Basic Concepts and Fundamentals of Data Communications and The Physical Layer

Textbook: Data and Computer Communications, by W. Stallings, 7th Edition, 2004, Pearson Prentice Hall.

A. Signal and Data Communications

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3.2 Analog and Digital Data Transmission (p.68)

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A. Signal and Data Communications

A1. What is the Physical Layer?

- The lowest layer of the OSI model.

- Functions to be performed by the local node:
  See Figure 2.6 (p.29).

  e.g. Physical layer specification of the EIA RS-232C (a data communications interface, or DTE-DCE interface);
  Physical layer specification of a LAN.

A2. Signals

- Data are transmitted across a medium in the form of electrical signals (or sinusoidal waves, such as electric current or electromagnetic waves).

- A signal s(t) is continuous if t (or time) is a continuous variable.
  e.g. sine waves, speech signals.

  Analog signal is a continuously varying electromagnetic wave that may be propagated over a variety of media, such as twisted pair, coaxial cable, fiber optic cable, and atmosphere.

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- A signal s(t) is discrete if t is a discrete variable.
  i.e., it takes on only a finite number of values.
  e.g. square waves, pulse signals.

  Digital signal is a sequence of specified voltage levels (or pulses) that may be transmitted over a wire medium.

  See Figure 3.1 (p.58).

- For any value of t, a function s(t) has a waveform such that
  $$s(t) = s(t + mT)$$
  the function s(t) is periodic with a period T,
  where T is a positive number and m is an integer.

  Otherwise s(t) is aperiodic or non-periodic.

  e.g.
  (a) a sine wave, $s(t) = A \sin(2\pi ft)$, for $-\infty < t < +\infty$.

  (b) a square wave, $s(t) = \begin{cases} A, & \text{for } 0 \le t < T/2 , \\ -A, & \text{for } T/2 \le t < T . \end{cases}$
  See Figure 3.2 (p.59).

- Attributes of a periodic signal s(t):
  (1) ***amplitude***, expressed in volts or amperes.
  (2) ***frequency***, expressed in cycles/second, or Hertz (Hz).
  (3) ***phase*** (***phase shift*** or ***phase angle***), expressed in radians or degrees.

e.g. the general sine wave, $s(t) = A \sin(2\pi ft + \phi)$
See Figure 3.3 (p.60).

- Other attributes of s(t):
  (1) ***period***: the reciprocal of frequency ($T = 1 / f$).
  (2) ***wavelength***: a measure of the length of a wave,
  $$\lambda \text{ (wavelength)} = \frac{v \text{ (velocity of the wave)}}{f \text{ (frequency of the wave)}}.$$
  (3) ***angular frequency*** (ω), expressed in radians per second: $\omega = 2 \pi f$.

A3. Signal Strength and Decibels

- Strength of a signal:
  power being transmitted in any transmission medium.

- Power (P) is given by,
  $$P = I V = I^2 r = \frac{V^2}{r} \text{ (in watts or W)}$$
  where
  I = the current in the transmission medium,
  V = the voltage level,
  r = the impedance of the medium.

- Distribution of power for a signal s(t):
  - at time t, the instantaneous power in $s(t) \propto |s(t)|^2$, where $|s(t)|$ may represent voltage or current.

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  - the normalized average power of s(t) is defined as
  $$P = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} |s(t)|^2 \, dt$$

- Signal attenuation:
  a loss of signal strength for all transmission media during transmission.

  (inserting amplifiers or repeaters at various points of a transmission line to impart a gain in signal strength.)

- Decibels or dB:
  a measure of signal attenuation or gain in relative values between the power levels at the input and output ends of the line.

- Decibel notations:

  (1) Number of decibels (dB) - two possible measurements:
  (a) the difference in two power levels:
  $$N_{dB} = 10 \log_{10} \frac{P_{out}}{P_{in}} \text{ dB}$$
  where P_{out} and P_{in} are output and input power levels respectively.

  Note that:

– 3 dB (a loss) halves the magnitude of P_{in} .
+ 3 dB (a gain) doubles the magnitude of P_{in} .

See Table 3.2 (p.90) and Example 3.6 (p.91).

(b) the difference in two voltage levels:

$$N_{dB} = 20 \log_{10} \frac{V_{out}}{V_{in}} \quad \text{dB}$$

(2) Decibel-Watt, dBW:

– used extensively in microwave applications.

– choosing 1W (or 0 dBW) as reference.

– the absolute decibel level of power is:

$$\text{Power} = 10 \log_{10} \frac{\text{Power (W)}}{1\,\text{(W)}} \quad \text{dBW}$$

e.g. a power of 1 kW is 30 dBW,
a power of 1 mW is –30 dBW.

See Example 3.8 (p.92).

- Applications of decibel values with simple addition and subtraction operations:
  See Example 3.7 (p.91).

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A4. Measures of Signaling Rates

- Signal element:
  – a signal component uniquely determined by the bit value in a bit string.

- Baud rate (or Modulation rate):
  – the rate at which signal elements can change.
  – the unit of measure is baud or signal elements per unit of time.

- Data rate:
  – the number of bits transmitted per unit of time.
  – the unit of measure is bits per second (bps).

- If n is the number of bits encoded in each signal element, then
  Data rate (R) = Baud rate $\times$ n bps.

- There is an important relationship between bandwidth and data rate (see Sections A5 and A6).

A5. Fourier Analysis, Spectrum, and Bandwidth

- Fourier analysis consists of two parts:
  Fourier series, for periodic signals;
  Fourier transform, for aperiodic signals.

- Consider only Fourier series, which is the mathematical expression for a periodic function, and its implications.

- The theory states that any periodic signal can be expressed as an infinite sum of sinusoids of varying amplitude, frequency, and phase shift. The sum is called a **Fourier series**.

- Suppose s(t) is a periodic function with period T. The sine-cosine representation for the Fourier series is given by

$$s(t) = \sum_{n=0}^{\infty} a_n \cos(\,2\pi n f_0 t\,) + \sum_{n=1}^{\infty} b_n \sin(\,2\pi n f_0 t\,)$$

The coefficients a_n, b_n are called the Fourier coefficients,

$$a_0 = \frac{1}{T}\int_0^T s(t)\ dt$$

$$a_n = \frac{2}{T}\int_0^T s(t)\cos(\,2\pi n f_0 t\,)\ dt, \quad n \neq 0$$

$$b_n = \frac{2}{T}\int_0^T s(t)\sin(\,2\pi n f_0 t\,)\ dt$$

- The frequency of f_0 is called the ***fundamental frequency*** and $f_0 = 1/T$; multiples of f_0 are referred to as ***harmonics***.

- The term a_0 is the average value or ***dc component*** of s(t).

  The term [$a_1 \cos(\,2\pi f_0 t\,) + b_1 \sin(\,2\pi f_0 t\,)$] is the ***fundamental component***.

  The term [$a_n \cos(\,2\pi n f_0 t\,) + b_n \sin(\,2\pi n f_0 t\,)$] is the ***nth-harmonic component***.

- The ***spectrum*** of a signal is the range of frequencies that it contains.

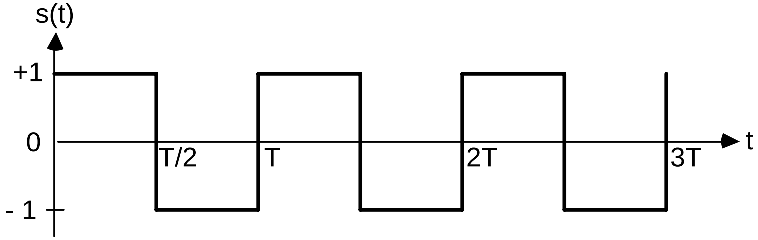
- The ***absolute bandwidth*** of a signal is the width of its spectrum.
  i.e., the difference between the highest and lowest frequencies.

- The ***effective bandwidth*** (or simply ***bandwidth***) of a signal is the narrower band within which most of the signal energy (or power) is confined.

  e.g. a telephone can handle voice frequencies between 300 and 3,300 Hz, or a bandwidth of 3,000 Hz.
  (or the signal between 300 and 3,300 Hz retains at least 50% of its power.)

- An example:

Find the trigonometric Fourier series for the square waveform shown below, where T is the period.



Given,

$$s(t) = \begin{cases} 1 & \text{for } 0 < t < T/2 \\ -1 & \text{for } T/2 < t < T \end{cases}$$

Calculate,

$$a_0 = \frac{1}{T} \int_0^T s(t)\, dt = 0$$

$$a_n = \frac{2}{T} \int_0^T s(t) \cos(2\pi n f_0 t)\, dt = 0$$

$$b_n = \frac{2}{T} \int_0^T s(t) \sin(2\pi n f_0 t)\, dt = \frac{2(1 - \cos n\pi)}{n\pi}$$

Hence,

$$s(t) = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(1 - \cos n\pi)}{n} \sin(2\pi n f_0 t)$$

Or,

$$s(t) = \frac{4}{\pi} [\sin(2\pi \times f_0 \times t) + \frac{1}{3} \sin(2\pi \times 3f_0 \times t) + \frac{1}{5} \sin(2\pi \times 5f_0 \times t) + \frac{1}{7} \sin(2\pi \times 7f_0 \times t) + \frac{1}{9} \sin(2\pi \times 9f_0 \times t) + \cdots\cdots]$$

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- Observations from the example:

(1) The given signal, a square waveform, is made up of components at various frequencies, in which each component is a sinusoid.

i.e., a signal can also be viewed as a function of frequency, s(f).

(2) The waveform has an infinite number of frequency components and hence an infinite bandwidth.

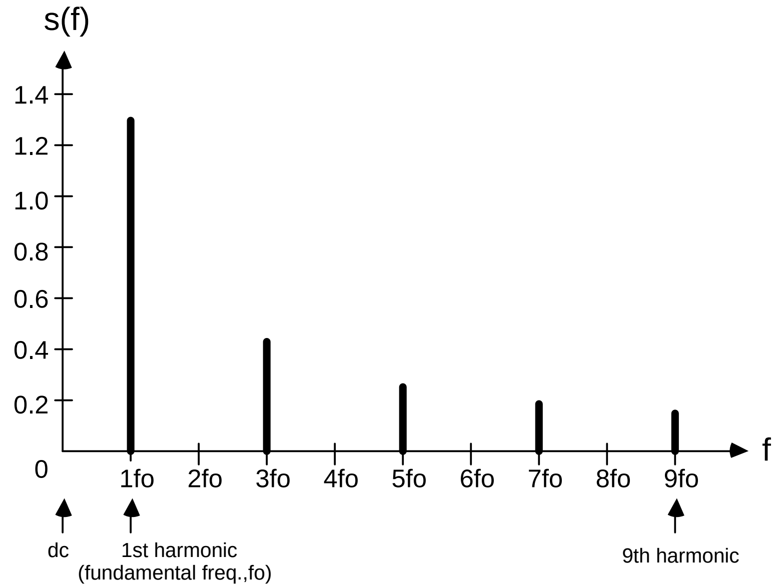
(3) All of the frequency components are integer multiples of the fundamental frequency f_0.

(4) The period of the signal obtained from the Fourier series is equal to the period of the original signal ($1/f_0$).

(5) The amplitude of the nth frequency component (nf_0) is only $2(1 – \cos n\pi)/n\pi$.

i.e., most of the energy in s(t) is in the first few frequency components.

(6) The frequency-domain function for the given periodic signal s(t) is that s(f) is discrete.



i.e., the spectrum of a periodic signal consists of discrete frequency components.

(7) Use a finite number of terms to approximate the square waveform.

i.e., as more odd multiples of f_0 are added to the fundamental frequency f_0, the resulting waveform approaches that of a square wave more and more closely.

See Figure 3.4 (p.61) and Figure 3.7 (p.65).

- The Fourier representations for some common periodic signals:

  See Figure B.1 (p.793).

- Relation between data rate and bandwidth (based on the example):

  – Assume that the square waveform represents the binary string 0101……,

  the data rate (R) = T/2 = 2f bps.

  – Some estimations:

Figure	f (MHz)	B (MHz)	R (Mbps)
3.7 (a)	1	5f – f = 4	2
3.7 (a)	2	5f – f = 8	4
3.4 (c)	2	3f – f = 4	4

⇒

♦ the higher the R of a signal, the greater is its required effective bandwidth.

♦ the transmission system has a limit on the bandwidth: the greater the B of the system, the higher is the R that can be transmitted over the system.

  – In general, if the data rate of the digital signal is W bps, then a very good representation can be achieved with a bandwidth of 2W Hz.

  See Figure 3.8 (p.67).

A6. Channel Capacity

- Channel capacity:

  the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions.

- Some related factors / conditions:

  data rate communicated
  bandwidth constrained by the transmission system
  noise (average level of noise over the path)
  error rate occurred

  See Figure 3.16 (p.82).

- For a noiseless communications channel:

  – Nyquist theorem:

  In general, with multilevel signaling (i.e., each signal element can represent more than one bit using more than two signal levels), the channel capacity (C) or maximum data rate is given by:

  $C = 2 \times B \times n$ bps,
  or, $C = 2 B \log_2 M$ bps,

  where n = no. of bits per signal element,
  and M = no. of distinct signal elements.

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  – It seems to imply there is no upper bound for the data rate (or channel capacity) given the maximum bandwidth.

  In practice,
  (1) for any given medium, the greater the bandwidth transmitted, the higher is the cost.
  (2) the more limited the bandwidth, the greater is the waveform distortion and, hence, the greater the potential for error in the received signal.
  (3) many channels are subject to noise.

- For a noisy, analog communications channel:

  – The signal-to-noise ratio (or SNR) is used to quantify how much noise there is in the presence of a signal (at the receiving point).

$$\left(\frac{S}{N}\right)_{dB} = 10 \log_{10} \frac{\text{signal power}}{\text{noise power}} \text{ dB} .$$

  – The Shannon's formula states that in a noisy transmission system, the maximum data rate is given by

$$C = B \log_2 (1 + SNR) \text{ bps.}$$

  See Example 3.3 (p.85).