Cooperative Communication—An Overview

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Credits

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Outline

• Motivation
• A new paradigm
  – Physical layer--Network
• The relay example:
  – Theoretical
  – Practical
• Potentials
Channel?

- Network is the channel
Routing?

- Physical layer is not *just* a bit pipe
- Packet *integrity* is not sacred
Physical Layer-Network Layer

- Cross layer optimization
  - Joint source and channel coding
- Feedback
- Explore all available dimensions
  - Signal, space, distributed hardware
Theoretical Implications

- Spatial dimensions
  - Multiple antennas
  - User cooperation
- New degrees of freedom
  - Diversity
  - Multiplexing

\[
\text{BER or } FER \propto \frac{1}{SNR^d}
\]

- Multiplexing

\[
R \propto mE[\log(1+|h|^2SNR)]
\]

Simple direct fading SISO link
Practical Implications

• Access--Scheduling
• Distributed coding
• Feedback
• Relaying protocols
Historical Account

- Introduced in 1971 [Van der Meulen]
- Degraded relay channel in 1979 [Cover & El Gamal]
- Isolated work in the 80’s and 90’s [Willems, Vodafone]
- Recent resurgence
Two Relays

- A broader configuration [Shein & Gallegar]
Butterfly Network

- Wired and wireless [Yeung & Ahlswede]
Multi Hop Network

• Large body of recent work
  [Gupta & Kumar, Gastpar & Vetterli, Reznik & Verdu & Kulkarni]
User Cooperation

• A multiuser perspective [Sendonaris & Erkip & Aazhang]
A Broader Picture: Network Coding
Relay Channel

• A building block
Gaussian Fading Model

• The channel qualities

\[ \gamma_0 = \frac{|h_{12}|^2}{N_1}, \quad \gamma_1 = \frac{|h_{10}|^2}{N_0}, \quad \gamma_2 = \frac{|h_{20}|^2}{N_0} \]

Source

\[ Y_0 = h_{10}X_1 + h_{20}X_2 + Z_0 \]

Relay

\[ Y_1 = h_{12}X_1 + Z_1 \]

Destination
Relay Operation

• Full Duplex
  – Relay can receive and transmit same time and same frequency band
    • RF isolation
    • Transmit signal may be 100-150 dB above received signal
Relay Operation

- Half duplex
  - Relay will not receive and transmit same time and same frequency band
    - Code division duplex
    - Frequency division duplex
    - Time division duplex

Broadcast

1st time slot

2nd time slot

Multiple access
Relay Function

• Fixed relaying
  – Decode and forward
  – Estimate and forward
  – Amplify and forward

• Adaptive relaying
  – Selection
  – Incremental
Theoretical Issues: Achievable Rates

- Mutual information
- Bounds on capacity
  - Max flow min cut
  - Multi-state max flow min cut
    - Half duplex
    - Fading

Achievable rate  Capacity

Lower bound on Capacity  Upper bound on Capacity
Outage

- Probability of outage

\[ \Pi_{out} = P[I(\gamma, P_s, P_r) < R] \]

- The frame error rate

\[ \Pi_{out} \leq FER \]
Diversity Gain in Outage

![Graph showing diversity gain in outage with curves for direct transmission, half-duplex multi-hop, amplify forward, and half-duplex decode forward.]
Practical Issues: Coding

- Convolutional codes
- Turbo codes
- LDPC
  - Half duplex
  - Full duplex
LDPC Codes for Relay Channels

- BC mode $X_{1,BC}$
  
  $\rho = E[X_{1,BC}X_{1,MAC}^*] \in [-1,1]$

- MAC mode $X_{1,MAC}$

- Modified density evolution

Broadcast  

1\textsuperscript{st} time slot  

2\textsuperscript{nd} time slot  

Multiple access
Asymptotic Performance
BER performance of LDPC constituent codes in relay coding scheme

- BC mode: $S \rightarrow D$
- BC mode: $S \rightarrow R$
- MAC mode: $S, R \rightarrow D$

Bit Error Rate vs. $E_b/N_0$ (dB)
Practical Issues: Feedback

• Feedback used to adjust
  – Codebook power
  – Codebook size

• Power control minimizes outage

• Rate and power control maximize throughput
Amplify and Forward ($R=1, \alpha=3, d=0.5$)

- Optimal power control
- Without feedback
- 1 bit feedback const Pr
- 1 bit feedback var Pr
Open Problems-Theory and Algorithm

• Multiple antennas
• Code construction
• Feedback for power and rate control
• Implementation
Research Platform
Board at Work
TAP: A Mesh Network
The Premise and the Promise

- The last few miles
  - Role of physical layer
  - Paradigm shift
- Mesh networks
- Diversity gain
- Rate increase
  - Scale?