EEE 432
Introduction to Data Communications

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DATA TRANSMISSION

Course Information

1. Data Communications and Networks
2. **Data Transmission**
3. Transmission Media
4. Signal Encoding Techniques
5. Digital Data Communication Techniques
6. Multiplexing
7. Networking and Protocol Architectures
8. Switching
9. Routing in Switched Networks
10. LANs and WANs
11. Ethernet
12. The Internet

Transmission Terminology

- Data transmission occurs between a transmitter and receiver via some medium
- Communication is in form of electromagnetic waves
- Medium may be:

  Guided: wires/cables, e.g. twisted pair, coaxial cable, optical fiber

  Unguided: wireless, e.g. air, water, vacuum
- Configuration may be:

  Point-to-point: only 2 devices share medium

  Multipoint: more than 2 devices share medium
- Direction of communications may be:

  Simplex: one direction, e.g. television

  Half duplex: either direction, but only one way at a time, e.g. police radio

  Full duplex: both directions at the same time, e.g. telephone

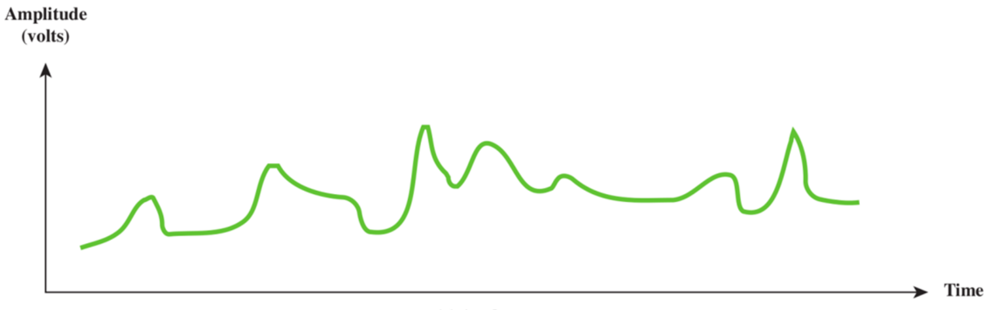
Frequency, Spectrum and Bandwidth

- Transmitter generates electromagnetic signals, which is transmitted over medium
- Electromagnetic signals represent data
- Electromagnetic signal consists of one or more component signals
- Electromagnetic signals can be viewed in two domains:

Time domain: Signal intensity vs time

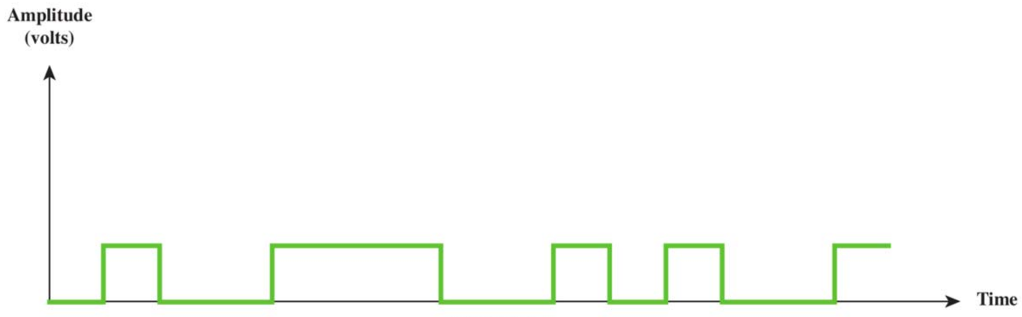
Frequency domain: Peak signal intensity of component vs frequency

Time Domain Concepts, Analog and Digital Waveforms



(a) Analog

Analog signal varies in continuous manner over time

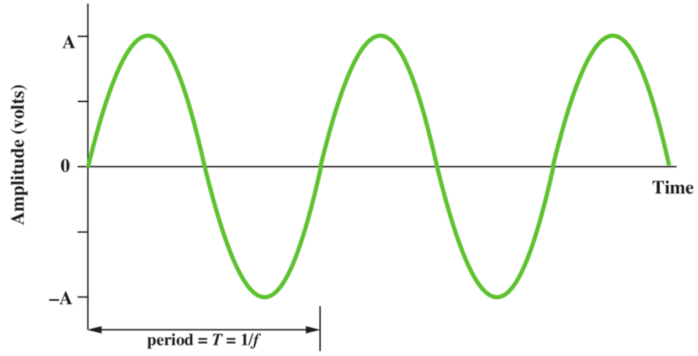


(b) Digital

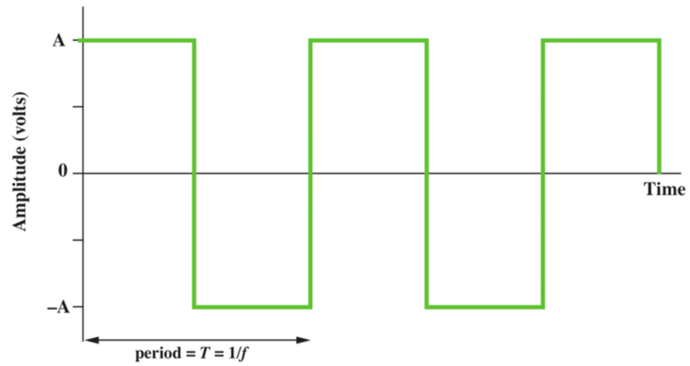
Digital signal maintains constant level for some period then changes to another constant level, in a discrete manner

Examples of Periodic Signals

Any signal is either periodic (the following two) or aperiodic



(a) Sine wave



(b) Square wave

Sinusoid Signals

- Sine wave is the fundamental periodic signal

$$s(t) = A\sin(2\pi ft + \emptyset)$$

- Communication signals are made up of sinusoid signals

Peak amplitude, A: maximum strength of signal over time [volts]

Frequency, f : rate at which signal repeats [cycles per second or Hertz]

Phase, Ø: relative position signal has advanced (or shifted) to some origin (usually 0) [radians]

- Other parameters:

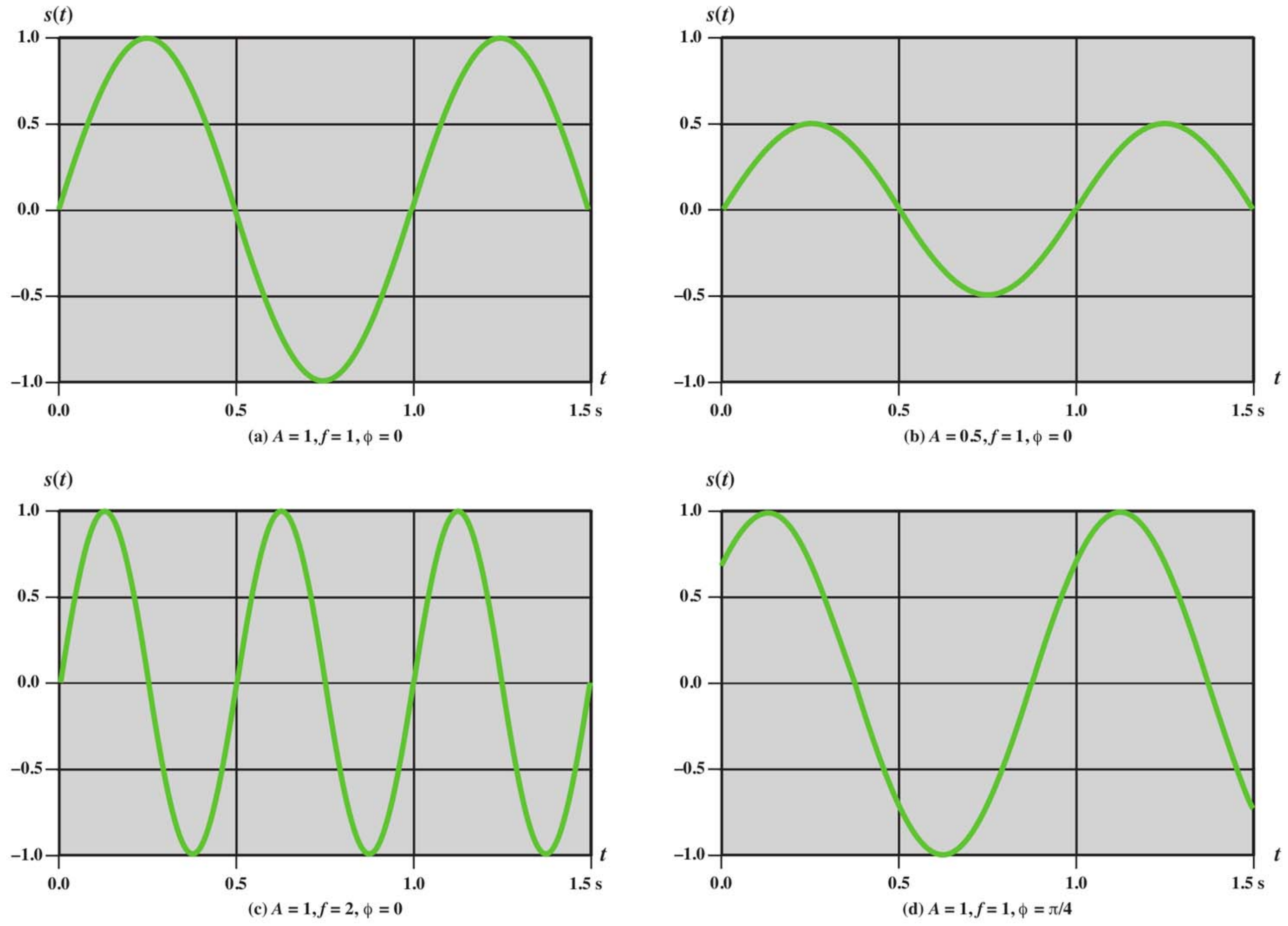
Period, T: time for one repetition or cycle;

$$T = 1/f$$

Wavelength, ʎ: distance occupied by one cycle;

ʎ = c/f where c is speed of light (c= $3x10^8$m/s)

Sinusoid Signal Examples



Frequency Domain Concepts

- Communication signals are composed of many component sinusoid signals at different frequencies, e.g.

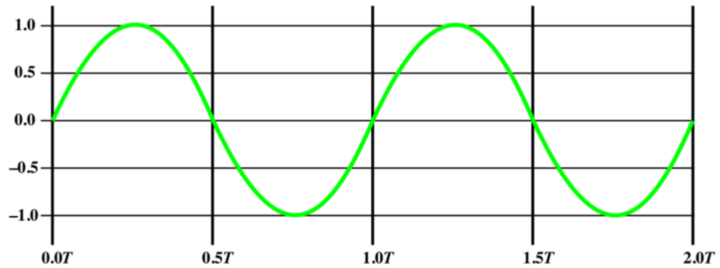
$$s(t) = (4/\pi) \times [\sin(200\pi t) + (1/3)\sin(600\pi t)]$$

- Or, if f = 100Hz:

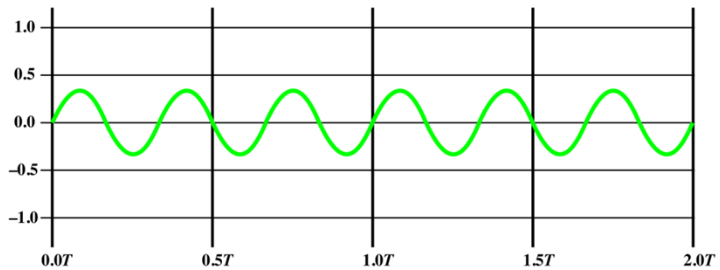
$$s(t) = (4/\pi) \times [\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t)]$$

- When all frequency components of signal are integer multiple of one frequency, that one is called **fundamental frequency**; the others are **harmonic frequencies**
- Period of resulting signal is equal to period of fundamental frequency component
- By adding together sine waves with different amplitudes, frequencies and phases, any desired communications signal can be constructed

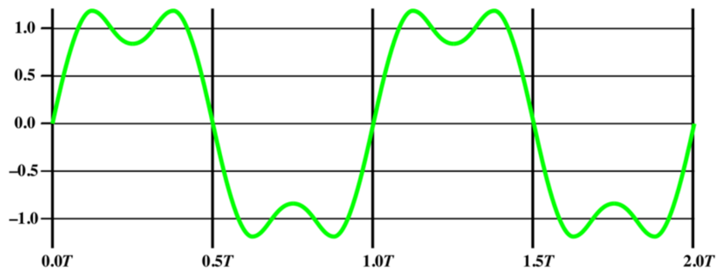
Addition of Frequency Components



(a) sin (2πft)



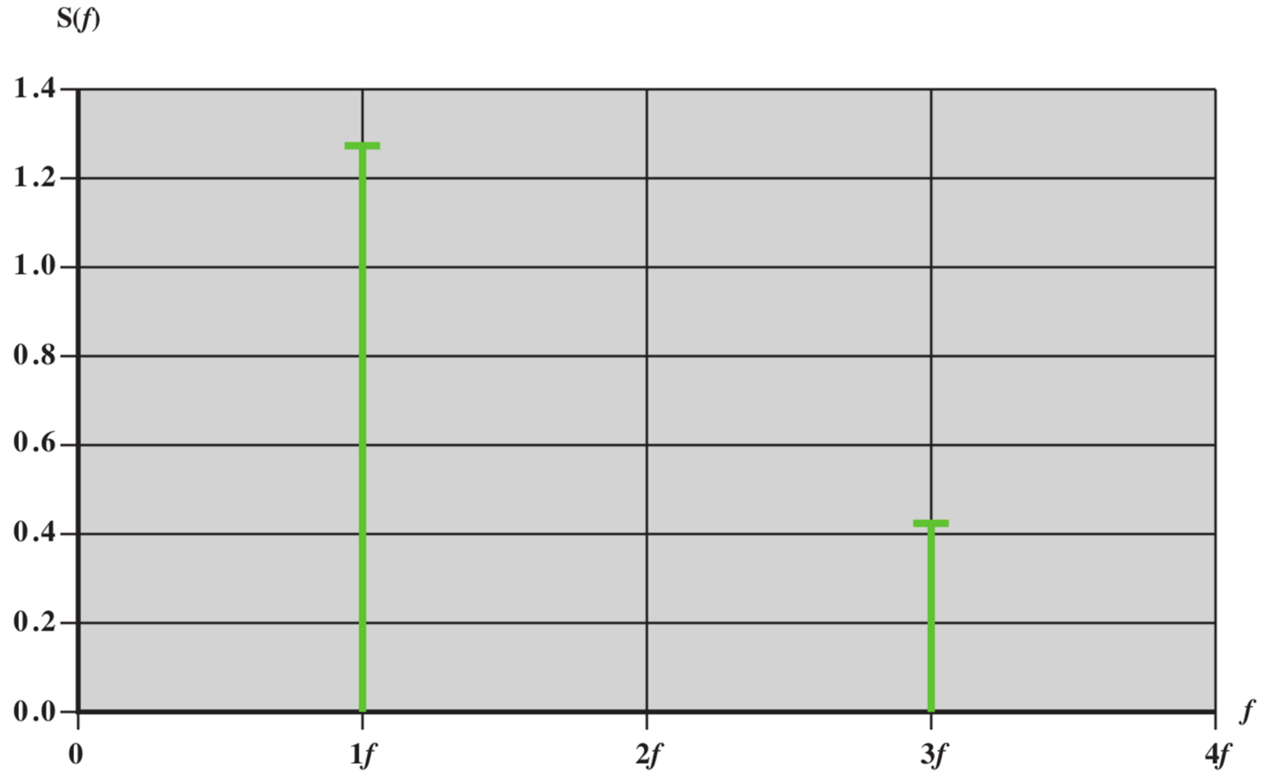
(b) (1/3) sin (2π(3f)t)



(c) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]

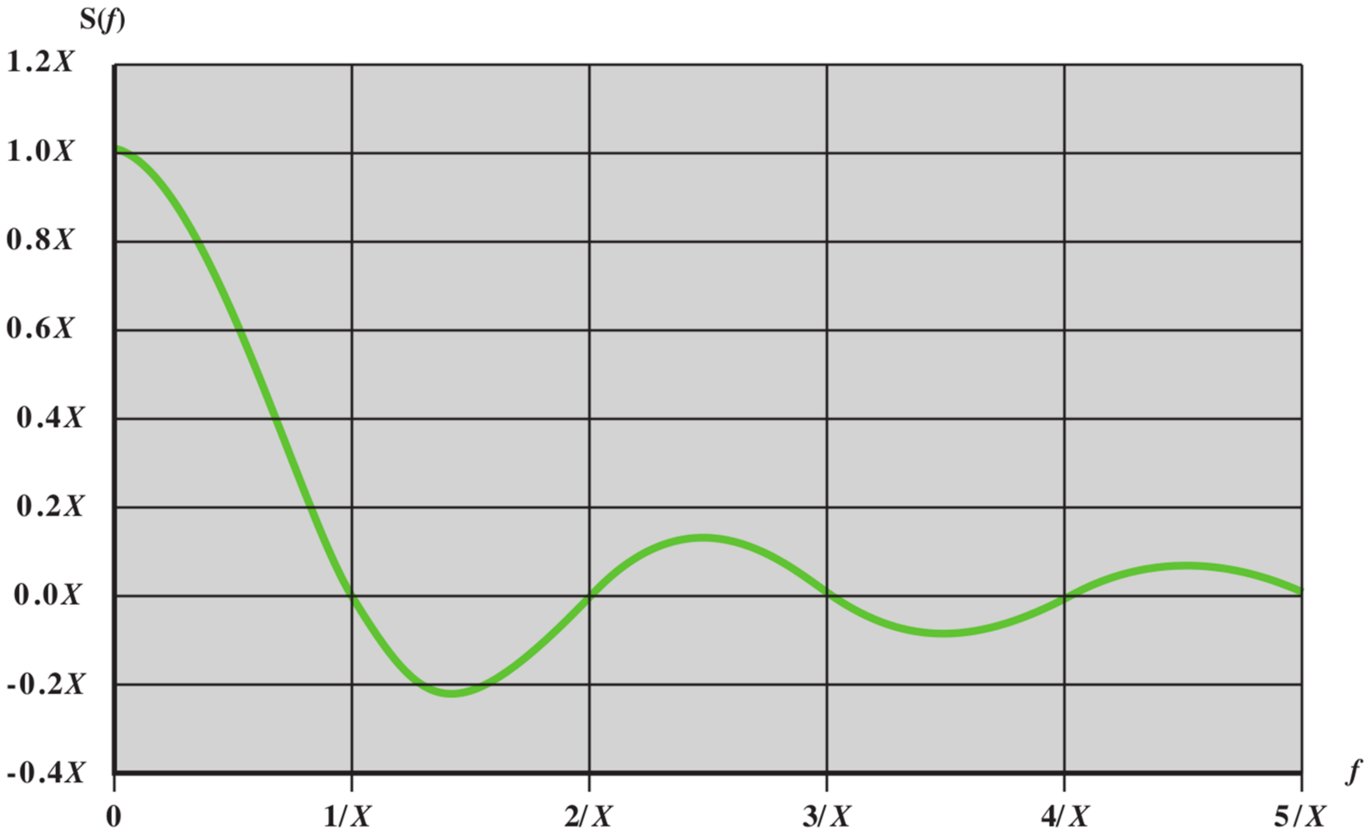
Frequency Domain Representations

Frequency domain function, S(f), species peak amplitude of component frequencies of signal



(a) $s(t) = (4/\pi)\,[\sin(2\pi f t) + (1/3)\sin(2\pi(3f)t)]$

Frequency Domain Representations

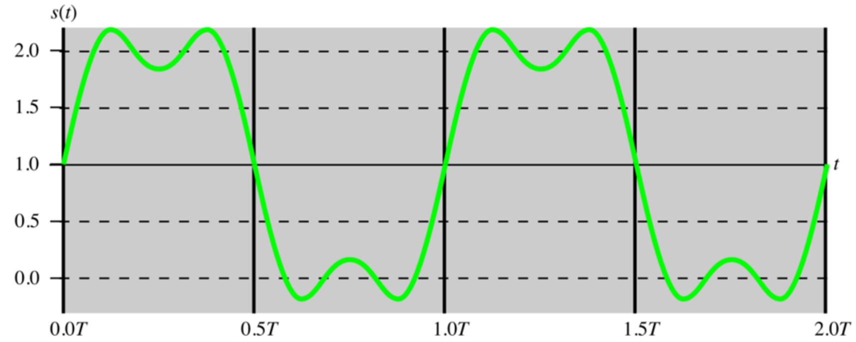


(b) $s(t) = 1 \quad -X/2 \leq t \leq X/2$

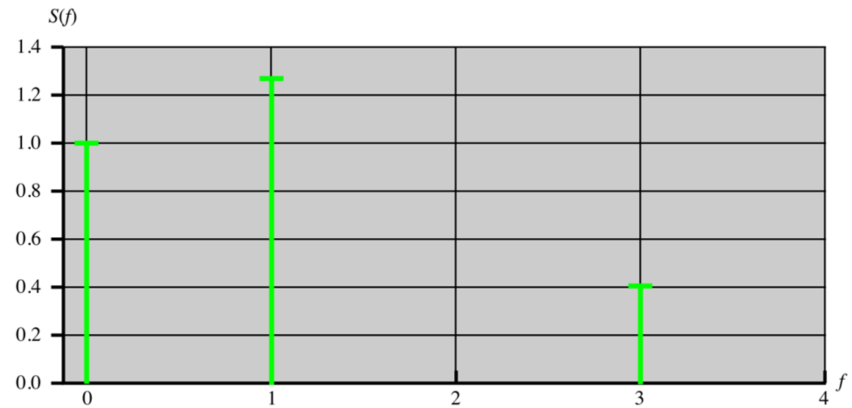
Spectrum, Bandwidth and Data Rate

- **Spectrum** of a signal is range of frequencies it contains
- **Absolute bandwidth** is width of spectrum, which can also be called as the distance (in terms of frequency) between the lower and upper operating frequency boundaries
- If signal contains component with zero frequency, signal has **DC component**
- Many signals have infinite absolute bandwidth, but most of the signal energy is contained in narrow band of frequencies; called Effective Bandwidth or just **Bandwidth**
- In practice, transmission system can only carry limited band of frequencies
- Bandwidth limit of system determines **data rate. Generally** the larger bandwidth of our signals or our transmission system, the larger data rate we can achieve.

Signal with DC Component

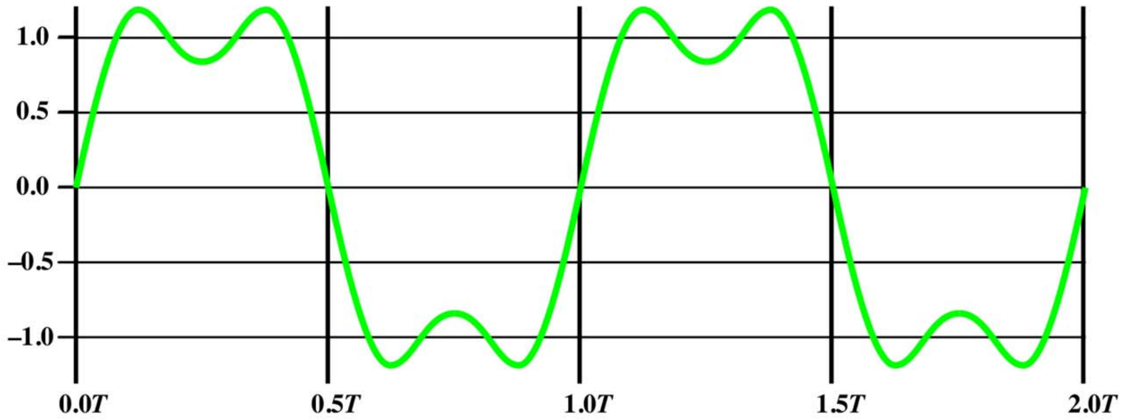


(a) s(t) = 1 + (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]

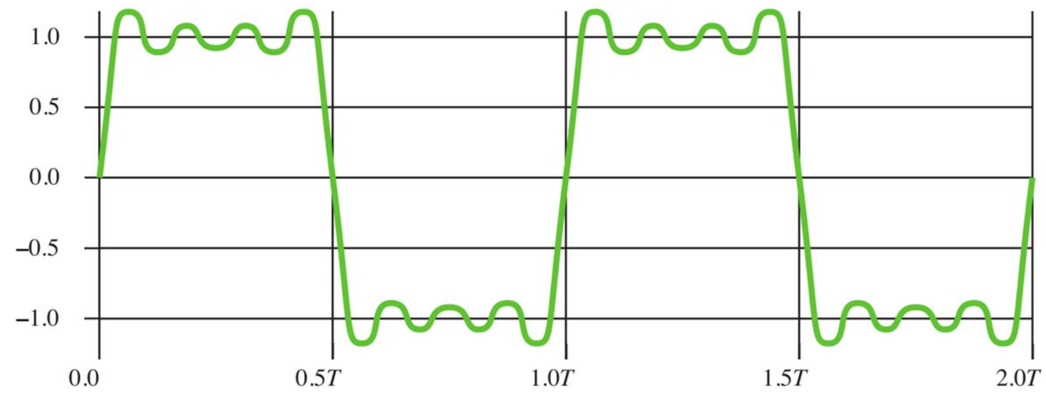


(b) S(f)

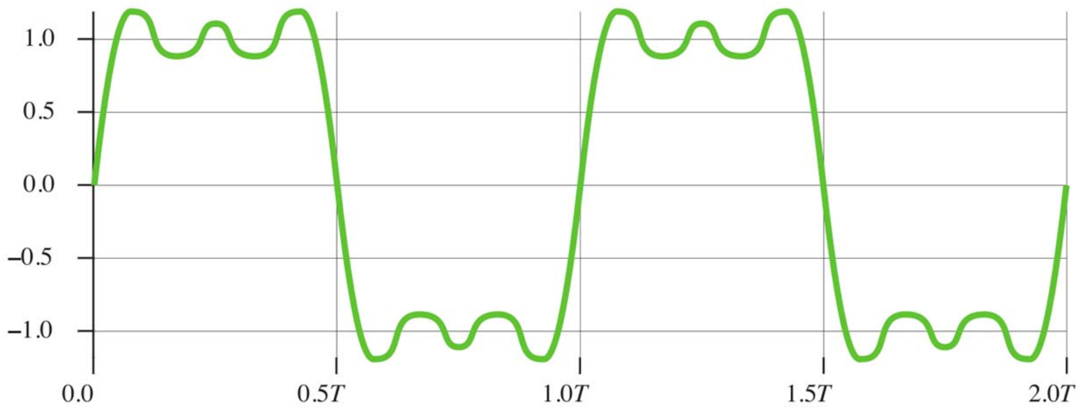
Frequency Components of Square Wave:



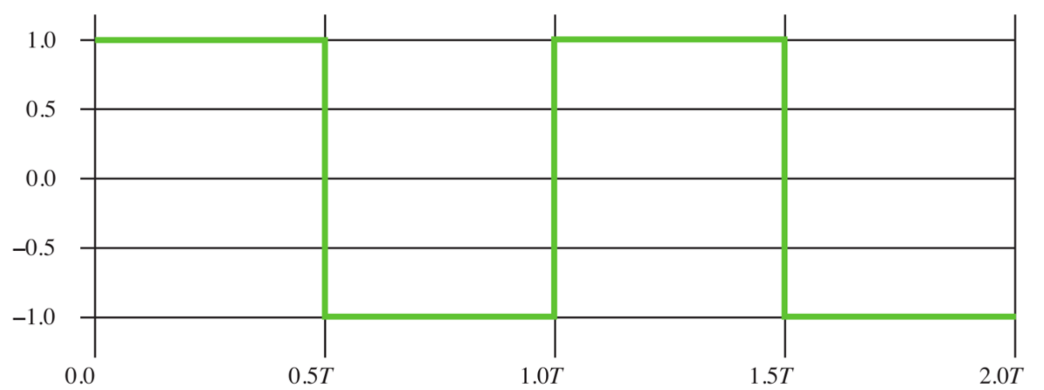
(c) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]



(b) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t) + (1/5) sin (2π(5f)t) + (1/7) sin (2π(7f)t)]



(a) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t) + (1/5) sin (2π(5f)t)]



(c) (4/π) ∑(1/k) sin (2π(kf)t), for k odd

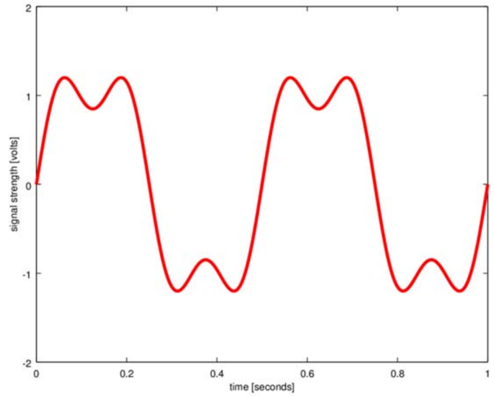
Examples…

Ex: If the signal s(t)=$\frac{4}{\pi}\left[\sin(4\pi t) + \frac{1}{3}\sin(12\pi t)\right]$,

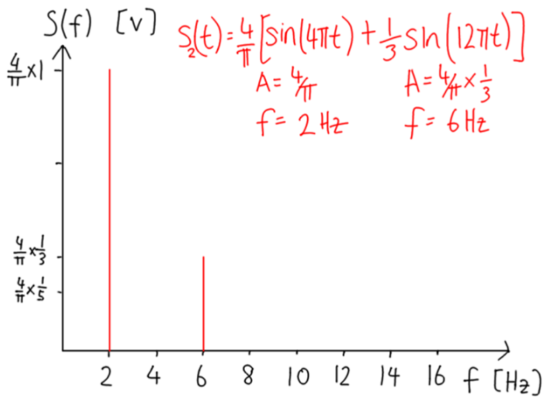
What are the fundamental frequency(FF) of s(t), amplitude of s(t)

set of frequencies in s(t) and Bandwidth of the spectrum and date rate?

Draw the frequency domain representation of s(t)



- **FF**=2Hz, because 2 is smallest integer multiplier of 2πt.
- **Amplitude** = A=$\frac{4}{\pi}$
- Set of frequencies are the existing ones in s(t), they are 2Hz and 6Hz.
- **Bandwidth = B.W=** Width of the spectrum= 6-2= 4Hz
- **Data rate** = 4b/s



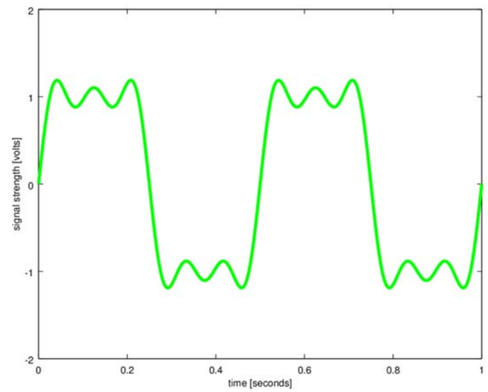
Examples…

Ex: If the signal s(t)=$\frac{4}{\pi}\left[\sin(4\pi t)+\frac{1}{3}\sin(12\pi t)+\frac{1}{5}\sin(20\pi t)\right]$,

What are the fundamental frequency(FF) of s(t), amplitude of s(t)

set of frequencies in s(t) and Bandwidth of the spectrum and date rate?

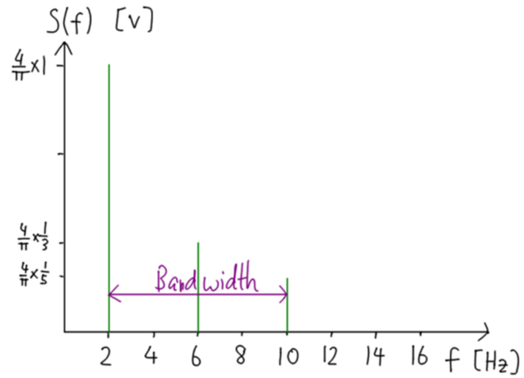
Draw the frequency domain representation of s(t)



- **FF=**2Hz because 2 is smallest integer multiplier of 2πt.
- **A=** $\frac{4}{\pi}$
- Set of frequencies are the existing ones in s(t), they are 2Hz, 6Hz

and 10Hz.

- **Bandwidth =** B.W= Width of the spectrum= 10-2= 8Hz
- **Data rate=** 4b/s

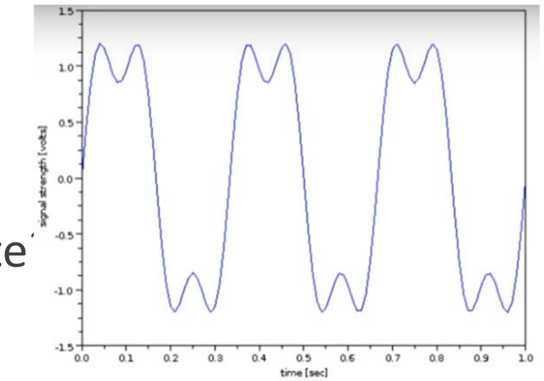


Example: Bandwidth and Data Rate

- Bandwidth impacts upon other factors but in practice, we want to use a signal which occupies a small bandwidth
- More bandwidth we use causes the cost be higher of this transmission system.
- There are surely more trade-offs to consider the transmission system but in terms of bandwidth, if the data rate is not improved, to have high bandwidth is senseless and costful.
- As a result, for the previous examples, signal in 1^{st} example is better.
- Even though 1^{st} signal is better in terms of bandwidth requirement, 2^{nd} signal is better in terms of **accuracy** due to its higher similarity to square wave, which can be interpreted more accurate in the receiver side

Examples…

Ex: What about the signal s(t)=$\frac{4}{\pi}\left[\sin(6\pi t)+\frac{1}{3}\sin(18\pi t)\right]$,

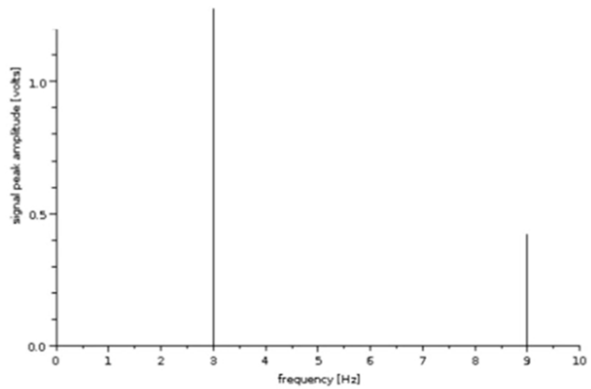


What are the fundamental frequency(FF) of s(t), amplitude of s(t)

set of frequencies in s(t) and Bandwidth of the spectrum and date rate

Draw the frequency domain representation of s(t)

- **FF=**3Hz because 3 is smallest integer multiplier of 2πt.
- **A=** $\frac{4}{\pi}$
- Set of frequencies are the existing ones in s(t), they are 3Hz and 9Hz.
- **Bandwidth** = B.W= Width of the spectrum= 9-3= 6Hz
- **Data rate=** 6b/s



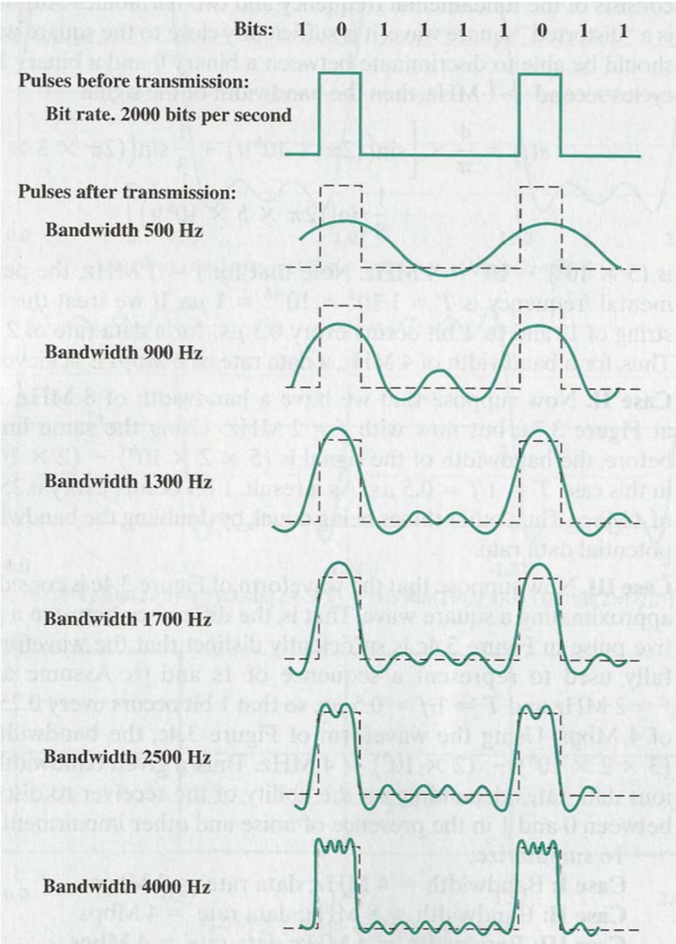
Increase in the frequency and bandwidth leads to a high data rate

Summarize…

- **Advantages**
  - Increased bandwidth→ Increased accuracy (less errors)
  - Increased frequency→ Increased data rate
- **Disadvantages**
  - Increased bandwidth→ Increased cost
  - Increased frequency→ Increased complexity (cost)

- Different frequencies have different characteristics
- A standard/regulation normally limits available frequency and bandwidth
- A designer chooses a signal that maximizes data rate, minimizes errors and minimizes cost.

Effect of Bandwidth on a Digital Signal



Assume if we want to send bit 1, we send a low signal and bit 0 is for high signal.

Plots are what we will see if we use different bandwidths and the main point is that as we increase the bandwidth available in our communication system, the signal transmitted gets more accurate to the ideal one.

4000Hz bandwidth is a close representation of this original square wave whereas the 500Hz bandwidth still has high but is not as accurate representation of the desired signal.

Increasing the bandwidth increases the accuracy of the signal and as a result, a more accurate signal produces less errors at the receiver.

Tradeoffs

Bandwidth

- Digital signal has infinite bandwidth; transmission systems impose limits on bandwidth of transmitted signals
- Bandwidth is a limited resource
- Greater the bandwidth, greater the cost

Data Rate

- Digital data is approximated by signal of limited bandwidth
- Greater the bandwidth, greater the data rate

Accuracy

- Receiver must be able to interpret received signal, even with transmission impairments
- Greater the bandwidth, greater the accuracy

Analog and Digital Data Transmission

Data

- Entities that convey meaning or information
- Analog data take continuous values over time, e.g. voice, video, sensor data
- Digital data take discrete values, e.g. text, integers

Signals

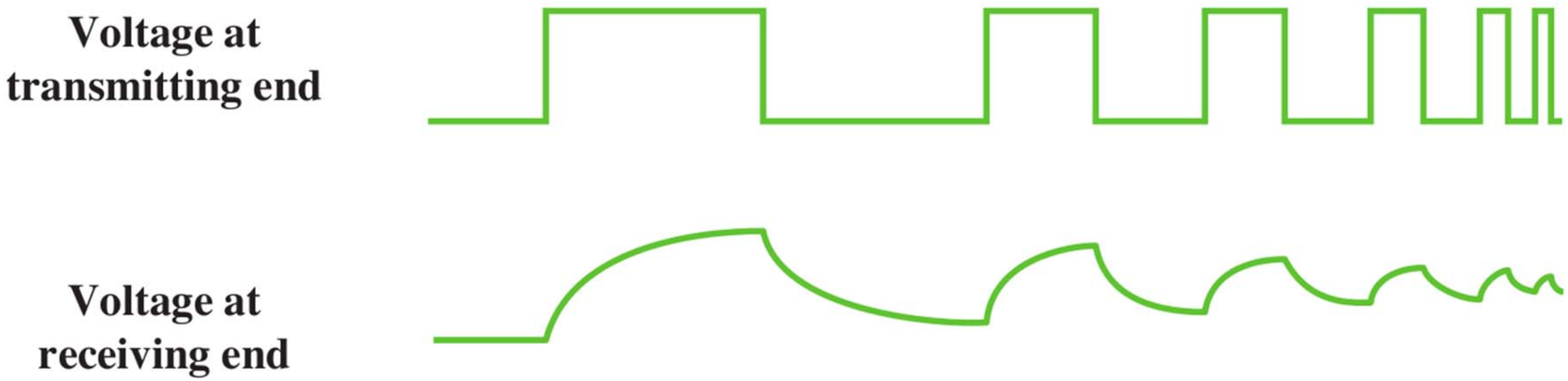
- Electric or electromagnetic representations of data

Transmission

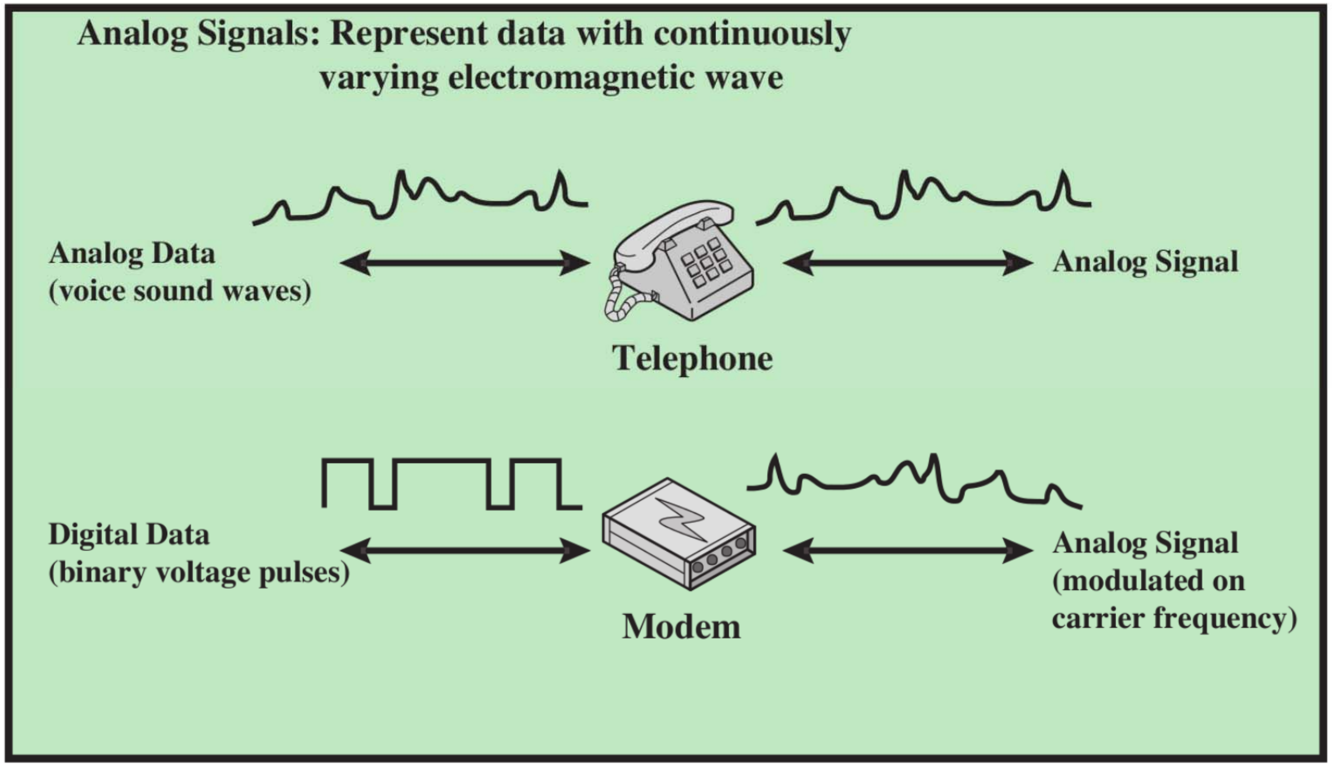
- Communication of data by propagating and processing signals

Analog vs Digital Signals

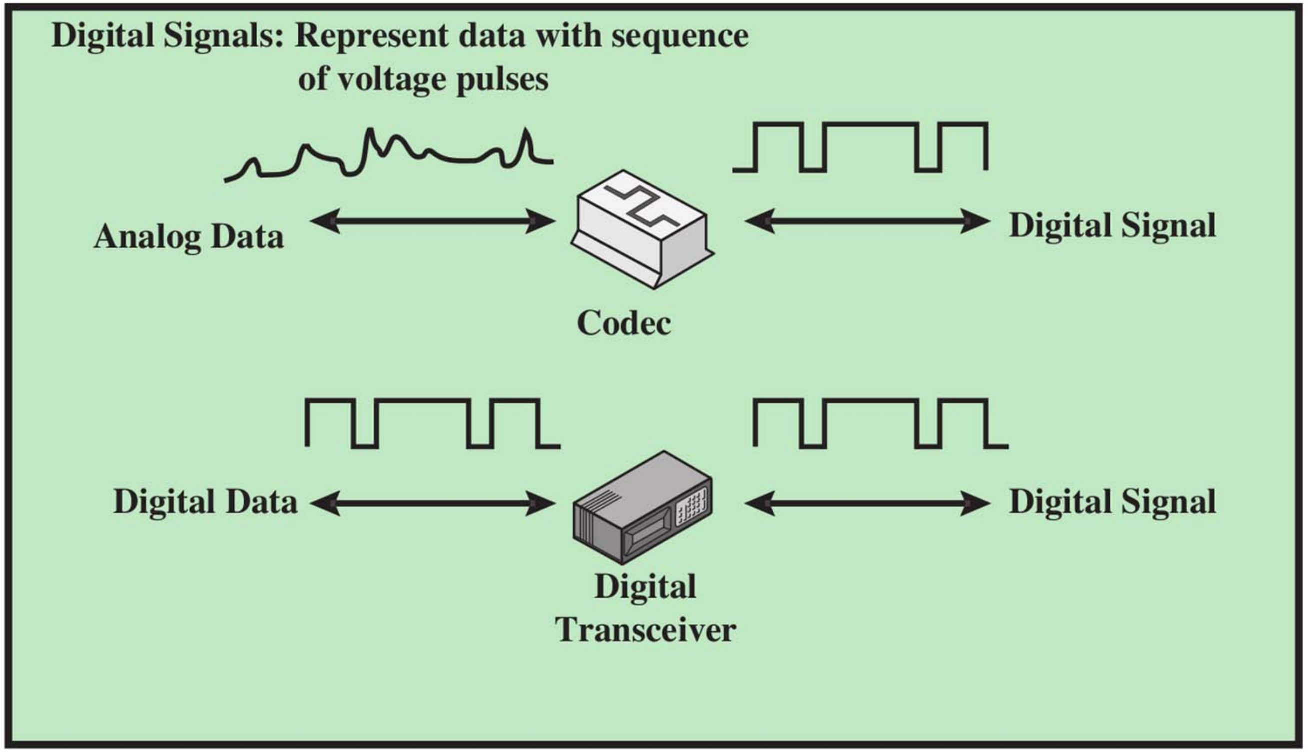
- Electric or electromagnetic representations of data
- Analog signal is continuously varying electromagnetic wave
- Digital signal is sequence of voltage pulses
- Digital signals generally cheaper and less susceptible to interference
- Digital signals suffer more from attenuation



Analog Signaling of Analog and Digital Data



Digital Signaling of Analog and Digital Data



Analog/Digital Signals and Data

	Analog Signal	Digital Signal
Analog Data	Two alternatives: (1) signal occupies the same spectrum as the analog data; (2) analog data are encoded to occupy a different portion of spectrum.	Analog data are encoded using a codec to produce a digital bit stream.
Digital Data	Digital data are encoded using a modem to produce analog signal.	Two alternatives: (1) signal consists of two voltage levels to represent the two binary values; (2) digital data are encoded to produce a digital signal with desired properties.

Analog vs Digital Transmission

- Analog transmission: analog signal is propagated through **amplifiers**
- Digital transmission: analog or digital signals are propagated through **repeaters**
- Digital transmission is preferred technology today: digital equipment, efficiently combine signals from different sources; security; repeaters can give more accurate data transmission

Treatment of Signals in Analog/Digital Transmission

	Analog Transmission	**Digital Transmission**
Analog Signal	Is propagated through amplifiers; same treatment whether signal is used to represent analog data or digital data.	Assumes that the analog signal represents digital data. Signal is propagated through repeaters; at each repeater, digital data are recovered from inbound signal and used to generate a new analog outbound signal.
Digital Signal	Not used	Digital signal represents a stream of 1s and 0s, which may represent digital data or may be an encoding of analog data. Signal is propagated through repeaters; at each repeater, stream of 1s and 0s is recovered from inbound signal and used to generate a new digital outbound signal.

Transmission Impairments

- Impairments are when things go wrong. We have our source transmitter as some data to send to the destination. We take that data, convert it into a signal, transmit the signal. Unfortunately, in real life, transmitted signal may degrade. There may be some impairments in the communication system such that the signal received is not the same as the signal transmitted

- Signal received may be different from signal transmitted causing:

- **Analog:** Degradation of signal quality
- **Digital:** Bit errors

- Most significant impairments:

1. Attenuation and attenuation distortion
2. Delay distortion
3. Noise

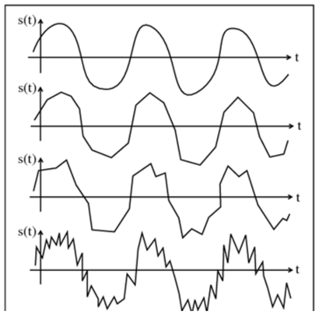


Fig. Signal Degradation

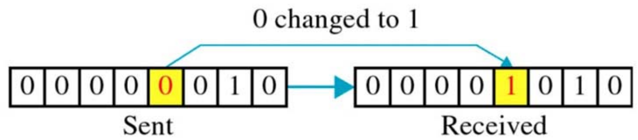


Fig. Bit error

Attenuation

- Signal strength reduces as a function of distance inevitably
- Designing a transmission system:

1. Received signal has sufficient strength to be interpreted by receiver electronics (receiver sensitivity)

2. Received signal is significantly higher than received noise to avoid errors (For ex: Two people trying to speak in a noisy place, they can hardly hear and understand each other if the noise is powerful. If he noise is more powerful than the power of their speech, they cannot hear each other, their speech will disappear in the noise)

- Attenuation distortion is a problem for analog signals:

- Attenuation is different at different frequencies
- Received signal has different strengths
- Apply equalization to overcome

Delay Distortion

- Component signals with different frequencies have different propagation delay through cable
- Some signal components representing a bit interfere with neighbour bits: intersymbol interference
- Apply equalization to overcome

Noise

- Noise is everything else that is transmitted in the system.
- **Thermal Noise**
  - Due to thermal agitation of electrons
  - **Always present** in all transmission devices and media (usually very small)
  - Noise as a function of temperature:

$$N = kTB$$

where k = Boltzmann's constant = 1.38 x 10^{-23} J/K,

B is bandwidth

T is temperature in Kelvins

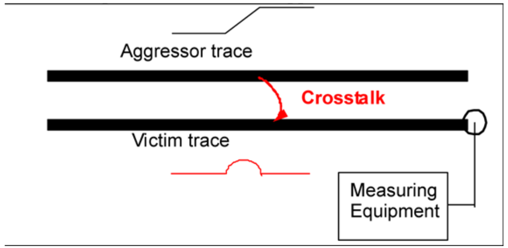
N is noise

- **Intermodulation Noise**
  - Caused when signals of different frequencies share the same medium

Noise

➢ **Crosstalk**

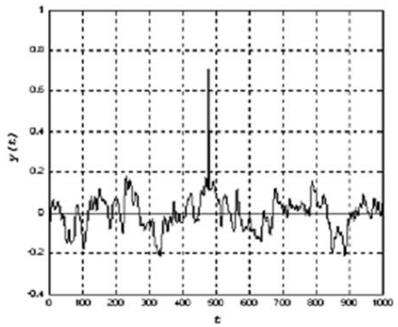
Unwanted coupling of different signals



Aggressor trace effects the victim trace

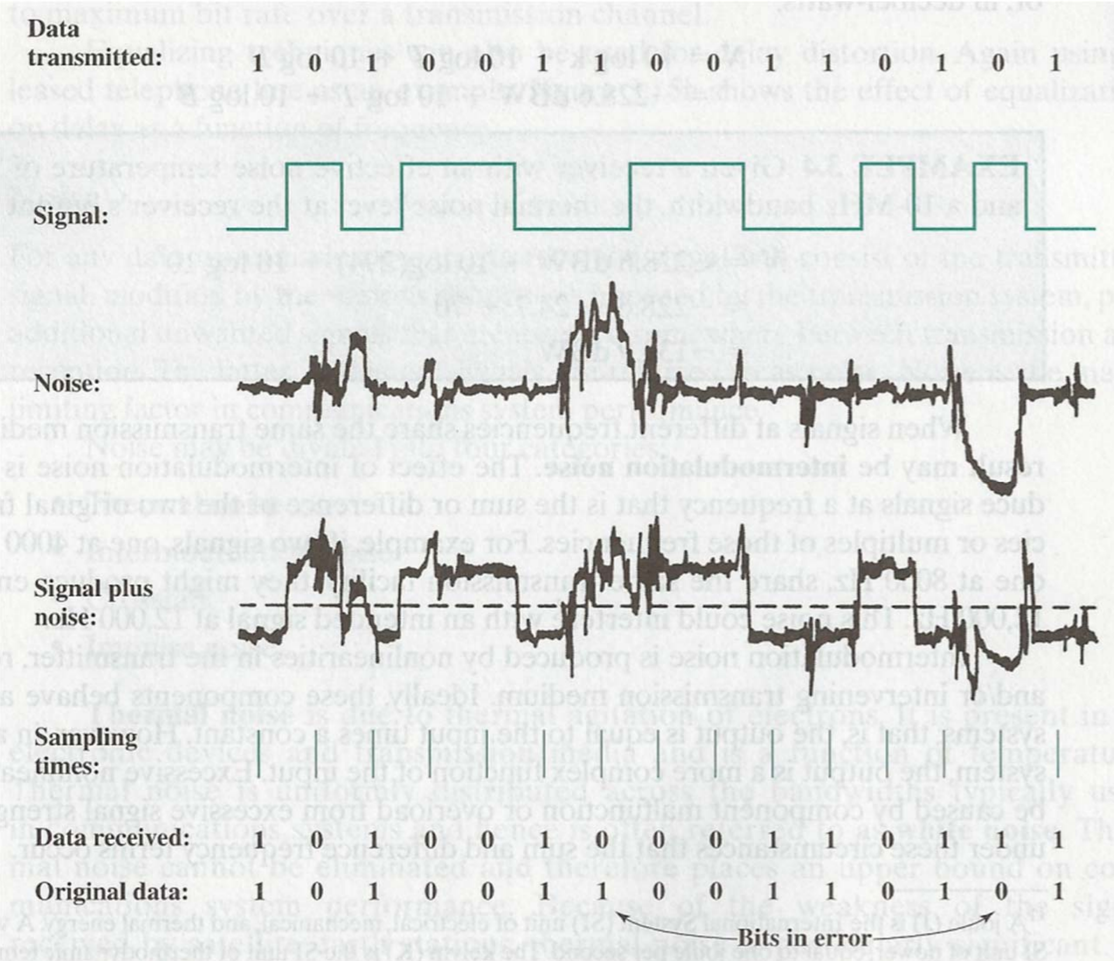
➢ **Impulse Noise**

Short peak of noise, e.g. lightning, electrical disturbances, flaws in communications system



Impulse noises are hard to predict and know how and when they are formed

Effect of Noise on a Digital Signal



Channel Capacity

- **Channel capacity:** Maximum data rate at which data can be transmitted over a given communication channel or link
- **Relate:**
  - Data rate, C (bits per second, b/s or bps)
  - Bandwidth, B (Hertz, Hz)
  - Noise
  - Error rate
- **Two theoretical models:**

  Nyquist Capacity: assumes noise-free environment

  Shannon Capacity: considers noise

Nyquist Capacity

- Assumes channel that is noise-free
- Given a bandwidth of B, the highest signal rate is 2B
- Single signal element may carry more than 1 bit; signal with M levels may carry $log_2 M$ bits. (In a typical digital signal, we have 2 levels, which are high meaning logic 1 and low meaning logic 0)

$$C = 2B\ log_2 M$$

- **Tradeoffs:**
  - Increase the bandwidth, increases the data rate
  - Increase the signal levels, increases the data rate
  - Increase the signal levels, harder for receiver to interpret the bits (practical limit to M)

Example

A telephone system with modem allows bandwidth of 3100Hz. What is the maximum data rate?

B=3100Hz (Realistic and typical telephone system bandwidth)

M=2 (Assume a typical digital signal)

C=$2B\log_2(M)$→ C=2*3100* $\log_2(2) = \mathbf{6200}$**bps**

If we use a simple signal with just two levels, the fastest data we can send, assuming there is no noise, is 6200bps.

Shannon Capacity

- With noise, some bits may be corrupted; higher data rate, more bits corrupted
- Increasing signal strength overcomes noise
- **Signal-to-noise ratio (SNR):**

$$SNR = \frac{signal\ power}{noise\ power}$$

- **Shannon capacity (C):**

$$C = B\log_2(1 + SNR)$$

- **Tradeoffs:**

  Increase bandwidth or signal power, increases data rate

  - Increase of noise, reduces data rate
  - Increase bandwidth, allows more noise
  - Increase signal power, causes increased intermodulation noise

Example

A channel uses spectrum of between 3MHz and 4MHz, with SNR=24dB. How many signal levels are required to achieve Shannon capacity?

B= 4MHz - 3MHz = 1MHz

$SNR_{dB} = 10\log(SNR)$ → 24= 10 log(SNR) → SNR≈251

C = $B\log_2(1 + SNR)$ → C= $1*10^6 * \log_2(1 + 251)$≈ **8Mbps**

We added the effect of the noise on the channel. Now we can use the Nyquist formula as if it is a noise-free channel. Therefore…

C = 2B $\log_2 M$→ $8*10^6$= $2*1*10^6 * \log_2(M)$ → **M=16**