EE442 Introduction
(A gentle but brief introduction)

EE442 Analog & Digital Communication Systems
Principles of Modern Communication Systems
Lecture 1

Assignment: Read Chapter 1 of Agbo & Sadiku

Textbook: Samuel O. Agbo and Matthew N. O. Sadiku
Principles of Modern Communication Systems
Definition of a Communication System (from Section 1.1)

A “communication system” is an apparatus that conveys information from a source (the transmitter) to a destination (the receiver) over a channel (the propagation medium carrying the signal).

Common sources of Information:

- **Audio/voice** – information in acoustic form
- **Text messages** – written text sent in digital format
- **Data** – computer generated information in digital format
- **Video** – electronic representation of images or pictures

Categories of information: Analog and Digital

Refer to Section 1.3, pages 3 to 6.
Signals Carry Content in Communication Systems

Data, messages, and information (i.e., useful content) are sent from transmitter to receiver over a channel often using electrical signals.

A signal is a sequence of values, or symbols, encoding the transmitted message.

Today’s communication systems mostly use electrical and optical signals that are time-varying, electrical quantities (e.g., voltages, currents, and electromagnetic field quantities) where time variation encodes (i.e., represents) data, messages, and information.

Important non-electrical signals include acoustic (voice and music).

A defined language or code is required between sender and receiver for communication. For digital signals we use various digital codes (e.g., binary).

Furthermore . . . for a signal to be information we require:

1. It is accurate and timely,
2. Has a specific and organized purpose or focus, and
3. Results in increased understanding or decreased uncertainty.
The Four Great Enablers of the Communication Age
(from ES 101A “Communications in the Information Age”)

<table>
<thead>
<tr>
<th>Enabler</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Harnessing of Electricity</td>
<td>1800</td>
</tr>
<tr>
<td>Electric Power Generation (1880s)</td>
<td></td>
</tr>
<tr>
<td>2. Radio Waves</td>
<td>1876</td>
</tr>
<tr>
<td>Radio Waves (began in 1896 with wireless telegraphy)</td>
<td></td>
</tr>
<tr>
<td>3. Digitization</td>
<td>1940</td>
</tr>
<tr>
<td>Started in 1940s (but accelerated in the 1970s)</td>
<td></td>
</tr>
<tr>
<td>4. Transistors &amp; Integrated Circuits</td>
<td>1958</td>
</tr>
<tr>
<td>Transistor 1948 (Jack Kilby &amp; Robert Noyce)</td>
<td></td>
</tr>
<tr>
<td>Moore’s Law</td>
<td></td>
</tr>
</tbody>
</table>

Source: D. B. Estreich from ES101
Selective History of Communication Technologies

1794 – Claude Chappe develops an armature signal telegraph (optical)
1837 – Samuel Morse independently develops and patents an electrical telegraph (leads to Morse Code)
1876 – Alexander Graham Bell demonstrates voice-based telephone
1896 – Wireless telegraphy (radio telegraphy) by Guglielmo Marconi
1901 – First transatlantic radio telegraph transmission (Marconi)
1906 – First AM radio broadcast by Reginald Fessenden (December 24th)
1920 – First commercial radio stations in US (KDKA in Pittsburgh)
1921 – First mobile radio service (Detroit Police Department)
1928 – First television station in United States (W3XK – Washington DC)
1935 – Edwin Armstrong demonstrates FM radio
1947 – Bell Telephone Laboratories (BTL); proposed cellular concept
1947 – BTL invents and demonstrates solid-state transistor
1958 – Integrated circuit invented (Kilby at TI & Noyce at Fairchild)
1980s – Fiber optic communication technology developed
1984 – Analog AMPS (1G) cellular mobile service by Motorola
1991 – GSM cellular service (digital) service begins (2G)
1997 – IEEE 802.11(b) wireless LAN standard
2007 – Apples introduces the smartphone (iPhone)

⇒ Table 1.1 (pp. 4-5) lists other milestones in communication.
Quiz – Great Communication Milestone!

What Communication Technology does this describe?

1. It demonstrated the “power of communication”
2. Its impact was Worldwide
3. It made the world smaller by instantaneous communication
4. It revolutionized and created new industries
5. Altered business: E-commerce became important
6. Security and privacy became very important issues
7. It gave new hope for peacemaking and diplomacy
8. Its technicians and operators became an elite group
9. New forms and schemes of fraud emerged
Greatest Communication Milestone Answer

What Communication Technology does this describe?

ANSWER: The Electric Telegraph (aka Victorian Internet)


https://en.wikipedia.org/wiki/The_Victorian_Internet
Wheatstone-Cook Telegraph Preceded Morse Telegraph

Charles Wheatstone & William Cooke developed the first demonstrated electrical telegraph. It was a “Five-needle telegraph” (1837) as shown below. There were two disadvantages: (1) it used a 20-character alphabet, and (2) it needed six parallel wires for operation. First commercial use in 1838 between railroad stations.

[Diagram of the Wheatstone-Cook Telegraph]

Used 6 wires to operate

Wheatstone-Cooke Telegraph


Supported 20 letters alphabet
The Telegraph Revolution

- Near instantaneous communication
- Adopted worldwide
- Became the *Victorian Internet*
- Used by railroads, newspapers, financial organizations, businesses of all kinds,
- Used in the Civil War by both North and South
Samuel F. B. Morse and Alfred Vail demonstrated a working telegraph in September 1837 – it was a simple, single wire telegraph. Their first practical long-distance telegraph system was built in 1844.

http://telegraph-history.org/samuel-morse/signature.html
Role of the Telegraph in the 19th Century

**Army Telegraph in the Civil War** – stringing the wire during battle.
[Sketch BY Mr. A. R. Waud.]

Lincoln used the telegraph to communicate with the Union Army during the Civil War.

**Telegraph lines running alongside a railway at a remote station in the Great Plains of America for managing railway logistics.**

[Image]

http://www.sonofthesouth.net/leefoundation/civil-war/1863/january/telegraph.htm

Civil War – 1861 to 1865

First Transcontinental Railroad in the U.S. was built across North America in the 1860s.

[Image]

Long Range Optical Communication: Heliograph

**Heliograph** – a “wireless solar telegraph” that signals with flashes of sunlight reflected by a mirror. The flashes are produced by momentarily pivoting the mirror or interrupting the beam with a shutter and uses codes such as the Morse code.

Sir Henry Mance (British Army Signal Corps) developed first apparatus in 1869 in India. The heliograph remained standard equipment in the Australian and British armies until the 1960s. Also used by the **U.S. Forrest Service**. Longest heliograph communication distance: slightly greater than 200 miles.


But Communication Systems Have Dramatically Advanced

- Radio broadcasting (AM and FM)
- Citizens’ band radio; ham short-wave radio; radio control; etc.
- Computer networks (LANs, MANs, WANs, and Internet)
- Aviation communication bands; Emergency bands; etc.
- Satellite systems (Commercial and Military communications)
- Cable television (originally CATV) for video and data
- Cellular networks (Five Generations – LTE or 4G → 5G)
- Wi-Fi LANs
- Bluetooth
- GPS

And of course many, many more . . . .
Transmitter will . . .
- Encode message data
- Add a carrier signal (modulation)
- Set signal parameters for channel transmission and transmit

Receiver will . . .
- Receive signal
- Remove the carrier signal (demodulation)
- Decode the data to put it into format for destination

Refer to Agbo & Sadiku Section 1.3, see primarily page 5.
Example: Human Speech is an Analog Signal

A microphone is a “transducer”

Carbon-Granular Microphone
Inventor: Thomas Edison 1877
This enabled the Telephone.

http://en.wikipedia.org/wiki/Carbon_microphone
Voice Bandwidth (Bell Determined 3400 Hz Was Adequate)

Human Speech Intensity and Frequency Boundaries

Acoustic signals

Human Hearing Chart

Discomfort Threshold

Music

Speech

Hearing Threshold

aging

Sound velocity 1100 ft/sec

Presbycusis is loss of hearing with age.

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Modern Communication Systems are Dominated by Wireless

https://www.researchgate.net/figure/A-proposed-5G-heterogeneous-wireless-cellular-architecture_fig1_260523836

VLC is visible light communication
Electromagnetic Spectrum (There is only one in the universe)

The gateway to wireless

http://www.mondialbioregulator.co.uk/electromagnetic-spectrum mondial-bioregulator.asp
Frequency Allocation is Determined by the FCC

National Telecommunications & Information Administration (NTIA) is an agency of the United States Department of Commerce
Some Frequency Allocations of Interest in EE442

- **AM radio**: 540 to 1720 kHz
- **TV broadcast**: 174 to 216; 470 to 806 MHz
- **FM radio**: 88 to 108 MHz
- **3G/4G LTE cellular**: See next slide
- **Wi-Fi**: 2.402 to 2.484 GHz
- **28 GHz – LMDS**: 27.5 to 28.35 GHz
- **5G cellular**: 38 GHz
- **60 GHz unlicensed WiGig**: 60 GHz
- **77 GHz vehicular radar**: See next slide

# Selected Frequency Allocations in Cellular Telephony

All US frequencies in megahertz (MHz)

<table>
<thead>
<tr>
<th>CARRIER</th>
<th>NETWORK</th>
<th>3G BANDS</th>
<th>3G FREQUENCIES</th>
<th>4G LTE BANDS</th>
<th>4G LTE FREQUENCIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT&amp;T</td>
<td>GSM/UMTS/HSPA+</td>
<td>2, 5</td>
<td>1900, 850</td>
<td>2, 4, 12, 17</td>
<td>1900, 1700 abcde, 700 bc</td>
</tr>
<tr>
<td>VERIZON</td>
<td>CDMA</td>
<td>0, 1</td>
<td>850, 1900</td>
<td>2, 4, 13</td>
<td>1900, 1700 f, 700 c</td>
</tr>
<tr>
<td>T-MOBILE</td>
<td>GSM/UMTS/HSPA+</td>
<td>2, 4</td>
<td>1900, 1700/2100</td>
<td>2, 4, 12</td>
<td>1900, 1700 def, 700 a</td>
</tr>
<tr>
<td>SPRINT</td>
<td>CDMA</td>
<td>10, 1</td>
<td>800, 1900</td>
<td>25, 26, 41</td>
<td>1900 g, 850, 2500</td>
</tr>
<tr>
<td>US CELLULAR</td>
<td>CDMA</td>
<td>0, 1</td>
<td>850, 1900</td>
<td>5, 12</td>
<td>850, 700 ab</td>
</tr>
</tbody>
</table>

[Link to source](https://www.droid-life.com/2015/02/05/us-wireless-carrier-bands-gsm-cdma-wcdma-lte-verizon-att-sprint-tmobile/)
Radio and Optical Windows in the Atmosphere

Just as sight depends upon the “Visible Window,” wireless communication depends upon the existence of the “Radio Window” in the EM spectrum.

Radio and Optical Windows in the Atmosphere

Total, Dry Air and Water-vapor Zenith Attenuation at Sea Level

W-band & V-band used in satellite communications

V-band is 50 to 75 GHz
W-band is 75 to 100 GHz

Why W/V band for satellite communications?

W & V bands have no crowding in frequency, hence, this provides reduced interference, large bandwidth availability, reduced antenna and electronic components size, and more security in point-to-point links due to smaller beamwidths.
Example: Unlicensed Spectrum – ISM and & UNII RF Bands

ISM: Industrial, Scientific & Medical &
UNII: Unlicensed National Information Infrastructure

<table>
<thead>
<tr>
<th>Band</th>
<th>Applications</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISM I</td>
<td>Cordless phones; 1G Wireless Cellular</td>
<td>902 – 928 MHz</td>
</tr>
<tr>
<td>ISM II</td>
<td>Wi-Fi; Bluetooth; ZigBee; Microwave ovens</td>
<td>2.4 – 2.4835 GHz</td>
</tr>
<tr>
<td>ISM III</td>
<td>Cordless phones; Wireless PBX</td>
<td>5.725 – 5.85 GHz</td>
</tr>
<tr>
<td>UNII I</td>
<td>Wi-Fi 802.11a/n</td>
<td>5.15 – 5.25 GHz</td>
</tr>
<tr>
<td>UNII II</td>
<td>Short-range indoor; Campus applications</td>
<td>5.25 – 5.35 GHz</td>
</tr>
<tr>
<td>UNII III</td>
<td>Long-range outdoor; Point-to-Point links</td>
<td>5.725 – 5.875 GHz</td>
</tr>
</tbody>
</table>

Other ISM bands: 24.0 to 24.25 GHz, 61 to 61.5 GHz, 122 to 123 GHz and 244 to 246 GHz.
Antennas are Required in Wireless Communication

- Cellular base station antennas
- Yagi antenna
- Mast antenna
- Parabolic antenna
- Cell phone antenna (internally mounted)
- Dipole antenna
Radiation from a Dipole Antenna

http://askthephysicist.com/ask_phys_q&a_old5.html
Fundamental Limitations in Electrical Communications

There are (1) Technological Constraints, and (2) Fundamental Physical Constraints in all communication systems.

Two fundamental physical constraints:

(A) Bandwidth limitation
Related to how rapidly we can change signals (a change in stored energy requires a non-zero amount of time). A good measure of signal change speed is bandwidth. Also, there are regulatory limits set by the FCC in the US.

(B) Noise limitation
Noise is always present and sets a lower signal level where the signal can be reliably detected. Sources of noise include atmospheric noise, electromagnetic interference (RFI), galactic noise, thermal and shot noise in circuits and devices, and others.
Wireless Channel Limitations and Challenges

- **Propagation loss** – The greater the distance, the greater the loss. (All channels are **lossy** unless they have gain built into them)
- **Frequency selectivity** – Most media are transmitted over selective frequency bands (FCC assigns these bands)
- **Time variation** – Many channels have natural varying conditions which change transmission properties (e.g., temperature and moisture content changes; motion in objects)
- **Nonlinearity** – Ideally a channel is linear; however, exceptions exist such as satellite communication through the ionosphere
- **Shared usage** – Most channels are not dedicated to a single user so they must contend with multiple users
- **Noise** – All channels contribute noise to the signal as it travels through the medium
- **Interference** – Channels can pick up adjacent communication signals and noise which interfere with the intended signals

All of these influence and/or limit the choice of modulation schemes & transmitter/receiver (transceiver) design.
Challenges in Wireless: Fading in Cellular Telephony

Radio Waves

Base Transceiver Station

Path loss

Multipath Reception

Mobile Station: MS or UE

Also, Moisture in atmosphere causes attenuation in radio signal strength.
Channel Distortion from Fading in Cellular Telephony

Multi-path is a dominant source of channel distortion

https://dsp.stackexchange.com/questions/51346/intersymbol-interference-due-to-limited-channel-bandwidth/51402
Why do we study Analog if Digital is so dominant today?

1. The world is fundamentally an analog world (People respond primarily to analog symbols, images & sounds)
2. Digital signals are actually “analog signals” encoded as “digital data” (e.g., bits still must be converted to physical waveforms)
3. Digital communication systems make use of components leveraged from analog communication systems (e.g., ADC & DAC converters, mixers, amplifiers, combiners, antennas, etc.)
4. Analog communication systems illustrate high-level issues and principles (this is especially true as we push data rate limits higher)
5. Analog communication systems are still in use (e.g., AM and FM radio)

IMPACT: We must be able to convert analog to digital & vice versa.
Analog Signals versus Digital Signals

- Analog Signals represent the values of physical parameters which are time varying.
  Amplitude can be any value within a range of values
  Amplitude is time-varying (equivalent to always changing data)

- Digital Signals represent a sequence of numbers.
  Values are restricted to a set of discrete values
  Example: Binary signal with only two values or states (1 and 0).
  Amplitude is time-varying (but absolute magnitude not so important)

All signal waveforms are analog – the difference is what they represent!
Advantages of Digital Over Analog

1. Digital is more robust than analog to noise and interference†
2. Digital is more viable when using regenerative repeaters
3. Digital hardware is more flexible by using microprocessors and VLSI
4. Can be coded to yield extremely low error rates with error correction
5. Easier to multiplex several digital signals than analog signals
6. Digital is more efficient in trading off SNR for bandwidth
7. Digital signals are easily encrypted for security purposes
8. Digital signal storage is easier, cheaper and more efficient
9. Reproduction of digital data is more reliable without deterioration
10. Cost is coming down in digital systems faster than in analog systems and DSP algorithms are growing in power and flexibility

† Analog signals vary continuously with time and their values are affected by noise.

SNR = signal-to-noise ratio
VLSI = very large-scale integration
DSP = digital signal processing
Information Capacity (Shannon Capacity) – Noise Dependent

- Data rate $R$ is limited by channel bandwidth, signal power, noise power and distortion in general

- Without distortion or noise, we could transmit without limit in the data rate. However, this is never reality.

- The **Shannon capacity** $C$ is the maximum possible data rate for a system with noise and distortion

  - Maximum rate approached with bit error probability close to 0. For additive white Gaussian noise (AWGN) channels,

    $$C = B \cdot \log_2 \left( 1 + \frac{\text{signal power}}{\text{noise power}} \right)$$

    in bits per second

- Shannon obtained $C = 32$ kbps for telephone channels

- In practice we are nowhere near capacity limit in wireless systems

Refer to Section 1.5 of Agbo & Sadiku; pages 10 to 12.
Nyquist Channel Capacity (Nyquist Theorem)

Nyquist channel capacity gives us the upper bound for the bit rate of a communication transmission system by considering the dependence of the bit rate from the number of bits in a symbol (or number of signal levels) and the bandwidth of the system. It assumes there are two symbols per cycle and considers only the first harmonic (fundamental) frequency.

For a noiseless channel:

\[
C = \text{channel capacity (bits/sec)} = 2B \times \log_2 (M)
\]

where \( B = \text{channel bandwidth (Hz)} \)

and \( M = \text{number of bits/symbol} \)
Additive White Gaussian Noise Corrupts Signals

AWGN = Additive White Gaussian Noise

“White” means noise power is uniform over all frequencies
Digital Signal Errors From Noise & Interference

Data transmitted: 0 1 0 1 1 0 0 1 1 0 0 1 0 1 0

Signal

Noise

Signal plus noise

Sampling times

Data received: 0 1 0 1 1 0 1 1 1 0 0 1 0 0 0

Original data: 0 1 0 1 1 0 0 1 1 0 0 1 0 1 0

2 errors out of 15 bits

https://slideplayer.com/slide/13937000/
Analog Signals are Strongly Corrupted by Noise

Question: Is it possible to recover an analog signal from noise after it has been corrupted (*i.e.*, a signal + noise waveform shown below)?
Signal Power in Decibels  
(Refer to Handout # 1)

The standard unit for signal power is watts (W).

Often signal power is expressed on a decibel scale. This requires the use ratios of power using the standard relationship:

\[ N \text{ Decibels (dB)} = 10 \log_{10} \left( \frac{P_2}{P_1} \right) . \]  

It is often useful to express power relative to a reference power. For example, we could use 1 watt as the reference power. In this case, we use the above equation with \( P_1 = 1 \text{ watt} \), so that the power level \( P_2 \) in watts is expressed on a decibel scale by

\[ P_2 \text{ (in dBW)} = 10 \log_{10} \left( \frac{P_2}{1 \text{ W}} \right) = 10 \log_{10} (P_2) \text{ dBW} \]

where \( P_2 \) is in watts (the unit of watts is cancelled by the denominator of 1 watt) and taking \( 10 \log_{10} \) of the power ratio gives \( P_2 \) in dBW rather than in watts. If instead, \( P_1 \) is one milliwatt (1 mW), then \( P_2 \) is expressed in units of milliwatts and the decibel scale is in units of dBm. Hence,

\[ P_2 \text{ (in dBm)} = 10 \log_{10} \left( \frac{P_2}{1 \text{ mW}} \right) = 10 \log_{10} (P_2) \text{ dBm} \]

Why is it convenient to use a decibel scale in expressing power levels?
Signal Power in Decibels  (Handout # 1)

Sometimes we want to work with voltage or current instead of power. Remember that power $P$ is related to voltage $V$ and current $I$ by introducing resistance $R$

$$P = \frac{V^2}{R} \quad \text{and} \quad P = I^2R.$$

Then we can write,

$$N \text{ (dB)} = 10 \cdot \log_{10} \left( \frac{P_2}{P_1} \right) = 10 \cdot \log_{10} \left( \frac{V_2^2}{R} \right) = 10 \cdot \log_{10} \left( \frac{V_1^2}{R} \right) = 10 \cdot \log_{10} \left( \frac{V_2^2}{V_1^2} \right)$$

10 by definition

$$N \text{ (dB)} = 20 \cdot \log_{10} \left( \frac{V_2}{V_1} \right) \quad \text{and} \quad N \text{ (dB)} = 20 \cdot \log_{10} \left( \frac{I_2}{I_1} \right)$$

Now it is 20
Expressing Power Gain in dB

Example:

Suppose we have an amplifier that delivers a tenth of a watt (0.1 W) into the load resistor $R_L$ when driven from a source delivering 2 milliwatts (0.002 W) at the amplifier’s input, what is the gain in decibels?

\[
G \text{ (dB)} = 10 \cdot \log_{10} \left( \frac{P_2}{P_1} \right) = 10 \cdot \log_{10} \left( \frac{0.1 \text{ W}}{0.002 \text{ W}} \right) \\
= 10 \cdot \log_{10} (50) = 10 \cdot 1.699 = 16.88 \text{ dB}
\]
## Decibel Table of Power Ratio & Amplitude Ratio

<table>
<thead>
<tr>
<th>dB</th>
<th>Amplitude ratio</th>
<th>Power ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100 dB</td>
<td>10^{-5}</td>
<td>10^{-10}</td>
</tr>
<tr>
<td>-50 dB</td>
<td>0.00316</td>
<td>0.00001</td>
</tr>
<tr>
<td>-40 dB</td>
<td>0.010</td>
<td>0.0001</td>
</tr>
<tr>
<td>-30 dB</td>
<td>0.032</td>
<td>0.001</td>
</tr>
<tr>
<td>-20 dB</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>-10 dB</td>
<td>0.316</td>
<td>0.1</td>
</tr>
<tr>
<td>-6 dB</td>
<td>0.501</td>
<td>0.251</td>
</tr>
<tr>
<td>-3 dB</td>
<td>0.708</td>
<td>0.501</td>
</tr>
<tr>
<td>-2 dB</td>
<td>0.794</td>
<td>0.631</td>
</tr>
<tr>
<td>-1 dB</td>
<td>0.891</td>
<td>0.794</td>
</tr>
<tr>
<td>0 dB</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1 dB</td>
<td>1.122</td>
<td>1.259</td>
</tr>
<tr>
<td>2 dB</td>
<td>1.259</td>
<td>1.585</td>
</tr>
<tr>
<td>3 dB</td>
<td>1.413</td>
<td>2 ≈ 1.995</td>
</tr>
<tr>
<td>6 dB</td>
<td>2 ≈ 1.995</td>
<td>3.981</td>
</tr>
<tr>
<td>10 dB</td>
<td>3.162</td>
<td>10</td>
</tr>
<tr>
<td>20 dB</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>30 dB</td>
<td>31.623</td>
<td>1000</td>
</tr>
<tr>
<td>40 dB</td>
<td>100</td>
<td>10000</td>
</tr>
<tr>
<td>50 dB</td>
<td>316.228</td>
<td>100000</td>
</tr>
<tr>
<td>100 dB</td>
<td>10^{5}</td>
<td>10^{10}</td>
</tr>
</tbody>
</table>

[https://www.rapidtables.com/electric/decibel.html](https://www.rapidtables.com/electric/decibel.html)
Multipath Effects - Rayleigh fading

In a radio link, the RF signal from the transmitter may be reflected from objects such as hills, buildings, or vehicles. This gives rise to multiple transmission paths at the receiver. The relative phase of multiple reflected signals can cause constructive or destructive interference at the receiver. This is experienced over very short distances (typically at half wavelength distances), thus is given the term fast fading. These variations can vary from 10-30dB over a short distance. The following figure shows the level of attenuation that can occur due to the fading.

Typical Rayleigh fading while the Mobile Unit is moving (for at 900MHz)

http://sna.csie.ndhu.edu.tw/~cnyang/MCCDMA/sld034.htm
Three Dimensions of Expansion of Data Rate in Communications

Bits per Symbol

Higher Frequency

Discrete Multitone (Greater bandwidth)

Four Modulation Methods

- **Analog Modulation**
  - Continuous Wave
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)

- **Digital Modulation**
  - Transmission of Binary Data
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Phase Shift Keying (PSK)
  - Quadrature Amplitude Modulation (QAM)

- **Pulse Modulation**
  - PAM, PWM, PPM and PCM

- **Spread Spectrum**
  - Frequency Hop and Direct Sequence Spread Spectrum

https://www.rohm.com/electronics-basics/wireless/modulation-methods