Physical Layer

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What is Information?

- Something not known apriori
- Related to the probability of an event
- Occurrence of a high probability event is very little information
- Occurrence of a certain event has no information

Measure of Information

- \( N \) possible events could occur
- When an event occurs the source has to convey the news to the destination
- Each event occurs with probability \( p_i, 1 \leq i \leq N \)
- \( p_1 + p_2 + \cdots + p_N = 1 \)
- What is the average information contained in any report?
- \[ H = \sum_{i=1}^{N} -p_i \log_2(p_i) \]

Example

- Suppose the two events are one and zero
- Each occurring with probability 0.5
- \( H = 2(-0.5 \log_2 0.5) + 2(-0.5 + 1) = 1 \) bit per transmission
- What if \( p_0 = 0.75, p_1 = 0.25 \)? \( H = 0.81128 \)
- 00 - 0.5625, 01 - 0.1875, 10 - 0.1875, 11 - 0.0625
- 0 \rightarrow 00, 01 \rightarrow 10, 10 \rightarrow 110, 11 \rightarrow 111
- 1 + 0.5625 + 2 \times 0.1875 + 3 \times 0.1875 + 3 \times 0.0625 = 1.6875, 1.6875/2 = 0.84375
- If \( p_1 = 1 \) and \( p_0 = 0 \)? \( H = 0 \)
- Information is maximum when events are equally likely

Transmission of Information

- Represent information in a generic form - example, bits
- Convert bits into signals (like voltage, current)
- Send signals over a medium
- Signals undergo modifications in the medium (noise, attenuation)
- Reconstruct signals at the receiver
- Convert to bits
- Interpret information
**Signals and Systems**

- Non-periodic signals $f(t)$
- Periodic signals $f_r(t)$
- What does a (analog) TV signal look like?
- Time domain and frequency domain
- Fourier transforms
- Fourier series for periodic signals
- Examples

**Information Transmission Needs Bandwidth**

- Source of information sends sequence of (unpredictable) “bits”
- How much information (bits) can be sent every second?
- How fast can fluctuations propagate over the medium?
- Every medium has an inherent “resistance” to changes
- Bandwidth of a medium imposes restrictions on the capacity

**Sampling of Bandwidth-Limited Signals**

- Any signal “emerging” from a medium is band-width limited
- Bandwidth - $H$ hertz (cycles/sec)
- A band-limited signal can be uniquely reconstructed from discrete samples
- $2H$ samples are enough for a signal of bandwidth $H$
- Nyquist sampling theorem

**Resolution of signal intensity**

- If we can unambiguously resolve 256 voltage levels, a single sample can be used to represent 8 bits
- For $V$ levels, $\log_2(V)$ bits per sample
- Nyquist capacity $C = 2H \log_2(V)$
- Resolution is affected by noise in the medium (channel)
- If noise is zero, $V \to \infty$, so $C \to \infty$
- Every medium has inherent noise
- Even at absolute zero (0 Kelvin)!

**Signal to Noise Ratio**

- Ratio of energies
- SNR decides the number of levels $V$ that can be employed
- Usually SNR is represented in Decibels
- Signal power $S$, noise power $N$
- $\text{SNR}_{\text{dB}} = 10 \log_{10} \left( \frac{S}{N} \right)$
- $S/N = 1000 \to 30$ dB
- $S/N = 100 \to 20$ dB
Shannons Theorem

\[ C = H \log_2(1 + \frac{S}{N}) \text{ bps} \]

- \( C \) is directly proportional to \( H \) (bandwidth)
- If \( S \to \infty \) or if \( N \to 0 \) or if \( \frac{S}{N} \to \infty \), then \( C \to \infty \).
- Theoretical limit.
- We can only approach this capacity. Never achievable in practice

Example. SNR = 25dB, \( H = 2000 \). \( 10 \log_{10}(S/N) = 25 \), \( \log_{10}(S/N) = 2.5 \), Or \( (S/N) = 10^{2.5} = 316.23 \),
\[ C = H \log_2(1 + \frac{S}{N}) = 2000 \log_2(317.23) = 2000 \times 8.3904 = 16,619 \text{ bps} \]

Under-Sampling and Over-Sampling

Consider a channel with a bandwidth of 1000 Hz
- And \( V = 256 \)
- Case 1: The output is sampled at 3000 Hz. What is the achievable bit-rate?
  - Still \( 2000 \times \log_28 = 16000 \text{ bps} \)
- Case 2: The output is sampled at 1000 Hz. What is the achievable bit-rate?
  - \( 1000 \times \log_28 = 8000 \text{ bps} \)

\( 2H \log_2 V \) is the maximum achievable bit-rate!

Need for Modulation

- Speech signals have frequencies between 1 to 3000 Hz
- Signals cannot propagate directly over any medium
- Speech signals \( s(t) \) can be sent directly over a copper cable
- But not over air or free-space
- We generally use “carrier” signals
- Modulation - process of mixing “information” signal and carrier signal to produce “modulated” signal
- Modulated signal transmitted over a medium
- Demodulation - extracting information signal from the modulated signal

Types of Modulation

- Amplitude modulation
- Phase modulation
- Frequency modulation

Bandwidth of Modulated Signals

- Usually the same as the bandwidth of the “information” signal
- The bandwidth is now around a “center” frequency - the frequency of the “carrier”
- Many signals can coexist simultaneously in the medium!
- By using different carrier frequencies
- Frequency division multiplexing ...we will look at this later
Transmission Media

- Two basic types
  - Guided
  - Unguided

Guided Transmission

- Magnetic media
- Twisted pair
- Coaxial cables
- Fiber optics

Twisted Pair

- Telephone cables
- Any wire is an antenna!
- Twisting substantially reduces interference
- Waves from different twists cancel out
- Number of twists per cm
- Categories 3 (16MHz), 5 (100 MHz), 6 (250), and 7(600)
- Ethernet cables

Coaxial Cables

- Upto 1 GHz
- Twisted pair cables are catching up!
- Better noise immunity than twisted pairs
- Used for TV signals, cable TV ...

Fiber Optics

- Extremely high bandwidth
- Single mode and multimode
- Single mode fibers can handle upto 50GHz over 100km!

Fiber vs Copper Wire

- Weight vs bandwidth
- Cost
- Security
**Electromagnetic Spectrum**

- **Radio**: 10^9 Hz to 10^12 Hz
- **Microwave**: 10^11 Hz to 10^12 Hz
- **Infrared**: 10^12 Hz to 10^14 Hz
- **Visible Light**: 10^14 Hz to 10^15 Hz
- **UV**: 10^15 Hz to 10^16 Hz
- **X-ray**: 10^16 Hz to 10^17 Hz
- **Gamma Ray**: 10^17 Hz to 10^18 Hz

**Satellites**

- Geo-stationary (about 36,000 km)
- Medium Earth Orbit (18,000 km, 6 hr orbits)
- Low Earth Orbit (less than 1000 km)

**Satellite vs Fiber**

- Remote / hostile areas
- Point-to-point vs Broadcast
- Mobile communications
- “Right of way” for laying cables

**Multiplexing**

- Multiplexing - many to one
- Demultiplexing - one to many

**Frequency division multiplexing**

- Telephone - 4000Hz per channel (450 + 3100 + 450)
### Wavelength Division Multiplexing

![WDM Diagram](image1.png)

- Fiber 1 spectrum
- Fiber 2 spectrum
- Fiber 3 spectrum
- Fiber 4 spectrum

### Time Division Multiplexing

- N signals, each having M samples per sec
- Interleaved together in a channel which can carry NM samples per sec
- Telephone (speech) channels - 8000 samples per sec (sent as 64000 bps)
- T1 lines - 1.544 Mbps, 24 channels

![TDM Diagram](image2.png)

### Code Division Multiple Access

- Sprint-PCS!
- TDM - different channels are split by time (same frequencies can be used)
- FDM - different frequencies at the same time
- CDMA - both frequencies and time may overlap!
- All users are given access to all bands at all times!
- How?
  - Division by code

![CDMA Diagram](image3.png)

### PSTN

- Each bit is converted to a sequence of chips
- Different users use different orthogonal chip sequences
- Orthogonal sequences do not interfere with each other!
- In practice difficult to obtain strict orthogonality
- “Tolerable” interference
- The main problem with FDM / TDM - need control channels for dynamic allocation of channels to users.
- No such thing needed in CDMA.
Local Loops

- Bringing connectivity home
- Telephone cables
- Coax Cables
- Wireless

Dial-up Internet

- 3000 Hz bandwidth used for voice over local loop
- Same used for dial-up Internet connection
- Baud rate 2400
- Each sample represent some bits
- For example 8 different levels implies 3 bits per sample
- How do we get 56 K?

Modem - Modulator / Demodulator

- Modulator - demodulator
- A group of bits covert to a signal by the modulator and sent out
- The received signal is converted back to bits by demodulator
- If we have b bits per sample, we need $2^b$ different signals to represent the bits
- Clipped sinusoid is the basic signal
- Variations achieved by modifying amplitude and phase
- Different signals can be represented on a constellation diagram

QPSK, QAM-16, QAM-64

Quadrature Phase Shift keying (2 bits per sample). Quadrature Amplitude Modulation

V.32 (4+1, 32) - 9600 bps, V.32 bis (6 + 1, 128) 14,400 bps
V.34 - 28,800 bps, V.34 bis - 36,600 bps
Shannon’s Limit

- Based on average length of local loops, limit is 35 kbps
- How do we achieve 56 kbps?
- 35 kbps is based on two local loops
- In practice, the connection to a server on the other end does not use telephone lines!
- So we could go up to 70 kbps (the noise introduced by the connection at the other end is insignificant)

Modern Modems

- Full duplex - transmissions possible in both directions at the same time
- Half-duplex - Both directions, but not at the same time
- Simplex - Only one direction
- V.90, V.92 - full duplex
- Dedicated uplink and downlink channel
- 56 kbps downlink, 33.6 kbps uplink (V.90)
- 48 kbps uplink (V.92) + facility to detect incoming calls while online

Unused Bandwidth!

- We have been sitting on a gold-mine!
- Telephones filter out higher frequencies to suppress noise
- 1.1 MHz spectrum divided into 256 channels - 4312 Hz each (DMT - Discrete Multitone)
- First channel used for POTS (plain old telephone service)

ADSL

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Cable Internet

- Usually the cable is a ring around the neighborhood (shared) connected to a head-end
- Over 750 MHz bandwidth - most used for TV channels

![Downstream frequencies](image)

**Upstream and Downstream**

- Contention in upstream

![Upstream and Downstream comparison](image)

**ADSL vs Cable**

- Bandwidth
- Peak performance
- Upstream / Downstream dynamics
- Contention
- Security
- QOS (Quality of Service)

**Message Switching**

- Store and forward
- Telegrams
- Mail?

**Packet Switching**

- Upper limit on block sizes
- Buffering of packets in routers
- Part-message forwarding
- No advance set-up required
- More fault tolerant
- QOS is difficult
- Efficiency
- Congestion
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<tr>
<th>Item</th>
<th>Circuit switched</th>
<th>Packet switched</th>
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<tbody>
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<td>Call setup</td>
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<td>Not needed</td>
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<td>Dedicated physical path</td>
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<td>Each packet follows the same route</td>
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<td>Packets arrive in order</td>
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<tr>
<td>Bandwidth available</td>
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<td>Time of possible congestion</td>
<td>At setup time</td>
<td>On every packet</td>
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<td>Store-and-forward transmission</td>
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<td>Charging</td>
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<td>Per packet</td>
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