CSE 445: Mobile and Wireless Communication

Lecture 2: Basic Concepts of Wireless Transmission, Noise

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Frequencies for Radio Transmission

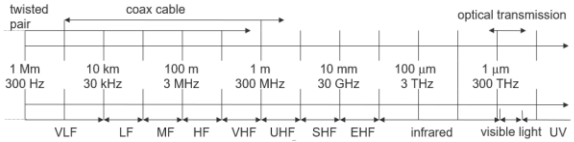
Frequencies for communication

VLF = Very Low Frequency
LF = Low Frequency
MF = Medium Frequency
HF = High Frequency
VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

Frequency and wave length

- $\lambda = c/f$
- wave length λ, speed of light $c \cong 3 \times 10^8$ m/s, frequency f



Example frequencies for mobile communication

- VHF-/UHF-ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - small antenna, beam forming
  - large bandwidth available
- Wireless LANs use frequencies in UHF to SHF range
  - some systems planned up to EHF
  - limitations due to absorption by, e.g., water (dielectric heating, see microwave oven)
    - weather dependent fading, signal loss caused by heavy rainfall etc.

Frequencies and regulations

Examples	Europe	USA	Japan
Cellular networks	**GSM** 880-915, 925-960, 1710-1785, 1805-1880 **UMTS** 1920-1980, 2110-2170 **LTE** 791-821, 832-862, 2500-2690	**AMPS, TDMA, CDMA, GSM** 824-849, 869-894 **TDMA, CDMA, GSM, UMTS** 1850-1910, 1930-1990	**PDC, FOMA** 810-888, 893-958 **PDC** 1429-1453, 1477-1501 **FOMA** 1920-1980, 2110-2170
Cordless phones	**CT1+** 885-887, 930-932 **CT2** 864-868 **DECT** 1880-1900	**PACS** 1850-1910, 1930-1990 **PACS-UB** 1910-1930	**PHS** 1895-1918 **JCT** 245-380
Wireless LANs	**802.11b/g** 2412-2472	**802.11b/g** 2412-2462	**802.11b** 2412-2484 **802.11g** 2412-2472
Other RF systems	27, 128, 418, 433, 868	315, 915	426, 868

In general: ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences); 3GPP specific: see e.g. [3GPP TS 36.101 V11.4.0 (2013-03)]

Signals for conveying information

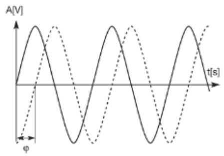
Signals I

- Physical representation of data
- Function of time and location
- Signal parameters: parameters representing the value of data

- Classification
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values

- Signal parameters of periodic signals:
  - period T, frequency f=1/T, amplitude A, phase shift φ
  - sine wave as special periodic signal for a carrier:

$$s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$$



Time Domain Concepts

- Frequency (f)
  - Rate, in cycles per second, or Hertz (Hz) at which the signal repeats
- Period (T) - amount of time it takes for one repetition of the signal
  - $T = 1/f$
- Phase (ϕ) - measure of the relative position in time within a single period of a signal
- Wavelength (λ) - distance occupied by a single cycle of the signal
  - Or, the distance between two points of corresponding phase of two consecutive cycles

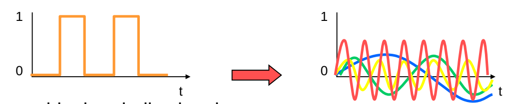
Time Domain Concepts contniued

- Analog signal - signal intensity varies in a smooth fashion over time
  - No breaks or discontinuities in the signal
- Digital signal - signal intensity maintains a constant level for some period of time and then changes to another constant level
- Periodic signal - analog or digital signal pattern that repeats over time
  - $s(t + T) = s(t)$ $-\infty < t < +\infty$
    - where T is the period of the signal
- Aperiodic signal - analog or digital signal pattern that doesn't repeat over time
- Peak amplitude (A) - maximum value or strength of the signal over time; typically measured in volts

Fourier representation of periodic signals

- Signals can also be expressed as a function of frequency
- Signal consists of components of different frequencies

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$



ideal periodic signal

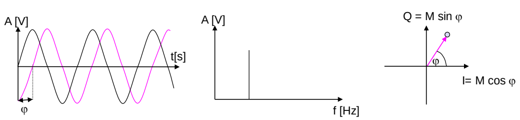
real composition (based on harmonics)

Frequency Domain Concepts

- Fundamental frequency - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency.
- Spectrum - range of frequencies that a signal contains.
- Absolute bandwidth - width of the spectrum of a signal.
- Effective bandwidth (or just bandwidth) - narrow band of frequencies that most of the signal's energy is contained in.
- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases.
- The period of the total signal is equal to the period of the fundamental frequency.

Signal representation

- Different representations of signals
  - amplitude (amplitude domain)
  - frequency spectrum (frequency domain)
  - constellation diagram (amplitude M and phase φ in polar coordinates)



- Composed signals transferred into frequency domain using Fourier transformation
- Digital signals need
  - infinite frequencies for perfect transmission
  - modulation with a carrier frequency for transmission (analog signal!)

ANALOG AND DIGITAL DATA TRANSMISSION

Data Communication Terms

- Data - entities that convey meaning, or information
- Signals - electric or electromagnetic representations of data
- Transmission - communication of data by the propagation and processing of signals
- Examples of Analog/Digital Data:
  - Analog
    - Video
    - Audio
  - Digital
    - Text
    - Integers

Analog and Digital Signals (Review)

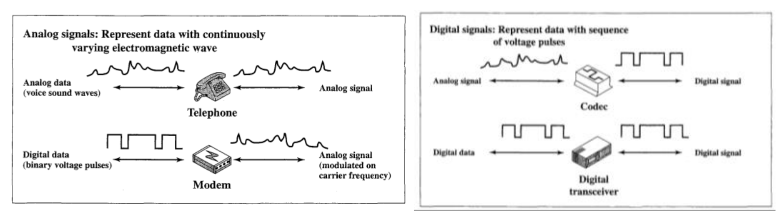
Analog

- A continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency
- Examples of media:
  - Copper wire media (twisted pair and coaxial cable)
  - Fiber optic cable
  - Atmosphere or space propagation
- Analog signals can propagate analog and digital data

Digital

- A sequence of voltage pulses that may be transmitted over a copper wire medium
- Generally cheaper than analog signaling
- Less susceptible to noise interference
- Suffer more from attenuation
- Digital signals can propagate analog and digital data

Analog and Digital Signaling of Analog and Digital Data



Reasons for Choosing Data and Signal Combinations

- Digital data, digital signal
  - Equipment for encoding is less expensive than digital-to-analog equipment
- Analog data, digital signal
  - Conversion permits use of modern digital transmission and switching equipment
- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - Examples include optical fiber and satellite
- Analog data, analog signal
  - Analog data easily converted to analog signal

Analog and Digital Transmission

Analog

- Transmitting analog signals without regard to their content.
- will suffer attenuation that limits the length of the transmission ink.
- To achieve longer distances, include amplifiers that boost the energy in the signal.
- But, the amplifier also boosts the noise components.
- With amplifiers cascaded to achieve long distance, the signal becomes more and more distorted.
- For analog data, small distortion can be tolerated and the data remain intelligible.
- But, for digital data transmitted as analog signals, cascaded amplifiers will introduce errors.

Digital

- is concerned with the content of the signal.
- can be propagated only a limited distance before attenuation endangers the integrity of the data.
- To achieve greater distances, repeaters are used.
- A repeater receives the digital signal, recovers the pattern of ones and zeros, and retransmits a new signal.
- Thus, the attenuation is overcome.

Channel Capacity

- Impairments, such as noise, limit data rate that can be achieved
- Channel Capacity – the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions
- Data rate - rate at which data can be communicated (bps)
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - Error = transmit 1 and receive 0; transmit 0 and receive 1

Relationship between Data Rate and Bandwidth

- There is a direct relationship between the information carrying capacity of a signal and its bandwidth
- The greater the bandwidth, the higher the information carrying capacity
- Conclusions
  - Any digital waveform will have infinite bandwidth
  - BUT the transmission system will limit the bandwidth that can be transmitted
  - AND, for any given medium, the greater the bandwidth transmitted, the greater the cost
  - HOWEVER, limiting the bandwidth creates distortions

Noise

Noise

- Noise is defined as any unwanted form of energy that tends to interfere with proper reception and reproduction of wanted signal.
- Noise can be classified into 2 broad types
  - External Noise (Whose source is external)
    - Atmospheric Noise
    - Extraterrestrial Noise
    - Man made Noise or industrial Noise
  - Internal noise (Whose source is internal, i.e. generated in the system)
    - Thermal Noise
    - Shot Noise
    - Miscellaneous Noise

External Noises

- Atmospheric Noise
  - It is caused by lightning discharge in thunderstorm and other natural electrical disturbance occurring in the atmosphere. These electrical impulses are random in nature.
- Extraterrestrial Noise
  - Solar Noise: This is the electrical noise emanating from the sun. Under quiet conditions there is a steady radiation of noise from the sun. The noises are due to the extreme high temperature of the sun.
  - Cosmic Noise: Distance stars are also sun-like and have very high temperature. They also emit noises. These noises are thermal noise.
- Industrial / Man-made Nosie
  - These are the noises produced by man made objects like automobile and aircraft engines, electrical motor and switchgears. They can only be analyzed statistically.

Internal Noise – Thermal Noise

- Thermal Noise also known as agitation noise, white noise, or jhonson noise is the random noise generated in a resistor or the resistive component of a complex impedance due to the random motion of the molecules, atoms and electrons.
- As per kinetic theory of thermodynamics, the temperature of a particle simply expresses its internal kinetic energy. As per this theory the kinetic energy of the system becomes 0 in absolute zero temperature.
- The noise power generated by a resistor is proportional to the absolute temperature.

Internal Noise – Thermal Noise

- The power is given by

$$P_n = \bar{k}TB$$

Here $\bar{k}$=Boltzmann constant = $1.38 \times 10^{-23} J/K$

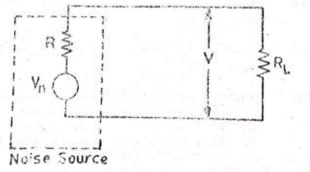
T= Absolute Temperature

B= Bandwidth in Hertz

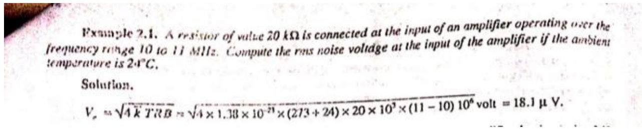
Again $P_n = \frac{V^2}{R_L} = \frac{V^2}{R} = \frac{\left(\frac{Vn}{2}\right)^2}{R} = \frac{V_n^2}{4R}$

Assuming $R_L = R$

$$V_n = \sqrt{4\bar{k}TBR}$$



Noise Example

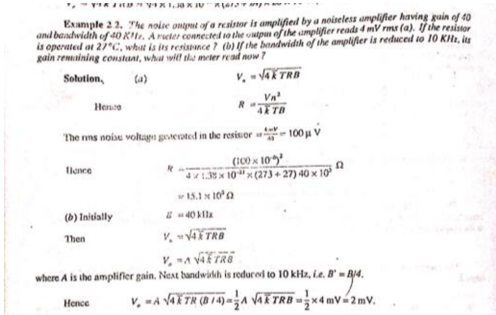


Example 2.1. *A resistor of value 20 kΩ is connected at the input of an amplifier operating over the frequency range 10 to 11 MHz. Compute the rms noise voltage at the input of the amplifier if the ambient temperature is 24°C.*

Solution.

$V_n = \sqrt{4\bar{k}TRB} = \sqrt{4 \times 1.38 \times 10^{-23} \times (273+24) \times 20 \times 10^3 \times (11-10)\,10^6}$ volt $= 18.1\ \mu$ V.

Noise Example



Example 2.2. *The noise output of a resistor is amplified by a noiseless amplifier having gain of 40 and bandwidth of 40 KHz. A meter connected to the output of the amplifier reads 4 mV rms (a). If the resistor is operated at 27°C, what is its resistance? (b) If the bandwidth of the amplifier is reduced to 10 KHz, its gain remaining constant, what will the meter read now?*

Solution. (a) $V_n = \sqrt{4\bar{k}TRB}$

Hence $R = \frac{Vn^2}{4\bar{k}TB}$

The rms noise voltage generated in the resistor $= \frac{4\,mV}{40} = 100\ \mu$ V

Hence $R = \frac{(100 \times 10^{-6})^2}{4 \times 1.38 \times 10^{-23} \times (273+27)\,40 \times 10^3}\ \Omega$

$= 15.1 \times 10^3\ \Omega$

(b) Initially $B = 40$ kHz

Then $V_n = \sqrt{4\bar{k}TRB}$

$V_o = A\sqrt{4\bar{k}TRB}$

where A is the amplifier gain. Next bandwidth is reduced to 10 kHz, *i.e.* $B' = B/4$.

Hence $V_o = A\sqrt{4\bar{k}TR\,(B/4)} = \frac{1}{2}A\sqrt{4\bar{k}TRB} = \frac{1}{2} \times 4\text{ mV} = 2\text{ mV}$.

Internal Noise – Shot Noise

- Shot noise results from the shot effect present in all amplifying devices.
- It is cause by the random variations in the arrival of electrons (or holes) at the output electrode (Collector in case of common emitter amplifier).
- For diodes the RMS shot noise current is given by

$$I_n = \sqrt{2qI_pB}$$

Here q=Charge of electron=$1.6 \times 10^{-19} C$

I_p= the direct diode current

B= Bandwidth of the system in hertz

Internal Noise – Miscelleneous Noise

- Transit Time Noise
- Flicker Noise
- Partition Noise
- Noise of frequency Mixers
- …..

Signal to Noise Ratio (SNR)

- Signal to Noise Ratio is defined as the ratio of signal power to noise power at the same point I the system.
- Typically measured at a receiver
- Mathematically it is

$$SNR = \frac{S}{N} = \frac{P_S}{P_n} = \frac{V_S^2/R}{V_n^2/R} = \left(\frac{V_S}{V_n}\right)^2$$

- SNR can be also represented in Decibell

$$SNR_{DB} = 10\log\frac{S}{N}$$

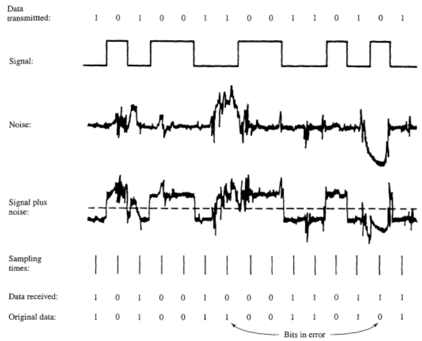
- A high SNR means a high-quality signal, low number of required intermediate repeaters
- SNR sets upper bound on achievable data rate

Noise Figure (NF or F)

- The Noise Figure is defined as the ratio of the signal-to-noise power supplied at the input to the signal-to-noise power supplied to the output load impedance
- Mathematically it is

$$F = \frac{S/N\ at\ the\ input}{S/N\ at\ the\ output}$$

Effect of Noise on a Digital Signal



Nyquist Bandwidth

- if the rate of signal transmission is 2B, then a signal with frequencies no greater than B is sufficient to carry the signal rate.
- Given a bandwidth of B, the highest signal rate that can be carried is 2B.
- This limitation is due to the effect of inter-symbol interference, such as is produced by delay distortion.
  - For binary signals (two voltage levels)
    - C=2B
  - With multilevel signaling
    - $C = 2B \log_2 M$
      - M= number of discrete signal or voltage levels

C= Bitrate or capacity
B= Bandwidth

Shannon Capacity Formula

- Nyquist's formula indicates that, all other things being equal, doubling the band- width doubles the data rate.
- Now consider the relationship among data rate, noise, and error rate.
- Shannon Equation:

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

C= Bitrate or capacity
B= Bandwidth
SNR used as ratio NOT in DB

- Represents theoretical maximum that can be achieved
- In practice, only much lower rates achieved
  - Formula assumes white noise (thermal noise)
  - Impulse noise is not accounted for
  - Attenuation distortion or delay distortion not accounted for

Example (From Forouzan)

Example 3.34

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as

$$\text{BitRate} = 2 \times 3000 \times \log2\ 2 = 6000 \text{ bps}$$

Example 3.35

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate can be calculated as

$$\text{BitRate} = 2 \times 3000 \times \log2\ 4 = 12{,}000 \text{ bps}$$

Example (From Forouzan)

Example 3.37

Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. For this channel the capacity C is calculated as

$$C = B \log2\ (1 + \text{SNR}) = B\ 10g_Z\ (1 + 0) = B \log2\ 1 = B \times 0 = 0$$

This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot receive any data through this channel.

Example 3.39

The signal-to-noise ratio is often given in decibels. Assume that SNR_{dB} = 36 and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as

$$SNR_{dB} = 10\ \text{loglO}\ SNR \rightarrow SNR = 10^{SNR_{dB}/10} \rightarrow SNR = 10^{3.6} = 3981$$

$$C = B \log2\ (1+ SNR) = 2 \times 10^6 \times \log2\ 3982 = 24 \text{ Mbps}$$

Example (From Forouzan)

- The Shannon capacity gives us the upper limit;
- the Nyquist formula tells us how many signal levels we need.

Example 3.41

We have a channel with a I-MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?

Solution

First, we use the Shannon formula to find the upper limit.

$$C = B \log2 (1 + \text{SNR}) = 10^6 \log2 (1 + 63) = 10^6 10g_2 64 = 6 \text{ Mbps}$$

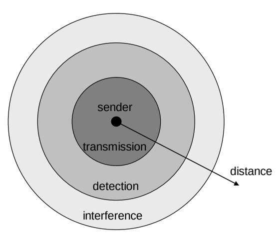
The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps, for example. Then we use the Nyquist formula to find the number of signal levels.

$$4\text{Mbps} = 2\text{x } 1 \text{ MHz x } log_2 L \Rightarrow L = 4$$

Signal Propagation

Signal propagation ranges

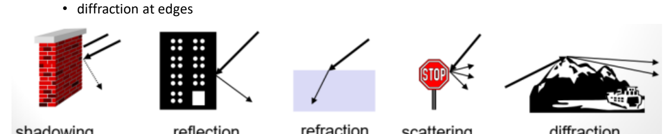
- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise



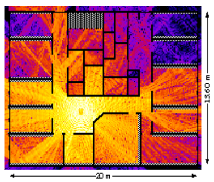
- Warning: figure misleading – bizarre shaped, time-varying ranges in reality!

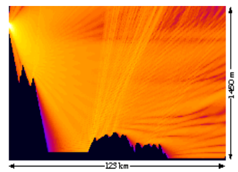
Signal Propagation

- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$ in vacuum – much less in real environments, e.g., $1/d^{3.5}...1/d^4$ (d = distance between sender and receiver)
- Receiving power additionally influenced by
  - fading (frequency dependent)
  - Shadowing
  - reflection at large obstacles
  - refraction depending on the density of a medium
  - scattering at small obstacles
  - diffraction at edges



Real world examples





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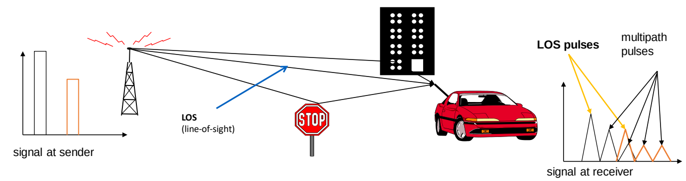
Multipath propagation

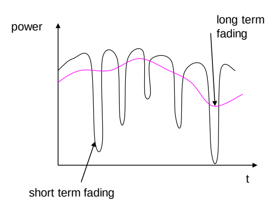
- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time
  - interference with “neighbor” symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
  - distorted signal depending on the phases of the different parts

Effects of mobility

- Channel characteristics change over time and location
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts
- ➔ quick changes in the power received (short term fading)



- Additional changes in
  - distance to sender
  - obstacles further away
- ➔ slow changes in the average power received (long term fading)

Signal Propagation

- Further details will be studied later

Recommended Text for this lecture

- Mobile Communications by Jochen Schiller
  - Chapter 2 [Up-to 2.2 and 2.4]
- Radio Engineering by G.K. Mitthal
  - Chapter 2 [Noise]
- Data Communications and Networking by Behrouz A. Forouzan
  - Chapter 3 [Practice Relevant examples about the topics discussed here]
- Communication Systems Engineering by John G. Proakis
  - Refer to chapter 2 to review frequency domain analysis

Disclaimer

- This Presentation contains some edited version of slides provided by Jochen Schiller writer of the book Mobile Communications.
- There is also some screenshots from different books.
- Some online images are also used.

*I have tried to cite any source. But if any citation is missed, kindly contact me to add your citation.

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