

# ECE-4603

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Supplement to Chapters 3 and 5

- Analog to Digital Conversion
- Bandwidth versus Capacity
- Nyquist and Shannon equations.
- Signal Degradation
- Baseband and Broadband Encoding

Data & Computer Comm., p 95-98, 148-155

ECE4603 5a

## Analog and Digital Signals

Analog Signal - value varies continuously

- Sound - air pressure wave, can be converted to analog voltage or current wave by microphone.
- Electrical (analog) voice frequency signals - can be converted to sound by loudspeaker.
- Picture - light (color, brightness) varies continuously with position.

Digital Signals - strings of discrete values which can be represented by binary numbers, strings of one's and zeros.

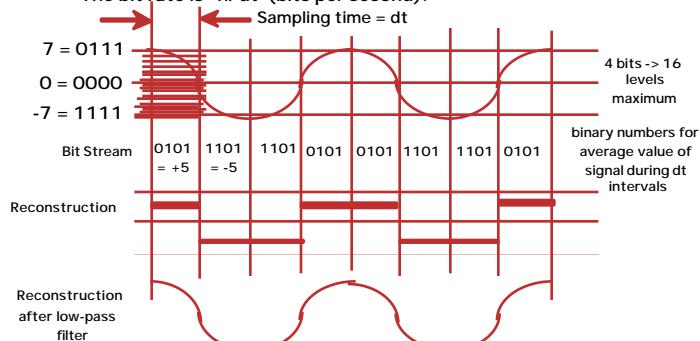
- Time-varying analog signals are converted by averaging the value over a time increment and assigning a binary value.
- Images are divided into small areas (pixels), then color and brightness are averaged over each pixel and transmitted are stored in digital memory sequentially.

## Conversion of Analog to Digital

Time increments,  $dt$ , must be small enough to capture highest-frequency components of interest.

The number of Amplitude Increments,  $n$ , must enough to give an adequately-accurate estimation of the analog signal.

The bit rate is  $n/dt$  (bits per second).



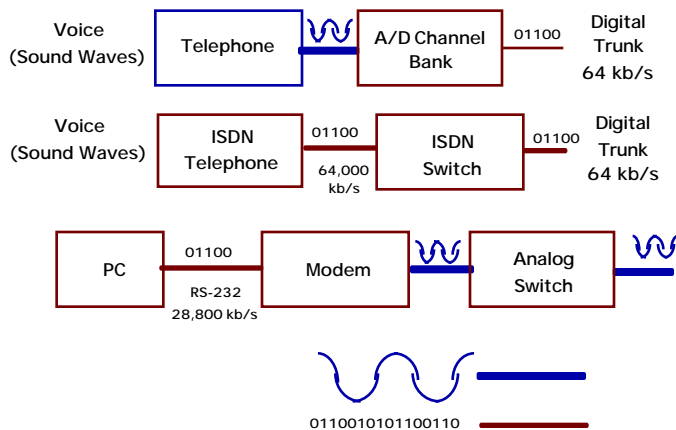
## Digital Voice

- Voice is recognizable and intelligible when frequency range is limited to 300 to 3400 Hz (Hertz = cycles/second) and quantization noise < -20 dB.
- Telephone standard is to digitize 8000 times per second ( $dt=125$  ms) and to use 128 levels (8 bits including sign).
- This results in a bit rate for a voice channel of 64,000 b/s.

## Digital Music

- Music requires a frequency range up to 18,000 Hz and quantization noise < -65 dB.
- CD music is digitized 44,100 times per second ( $dt=23 \mu s$ ) into 32,000 levels (16 bits including sign).
- This results in a bit rate for a CD music channel of 710,000 b/s (times 2 for stereo).

## Analog and Digital Signals



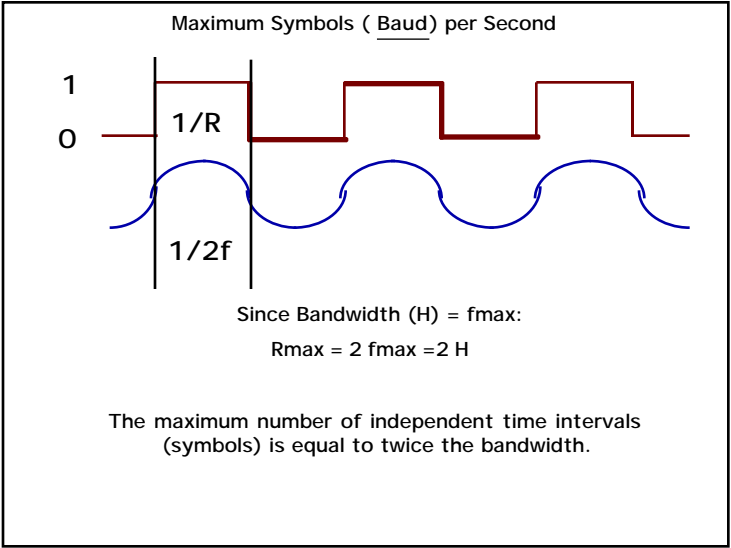
## Channel Bandwidth versus Capacity

- Capacity = Rate in bits/second (b/s) that bits can be transmitted.
- Bandwidth = Frequency range (width) of the channel (Hertz).
- Maximum Baud Rate (symbols/sec),  $B = 2 H$
- Noise = Unpredictable deviation of received value due to all causes (probability bounded by acceptable error rate).
  - Thermal noise, Crosstalk, Impulse, Intermodulation, ...
- Nyquist Theorem for a noiseless channel: given a bandwidth  $H$  and a signal with  $L$  different levels, the capacity  $C$  is given by:

$$\text{Maximum Data Rate (bits/sec), } C = 2 H \log_2(L)$$

- Shannon's Theorem for a noisy channel with signal to noise ratio  $S/N$  is given by:

$$C = H \log_2(1 + S/N)$$



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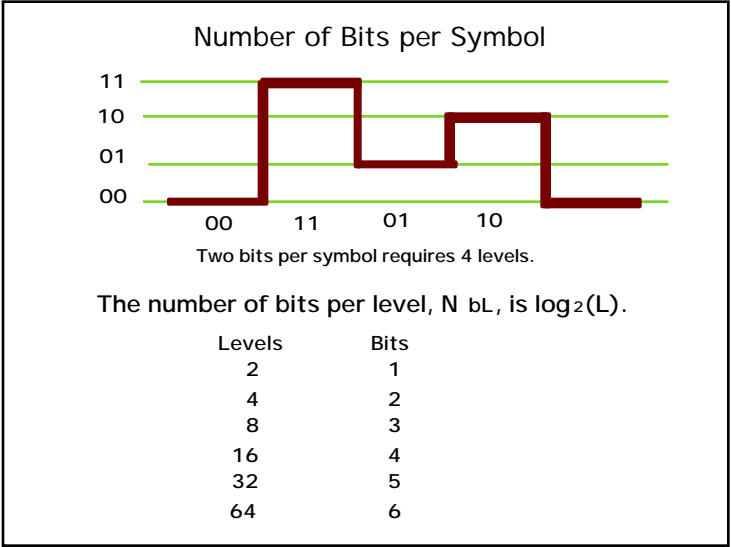
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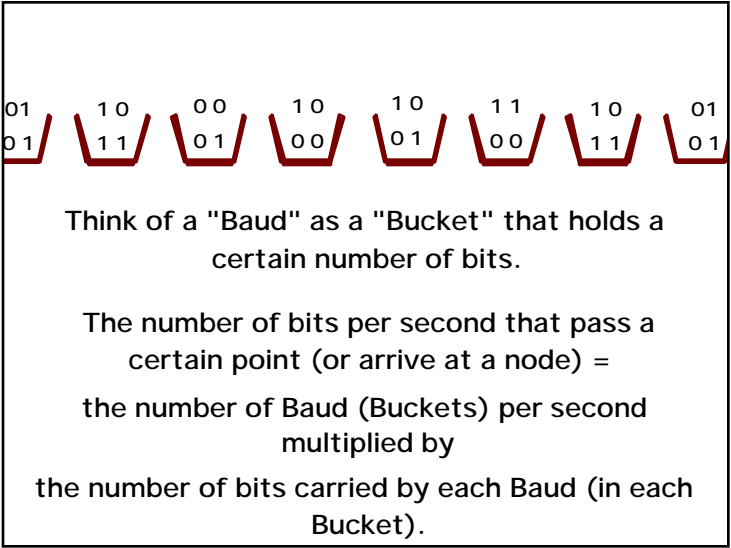
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## Simplified Concept of Shannon's Law

The Capacity (maximum bit rate) is equal to the maximum number of symbols per second ( $2 \times \text{Bandwidth}$ ) multiplied by the number of bits per symbol ( $\log_2(L)$ ).

$$\text{Nyquist: } C = 2 H \log_2(L)$$

Intuitively, the maximum number of levels with an maximum signal voltage  $V_s$  is approximately  $V_s/V_n$ , where  $V_n$  is the noise voltage (separation voltage between levels needed to reduce errors due to noise to acceptable value). Claude Shannon (father of Information theory) found a more exact value as a function of the ratio of signal power  $S$  to noise power  $N$ .

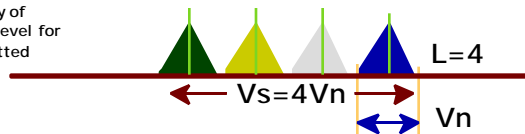
$$\text{Shannon: } C \leq 2H \log_2(\sqrt{(S+N)/N})$$

$$\leq H \log_2(S/N + 1)$$

$$\text{to match Nyquist: } L \leq \sqrt{(S/N + 1)} = \sqrt{(S+N)/N}$$

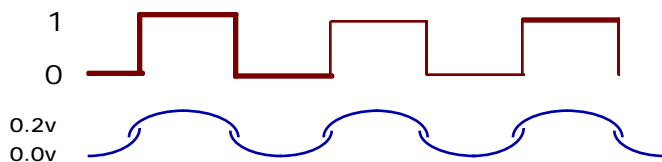
$$L \leq (\text{signal} + \text{noise voltage})/(\text{noise voltage})$$

Probability of received level for 4 transmitted levels.



## Signal Degradation

All real signals are analog by nature. While the transmitter may send exact discrete levels into a physical transmission line, the receiver sees a degraded signal and must decide which discrete level expected is closest.



Attenuation - lost of strength (amplitude)  
Bandwidth cutoff - lost of high-frequency components.

## Data Transmission Types

### Analog Baseband

- Voice Telephone

### Analog Broadband

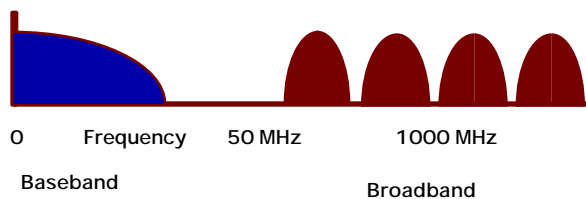
- AM, FM, TV, Cellular (AMPS)

### Digital Baseband

- ISDN Voice
- Ethernet
- PC Comm Port

### Digital Broadband

- Direct-TV (satellite)
- PCS, Digital Cellular
- Digital CATV



## Data Encoding Schemes

Baseband - frequency range is from 0 Hz to  $f_{\max}$   
( $B = f_{\max}$ )

Broadband - frequency range is from  $f_{\min}$  to  $f_{\max}$   
( $B = f_{\max} - f_{\min}$ )

With broadband signals, data is modulated onto a carrier wave whose frequency is at the center of the band. Common types of modulation are:

- Amplitude Shift Keying (ASK)
- Frequency Shift Keying (FSK)
- Phase Shift Keying (PSK)
- Quadrature Phase Shift Keying (QPSK)
- Quadrature Amplitude Modulation (QAM)

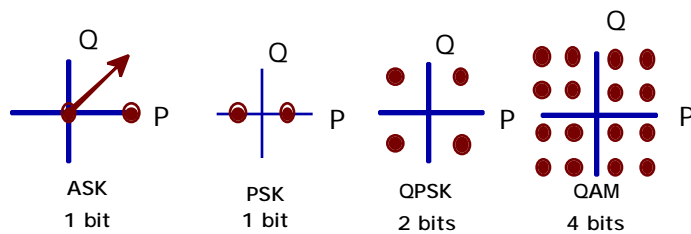
With all commonly-used Broadband modulation schemes:

$$\text{Bandwidth (Hz)} = \text{Baud Rate (Baud/second)}$$

## Broadband Modulation Encoding

A sine wave with arbitrary amplitude  $A$  and phase  $\phi$  can be represented by the amplitude of the in-phase and quadrature components,  $P$  &  $Q$ :

$$V(t) = A \sin(\omega t + \phi) = P \sin(\omega t) + Q \sin(\omega t + 90^\circ)$$



Each state is represented by a dot in the "constellation" diagram.

## Baseband Encoding Schemes

Problems to overcome

- Transitions needed to synchronize receiver bit clock
- DC reference level needs to be maintained

