Physical-Layer Communications Research: The Road Ahead

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January 20, 2005
The Prime Movers

- Information Theory
- Channel Coding Theory
- Signal Processing
- Data Compression
A Mathematical Theory of Communication

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INTRODUCTION

THE recent development of various methods of modulation such as PCM and PPM which exchange bandwidth for signal-to-noise ratio has intensified the interest in a general theory of communication. A basis for such a theory is contained in the important papers of Nyquist and Hartley on this subject. In the present paper we will extend the theory to include a number of new factors, in particular the effect of noise in the channel, and the savings possible due to the statistical structure of the original message and due to the nature of the final destination of the information.

The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point. Frequently the messages have meaning; that is they refer to or are

Published in The Bell System Technical Journal
Vol. 27, pp. 379-423, 623-656, July, October, 1948
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Printed in U. S. A.
Information Theory

- Increasingly relevant
- Drives system design
- Open Problems
Information Theory: Open Problems

- Delay – Finite Blocklength
- Feedback
- Joint Source/Channel Coding
- Network Information Theory
  - Are bits the universal currency?
- Incorporating Protocols
- Rate Distortion Theory and Lossy Data Compression: Gap between theory and Practice
- New Habitats
Information Theory: Driving Design

- Noise/Channel Structure: Destroy or Exploit?
- Low-Power Design
- Wideband Channels
- Fading: Friend and Foe
- Multiantenna Capacity
Noise/Channel Structure: Destroy or Exploit?

- **Destroy**: Simpler Design
  - Interleaving against channel memory
  - Single-user matched filtering against multiaccess interference

- **Exploit**: Higher Efficiency
  - Burst-error correcting codes
  - Multiuser detection
Exploiting Multiaccess Interference in CDMA

**Figure 2.** CDMA spectral efficiencies with optimum coding-spreading trade-off.
Low-Power Design

- Battery life does not follow Moore’s law
- Transmitted Power + Dissipated Power
- More sophisticated signal processing → more dissipated power
- VLSI Technology progresses → Transmitted Power vs Dissipated Power
Wideband – Power Limited Regime

Major Driving Forces:

- Energy per information bit close to the minimum one.
- Diversity against frequency-selective fading.
- Ease of multiplexing/multiaccess/cellular frequency assignment.
- Ability to coexist with other systems using the same band.
3G: Wideband @ $600/Hz
Effect of Coherence at Low SNR

Figure 1. Spectral efficiency of the AWGN channel and the Rayleigh flat fading channel with and without receiver knowledge of fading coefficients.

Fading: Friend and Foe

Foe:
- Average performance dominated by deep fading
- Outage Probability

Friend:
- If transmitter knows fading coefficients → Opportunistic Signaling
- Interference Population Control
Diversity against Fading

♣  Time
♦  Frequency
♠  Space
♥  Multiuser
Multiantenna Arrays
Multiantenna Capacity

- Capacity of Coherent MIMO: grows as $\min\{n_T, n_R\}$ (Foschini, Telatar, 1995)

- Low SNR?

- Antenna Correlation?

- Line of Sight Components?

- Noncoherent Reception?

- Minimum Outage Transmitter Design?
Coding Theory: The great Revolution

1948-2000: Algebraic Coding Theory

1995-present: Sparse-Graph Codes

- Regular Low-Density Parity-Check Codes (1961)
- Turbo Codes (1995)
- Irregular Low-Density Parity-Check Codes (2000)
- Irregular Repeat-Accumulate Codes (2000)
- Fountain Codes (2002)
- Multi-edge Low-Density Parity-Check Codes (2004)
C. Berrou, “The 10-year-old turbo codes are entering into service,” IEEE Comm Mag, 2003
Coding Theory: Emerging Challenges

- Dirty-Paper codes
- Lattice codes
- Broadcast Channel codes
- Space-Time codes
- Quantum codes
- Network codes
Network Coding
Signal Processing

- Channel Equalization and Adaptive Matched Filtering
- Multiuser Detection
  - MIMO Signal Processing
  - 3G, 4G
  - VDSL
  - GPS/Galileo
- Denoising: Analog and Discrete
- Probability-Distribution Signal Processing
  - Conditional Marginal Probability Distributions
  - Iterative Algorithms
  - Factor Graphs
  - Analog VLSI
  - Particle Filtering
Data Compression

- Universal Lossless Compression
- Universal Lossy Compression?
Lossless Data Compression

- Lempel-Ziv
- BWT, PPM, CTW, ...

- zero-error variable length
- universal compression
- linear compression/decompression time
- achieve entropy-rate for stationary ergodic sources
Lossless Data Compression – Applications

UNIX, WINDOWS, LINUX: arc, compress, lizexe, zip, gzip, bzip, pkzip, gif,...

Fast Modems: V.32bis, V.42bis

Lossy Data Compresors: JPEG, MPEG,...
Lossless Data Compression – Non-Applications

**UMTS:** WCDMA

**Qualcomm:** HDR™
( CDMA2000 1xEV )

**Flarion:** flash-OFDM™
Existing Lossless Data Compressors – Shortcomings

- Lack of resilience to transmission errors.
- Error propagation across packets.
- Do not lend themselves to joint source-channel coding.
- Compression efficiency for short-moderate blocklengths?
New Approach: Caire, Shamai, Verdú, 2003
Random ensemble of Markov sources

Figure 1: Histogram of redundancies; blocklength = 3,000
New Paradigms

- High-speed Wireless Wide Area Networks
- Ultra-Wideband
- Ad-hoc Sensor Networks
- Hybrid Terrestrial-Satellite Networks
- Cooperative Multi-cell Processing
New Mathematical Tools

- Statistical Physics
- Random Matrix Theory
- Convex Optimization
Ever Closer Union

- Information Theory
- Channel Coding Theory
- Signal Processing
- Data Compression
- Networks
The Twilight of the Great -DMA Wars

**GSM**  TDMA

**IS-95**  DS-CDMA

**UMTS**  DS-CDMA [FDD & TDD]

**IS-856 1xEV-DO**  TDMA + DS-CDMA

**Flash OFDM**  OFDMA + FH-CDMA