receiver (RF/wireless/bandpass)




- **IF amplifier (IFA):** amplifies the IF signal significantly, rejects adjacent channel signals and interference (frequency selectivity). Its bandwidth is the same as the signal bandwidth.
- **Demodulator:** demodulates the modulated signal
- **Channel decoder**: decodes the channel code
- **Source decoder**: decodes the source-encoded message

# Channel

- The physical medium between the transmitter and the receiver. Can be wired (cable) or wireless (RF/radio)
- Wireless channel is almost completely out of designer's control
- Corrupts signal by noise and interference (e.g., thermal noise, lightning discharge, automobile ignition noise, interference from other users & frequency re-use in cellular and WiFi)
- Can be highly non-stationary (time-varying, e.g. fading)
- Significant signal attenuation (100-200 dB)
- Other types of signal distortions, e.g., spectrum distortion, inter-symbol interference

# Wireline Channels

**Types (bandwidth):**

- twisted-wire pair (10s kHz to 30 MHz)
- coaxial cable (10s GHz)
- waveguides (100s GHz)
- optical fiber (10-100 THz)

Signals are distorted in amplitude and phase. Some measures are required to reduce the effect of distortions.

# Wireless (RF/optical) Channels

- Unguided electromagnetic wave (radiated by the Tx antenna) is a carrier of the signal
- Strong signal attenuation (up to 100-200 dB). Hence, high Tx power or/and directional (multiple) antennas are required
- Susceptible to external interference
- Antennas are required. Size of antenna: comparable with wavelength, or much larger (for high directivity)

# Typical Carrier Frequencies

- Cell phone: 1-2 GHz
- Cordless phone: 43–50 MHz, 900 MHz, 2.4 and 5.8 GHz.
- Cable phone: 300–3400 Hz
- WiFi: 2.5, 5 GHz
- VDSL-2 (Internet over phone cable): 30 kHz–30MHz
- TV (satellite): 10–12 GHz
- TV (cable/broadcast): 50–950 MHz
- AM broadcast: 300kHz–1.5 MHz
- FM broadcast: 80–110 MHz
- Optical: 100s THz

# A Wireless Communication System

Major challenges, due to the wireless propagation channel

- out of designer's control
- low SNR (large path loss, 100s dB)
- multipath propagation → fading
  - frequency selectivity (delay spread)
  - time selectivity/variability (Doppler spread)
  - inaccurate/unavaiable channel state information
- interference
- limited/expensive bandwidth

How to combat? → current research activities (5/6G etc.)

# Mathematical Model of Channel

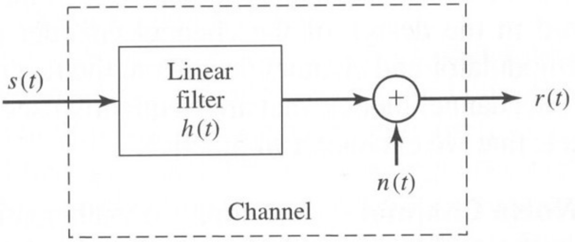



Figure: Channel as a linear time-invariant (LTI) system[3]

$$r(t) = s(t) * h(t) + n(t) \quad (1)$$

$$= \int_{-\infty}^{+\infty} h(\tau)s(t-\tau)d\tau + n(t) \quad (2)$$

[3] J.Proakis, M.Salehi, Communications Systems Engineering, Prentice Hall, 2002.

# Digital Communications: Key Performance Metrics

- transmission rate, [bit/s], or
- spectral efficiency, [bit/s/Hz]
- bandwidth, [Hz]
- energy efficiency, [J/bit]
- error rate/probability, BER/SER
- fading: outage probability

# Digital Communications: fundamental limits

- from information theory[4]
- single user: channel capacity: [bit/s] or [bit/ch. use]
- fading: outage capacity
- benchmark for actual system performance
- optimal system design (Tx, Rx)
- much less is known about networks

[4] T.M. Cover, J.A. Thomas, Elements of Information Theory, John Wiley & Sons, 2006.

# Digital Communications: channel model

- AWGN channel (discrete-time)

$$y_k = x_k + \xi_k \tag{3}$$

  - $x_k$ = Tx signal
  - $y_k$ = Rx signal
  - $\xi_k$ = noise (i.i.d. Gaussian)

# Fundamental Limit: Channel Capacity

- largest transmission rate s.t. power & reliability constraints

$$R < C = \Delta f \log(1+\gamma) \text{ [bit/s]} \tag{4}$$

  - $\Delta f$ = channel bandwidth
  - $\gamma = P_x / P_\xi$ = SNR
  - power constraint: $\sigma_x^2 \leq P_x$
  - relaibility constraint: arbitrary-low error probability

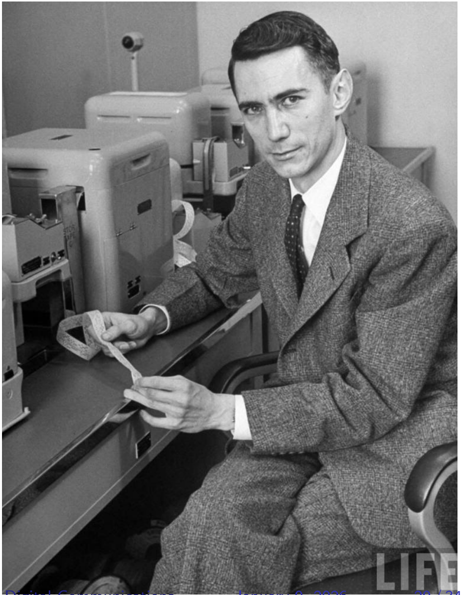
- equivalently, spectral efficiency:

$$C = \log(1+\gamma) \text{ [bit/s/Hz]} \tag{5}$$

# Fundamental Limit: Channel Capacity

Claude Shannon, Farther of Information Theory:

Apr. 30, 1916 (Petoskey, Michigan, US) - Feb. 24, 2001 (Medford, Massachusetts, US).



# Progress Towards the Capacity[5]

## Progress toward the Shannon limit

***The original turbo codes:*** about **0.7 dB** from capacity

**C. Berrou, A. Glavieux, and P. Thitimajshima**, Near Shannon limit error-correcting coding and decoding: Turbo codes, *IEEE Int. Communications Conference*, 1993.

***Irregular LDPC codes:*** about **0.1 dB** from capacity

**T.J. Richardson and R. Urbanke**, The capacity of low-density parity-check codes, *IEEE Transactions on Information Theory*, February 2001.

**How about 0.01 dB from capacity? And 0.001 dB?**

**J. Boutros, G. Caire, E. Viterbo, H. Sawaya, and S. Vialle**, Turbo code at 0.03 dB from capacity limit, *IEEE Symp. Inform. Theory*, July 2002.

**S-Y. Chung, G.D. Forney, Jr., T.J. Richardson, and R. Urbanke**, On the design of low-density parity-check codes within 0.0045 dB of the Shannon limit, *IEEE Communications Letters*, February 2001.

***Conclusion: For all practical purposes, Shannon's puzzle has been now solved and Shannon's promise has been achieved!***

[5] A.Vardy, What's New and Exciting in Algebraic and Combinatorial Coding Theory? Plenary Talk at ISIT-06.

# Channel Capacity: two fundamental resources

From the capacity expression,

$$C = \Delta f \log(1 + \gamma) \text{ [bit/s]} \tag{6}$$

$C$ can be increased by increasing

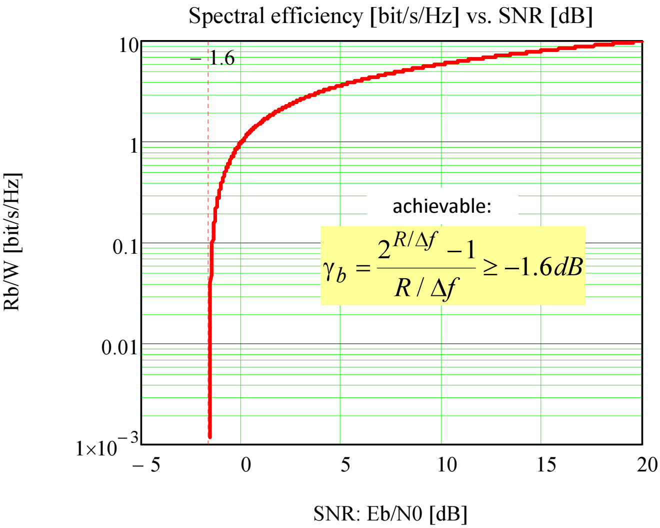
1. bandwidth $\Delta f$ (expensive in wireless)
2. power $P_x$, via the SNR $\gamma = P_x / P_\xi$
3. anything else?

# Spectral/Power Efficiency: Fundamental Tradeoff

- power efficiency: $\gamma_b = \text{SNR(energy)/bit}$
- spectral efficiency: $R/\Delta f$ [bit/s/Hz]
- the tradeoff:

$$\gamma_b \geq \frac{2^{R/\Delta f} - 1}{R/\Delta f} \geq \ln 2 = \text{-1.6 dB} \tag{7}$$

# Spectral/Power Efficiency: Fundamental Tradeoff



# Summary

- introduction to communication systems
- historical review
- types of systems
- block diagrams, main blocks, their functions
- performance metrics
- fundamental limits