

18-345 – Fall 08

Lecture 3 Digital Transmission Fundamentals

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reading: Chapter 3

Outline Physical Layer Lectures

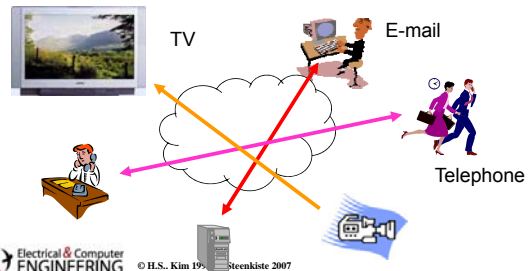
- Digital representation of information
 - Digital representation of analog signals
- Analog versus digital transmission
- Basic properties of dig. transmission
- Fundamental limits of dig. transmission
- Line coding, modulation
 - Amplitude, frequency, and phase modulation
- Properties of transmission media
- Synchronization
- Error detection and error correction

Outline Today's Lecture

- Types of information
- Analog versus digital data
- Data representations and their networking requirements
- Digital representation of analog signals
- Analog versus digital transmission

Digital Networks

- Digital transmission enables networks to support many services



Questions of Interest

- How long will it take to transmit a message?
 - How many bits are in the message (text, image)?
 - How fast does the network/system transfer information?
- Can a network/system handle a voice (video) call?
 - How many bits/second does voice/video require? At what quality?
- How long will it take to transmit a message without errors?
 - How are errors introduced?
 - How are errors detected and corrected?
- What transmission speed is possible over radio, copper cables, fiber, infrared, ...?

Digital Representation of Information

Reading: Section 3.1

Bits, numbers, information

- Bit: "Binary digit" = number with value 0 or 1
 - n bits: digital representation for 0, 1, ..., 2^n
 - Byte or Octet, $n = 8$
 - Computer word, $n = 16, 32, \text{ or } 64$
- n bits allows enumeration of 2^n possibilities
 - n -bit field in a header
 - n -bit representation of a voice sample
 - Message consisting of n bits
- *The number of bits required to represent a message is a measure of its information content*
 - More bits → More content

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Analog versus Digital Information

- Analog information takes on continuous values
 - Sound, images, etc.
- Digital information takes on discrete values
 - Text, banking data, etc.
- Can convert between the two representations of information
 - Sampling and interpolation

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Block vs. Stream Information

<p>Block</p> <ul style="list-style-type: none"> • Information that occurs in a single block <ul style="list-style-type: none"> – Text message – Data file – JPEG image – MPEG file • Size = Bits / block or bytes/block <ul style="list-style-type: none"> – 1 kbyte (kB) = 10^3 bytes – 1 Mbyte (MB) = 10^6 bytes – 1 Gbyte (GB) = 10^9 bytes 	<p>Stream</p> <ul style="list-style-type: none"> • Information that is produced & transmitted <i>continuously</i> <ul style="list-style-type: none"> – Real-time voice – Streaming video • Bit rate = bits / second <ul style="list-style-type: none"> – 1 kbps = 10^3 bps – 1 Mbps = 10^6 bps – 1 Gbps = 10^9 bps <p>Note : In storage, kB=2¹⁰, MB=2²⁰, GB=2³⁰ bytes</p>
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Many Types of Information

	Analog	Digital
Stream	Voice, video	Stock market,
Block	Images, radar map, ...	Spreadsheets, text file, ...

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Traditional Communication Options

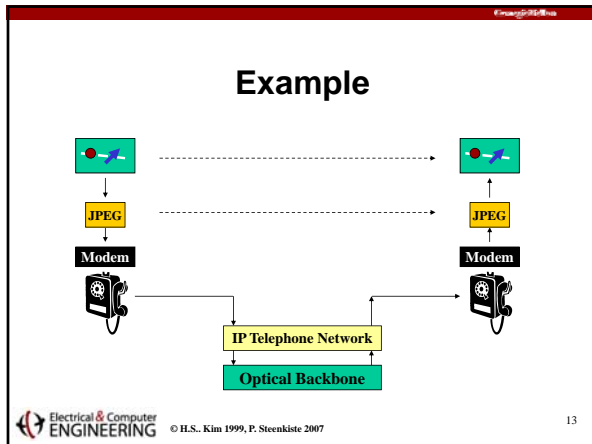
- Send analog information over analog networks
 - Voice over the telephone network
 - Video using broadcast TV
 - Pictures using the USPS
- Send digital information over digital networks
 - Original Internet applications were ftp, (text) e-mail, bboards, telnet, etc.

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But Can Mix and Match

- Analog information can be digitized and sent over digital network
 - Video becomes MPEG
 - Image becomes JPEG
- Digital networks use analog channels
 - Bits are encoded on analog waveforms
 - But switching is done based on the bits

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Why Use a Single Digital Network?

- Economically advantageous to have a single network
- Multimedia applications want to mix different types of data
 - More convenient if a single networks is used
- Computers operate only on digital data
- Digital transmission can recover from errors (e.g. noise, distortion)
 - Not possible when transmitting analog information over an analog network

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Transmission Delay

- L number of bits in message
- R bps speed of digital transmission system
- L/R time to transmit the information
- t_{prop} time for signal to propagate across medium
- d distance in meters
- c speed of light (3×10^8 m/s in vacuum)

$$Delay = t_{prop} + L/R \text{ seconds}$$

$$= d/c + L/R \text{ seconds}$$

Use data compression to reduce L
Use higher speed modem to increase R
Place server closer to reduce d

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Example

- Sending a 16 Kbyte message over a link of length 300 km using a 54 Kbs modem.
 - $T_{prop} = 300 \text{ km} / 3 \times 10^8 \text{ m/s} = 1 \text{ msec}$
 - $L = 16 \times 2^{10} \times 8 \text{ bits}$
 - $R = 54 \times 10^3 \text{ b/s}$
 - $L/R = 2.427 \text{ sec}$

The diagram shows a green trapezoid representing a transmission link between a 'Sender' on the left and a 'Receiver' on the right. Vertical arrows point down from each label to the corresponding end of the link.

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Compression

- Information usually not represented efficiently
- Data compression algorithms
 - Represent the information using fewer bits
 - Noiseless: original information recovered exactly
 - E.g. zip, compress, GIF, fax
 - Noisy: recover information approximately
 - JPEG
 - Tradeoff: # bits vs. quality
- Compression Ratio
 - #bits (original file) / #bits (compressed file)

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Color Image

The diagram shows a large box labeled 'Color image' with width W and height H . This is equated to the sum of three smaller boxes: 'Red component image', 'Green component image', and 'Blue component image', each with width W and height H .

$$\text{Total bits} = 3 \times H \times W \text{ pixels} \times B \text{ bits/pixel} = 3HWB$$

Example: 8×10 inch picture at 400×400 pixels per in²
 $400 \times 400 \times 8 \times 10 = 12.8$ million pixels
 8 bits/pixel/colour
 $12.8 \text{ megapixels} \times 3 \text{ bytes/pixel} = 38.4 \text{ megabytes}$

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Examples of Block Information

Type	Method	Format	Original	Compressed (Ratio)
Text	Zip, compress	ASCII	Kbytes-Mbytes	(2-6)
Fax	CCITT Group 3	A4 page 200x100 pixels/in ²	256 kbytes	5-54 kbytes (5-50)
Color Image	JPEG	8x10 in ² photo 400 ² pixels/in ²	38.4 Mbytes	1-8 Mbytes (5-30)

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Stream Information

- A real-time voice signal must be digitized & transmitted as it is produced
- Analog signal level varies continuously in time

The speech signal level varies with time

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Digitization of Analog Signal

- Sample analog signal in time and amplitude
- Find closest approximation

$R_s = \text{Bit rate} = (\# \text{ bits/sample}) \times (\# \text{ samples/second})$

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Bit Rate of Digitized Signal

- $R_s = \text{Bit rate} = (\# \text{ bits/sample}) \times (\# \text{ samples/second})$
- Bandwidth W_s Hertz: how fast the signal changes
 - Higher bandwidth \rightarrow more frequent samples
 - Minimum sampling rate = $2 \times W_s$ samples/second
 - More details later
- Representation accuracy: depends on range of approximation error
 - Higher accuracy requires:
 - \rightarrow smaller spacing between approximation values
 - \rightarrow thus, more bits per sample

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Example: Voice & Audio

Telephone voice <ul style="list-style-type: none"> $W_s = 4 \text{ kHz} \rightarrow 2W_s = 8000 \text{ samples/sec}$ 8 bits/sample $R_s = 8 \times 8000 = 64 \text{ kbps}$ Cellular phones use more powerful compression algorithms: 8-12 kbps 	CD Audio <ul style="list-style-type: none"> $W_s = 22 \text{ kHz} \rightarrow 2W_s = 44000 \text{ samples/sec}$ 16 bits/sample $R_s = 16 \times 44000 = 704 \text{ kbps per audio channel (left/right)}$ MP3 uses more powerful compression algorithms: 50 kbps per audio channel
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Video Signal


- Sequence of picture frames
 - Each picture digitized & compressed
- Frame repetition rate
 - 10-30-60 frames/second depending on quality
- Frame resolution
 - Small frames for videoconferencing
 - Standard frames for conventional broadcast TV
 - HDTV frames

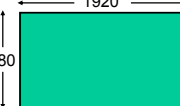
Rate = $M \text{ bits/pixel} \times (W \times H) \text{ pixels/frame} \times F \text{ frames/second}$

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Video Frames

QCIF videoconferencing 176 pixels
 144  at 30 frames/sec = 760,000 pixels/sec

Broadcast TV 720
 480  at 30 frames/sec = 10.4×10^6 pixels/sec

HDTV 1920
 1080  at 30 frames/sec = 67×10^6 pixels/sec

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Digital Video Signals

Type	Method	Format	Original	Compressed
Video Conference	H.261	176x144 or 352x288 pix @10-30 fr/sec	2-36 Mbps	64-1544 kbps
Full Motion	MPEG2	720x480 pix @30 fr/sec	249 Mbps	2-6 Mbps
HDTV	MPEG2	1920x1080 @30 fr/sec	1.6 Gbps	19-38 Mbps

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Transmission of Stream Information

- Constant bit-rate
 - Signals such as digitized telephone voice produce a steady stream: e.g. 64 kbps
 - Network must support steady transfer of signal, e.g. 64 kbps circuit
- Variable bit-rate
 - Signals such as digitized video produce a stream that varies in bit rate, e.g. according to motion and detail in a scene
 - Network must support variable transfer rate of signal, e.g. packet switching or rate-smoothing with constant bit-rate circuit

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Stream Service Quality Issues

Network Transmission Impairments

- Delay: Is information delivered in timely fashion? (Average delay)
- Jitter: Is information delivered in sufficiently smooth fashion? (Std deviation of delay)
- Loss: Is information delivered without loss? If loss occurs, is delivered signal quality acceptable?
- Applications & application layer protocols developed to deal with these impairments

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Digital Representation of Analog Signals

Reading: Section 3.3

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Digitization of Analog Signals

1. Sampling: obtain samples of $x(t)$ at uniformly spaced time intervals
2. Quantization: map each sample into an approximation value of finite precision
 - Pulse Code Modulation: telephone speech
 - CD audio
3. Compression: to lower bit rate further, apply additional compression method
 - Differential coding: cellular telephone speech
 - Subband coding: MP3 audio
 - Compression discussed in Chapter 12

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How Many Samples Do I Need?

$x_2(t)$

1 1 1 1 0 0 0 0

1 ms

$x_1(t)$

1 0 1 0 1 0 1 0

1 ms

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Sampling Rate and Bandwidth

- A signal that varies faster needs to be sampled more frequently
- Bandwidth** measures how fast a signal varies

$x_1(t)$

1 0 1 0 1 0 1 0

1 ms

$x_2(t)$

1 1 1 1 0 0 0 0

1 ms

- What is the bandwidth of a signal?
- How is bandwidth related to sampling rate?

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Spectra & Bandwidth

- Spectrum of a signal: measures power of signal as function of frequency
- $x_1(t)$ varies faster in time & has more high frequency content than $x_2(t)$
- Bandwidth W_s is defined as range of frequencies where a signal has non-negligible power, e.g. range of band that contains 99% of total signal power

Spectrum of $x_1(t)$

Spectrum of $x_2(t)$

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Simpler Example

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Bandwidth of General Signals

"speech"

s (noisy) | p (air stopped) | ee (periodic) | t (stopped) | sh (noisy)

- Not all signals are periodic
 - E.g. voice signals varies according to sound
 - Vowels ("a", "e", ...) are periodic, while "s" is noisielike
- Spectrum of long-term signal
 - Averages over many sounds, many speakers
 - Involves Fourier transform
- Telephone speech: 4 kHz
- CD Audio: 22 kHz

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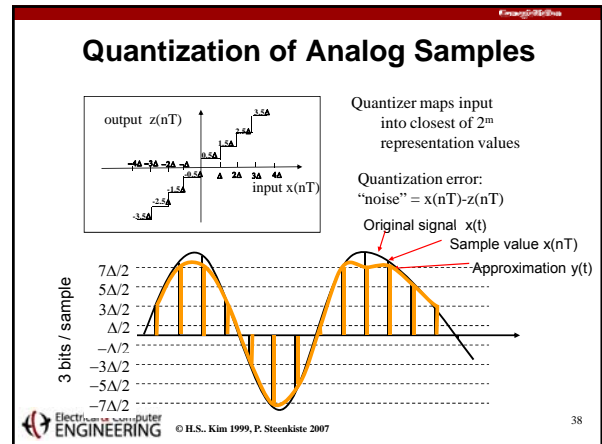
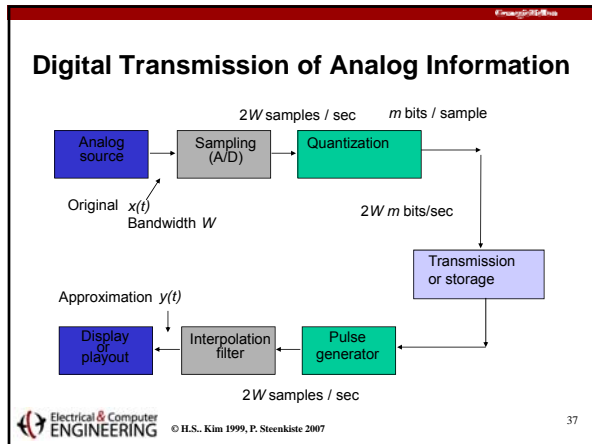
Nyquist's Sampling Theorem

Nyquist: Perfect reconstruction is always possible if and only if sampling rate $1/T > 2W_s$

(a)

(b)

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Comparison of Analog and Digital Transmission

Reading: Section 3.2.1

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A Communications System

Transmitter

Communication channel

Receiver

Transmitter

- Converts information into a *signal* suitable for transmission
- Injects energy into communications medium or channel
 - Telephone converts voice into electric current
 - Wireless LAN card converts bits into electromagnetic waves

Receiver

- Receives energy from medium
- Converts received signal into a form suitable for delivery to user
 - Telephone converts current into voice
 - Wireless LAN card converts electromagnetic waves into bits

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Communication Channel

Transmitter

Transmitted Signal

Communication channel

Received Signal

Receiver

Examples

- Pair of copper wires
- Coaxial cable
- Radio
- Light in optical fiber
- Infrared
- Interconnects in ICs

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Transmission Impairments

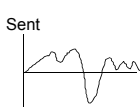
- Signal attenuation
- Signal distortion
- Noise in the medium
- Interference from other signals
- Channel variability

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Analog Transmission

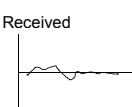
All details must be reproduced accurately

Sent



**Distortion
Attenuation**

Received



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Why digital? Problem with Analog Long-Distance Communications

Transmission segment

Source

Repeater

...

Repeater

Destination

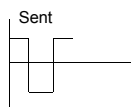
- Each repeater attempts to restore analog signal to its original form
- Restoration is imperfect
 - Distortion is not completely eliminated
 - Noise & interference is only partially removed
- Signal quality decreases with # of repeaters
- Communications becomes distance-limited
- Still used in analog cable TV systems
- Analogy: Copy a song using a cassette recorder

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Digital Transmission

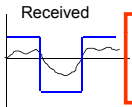
Only discrete levels need to be reproduced

Sent



**Distortion
Attenuation**

Received



Simple Receiver:
Was original pulse
positive or
negative?

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Digital Long-Distance Communications

Transmission segment

Source

Regenerator

...

Regenerator

Destination

- Regenerator recovers original data sequence and retransmits on next segment
- Can design so error probability is very small
- Then each regeneration is like the first time!
- Analogy: copy an MP3 file
- Communications is possible over very long distances
- Digital systems advantage over analog systems
 - Less power, longer distances, lower system cost
 - Monitoring, multiplexing, coding, encryption, protocols...

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