Analog vs. Digital Communications

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- Communication vs. Communications
  - an episode
  - cf. telecommunications

- 3 elements of communications
  - transmitter (Tx, TX)
  - channel
  - receiver (Rx, RX)
  - cf. transceiver = Tx + Rx

- 5 elements of communications
  - Information source
  - Encoder (ENC)
  - Channel
  - Decoder (DEC)
  - Information sink/destination

- A classification of communications: numbers of sources and destinations
  - point-to-point communications over a single-user channel
    - Given an information source, an information sink/destination, and a communication channel,
    - design an encoder and a decoder pair that enables a reliable communication.
  - point-to-multipoint communications over a broadcasting channel (BC)
  - multipoint-to-point communications over a multiple access channel (MAC)
  - multipoint-to-multipoint communications

- Another classifications of communications
  - one-way versus two-way communications
  - single hop versus multihop communications
  - acoustic wave versus electromagnetic wave communications
  - analog versus digital communications
  - ...

- Radio Communications
  - 3 kHz – 300 GHz Radio Frequency (RF) band of electromagnetic (EM) wave is used for communications.
    - 3-30 Hz: Extremely Low Frequency (ELF)
    - 30-300 Hz: Super Low Frequency (SLF)
    - 300-3000 Hz: Ultra Low Frequency (ULF)
    - 3-30 kHz: Very Low Frequency (VLF)
    - 30-300 kHz: Low Frequency (LF)
    - 300 kHz - 3 MHz: Medium Frequency (MF)
    - 3-30 MHz: High Frequency (HF)
    - 30-300 MHz: Very High Frequency (VHF)
    - 300 MHz - 3 GHz: Ultra High Frequency (UHF)
    - 3-30 GHz: Super High Frequency (SHF)
    - 30- 300 GHz: Extremely High Frequency (EHF)
    - 300 GHz - 3000 GHz: Tremendously High Frequency (THF)
  - Transmit and receive antennas are used for RF communications.

- Analog versus digital communications
  - whether the source output is digitized or not
    - discrete-time (DT) or vector-valued signal
    - finite precision, finite number of bits
  - Why?
    - It is easier to systematically insert redundancy that matches the channel characteristic.
    - More reliable and secure communication is possible.
    - low cost, low power, small size
    - any time, any where, any person, any application, etc.

- carrier
  - $\cos(2\pi f_c t + \theta) = \mathrm{Re}\{e^{\mathrm{j}(2\pi f_c t + \theta)}\}$
  - continuous wave (CW), tone signal
  - carrier frequency
  - magnitude, phase
  - amplitude, angle
  - modulation
    - amplitude modulation
    - angle modulation
  - demodulation

- Amplitude Modulation (AM)

$$X(t) = (A + m(t)) \cos(2\pi f_c t + \theta)$$

  where

  - $X(t)$: proportional to the current applied to the transmit antenna. real-valued.
  - $m(t)$: usually an electric signal that is converted from acoustic signal by a microphone
  - A: a bias used for envelope detection in a receiver
  - f_c: carrier frequency. 535-1605 kHz in Korea
  - θ: phase of carrier
  - Information is conveyed in signal amplitude.
  - $m(t)$ amplitude modulates the carrier signal.

- The received signal is modeled by

$$Y(t) = \sum_{l=1}^{L} \alpha_l X(t - \tau_l) + N(t)$$

  where

  - $Y(t)$: proportional to the current induced as the receive antenna. real-valued.
  - There are multiple paths from the source to the destination.
  - α_l: gain of the lth path
  - τ_l: propagation delay of the lth path

– If $A = 0, L = 1$, and $N(t) = 0$ then $m(t)$ can be recovered by lowpass filtering the signal

$$Y(t)\cos(2\pi f_c(t-\tau_1)+\theta) = \alpha_1 m(t-\tau_1)\cos^2(2\pi f_c(t-\tau_1)+\theta)$$
$$= \alpha_1 m(t-\tau_1)\frac{1+\cos(4\pi f_c(t-\tau_1)+2\theta)}{2}.$$

– Since θ is not known to the receiver, we choose $A \geq \max_t |m(t)|$ to implement an envelope detector (ED) that enables low complexity reception without phase estimation.

- Frequency Modulation (FM)

$$X(t) = \cos\left(2\pi f_c t + h\int_{-\infty}^{t} m(s)ds + \theta\right)$$

  where

  - h: a constant used to adjust the bandwidth of the signal
  - f_c: carrier frequency. 88-108 MHz in Korea
  - θ: phase of carrier
  - Information is conveyed in carrier angle. Effectively, in the carrier frequency.
  - AM vs. FM: quality, stereo sound
  - Note that the instantaneous frequency is

$$\frac{1}{2\pi}\frac{d}{dt}\left(2\pi f_c t + h\int_{-\infty}^{t} m(s)ds + \theta\right) = f_c + \frac{h}{2\pi}m(t).$$

  - $m(t)$ frequency modulates the carrier.

- The received signal is similarly modeled.
  - Also note that the differentiation of $X(t)$ gives

$$\frac{dX(t)}{dt} = -(2\pi f_c + hm(t)) \cos\left(2\pi f_c t + h\int_{-\infty}^{t} m(s)ds + \theta\right)$$

  - If f_c is sufficiently large, then an envelope detection of $dX(t)/dt$ will recover $m(t)$.
  - This is because $dX(t)/dt$ looks like an AM signal.

- Amplitude-Shift Keying (ASK)

$$X(t) = A(t)\cos(2\pi f_c t + \theta)$$

with the carrier amplitude being given by

$$A(t) = \sum_{n=-\infty}^{\infty} a[n]p_T(t - nT) + \theta$$

where

  - f_c: carrier frequency
  - $a[n] \in \{0, 1\}$: on-off keying (OOK)
  - $a[n] \in \{-1, 1\}$: binary amplitude-shift keying (2-ASK), binary antipodal signaling
  - $\theta[n] \in \{-1, 0, 1\}$: ternary amplitude-shift keying (4-ASK)
  - key, keying
  - $p_T(t)$: a rectangular pulse with height 1 and width T

- Phase-Shift Keying (PSK)

$$X(t) = \cos\left(2\pi f_c t + \theta(t)\right)$$

with the carrier phase being given by

$$\theta(t) = \sum_{n=-\infty}^{\infty} \theta[n] p_T(t - nT) + \theta$$

where

  - f_c: carrier frequency
  - $\theta[n] \in \{0, \pi\}$: binary phase-shift keying (BPSK)
  - $\theta[n] \in \{\pi/4, 3\pi/4, 5\pi/4, 7\pi/4\}$: quaternary phase-shift keying (QPSK)
  - $\theta[n] \in \{1 \cdot 2\pi/M, 2 \cdot 2\pi/M, ..., M \cdot 2\pi/M\}$: M-ary phase-shift keying (MPSK)