# Physical-Layer Communications Research: The Road Ahead

**Sergio Verdú**
Princeton University

EURECOM
Sophia Antipolis

January 20, 2005

# The Prime Movers

- Information Theory
- Channel Coding Theory
- Signal Processing
- Data Compression

# A Mathematical Theory of Communication

By C. E. SHANNON

## 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[1] and Hartley[2] 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

# 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

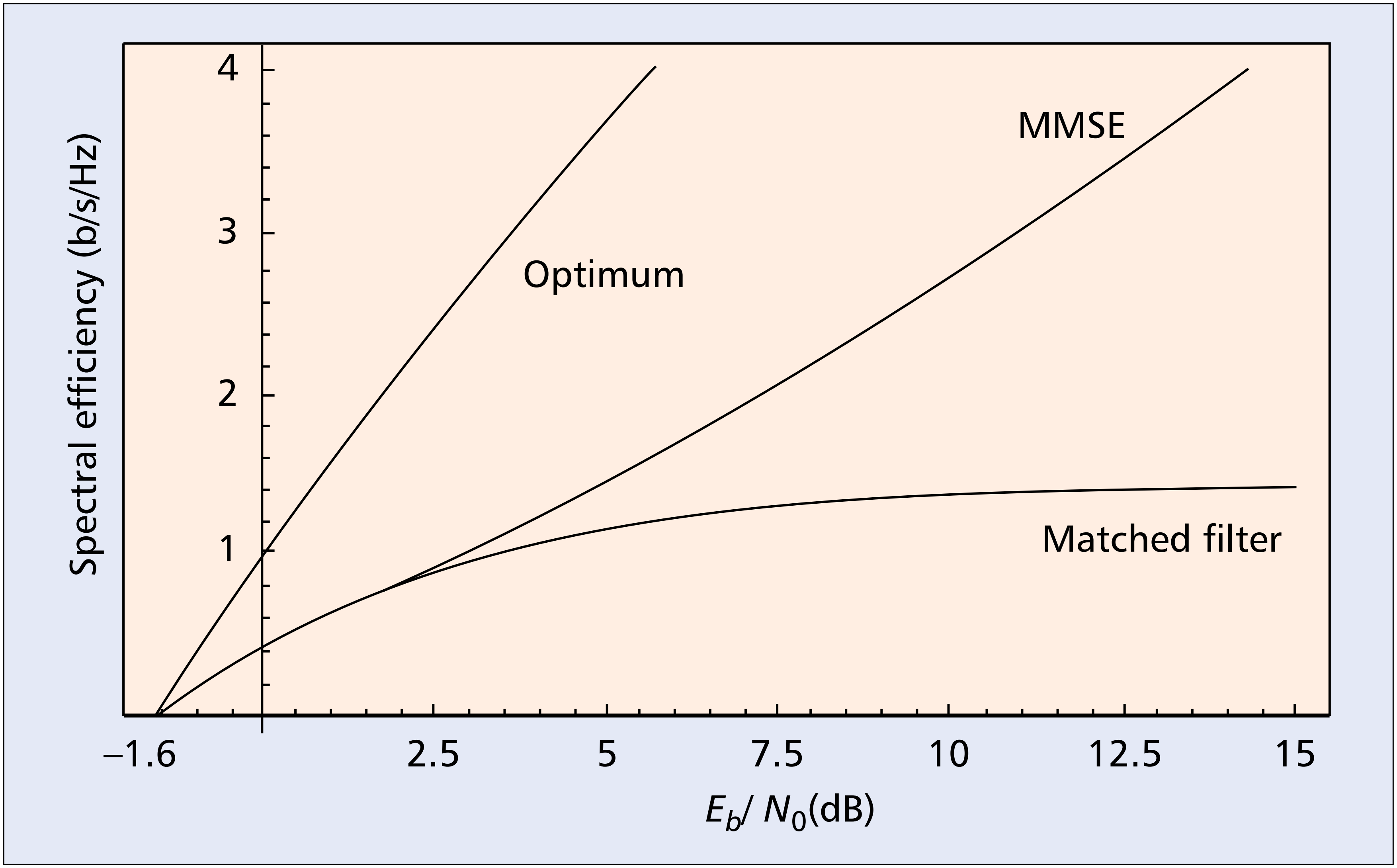



**Figure 2.** *CDMA spectral efficiencies with optimum coding-spreading trade-off.*

# Low-Power Design

- Battery life does not follow Moore's law
- Transmitted Power + Dissipated Power
- More sophisticated signal processing $\longrightarrow$ more dissipated power
- VLSI Technology progresses $\longrightarrow$ 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

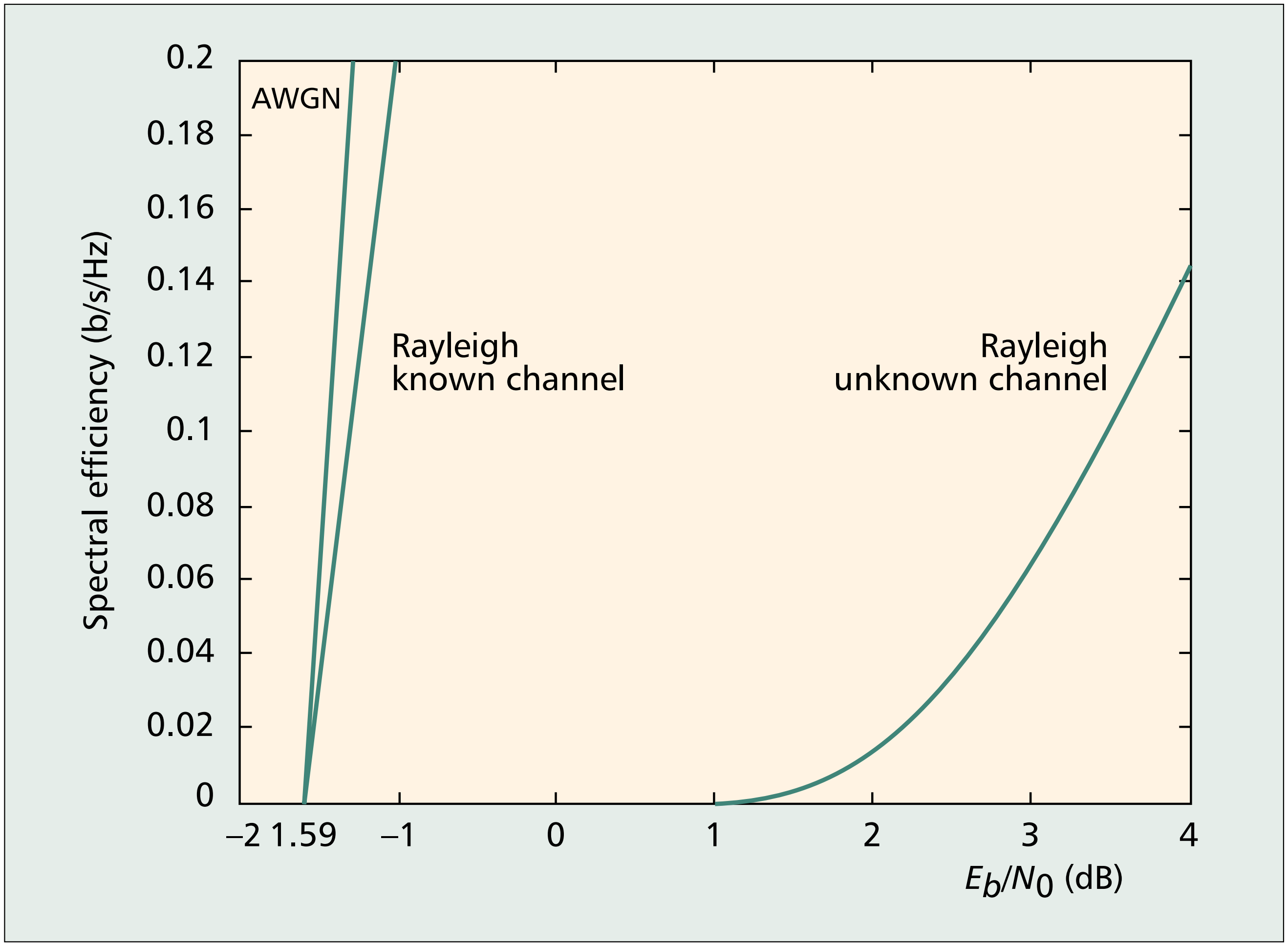



Figure 1. *Spectral efficiency of the AWGN channel and the Rayleigh flat fading channel with and without receiver knowledge of fading coefficients.*

S. Verdú, "Spectral Efficiency in the Wideband Regime," IEEE Trans. Inform. Theory, 2002

# Fading: Friend and Foe

**Foe:**

- Average performance dominated by deep fading
- Outage Probability

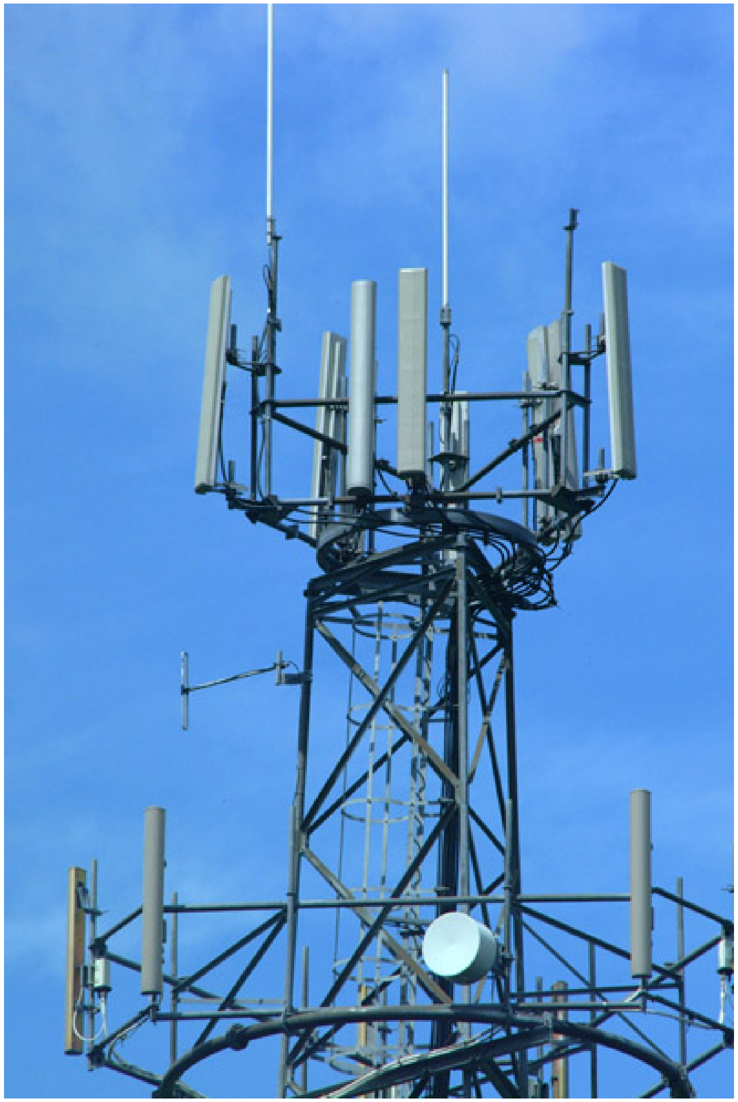
**Friend:**

- If transmitter knows fading coefficients $\rightarrow$ 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?

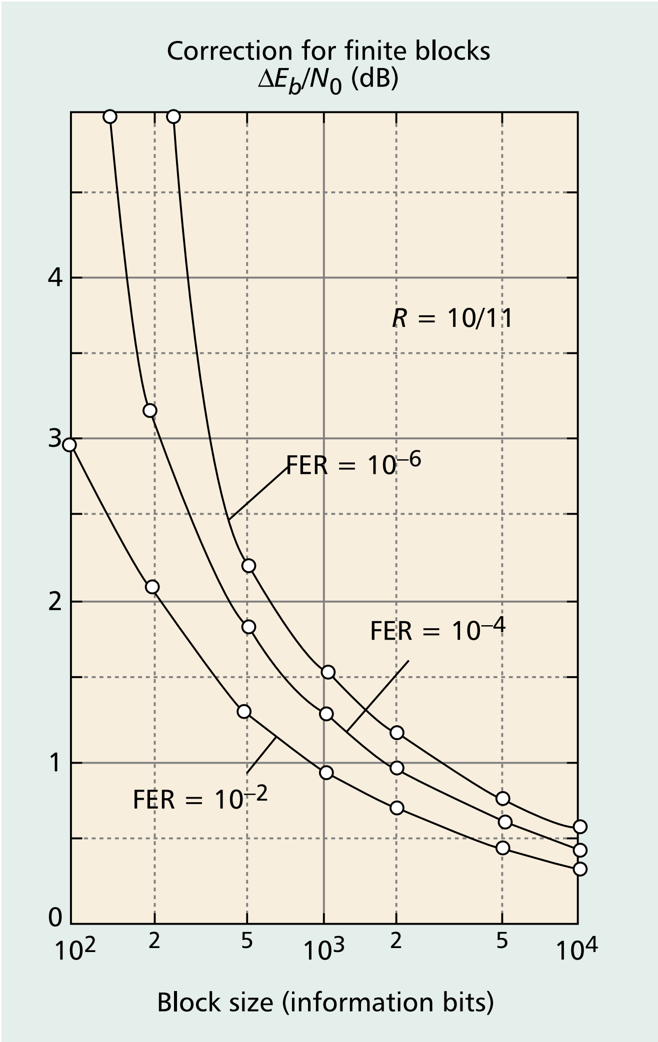
# Coding Theory: The great Revolution

**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)

# Distance from Capacity

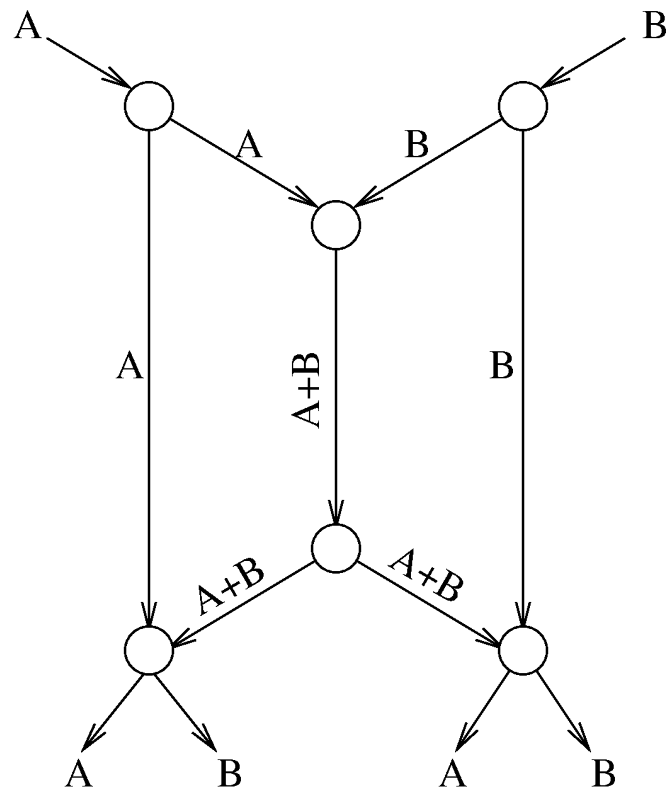



C. Berrou, “The 10-year-old turbo codes are entering into service,” IEEE Comm Mag, 2003

# 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, lzexe, zip, gzip, bzip, pkzip, gif,...

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

**Lossy Data Compresors:** JPEG, MPEG,...

# Lossless Data Compression –Non-Applications

**UMTS:** WCDMA

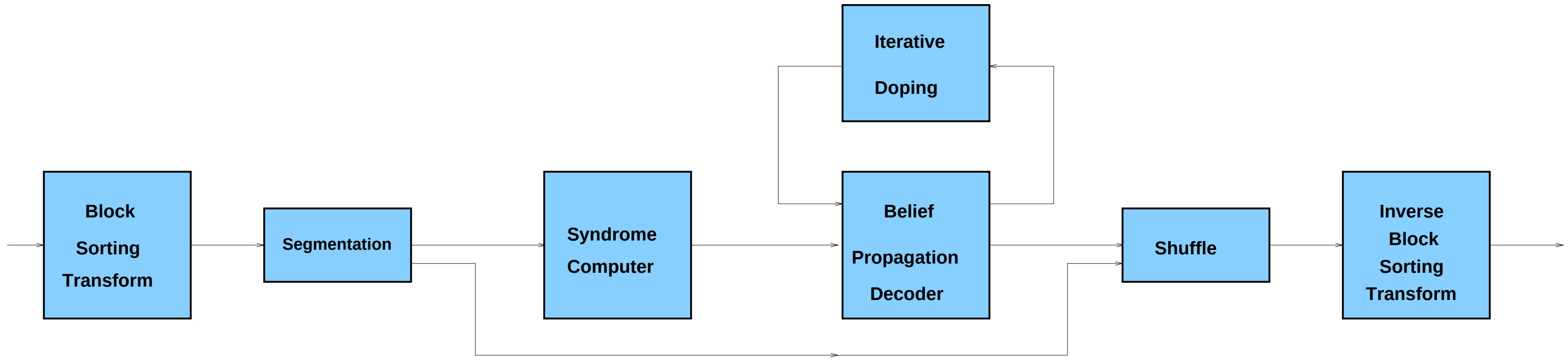
**Qualcomm:** HDR™
(CDMA2000 1xEV)

**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

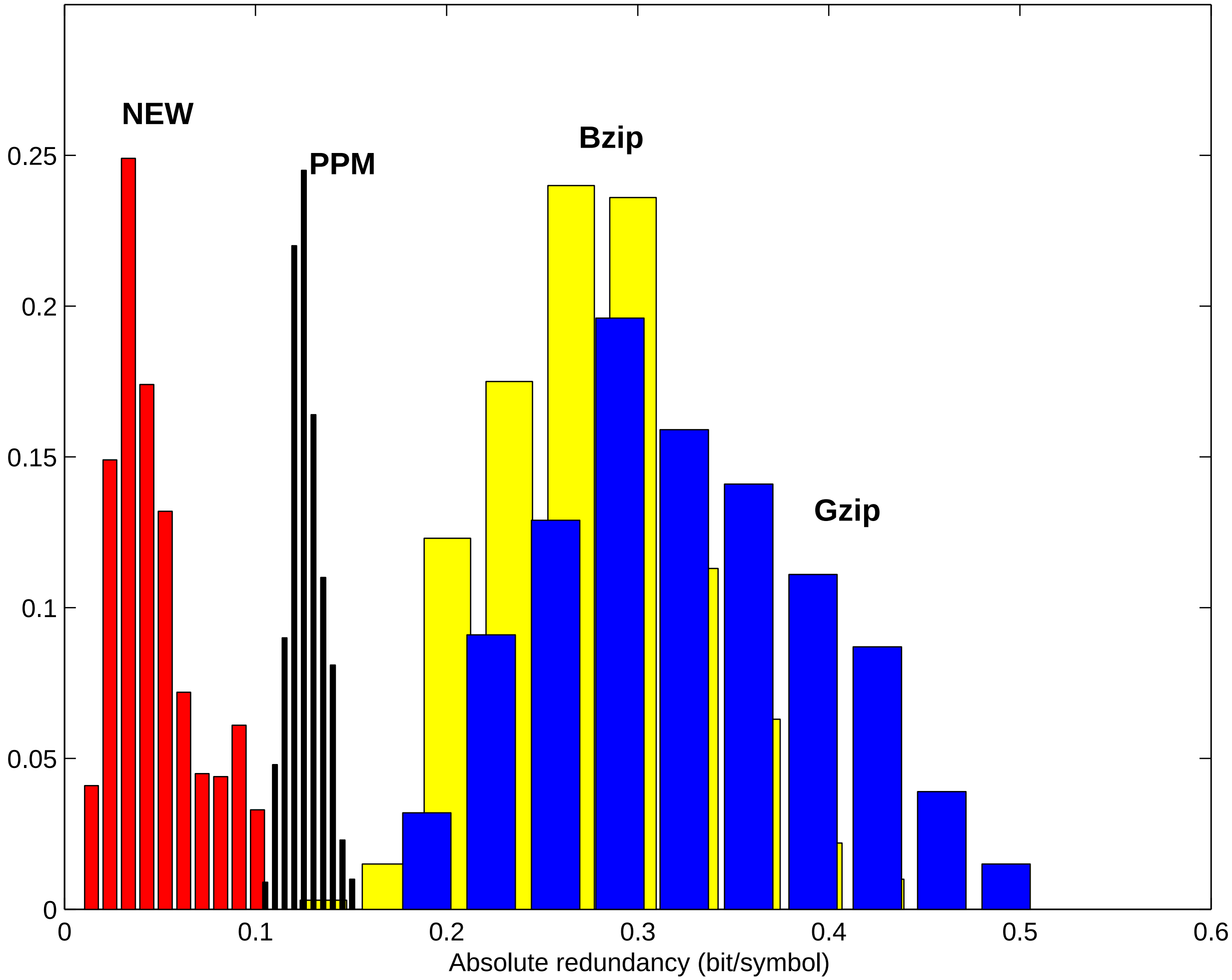



Figure 1: Histogram of redundancies; blocklength = 3,000

# 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