Digital Communication
Basic Concept and Definitions, Signals and Systems

Lecture-1

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Scope of the course

- Communication is a process by which information is exchanged between individuals through a common system of symbols, signs, or behavior

- Communication systems are reliable, economical and efficient means of communications
  - Public switched telephone network (PSTN), mobile telephone communication (GSM, 3G, ...), broadcast radio or television, navigation systems, ...

- The course is aiming at introducing fundamental issues in designing a (digital) communication system
Scope of the course ...

- Example of a (digital) communication systems:
  Cellular wireless communication systems
Scope of the course ...

General structure of a communication systems

- **Source**
  - Formatter
  - Transmitter
    - Source encoder
    - Channel encoder
    - Modulator
  - Transmitted signal
  - Noise
  - Received signal
- **Channel**
  - Received info.
- **Receiver**
  - Demodulator
  - Decoder
  - Decoder
  - Received info.
- **User**
Scope of the course ...

- Learning fundamental issues in designing a digital communication system (DCS):
  - Utilized techniques
    - Formatting and source coding
    - Modulation (Baseband and bandpass signaling)
    - Channel coding
    - Equalization
    - Synchronization
    - 
  - Design goals
  - Trade-offs between various parameters
Digital communication system

• Important features of a DCS:
  – Transmitter sends a waveform from a finite set of possible waveforms during a limited time
  – Channel distorts, attenuates the transmitted signal and adds noise to it.
  – Receiver decides which waveform was transmitted from the noisy received signal
  – Probability of erroneous decision is an important measure for the system performance
Digital versus analog

- Advantages of digital communications:
  - Regenerator receiver
  - Different kinds of digital signal are treated identically.

\[\text{Original pulse} \rightarrow \text{Regenerated pulse}\]

- A bit is a bit!
Classification of signals

- Deterministic and random signals
  - Deterministic signal: No uncertainty with respect to the signal value at any time.
  - Random signal: Some degree of uncertainty in signal values before it actually occurs.
    - Thermal noise in electronic circuits due to the random movement of electrons
    - Reflection of radio waves from different layers of ionosphere
Classification of signals ...

- Periodic and non-periodic signals

A periodic signal

A non-periodic signal

- Analog and discrete signals

Analog signals

A discrete signal
Classification of signals ..

• Energy and power signals
  – A signal is an energy signal if, and only if, it has nonzero but finite energy for all time:

\[
E_x = \lim_{T \to \infty} \int_{T/2}^{T} |x(t)|^2 dt = \int_{-\infty}^{\infty} |x(t)|^2 dt
\]

\[(0 < E_x < \infty)\]

  – A signal is a power signal if, and only if, it has finite but nonzero power for all time:

\[
P_x = \lim_{T \to \infty} \frac{1}{T} \int_{T/2}^{T} |x(t)|^2 dt
\]

\[(0 < P_x < \infty)\]

  – General rule: Periodic and random signals are power signals. Signals that are both deterministic and non-periodic are energy signals.
Random process

- A random process is a collection of time functions, or signals, corresponding to various outcomes of a random experiment. For each outcome, there exists a deterministic function, which is called a sample function or a realization.
Random process ...

- **Strictly stationary**: If none of the statistics of the random process are affected by a shift in the time origin.

- **Wide sense stationary (WSS)**: If the mean and autocorrelation function do not change with a shift in the origin time.

- **Cyclostationary**: If the mean and autocorrelation function are periodic in time.

- **Ergodic process**: A random process is ergodic in mean and autocorrelation, if

  \[ m_X = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} X(t) dt \]

  and

  \[ R_X(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} X(t)X^*(t - \tau) dt \]
Autocorrelation

• Autocorrelation of an energy signal
  \[ R_x(\tau) = x(\tau) \ast x^*(-\tau) = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)dt \]

• Autocorrelation of a power signal
  \[ R_x(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t)x^*(t-\tau)dt \]
  - For a periodic signal:
  \[ R_x(\tau) = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} x(t)x^*(t-\tau)dt \]

• Autocorrelation of a random signal
  \[ R_X(t_i, t_j) = E[X(t_i)X^*(t_j)] \]
Spectral density

- **Energy signals:**
  \[ E_x = \int_{-\infty}^{\infty} |x(t)|^2 dt = \int_{-\infty}^{\infty} |X(f)|^2 df \quad X(f) = \mathcal{F}[x(t)] \]

  - Energy spectral density (ESD):
    \[ \Psi_x(f) = |X(f)|^2 \]

- **Power signals:**
  \[ P_x = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} |x(t)|^2 dt = \sum_{n=-\infty}^{\infty} |c_n|^2 \quad \{c_n\} = \mathcal{F}[x(t)] \]

  - Power spectral density (PSD):
    \[ G_x(f) = \sum_{n=-\infty}^{\infty} |c_n|^2 \delta(f - nf_0) \quad f_0 = 1/T_0 \]

- **Random process:**
  - Power spectral density (PSD):
    \[ G_X(f) = \mathcal{F}[R_X(\tau)] \]
Noise in communication systems

- Thermal noise is described by a zero-mean Gaussian random process, \( n(t) \).
- Its PSD is flat, hence, it is called white noise.

\[
p(n) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left[ -\frac{n^2}{2\sigma^2} \right]
\]

Power spectral density

\[
G_n(f) = \frac{N_0}{2} \text{ [w/Hz]}
\]

Autocorrelation function

\[
R_n(\tau) = \frac{N_0}{2} \delta(\tau)
\]
Signal transmission through linear systems

- Deterministic signals:
  \[ Y(f) = X(f)H(f) \]

- Random signals:
  \[ G_Y(f) = G_X(f)|H(f)|^2 \]

- Ideal distortion less transmission:
  All the frequency components of the signal not only arrive with an identical time delay, but also are amplified or attenuated equally.

  \[ y(t) = Kx(t - t_0) \quad \text{or} \quad H(f) = Ke^{-j2\pi ft_0} \]
Signal transmission … - cont’d

- **Ideal filters:**

  - **Low-pass**
  
  \[ |H(f)| \]

  - **Band-pass**
  
  \[ |H(f)| \]

  - **High-pass**
  
  \[ |H(f)| \]

- **Realizable filters:**

  - **RC filters**
  
  \[ H(f) = \frac{1}{1 + j2\pi f RC} \]

  - **Butterworth filter**
  
  \[ |H_n(f)| = \frac{1}{\sqrt{1+(f/f_u)^{2n}}} \]
Bandwidth of signal

- Baseband versus bandpass:

\[ x(t) \xrightarrow{\text{Local oscillator}} x_c(t) = x(t) \cos(2\pi f_c t) \]

- **Bandwidth dilemma:**
  - Bandlimited signals are not realizable!
  - Realizable signals have infinite bandwidth!
Bandwidth of signal ...

- Different definition of bandwidth:
  a) Half-power bandwidth
  b) Noise equivalent bandwidth
  c) Null-to-null bandwidth
  d) Fractional power containment bandwidth
  e) Bounded power spectral density
  f) Absolute bandwidth