The Physical Layer
Physical Layer - Part 1

• Definitions
• Nyquist Theorem - noiseless
• Shannon’s Result – with noise
• Analog versus Digital
• Amplifier versus Repeater
A Very Simple Abstraction

Transmitter \[\rightarrow\] Communication channel \[\rightarrow\] Receiver

Leon-Garcia & Widjaja: Communication Networks

Copyright ©2000 The McGraw Hill Companies
Physical Layer definitions

• the time required to transmit a character depends on both the encoding method and the signaling speed (i.e., the modulation rate - the number of times/sec the signal changes its voltage)

• baud (D) - the number of changes per second

• bandwidth (H) - the range of frequencies that is passed by a channel. The transmitted signal is constrained by the transmitter and the nature of the transmission medium in cycles/sec (hertz)

• channel capacity (C) – the rate at which data can be transmitted over a given channel under given conditions. {This is also referred to as data rate (R).}
Modulation Rate

Figure 5.5 A Stream of Binary Ones at 1 Mbps
Nyquist Theorem
{assume a noiseless channel}

If an arbitrary signal is run through a low-pass filter of bandwidth \( H \), the filtered signal can be completely reconstructed by making \( 2H \) samples/sec.

This implies for a signal of \( V \) discrete levels,

\[
\text{Max. data rate} \::\; C = 2H \log_2(V) \text{ bits/sec.}
\]

Note – a higher sampling rate is pointless because higher frequency signals have been filtered out.
(a) Lowpass and idealized lowpass channel

(b) Maximum pulse transmission rate is $2H$ pulses/second
Example 1. \{sampling rate\}
\[
\begin{align*}
H &= 4000 \text{ Hz} \\
2H &= 8000 \text{ samples/sec.}
\end{align*}
\]
\Rightarrow \text{sample every 125 microseconds!!}

Example 2. \{noiseless capacity\}
\[
\begin{align*}
D &= 2400 \text{ baud} \quad \{\text{note } D = 2H\} \\
V &= \text{each pulse encodes 16 levels} \\
C &= 2H \log_2 (V) = D \times \log_2 (V) \\
    &= 2400 \times 4 = 9600 \text{ bps.}
\end{align*}
\]
Signal Constellations

4 “levels”/ pulse
2 bits / pulse
2D bits per second

16 “levels”/ pulse
4 bits / pulse
4D bits per second

Figure 3.34

Leon-Garcia & Widjaja: Communication Networks

Copyright ©2000 The McGraw Hill Companies

Computer Networks: Physical Layer 9
Constellation Diagrams

(a) QPSK.          (b) QAM-16.          (c) QAM-64.

Figure 2-25.
High SNR

Signal + Noise

Low SNR

SNR = \frac{\text{Average Signal Power}}{\text{Average Noise Power}}

\text{SNR (dB)} = 10 \log_{10} \text{SNR}
Shannon’s Channel Capacity

Result

{assuming only thermal noise}

For a noisy channel of bandwidth $H$ Hz. and a signal-to-noise ratio $\text{SNR}$, the max. data rate:

$$C = H \log_2 (1 + \text{SNR})$$

Regardless of the number of signal levels used and the frequency of the sampling.
Shannon Example - Noisy Channel  

Telephone channel (3400 Hz) at 40 dB SNR

\[ C = H \log_2 (1+\text{SNR}) \text{ b/s} \]

\[ \text{SNR} = 40 \text{ dB} ; \quad 40 = 10 \log_{10} (\text{SNR}) ; \]

\[ 4 = \log_{10} (\text{SNR}) ; \quad \text{SNR} = 10,000 \]

\[ C = 3400 \log_2 (10001) = 44.8 \text{ kbps} \]
Analog and digital correspond roughly to continuous and discrete. These two terms can be used in three contexts:

1. **data::** entities that convey meaning.
   
   analog – voice and video are continuously varying patterns of intensity
   
   digital - take on discrete values (e.g., integers, ASCII text)

   *Data are propagated from one point to another by means of electrical signals.*
### Analog versus Digital

#### (a) Data and signals

<table>
<thead>
<tr>
<th>Analog data</th>
<th>Digital data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two alternatives: (1) signal occupies the same spectrum as the analog data; (2) analog data are encoded to occupy a different portion of spectrum.</td>
<td>Analog data are encoded using a codec to produce a digital bit stream.</td>
</tr>
<tr>
<td>Digital data are encoded using a modem to produce analog signal.</td>
<td>Two alternatives: (1) signal consists of two voltage levels to represent the two binary values; (2) digital data are encoded to produce a digital signal with desired properties.</td>
</tr>
</tbody>
</table>

#### (b) Treatment of signals

<table>
<thead>
<tr>
<th>Analog signal</th>
<th>Digital signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is propagated through amplifiers; same treatment whether signal is used to represent analog data or digital data.</td>
<td>Assumes that the analog signal represents digital data. Signal is propagated through repeaters; at each repeater, digital data are recovered from inbound signal and used to generate a new analog outbound signal.</td>
</tr>
<tr>
<td>Not used</td>
<td>Digital signal represents a stream of 1s and 0s, which may represent digital data or may be an encoding of analog data. Signal is propagated through repeaters; at each repeater, stream of 1s and 0s is recovered from inbound signal and used to generate a new digital outbound signal.</td>
</tr>
</tbody>
</table>
Analog and Digital Signaling

signals:: electric or electromagnetic encoding of data.

2. signaling :: is the act of propagating the signal along a suitable medium.

Analog signal – a continuously varying electromagnetic wave that may be propagated over a variety of medium depending on the spectrum (e.g., wire, twisted pair, coaxial cable, fiber optic cable and atmosphere or space propagation).
Analog and Digital Signaling

digital signal – a sequence of voltage pulses that may be transmitted over a wire medium.

Note – analog signals to represent analog data and digital signals to represent digital data are not the only possibilities.
Signals [DCC 6th Ed. W.Stallings]

- Means by which data are propagated
- Analog
  - Continuously variable
  - Various media
    - wire, fiber optic, space
  - Speech bandwidth 100Hz to 7kHz
  - Telephone bandwidth 300Hz to 3400Hz
  - Video bandwidth 4MHz
- Digital
  - Use two DC components
Analog and Digital Signaling

- Digital data can be represented by analog signals using a modem (modulator/demodulator).
  
  *The digital data is encoded on a carrier frequency.*

- Analog data can be represented by digital signals using a codec (coder-decoder).
Analog Signals Carrying Analog and Digital Data

Analog Signals: Represent data with continuously varying electromagnetic wave

Analog Data (voice sound waves) → Telephone → Analog Signal

Digital Data (binary voltage pulses) → Modem → Analog Signal (modulated on carrier frequency)
Digital Signals Carrying Analog and Digital Data

Digital Signals: Represent data with sequence of voltage pulses

- Analog Signal
  - CODEC
  - Digital Signal

- Digital Data
  - Digital Transmitter
  - Digital Signal
Analog and Digital Signaling Comparison

• Digital signaling is:
  – Cheaper
  – Less susceptible to noise interference
  – Suffers more attenuation.
**Attenuation**

*attenuation of a signal*: the reduction or loss of signal strength (power) as it transferred across a system.

Attenuation is an increasing function of frequency.

The strength of the received signal must be strong enough for detection and must be higher than the noise to be received without error.
FIGURE 2.1 Attenuation of Digital Signals
Figure 3.37

Attenuation (dB/mi) vs. Frequency (kHz)

- 26 gauge
- 24 gauge
- 22 gauge
- 19 gauge

Leon-Garcia & Widjaja: Communication Networks

Copyright ©2000 The McGraw Hill Companies
Analog and Digital Transmissions

{Stalling’s third context}

3. Transmissions :: communication of data by the propagation and processing of signals.

- Both analog and digital signals may be transmitted on suitable transmission media.
- [Stalling’s argument] The way the signals are “treated” is a function of the transmission system and here lies the crux of the distinction between transmission types.
(a) Analog transmission: all details must be reproduced accurately

- e.g. AM, FM, TV transmission

(b) Digital transmission: only discrete levels need to be reproduced

- e.g. digital telephone, CD Audio
## Analog versus Digital

<table>
<thead>
<tr>
<th>Analog data</th>
<th>Digital data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two alternatives: (1) signal occupies the same spectrum as the analog data; (2) analog data are encoded to occupy a different portion of spectrum.</td>
<td>Analog data are encoded using a codec to produce a digital bit stream.</td>
</tr>
<tr>
<td>Digital data are encoded using a modem to produce analog signal.</td>
<td>Two alternatives: (1) signal consists of two voltage levels to represent the two binary values; (2) digital data are encoded to produce a digital signal with desired properties.</td>
</tr>
</tbody>
</table>

### (a) Data and signals

<table>
<thead>
<tr>
<th>Analog signal</th>
<th>Digital transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is propagated through amplifiers; same treatment whether signal is used to represent analog data or digital data.</td>
<td>Assumes that the analog signal represents digital data. Signal is propagated through repeaters; at each repeater, digital data are recovered from inbound signal and used to generate a new analog outbound signal.</td>
</tr>
<tr>
<td>Not used</td>
<td>Digital signal represents a stream of 1s and 0s, which may represent digital data or may be an encoding of analog data. Signal is propagated through repeaters; at each repeater, stream of 1s and 0s is recovered from inbound signal and used to generate a new digital outbound signal.</td>
</tr>
</tbody>
</table>

### (b) Treatment of signals
Analog Transmissions

Analog transmission :: a means of transmitting analog signals without regard to their content (i.e., the signals may represent analog data or digital data). Transmissions are attenuated over distance.

Analog signal – the analog transmission system uses amplifiers to boost the energy in the signal.
Analog Transmissions

Amps boost the energy ➔

amplifies the signal and amplifies the noise.

The cascading of amplifiers distorts the signal.

Note – voice (analog data) can tolerate much distortion but with digital data distortion introduces errors.
Digital Transmissions

Digital transmissions are concerned with the content of the signal. Attenuation is overcome without amplifying the noise.

**Analog signals** \(\{\text{assumes digital data}\} :\)

With retransmission devices [analog repeater] at appropriate points the device recovers the digital data from the analog signal and generates a new clean analog signal.

*the noise is not cumulative!!*
Digital Transmissions

digital signals – digital repeaters are used to attain greater distances.
The digital repeater receives the digital signal, recovers the patterns of 0’s and 1’s and retransmits a new digital signal.
The treatment is the same for analog and digital data.
Analog Transmission

Attenuated & distorted signal + noise

Amp.

Equalizer

Recovered signal + residual noise

Amplifier
Digital Transmission

Amplifier Equalizer \(\rightarrow\) Decision Circuit & Signal Regenerator

Timing Recovery

Repeater (digital signal)
Digital versus Analog Transmissions

Digital transmission advantages

• Superior cost of digital technology
  – Low cost LSI/VLSI technology
  – Repeaters versus amplifiers costs

• Superior quality {Data integrity}
  – Longer distances over lines with lower error rates

• Capacity utilization
  – Economical to build high bandwidth links
  – High degree of multiplexing easier with digital techniques
  • TDM (Time Division Multiplexing) is easier and cheaper than FDM
    (Frequency Division Multiplexing)
Digital versus Analog Transmissions

[DCC 6th Ed. W.Stallings]

Digital transmission advantages

• Security & Privacy
  – Encryption techniques readily applied to digitized data

• Integration
  – Can treat analog and digital data similarly
  – Economies of scale from integrating voice, video and data

Analog transmission advantages

  – Digital signaling not as versatile or practical (digital impossible for satellite and microwave systems)
  – LAN star topology reduces the severity of the noise and attenuation problems.