Data Transmission

ITS323: Introduction to Data Communications
CSS331: Fundamentals of Data Communications

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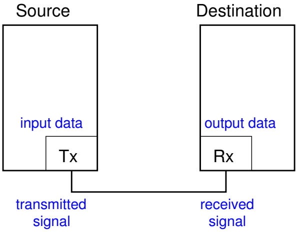
Contents

Data and Signals

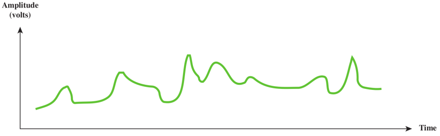
- Data communications involves transmitting data between a transmitter and receiver via some medium



- Communication is in form of electromagnetic waves or signals
- Signals used to represent data
- Design of signals and characteristics of medium impact on how effective the communications are
  - Can the signal be received?
  - Are there any errors in the data received?
  - Is the data received in timely manner?

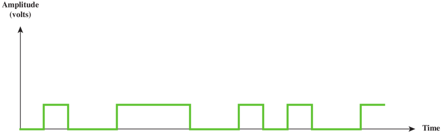
Analog and Digital Communication Signals

- Data can be analog or digital
- Signals can also be analog or digital



(a) Analog

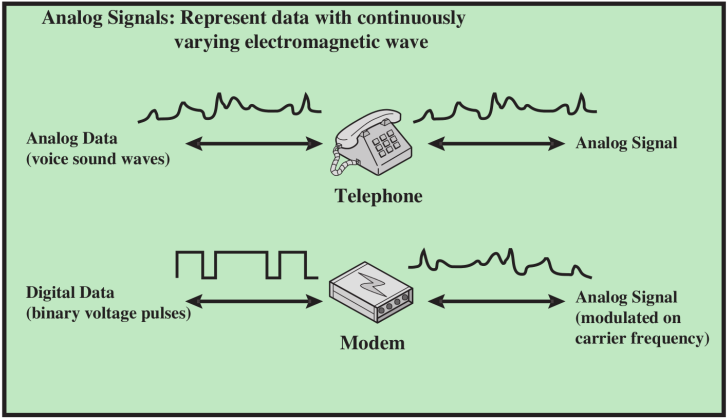
Analog signal varies in continuous manner over time



(b) Digital

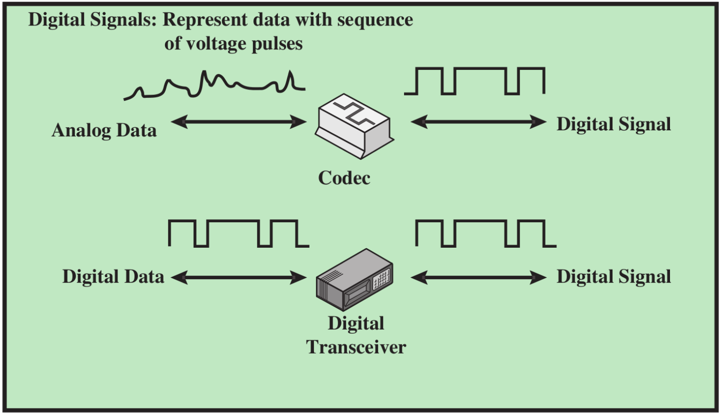
Digital signal maintains constant level for some period then changes to another constant level, in a discrete manner

Transmitting Data with Analog Signals



- Analog signals: telephone lines, audio systems, microwave wireless, . . .
- Efficient use of bandwidth, but noise is a problem

Transmitting Data with Digital Signals



- Digital signals: LANs, WANs, mobile telephones, ...
- Can tolerate noise better than analog; easier to implement transmitters/receivers (can use software)

Transmission Medium

- 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
- Examples in "Transmission Media" topic

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Communication Signal Design

- Designers of communications equipment and standards design signals that will achieve effective communications for the designated medium
- To simplify design, analysis, generation and reception, a signal is represented as the sum of one or more sinusoids (Fourier analysis)
- Data is represented in signals by varying properties of the sinusoids
- (Even digital signals can be viewed as summation of sinusoids)

Properties of Sinusoids

Signal amplitude, s, as a function of time, t:

$$s(t) = A \sin(2\pi f t + \phi)$$

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

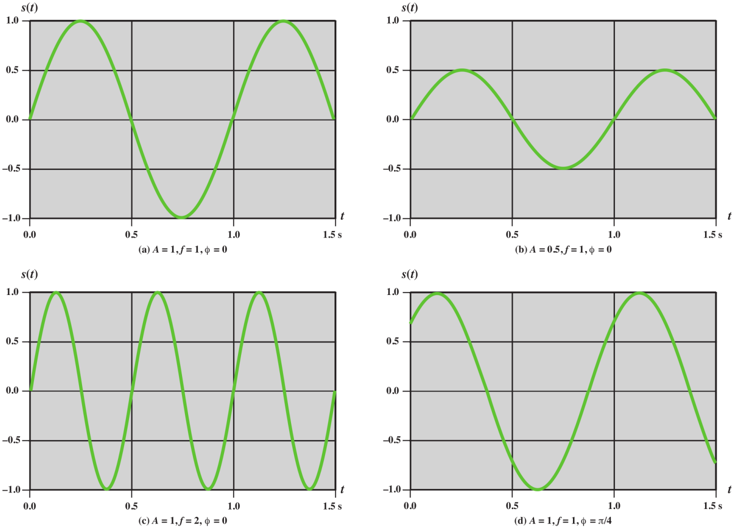
Frequency, f: rate at which signal repeats [cycles per second or Hertz]

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

Period, T: time for one repetition or cycle [seconds] ; $T = 1/f$

Wavelength, λ: distance occupied by one cycle [metres]; $\lambda = c/f$ where c is speed of light ($\approx 3 \times 10^8$m/s)

Sinusoid Signal



Example: Representing Digital Data in Signals

See "Communication Signals Example" handout

- What is a signal element?
- What is signalling rate?
- What is data rate?

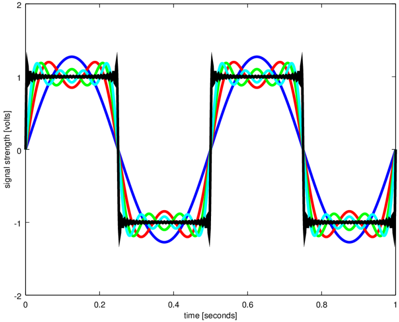
Complex Communication Signals

- Any periodic signal can be decomposed into the sum of a set of simple sinusoids
- See "Communication Signal Examples" handout
- A signal made up of component sinusoids has:
  - Fundamental frequency: lowest component frequency
  - Harmonic frequencies: integer multiples of fundamental frequency
  - Spectrum: range of frequencies of the components
  - Bandwidth: width of spectrum

Creating Square Wave from Sinusoids

For frequency f and peak amplitude A:

$$s_{square}(t) = A\frac{4}{\pi}\sum_{k=1}^{\infty}\frac{1}{(2k-1)}sin(2\pi f(2k-1)t)$$



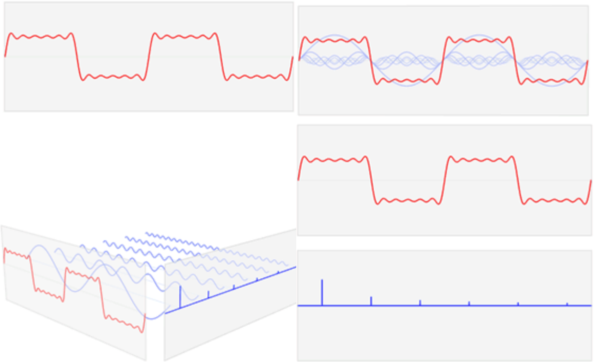
See "Communication Signal Examples" handout

Time Domain vs Frequency Domain

- Time Domain: signal amplitude vs time, $s(t)$
- Frequency Domain: signal peak amplitude vs frequency, $S(f)$
- To simplify design and analysis, communication signals often represented in frequency domain
- Important practical characteristics are easily visualised:

Cutoff Frequencies	lowest and highest frequency component for which amplitude is significantly lower than peak
Bandwidth	width between cutoff frequencies
Center Frequency	mean of cutoff frequencies
Channel	refers to medium that carries signals with particular bandwidth and center frequency

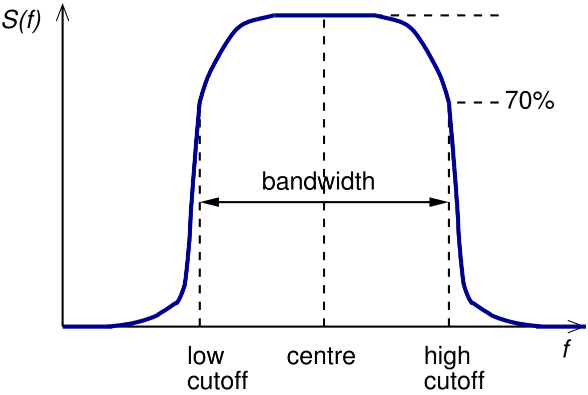
Example: Time to Frequency Domain



See animation at https://commons.wikimedia.org/wiki/File:Fourier_series_and_transform.gif

Credit: Lucas V. Barbosa, Wikimedia Commons, CC0 1.0 Universal Public Domain Dedication

Bandwidth of Signal in Practice



Cutoff frequencies are often defined in standards, e.g. 70% of peak voltage, 50% of peak power, 3 dB lower than peak power

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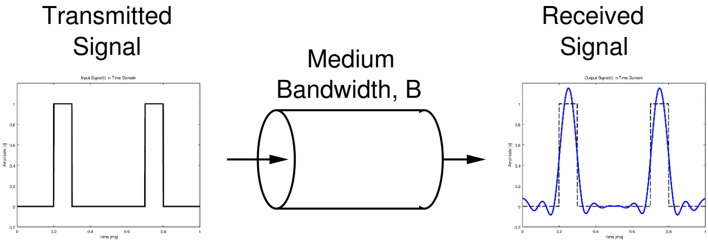
Practical Concerns of Frequency and Bandwidth

- Why do we care about signal frequency and bandwidth?
- Electromagnetic spectrum is limited resource: more frequencies used, higher the cost
- Signals of different frequencies propagate in different ways, impaired differently
- Range of frequencies (bandwidth) impacts on amount of data that can be transferred
- In practice, bandwidth of transmission medium is limited (either physically or by regulations; see “Transmission Media” topic)
- Medium will only carry frequencies within allowed bandwidth
- Challenge: given bandwidth B, design a signal that maximises data rate and minimises errors

Signal in Bandwidth Limited Medium



- Assume medium has bandwidth limit of B
- Transmit a digital signal, e.g. 1000 bits/second
- Transmitted signal has infinite bandwidth
- Received signal has bandwidth of B
- For what values of B is received signal adequate representation of data?

See "Communication Signal Examples" handout

Tradeoffs

Bandwidth

- Digital signal has infinite bandwidth; transmission systems impose limits on bandwidth of 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
- Limited bandwidth leads to more errors

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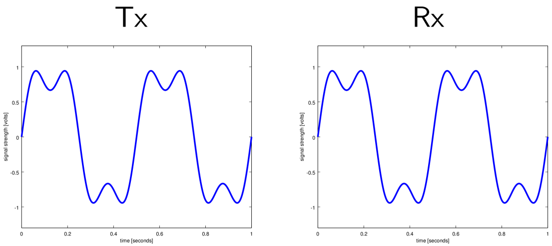
Transmission Impairments

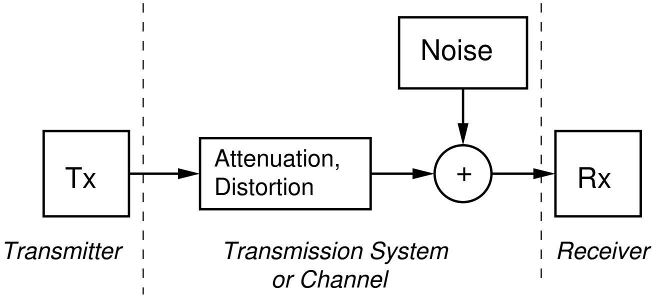
Perfect communications system: received signal is identical to that transmitted



Real communications system: received signal is different from that transmitted due to impairments

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

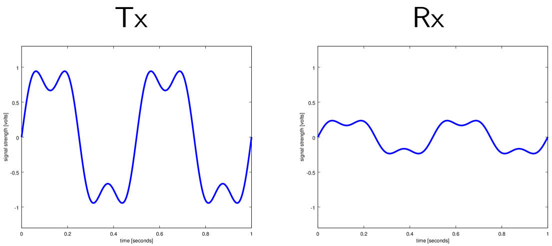
Model of Transmission Impairments



- Received signal is the attenuated/distorted transmitted signal plus noise
- Challenge for receiver: from the received signal, interpret the transmitted data

Attenuation

As signal propagates its strength reduces (attenuates) with distance travelled

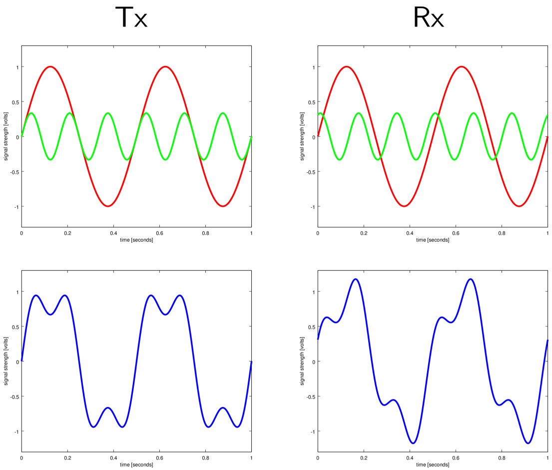


- Higher frequency components are attenuated more than lower frequency (attenuation distortion)
- Attenuation approx. proportional to distance squared (see Transmission Media topic for detailed models)

$$attenuation \propto d^2$$

Delay Distortion

Component signals with different frequencies travel at different speeds through medium



Noise: "Any unwanted input"

Different sources of noise:

Thermal due to thermal agitation of electrons; present in all transmission devices and media

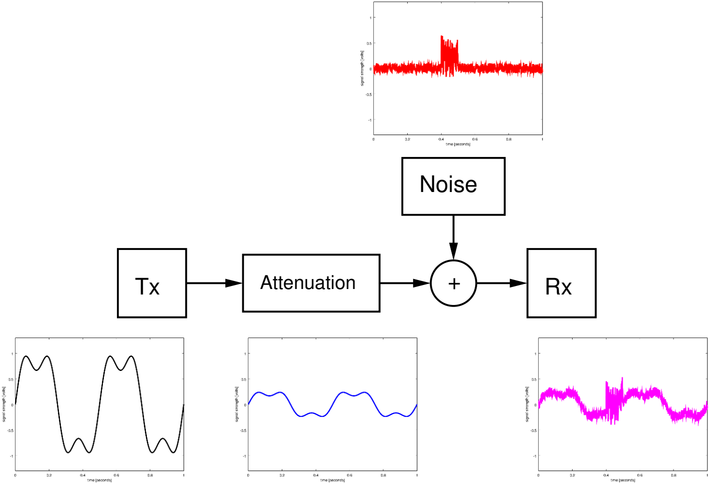
Intermodulation Interference from different frequencies sharing medium; caused by malfunctions or excessive signal strength

Crosstalk transmission from another source interferes with transmitted signal; from nearby cables, interference from other wireless transmitters

Impulse short spikes of noise from lightning, electrical disturbances, incorrectly operating devices

Noise is additive: noise from all sources is added together to get total noise (N); total noise is added to (attenuated/distorted) transmitted signal to get received signal

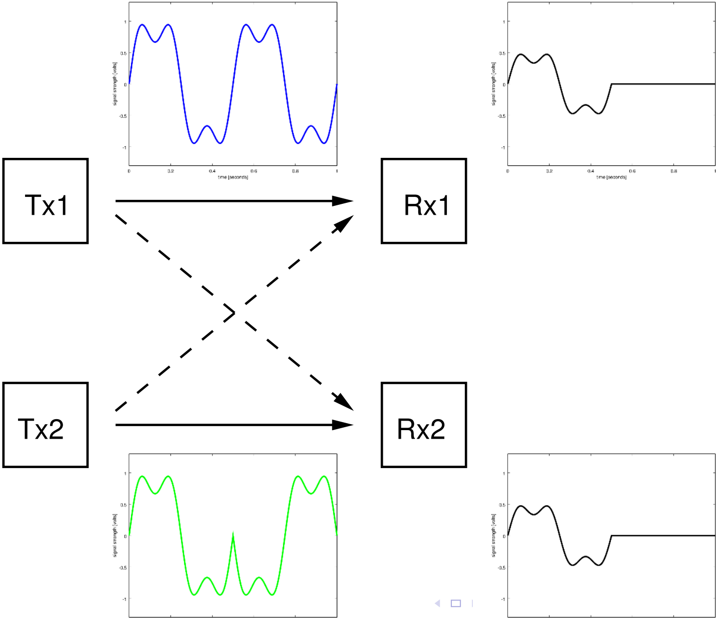
Attenuation and Noise



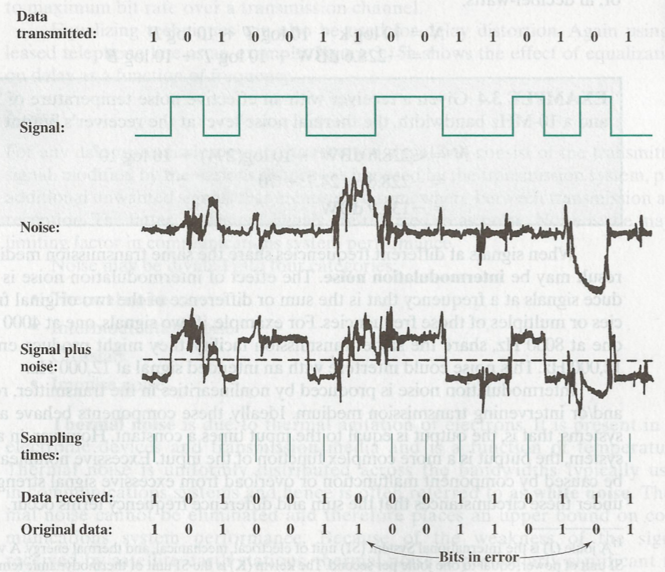
Crosstalk and Co-Channel Interference

- Signal transmitted on one channel has undesired effect on signal on another channel
- Example: two nearby wires with signal transmissions; one causes crosstalk noise on the other
- In wireless systems called co-channel interference
- Example: two radio devices transmit at same time on same center frequency; receiver receives both signals and unable to determine the correct data
  - Possible solution: devices transmit on different channels

Example: Co-Channel Interference



Effect of Noise on a Digital Signal



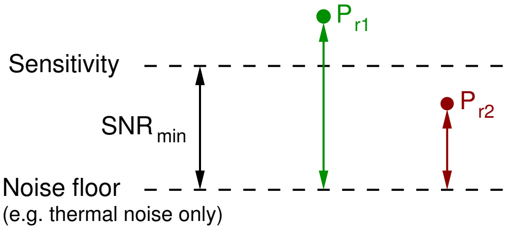
Credit: Figure 3.16 in Stallings, *Data and Computer Communications*, 9th ed., Pearson, 2011

Transmitter and Channel Characteristics

- Signal strength: peak amplitude of signal
  - power [Watts] $\propto$ voltage^2 [Volts]
- Transmit Power, P_t
- Transmission system or channel:
  - Loss, L: attenuation means signal loses power
  - Noise, N: amount of noise introduced
- Receiver receives attenuated signal plus noise
- Received signal must be such that receiver can "understand" the data

Receiver Characteristics

- Minimum signal-to-noise ratio, SNR_{min}: received signal must be greater than noise to be "understood"
- Noise floor: minimum amount of noise received, e.g. thermal noise
- Sensitivity: minimum received power for which signal can be "understood"



- P_{r1}: successfully received since $P_{r1} > sensitivity$ or $SNR_{r1} > SNR_{min}$
- P_{r1}: not received since $P_{r1} < sensitivity$ or $SNR_{r1} < SNR_{min}$

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Channel Capacity

- Channel capacity: maximum data rate at which data can be transmitted over a given communication channel
- Terminology: capacity, data rate, bit rate, . . .

  (unless stated otherwise, assume they are the same in this course)
- In practice complex relationship between data rate and:
  - Bandwidth
  - Signal power
  - Signal encoding
  - Noise
  - Error rate
- Theoretical models allow for easy analysis and knowing upper limits

  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

$$C = 2B \log_2 M$$

- 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 of Nyquist Capacity

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

Shannon Capacity

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

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

- Shannon capacity:

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

- 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 of Shannon and Nyquist Capacity

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