The Foundations of the Digital Wireless World

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March 5, 2010

Pre-Digital Wireless History 1870-1948

- Maxwell's Equations predicting electromagnetic propagation
- Hertz: experimental verification of propagation
- Marconi: wireless telegraph to ships at sea
- Broadcast Radio
- Military Uses in WW I and WW II – Radar
- Broadcast Television

Information Theory, Satellites, and Moore's Law 1948-1990

Information Theory and Its Precedents

- Statistical Precedents: C.R. Rao; H. Cramèr
- Statistical Communications: N. Wiener; S.O. Rice
- Information Theory: Claude Shannon "Mathematical Theory of Communication", Bell System Technical Journal (1948)

  Source Coding Theorem

  Channel Coding Theorem

Space and Satellites

- Soviet Sputnik: October 1957
- U.S. Explorer I: January 1958

Initially for telemetry at very low rates--why?

very low received signal power

from 40,000 Km, corrupted by noise

Signal-to-Noise, $S/N<<1$

Within 20 years, transmission of several Megabits per Second from same orbit—how?

Solid-State Circuit Integration

- Transistor at Bell Laboratories 1947

  Bardeen, Brattain, Shockley
- Integration—multiple devices on a chip

  R. Noyes, G. Moore
- **Moore’s Law (1965)** : Integration doubles every 18 months, with proportional

  Power decrease, Speed Increase

  and especially **Decreased Cost**.

Increasing Satellite Communication Rates

- Increase Transmitted Signal Power
  increases launch weight
- Increase Receiving Antenna Diameter
  beyond 20 meters ?
- Reduce Receiver Noise Temperature
  Cryogenically
- Reduce the Required S/N – how?
  by Information Theory Methods
- Why Satellite Communication - not Terrestrial?
  Low Received Power and Perfect Model

Shannon's Two Rate Bounds

- Minimum Number of Bits/Second to accurately represent an Information Source (Source Coding Theorem)

- Maximum Number of Bits/Second which may be transmitted error-free over a perturbed medium (Channel Coding Theorem)

Source Compression

- Source Coding (Rate-Distortion)Theorem
- For data, very effective even without prior statistics (universal coding)
- For voice and images, it fails to account for **Psychoacoustic** and **Psychovisual** effects.

Compressed Voice

- Voice mostly within 4 KHz Bandwidth

- Nyquist Rate: 8K Samples/Sec.
- With 8 bit Quantization: 64 Kbits/sec.

- CELP Compression to 8 Kbits/Sec. (8:1)

CELP Voice Compression

- Model Vocal Tract and Vocal Chords by Digital Filter driven by small set of Excitations contained in a codebook.

- Linear Predictive Coder with

  Codebook Excitation (CELP)

- Transmit only Filter Parameters and Index of Codebook Sample

Digital Images

- Analogue TV samples horizontally (approximately 450 lines per frame)
- Digital Images (Cameras and TV) sample entire frame
- 1M to 8M picture elements “pixels”-- in 3 primary colors

- High Definition TV: 1 M Pixels/Frame; 60 Frames/Sec.
- Results in 180M Pixels/Sec.;
- with 8-Bit Quantization, 1.44 Gbits/Sec.

- With MPEG Compression, 30 Mbits/sec. (48:1)

Image Compression (JPEG/MPEG)

- Divide total Pixel Grid into 16 X 16 Sub-grids.
- Perform Spatial Frequency Transform
- (Discrete Cosine Transform—DCT)
- Quantize Low Frequency Components finely; High Frequency Components coarsely (8:1)
- Utilize Correlation among Colors (3:1)
- For TV, Utilize Correlation between Frames (2:1)

Channel Coding for Gaussian Noise

Shannon Channel Coding Theorem when Perturbation is Additive Gaussian Noise,

$$R < W \, Log_2(1 + S/N)$$

Rate R bits/sec.; Bandwidth W Hz

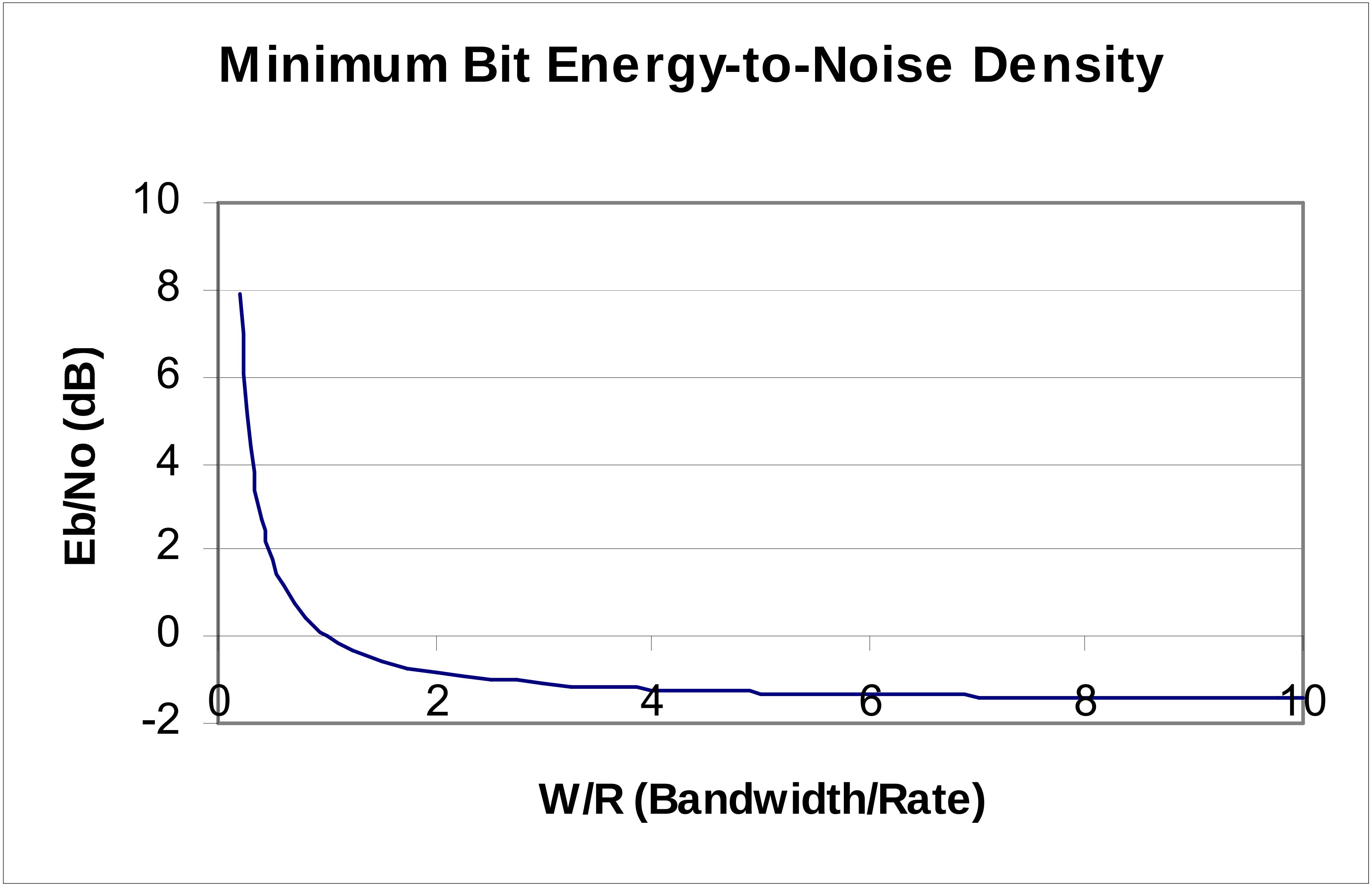
Minimum Bit Energy/Noise Density

$R < W \, \mathrm{Log}_2(1 + S/N)$

$S/N = (E_b R)/(N_0 W)$

Thus $R/W < \mathrm{Log}_2 \, [\, 1 + (E_b/N_0)(R/W)]$

And $E_b/N_0 > (W/R)(2^{R/W}-1)$


Minimum Bit Energy-to-Noise Density
Eb/No (dB)
10
8
6
4
2
0
-2
0
2
4
6
8
10
W/R (Bandwidth/Rate)

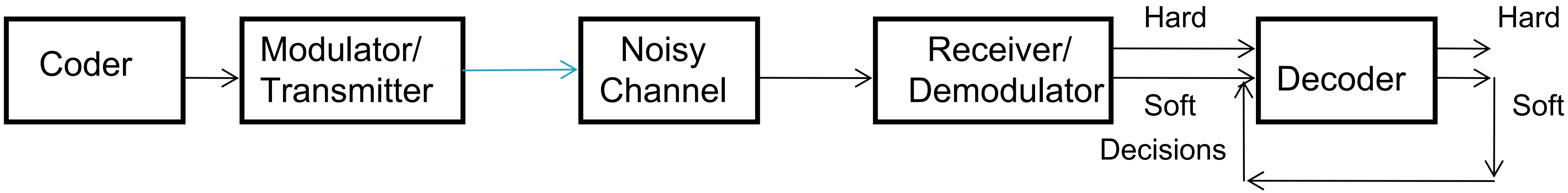
Potential Coding Gain

- To keep error rate below 10^{-6} (one in a million),
- Uncoded digital communication requires E_b/N_0=10.5 dB

- From graph, with coding,
- Min $E_b/N_0 = \begin{cases} 0 \text{ dB}, & W/R = 1 \\ -1.6 \text{ dB}, & \text{as } W/R \rightarrow \infty \end{cases}$

- **Thus Potential Coding Gain: 10 to 12 dB**
- Early attempts (Block Codes) achieved 3 dB gain.
- Convolutional Codes achieved 6 dB gain.
- Iterative Decoding achieved over 9 dB gain (8:1)

Channel Coding and Decoding:
Half Century Quest to Approach Shannon Limit



Chronology:

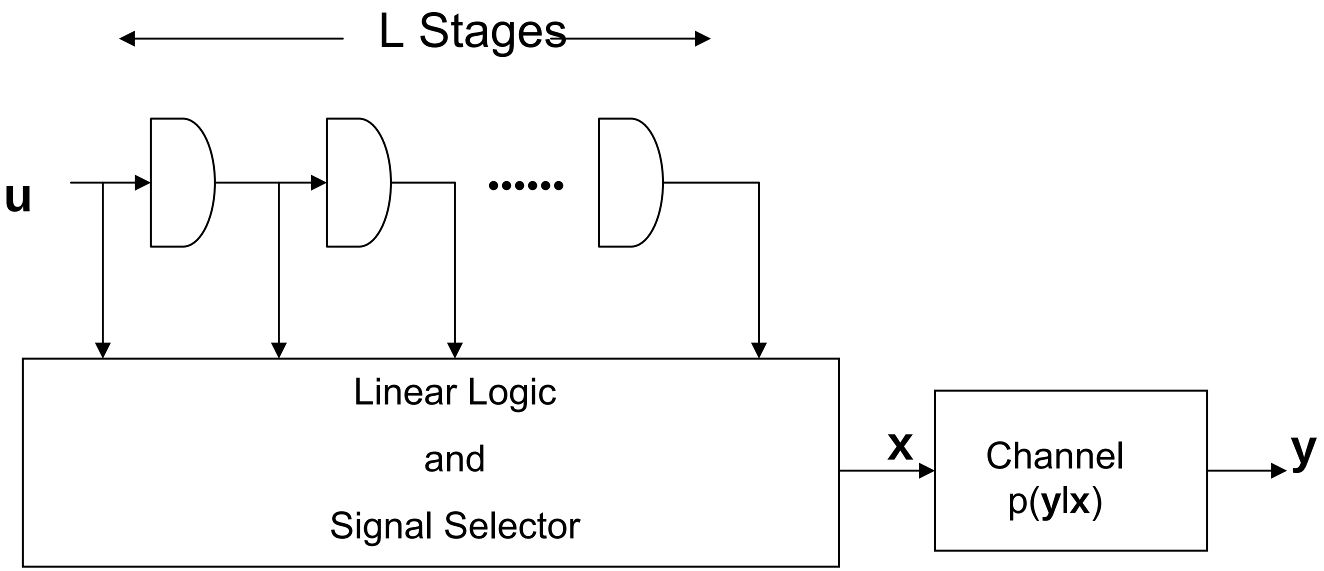
Algebraic Block Codes (Hard Decisions)

Convolutional Codes (Soft Decisions In)

Iterative Decoding (Soft In-Soft Out—SISO)

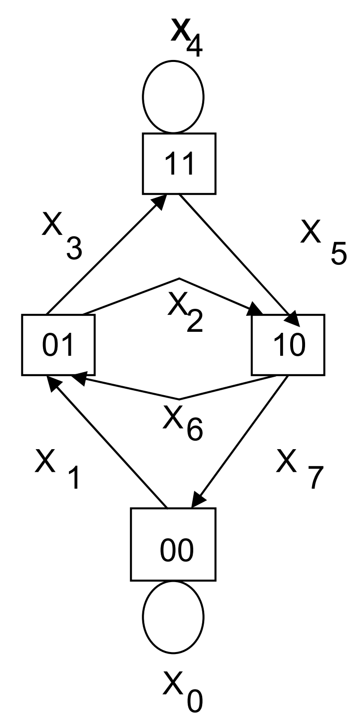
Turbo (Convolutional) Codes
Low Density Parity (Block) Codes--LDPC

Convolutional Codes (Markov State Model)



State Diagram

(L = 2)



Decoder Problem: Given Likelihood Functions **(Soft Inputs**), Find Most Likely Path Traversed through Diagram

Solution: Simple Algorithm– 2^L Adders/Comparators followed by Traceback

Convolutional Codes

Soft <u>Input</u> Only—

gets only part way to Shannon Limit

But there have evolved Much <u>Broader</u> Applications of

Markov Model Concept (e.g.):

Speech Recognition

Magnetic Recording

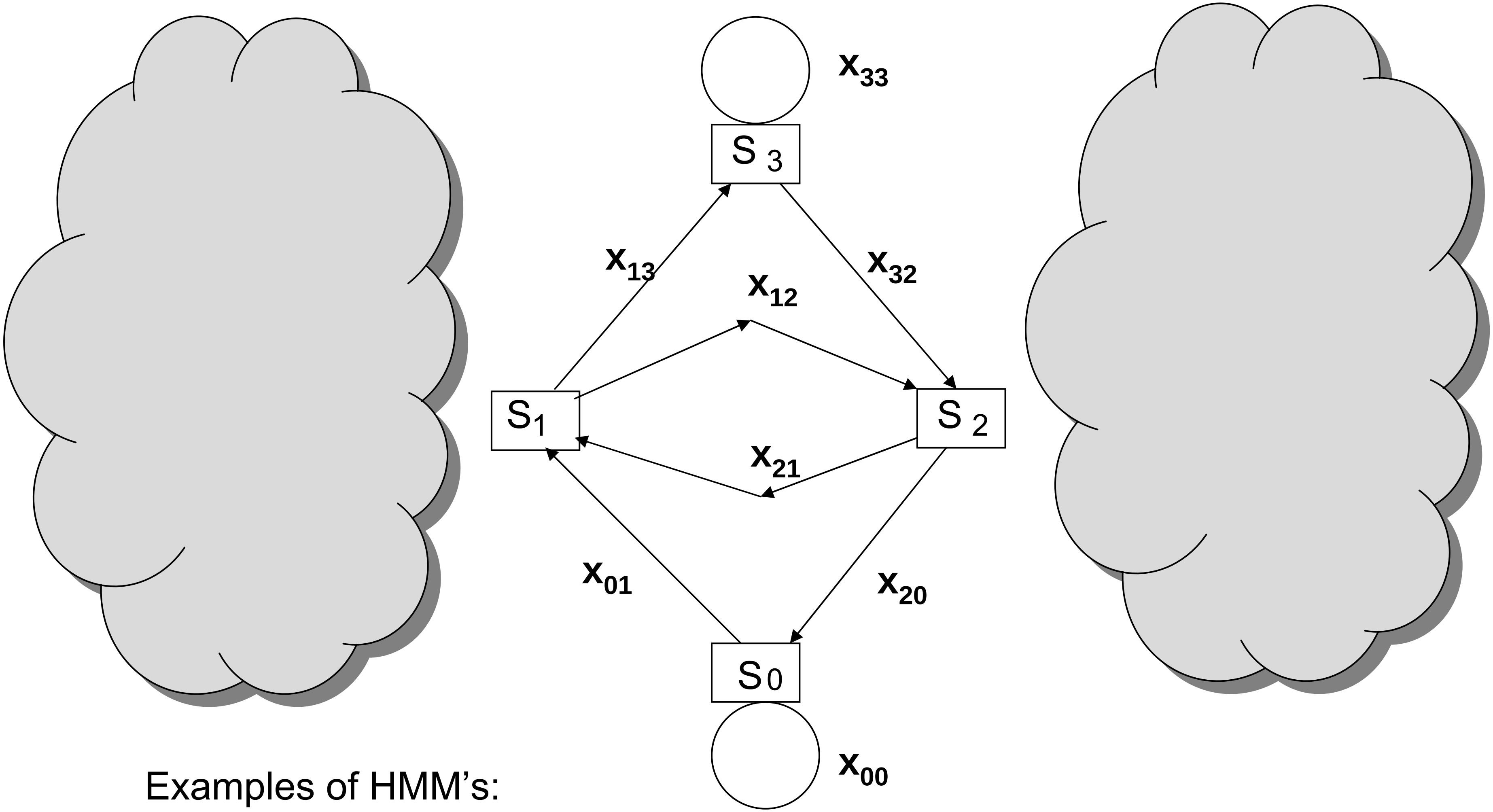
DNA Sequence Analysis

Hidden

Markov

Model

Parting the Clouds



Examples of HMM's:
  Speech Recognition
  DNA Sequence Alignment

Decoder Technology Evolution

- 1960's: Rack of Equipment
- 1970's: Single Drawer (some integration)
- 1980's: Silicon Chip (full integration)
- 1990's +: Fraction of Chip

Digital Wireless Evolution

Theoretical Foundations: Information Theory

Application: Satellite Communication
(Commercial and Direct Broadcast)

Enabling Technology: Solid-state Integration

Primary Beneficiary:
Personal Mobile Communication