Physical Layer

Position of the physical layer

Physical aspects of data communications

- differences between and characteristics of analog and digital signals
- encoding and modulation
- transmitting digital data using modems, digital subscriber lines, and cable modems
- the guided and radiated media used to transmit signals
- multiplexing and its use in current communications systems
- methods of detecting and correcting errors

Services

Duties of physical layer
Bit-signal transformation
Bit-rate control
Bit synchronization
Multiplexing
Circuit switching

Analog and Digital

To be transmitted, data must be transformed to electromagnetic signals.

Analog and Digital Data
Analog and Digital Signals
Periodic and Aperiodic Signals

Analog and Digital Data

Data can be analog or digital.

- *Analog data are continuous and take continuous values.*
- *Digital data have discrete states and take discrete values.*

Analog and Digital Signals

Signals can be analog or digital

- ***Analog signals can have an infinite number of values in a range;***
  - ***Analog refers to something that is continuous, i.e., a set of specific points and all the points between them.***
- ***Digital signals can have only a limited number of values;***
  - ***Digital refers to something that is discrete, e.g., a set of specific points and no points between them.***

a. Analog signal

b. Digital signal

PERIODIC ANALOG SIGNALS

In data communications, we commonly use periodic analog signals and nonperiodic digital signals.

Periodic analog signals can be classified as simple composite.

- ***A simple periodic analog signal, a sine wave, cannot be decomposed into simpler signals.***
- ***A composite periodic analog signal is composed of multiple sine waves.***

Analog Signals

Sine Wave
Phase
Examples of Sine Waves
Time and Frequency Domains
Composite Signals
Bandwidth

Sine Wave

- Peak Amplitude (A)
  - maximum strength of signal
  - volts
- Frequency (f)
  - Rate of change of signal
  - Hertz (Hz) or cycles per second
  - Period = time for one repetition (T)

$$f = \frac{1}{T} \quad \text{and} \quad T = \frac{1}{f}$$

- Phase (ϕ)
  - Relative position in time

Wavelength

- Distance occupied by one cycle
- Distance between two points of corresponding phase in two consecutive cycles
- λ
- Assuming signal velocity v
  - $\lambda = vT$
  - $\lambda f = v$
  - $c = 3*10^8\ ms^{-1}$ (speed of light in free space)

Varying Sine Waves
$s(t) = A \sin(2\pi ft + \Phi)$

Two signals with the same amplitude and phase, but different frequencies

a. A signal with a frequency of 12 Hz

b. A signal with a frequency of 6 Hz

Units of periods and frequencies

Unit	Equivalent	Unit	Equivalent
Seconds (s)	1 s	hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	kilohertz (KHz)	10^{3} Hz
Microseconds (ms)	10^{-6} s	megahertz (MHz)	10^{6} Hz
Nanoseconds (ns)	10^{-9} s	gigahertz (GHz)	10^{9} Hz
Picoseconds (ps)	10^{-12} s	terahertz (THz)	10^{12} Hz

Phase describes the position of the waveform relative to time zero.

a. 0 degrees

b. 90 degrees

c. 180 degrees

Sine wave examples : s(t) = A sin(2πft +Φ)

Frequency is the rate of change with respect to time.

- ***Change in a short span of time means high frequency.***
- ***Change over a long span of time means low frequency.***

- ***If a signal does not change at all, its frequency is zero.***
- ***If a signal changes instantaneously, its frequency is infinite.***

The time domain and frequency

A complete sine wave in the time domain can be represented by one single spike in the frequency domain.

The frequency domain is more compact and useful when we are dealing with more than one sine wave.

a. Time-domain representation of three sine waves with frequencies 0, 8, and 16

b. Frequency-domain representation of the same three signals

Signals and Communication

- A single-frequency sine wave is not useful in data communications
- We need to send a composite signal, a signal made of many simple sine waves.
- ***According to Fourier analysis, any composite signal is a combination of simple sine waves with different frequencies, amplitudes, and phases.***

Composite Signals and Periodicity

- If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies.
- If the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies.

Three harmonics

Adding first three harmonics

Decomposition of a composite periodic signal in the time and frequency domains

a. Time-domain decomposition of a composite signal

b. Frequency-domain decomposition of the composite signal

The time and frequency domains of a nonperiodic signal

a. Time domain

b. Frequency domain

Signal corruption

Bandwidth

The bandwidth is a property of a medium:

It is the difference between the highest and the lowest frequencies that the medium can satisfactorily pass.

a. Bandwidth of a periodic signal

b. Bandwidth of a nonperiodic signal

Example

If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is the bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.

$B = f_h - f_l = 900 - 100 = 800$ Hz

The spectrum has only five spikes, at 100, 300, 500, 700, and 900

Example

A signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all integral frequencies of the same amplitude.

$B = f_h - f_l$

$20 = 60 - f_l$

$f_l = 60 - 20 = 40$ Hz

Example

A signal has a spectrum with frequencies between 1000 and 2000 Hz (bandwidth of 1000 Hz).

A medium can pass frequencies from 3000 to 4000 Hz (a bandwidth of 1000 Hz).

Can this signal faithfully pass through this medium?

The answer is definitely no.

Although the signal can have the same bandwidth (1000 Hz), the range does not overlap. The medium can only pass the frequencies between 3000 and 4000 Hz;

the signal is totally lost.

Digital Signals

Bit Interval and Bit Rate

As a Composite Analog Signal

Through Wide-Bandwidth Medium

Through Band-Limited Medium

Versus Analog Bandwidth

Higher Bit Rate

Bit rate and bit interval

Digital versus analog

a. Best case, bit rate = 6, $f = 0$

b. Worst case, bit rate = 6, $f = 3$

Fourier Analysis

Fourier analysis is a tool that changes a time domain signal to a frequency domain signal and vice versa.

- Every composite periodic signal can be represented with a series of sine and cosine functions.
- The functions are integral harmonics of the fundamental frequency “f” of the composite signal.
- Using the series we can decompose any periodic signal into its harmonics.

Fourier Series

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Fourier series

$$s(t) = A_0 + \sum_{n=1}^{\infty} A_n \sin(2\pi nft) + \sum_{n=1}^{\infty} B_n \cos(2\pi nft)$$

$$A_0 = \frac{1}{T}\int_0^T s(t)\,dt \qquad A_n = \frac{2}{T}\int_0^T s(t)\cos(2\pi nft)\,dt$$

$$B_n = \frac{2}{T}\int_0^T s(t)\sin(2\pi nft)\,dt$$

Coefficients

Signals and the Fourier Series Representation

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Time domain

http://falstad.com/fourier/

$$A_0 = 0 \qquad A_n = \begin{cases} \dfrac{4A}{n\pi} & \text{for } n = 1, 5, 9, \ldots \\ -\dfrac{4A}{n\pi} & \text{for } n = 3, 7, 11, \ldots \end{cases} \qquad B_n = 0$$

$$s(t) = \frac{4A}{\pi}\cos(2\pi ft) - \frac{4A}{3\pi}\cos(2\pi 3ft) + \frac{4A}{5\pi}\cos(2\pi 5ft) - \frac{4A}{7\pi}\cos(2\pi 7ft) + \cdots$$

Frequency domain

Sawtooth Signal

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Time domain

$$A_0 = 0 \qquad A_n = 0 \qquad B_n = \begin{cases} \dfrac{2A}{n\pi} & \text{for } n \text{ odd} \\ -\dfrac{2A}{n\pi} & \text{for } n \text{ even} \end{cases}$$

$$s(t) = \frac{2A}{\pi}\sin(2\pi ft) - \frac{2A}{2\pi}\sin(2\pi 2ft) + \frac{2A}{3\pi}\sin(2\pi 3ft) - \frac{2A}{4\pi}\sin(2\pi 4ft) + \cdots$$

Frequency domain

Fourier Transform

Fourier Transform gives the frequency domain of a nonperiodic time domain signal

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A digital signal is a composite signal with an infinite bandwidth.

To improve the shape of the signal for better communication, particularly for high data rates, we need to add some harmonics.

B=n/2+3n/2+5n/2 …. (n=bps)

Final B>=n/2 or n<= 2B

Bandwidth Requirement

Bit Rate	Harmonic 1 B=n/2	Harmonics 1, 3 B=4n/2	Harmonics 1, 3, 5 B=9n/2	Harmonics 1, 3, 5, 7 B=16n/2
1 Kbps	500 Hz	2 KHz	4.5 KHz	8 KHz
10 Kbps	5 KHz	20 KHz	45 KHz	80 KHz
100 Kbps	50 KHz	200 KHz	450 KHz	800 KHz

The bit rate and the bandwidth are proportional to each other.

Analog versus Digital

Low-pass versus Band-pass

Digital Transmission

Analog Transmission

Low-pass and band-pass

Digital transmission needs a low-pass channel.

Analog transmission can use a band-pass channel.

The analog bandwidth of a medium is expressed in hertz;

The digital bandwidth, in bits per second.

DATA RATE LIMITS

A very important consideration in data communications is how fast we can send data, in bits per second, over a channel. Data rate depends on three factors:

1. ***The bandwidth available***
2. ***The level of the signals we use***
3. ***The quality of the channel (the level of noise)***

Two digital signals: one with two signal levels and the other with four signal levels

a. A digital signal with two levels

b. A digital signal with four levels

Increasing the levels of a signal increases the probability of an error occurring, in other words it reduces the reliability of the system. Why??

- The bit rate of a system increases with an increase in the number of signal levels we use to denote a symbol.
- A symbol can consist of a single bit or "n" bits.
- The number of signal levels = 2^n.
- As the number of levels goes up, the spacing between level decreases -> increasing the probability of an error occurring in the presence of transmission impairments.

Data Rate Limit

Noiseless Channel: Nyquist Bit Rate

Bit Rate = 2 × Bandwidth × $\log_2$ Signal_levels

Noisy Channel: Shannon Capacity

Capacity = Bandwidth* $\log_2$ (1 + SNR) ;

where SNR=signal-to-noise ratio

Using Both Limits

In practice we need to use both methods

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

Example

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

$$\text{Bit Rate} = 2 \times \text{Bandwidth} \times \log_2 \text{Signal_levels}$$

$$\text{Bit Rate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}$$

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

$$\text{Bit Rate} = 2 \text{ x } 3000 \text{ x } \log_2 4 = 12{,}000 \text{ bps}$$

Example

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 is calculated as

$$C = B \log_2 (1 + SNR) = B \log_2 (1 + 0)$$

$$= B \log_2 (1) = B \times 0 = 0$$

Example

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000 Hz (300 Hz to 3300 Hz).

The signal-to-noise ratio is usually 3162.

For this channel the capacity is calculated as:

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

$$3000 \log_2 (1 + 3162)$$

$$= 3000 \log_2 (3163)$$

$$C = 3000 \times 11.62 = 34{,}860 \text{ bps}$$

Example

We have a channel with a 1 MHz bandwidth. The SNR for this channel is 31;

What is the appropriate bit rate and signal level?

Solution

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

$$C = B \log_2 (1 + SNR) = 10^6 \log_2 (1 + 31) = 10^6 \log_2 (32) = 5 \text{ Mbps}$$

Then we use the Nyquist formula to find the number of signal levels.

$$5\text{Mbps} = 2 \times 1 \text{ MHz} \times \log 2\, L \rightarrow L = 5.6$$

$$4\text{Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \rightarrow L = 4$$

Transmission Impairment

Attenuation

Attenuation means loss of energy.
To compensate for this lost amplifiers are used to amplify the signal

Decibel (dB) measures the relative strengths of two signals or a signal at two different points.

$$dB = 10 \log_{10} (P2/P1)$$

where P1 and P2 is the power of the signal at point 1 and Point 2, respectively

Note:

The decibel is negative if the signal is attenuated
The decibel is positive if the signal is amplified

Example

Imagine a signal travels through a transmission medium and its power is reduced to half.

This means that P2 = 1/2 P1.

In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} (P2/P1) = 10 \log_{10} (0.5P1/P1) = 10 \log_{10} (0.5)$$
$$= 10(-0.3) = -3 \text{ dB}$$

Example

Imagine a signal travels through an amplifier and its power is increased ten times.

This means that P2 = 10 * P1.

In this case, the amplification (gain of power) can be calculated as

$$10 \log_{10} (P2/P1) = 10 \log_{10} (10P1/P1)$$

$$= 10 \log_{10} (10) = 10 (1) = 10 \text{ dB}$$

Example

One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are talking about several points instead of just two (cascading).

- A signal travels a long distance from point 1 to point 4.
  - The signal is attenuated by the time it reaches point 2.
  - Between points 2 and 3, the signal is amplified.
  - Again, between points 3 and 4, the signal is attenuated.

We can find the resultant decibel for the signal just by adding the decibel measurements between each set of points.

$$dB = -3 + 7 - 3 = +1$$

Distortion

Distortion means that the signal changes its form or shape. Distortion occurs in a composite signals, made of different frequencies. Each component has its own propagation speed

At the sender

At the receiver

Noise

There are several type of noises:

Thermal noise – is the random motion of the electrons in a wire which create an extra signal;

Induced noise – comes from sources as motors and appliances;

Crosstalk noise- is the effect of one wire on the other;

Impulse noise – is a spike

Two cases of SNR: a high SNR and a low SNR

a. Large SNR

b. Small SNR

More About Signals

Throughput

Propagation Speed

Propagation Time

Wavelength

Throughput

Throughput is measurement of how data can pass through an entity

Propagation time

Propagation time measures the time required for a signal (or a bit) to travel from one point of the transmission to another.

Wavelength

Wavelength (λ) is the distance a single signal can travel in one period

Wavelength = Propagation speed x Period

Wavelength = Propagation speed / Frequency

λ = c/f