Data Transmission

Concepts and terminology

- Transmission terminology
  - Transmission from transmitter to receiver goes over some transmission medium using electromagnetic waves

    Guided media. Waves are guided along a physical path; twisted pair, optical fiber, coaxial cable

    Unguided media. Waves are not guided; air waves, radio

    Direct link. Signal goes from transmitter to receiver with no intermediate devices, other than amplifiers and repeaters

    Point-to-point link. Guided media with direct link between two devices, with those two devices being the only ones sharing the medium

    Multipoint guided configuration. More than two devices can share the same medium
  - Simplex, half duplex, and full duplex transmission
- Frequency, spectrum, and bandwidth
  - Signal is generated by a transmitter and transmitted over a medium
  - Signal is a function of time or frequency (components of different frequency)
  - Time-domain concepts

    Continuous signal. Signal intensity varies in a smooth fashion over time; no breaks or discontinuities in signal

    Discrete signal. Signal intensity can take one of two prespecified values for any amount of time

    Periodic signal. Same signal pattern repeats over time; signal is said to be periodic if

    $$s(t+T) = s(t) \qquad -\infty < t < \infty$$

    T is the period of the signal; sine wave

    Aperiodic signal. Signal that is not periodic

    Peak amplitude. Maximum signal intensity over time; typically measured in volts

    Frequency f. Rate at which signal repeats; measured in cycles per second or Hz

    Period T. Amount of times required for one repetition of signal

    $$T = \frac{1}{f}$$

    Phase. Measure of relative position in time within a single period of a signal

    * For a periodic signal $f(t)$, phase is fractional part $\frac{t}{p}$ of the period P through which t has advanced relative to an arbitrary origin

    General sine wave can be written as

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

    Wavelength λ. Distance occupied by a single cycle

    * Consider a signal traveling at velocity ν
    * Wavelength is related to period as $\lambda = \nu T$
    * Also, $\lambda f = \nu$
  - Frequency-domain concepts
    * A signal can be made up of many components

  * The signal

$$s(t) = \frac{4}{\pi}\sin(2\pi ft) + \frac{1}{3}\sin(2\pi(3f)t)$$

  is obviously made up of two components

Fundamental frequency. Base frequency such that the frequency of all components can be expressed as its integer multiples; the period of the aggregate signal is the same as the period of fundamental frequency

  * We can show that each signal can be decomposed into a set of sinusoid signals by making use of Fourier analysis
  * The time domain function $s(t)$ specifies a signal in terms of its amplitude at each instant of time
  * The frequency domain function $S(f)$ specifies the signal in terms of peak amplitude of constituent frequencies

Spectrum. Range of frequencies contained in a signal

Absolute bandwidth. Width of the spectrum

Effective bandwidth. Narrow band of frequencies containing most of the energy of the signal

DC component. Component of zero frequency; changes the average amplitude of the signal to non-zero

– Relationship between data rate an bandwidth
  * Any transmitter/receiver system can accommodate only a limited range of frequencies
    · The range for FM radio transmission is 88–108 MHz
  * This limits the data rate that can be carried over the transmission medium
  * Consider a sine wave of period f
    · Consider the positive pulse to be binary 1 and the negative pulse to be binary 0
    · Add to it sine waves of period $3f$, $5f$, $7f$, ...
    · The resultant waveform starts to approximate a square wave
    · Frequency components of a square wave with amplitude A and $-A$ can be expressed as

$$s(t) = A \times 4\pi \times \sum_{k \text{ odd},\ k=1}^{\infty} \frac{\sin(2\pi kft)}{k}$$

    · This waveform has infinite number of frequency components and infinite bandwidth
    · Peak amplitude of kth frequency component is $\frac{1}{k}$ so most of the energy is concentrated in the first few frequencies
    · Limiting the bandwidth to only the first few frequencies gives a shape that is *reasonably close* to square wave
    · Digital transmission system capable of transmitting signals with a bandwidth of 4 MHz

Case I. Approximate square wave with a waveform of first three sinusoidal components

$$\frac{4}{\pi}\left[\sin(2\pi ft) + \frac{1}{3}\sin(2\pi(3f)t) + \frac{1}{5}\sin(2\pi(5f)t)\right]$$

If $f = 10^6$ cycles per second, or 1 MHz, the bandwidth of the signal

$$s(t) = \frac{4}{\pi}\left[\sin(2\pi \times 10^6 \times t) + \frac{1}{3}\sin(2\pi \times 3 \times 10^6 \times t) + \frac{1}{5}\sin(2\pi \times 5 \times 10^6 \times t)\right]$$

is $5 \times 10^6) - 10^6 = 4$ MHz

For $f = 1$ MHz, period of fundamental frequency is $T = \frac{1}{10^6} = 10^{-6} = 1\mu$s

If the waveform is a bit string of 1's and 0's, one bit occurs every 0.5 μs, for a data rate of 2×10^6 bps or 2 Mbps

Case II. Assume a bandwidth of 8 MHz and $f = 2$ MHz; this gives us the signal bandwidth as

$$(5 \times 2 \times 10^6) - (2 \times 10^6) = 8\text{MHz}$$

But $T = \frac{1}{f} = 0.5\mu$s, so that the time for one bit is 0.25μs giving a data rate of 4 Mbps
Other things being equal, doubling of bandwidth doubles the potential data rate

Case III. Let us represent the signal by the first two components of the sinusoid as

$$\frac{4}{\pi}\left[\sin(2\pi ft) + \frac{1}{3}\sin(2\pi(3f)t)\right]$$

Assume that $f = 2$ MHz and $T = \frac{1}{f} = 0.5\mu$s so that the time for one bit is 0.25μs giving a data rate of 4 Mbps
Bandwidth of the signal is

$$(3 \times 2 \times 10^6) - (2 \times 10^6) = 4\text{MHz}$$

A given bandwidth can support various data rates depending on the ability of the receiver to discern the difference between 0 and 1 in the presence of noise and other impairments

* Any digital waveform has infinite bandwidth
  - The transmission system limits the waveform as a signal over any medium
  - For any given medium, cost is directly proportional to bandwidth transmitted
  - Signal of limited bandwidth is preferable to reduce cost
  - Limiting the bandwidth creates distortions making it difficult to interpret the received signal

Center frequency. Point where bandwidth of a signal is centered

* Higher the center frequency, higher the potential bandwidth

Analog and digital data transmission

- Analog vs digital (continuous vs discrete)
- Data – Entities that convey information
- Signaling – Physical propagation of signal along suitable medium
- Transmission – Communication of data by propagation and processing of signals

Transmission Impairments

- Attenuation
  - To reduce the amplitude of an electrical signal with little or no distortion
  - Logarithmic in nature for guided media; expressed as a constant number of decibels per unit distance
  - For unguided media, complex function of distance and atmospheric conditions
  - Three considerations for transmission engineer
    1. Received signal must have sufficient strength to enable detection
    2. Signal must maintain a level sufficiently higher than noise to be received without error
    3. Attenuation is an increasing function of frequency
  - Signal strength must be strong but not too strong to overload the circuitry of transmitter or receiver, which will cause distortion

  - Beyond a certain distance, attenuation becomes large to require the use of repeaters or amplifiers to boost the signal
  - Attenuation distorts the received signal, reducing intelligibility
    - Attenuation can be equalized over a band of frequencies
    - Use amplifiers than can amplify higher frequencies more than low frequencies

- Delay distortion
  - Peculiar to guided transmission media
  - Caused by the fact that the velocity of signal propagation through a guided medium varies with frequency
    - In bandlimited signal, velocity tends to be highest near the center frequency and falls off towards the two edges of band
    - Varying frequency components arrive at the receiver at different times, resulting in phase shifts between different frequencies
  - In digital data transmission, some signal components of one bit position will spill over into other bit positions, causing intersymbol interference
  - May be reduced by using equalization techniques

- Noise
  - Undesired signals that are inserted into the real signal during transmission
  - Four types of noise
    1. Thermal noise
       - Also called *white noise*
       - Occurs due to thermal agitation of electrons
       - Function of temperature and present in all electronic devices
       - Uniformly distributed across frequency spectrum
       - Cannot be eliminated and places an upper bound on system performance
       - Thermal noise in a bandwidth of 1 Hz in any device or conductor is

$$N_0 = \mathrm{k}T \text{ W/Hz}$$

where

$$\begin{array}{lcl} N_0 & = & \text{Noise power density in watts per 1 Hz of bandwidth} \\ \mathrm{k} & = & \text{Boltzmann's constant} = 1.3803 \times 10^{-23} \text{ J/°K} \\ T & = & \text{temperature in degree kelvin} \end{array}$$

       - At room temperature, $T = 17°\mathrm{C}$, or $290°\mathrm{K}$, and the thermal noise power density is

$$\begin{aligned} N_0 &= 1.3803 \times 10^{-23} \times 290 \\ &= 4 \times 10^{-21} \text{ W/Hz} \\ &= -204 \text{ dBW/Hz} \end{aligned}$$

       - Noise is assumed to be independent of frequency
         - Thermal noise in a bandwidth of B Hz can be expressed as

$$N = \mathrm{k}TB$$

or, in decibel-watts

$$\begin{aligned} N &= 10 \log k + 10 \log T + 10 \log B \\ &= -228.6 + 10 \log T + 10 \log B \text{dBW} \end{aligned}$$

- Given a receiver with an effective noise temperature of 100° K and a 10 MHz bandwidth, thermal noise level at the output is

$$\begin{aligned} N &= -228.6 + 10\log 10^2 + 10\log 10^7 \\ &= -228.6 + 20 + 70 \\ &= -138.6\text{dBW} \end{aligned}$$

2. Intermodulation noise
   * Signals at different frequencies share the same transmission medium
   * May result in signals that are sum or difference or multiples of original frequencies
   * Occurs when there is some nonlinearity in the transmitter, receiver, or intervening transmission system
     - Nonlinearity may be caused by component malfunction or excessive signal strength
3. Crosstalk
   * Unwanted coupling between signal paths
   * Occurs due to electric coupling between nearby twisted pairs, multiple signals on a coaxial cable, or unwanted signals picked up by microwave antennas
   * Typically same order of magnitude or less than thermal noise
4. Impulse noise
   * Noncontinuous noise, consisting of irregular pulses or noise spikes of short duration and high amplitudes
   * May be caused by lightning, or flaws in communications system
   * Not a major problem for analog data but can be significant for digital data
     - A spike of 0.01 s will not destroy any voice data but will destroy 560 bits being transmitted at 56 kbps

- Channel capacity
  - Maximum rate at which data can be transmitted over a communication path or channel
  - Depends on four factors
    1. Data rate – in bps
    2. Bandwidth – constrained by transmitter and nature of transmission medium, expressed in cycles per second, or Hz
    3. Noise – Average noise level over channel
    4. Error rate – Percentage of time when bits are flipped
  - Bandwidth is proportional to cost
    * For digital data, we'll like to get as high a data rate as possible within a limit of error rate for a given bandwidth
  - Nyquist bandwidth
    * Limitation on data rate for a noise free channel; equals that of channel 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 B, the highest possible signal rate is $2B$
    * The above is true for signals with two voltage levels
    * With multilevel signaling, Nyquist formulation is

$$C = 2B\log_2 M$$

    * For a given bandwidth, data rate can be increased by increasing the number of different signal elements
    * Value of M is practically limited by noise and other impairments on transmission line

- Shannon capacity formula
  * Nyquist formula gives the relationship between bandwidth and data rate
  * Noise can corrupt bits of data
    · Shorter bits imply that more bits get corrupted by a given noise pattern
    · Higher data rate means higher error rate
  * Higher signal strength can lead to better discrimination of signal in the presence of noise
  * Signal-to-noise (SNR) ratio
    · Ratio of power in signal to the power in noise present at a particular point in the noise
    · Typically measured at the receiver to process the signal and eliminate unwanted noise
    · Often measured in decibels

$$(\textsc{snr})_{\mathrm{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

    · SNR expresses the amount by which the intended signal exceeds the noise level
    · High SNR implies a high quality signal while low SNR indicates the need for repeaters
  * SNR sets the upper bound on achievable data rate
    · Maximum channel capacity C, in bps, is given by

$$C = B\log_2(1+\textsc{snr})$$

    where B is the bandwidth of the channel in Hz
    · Shannon formula gives the maximum possible capacity assuming only white noise; it does not take into account the impulse noise, delay distortion, and attenuation