Exploiting Interference through Cooperation and Cognition

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Joint work with
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The Role of Wireless in the Future
The Role of Wireless in the Future

- Integrated voice, mobile data and video streaming at high rates and high quality
  - Several billions of wireless devices
The Role of Wireless in the Future

- Integrated voice, mobile data and video streaming at high rates and high quality
  - Several billions of wireless devices
- Sensor networks in everyday life

Environmental monitoring

Smart environments

Surveillance

Smart highways today

Tomorrow

Ivana Marić Exploiting Interference through Cooperation and Cognition
Challenges

- Higher data rates and better coverage
- Dynamic nature: time-varying channel, users’ mobility, stochastically varying traffic
- Efficient spectrum allocation and coexistence of users
- Energy efficiency
- Operating large ad hoc networks
- Guaranteed rate (Quality-of-Service)
- Providing security
Challenges

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What is the role of cooperation?
Cooperation Today

Ad hoc and sensor networks
Cooperation Today

Ad hoc and sensor networks

Infrastructure based
Cooperation Today

Ad hoc and sensor networks

Infrastructure based
Cooperation Today

Ad hoc and sensor networks

Infrastructure based
Cooperative Gains

- Capacity
- Energy efficiency
- Extended coverage
- Cooperative diversity
- Improved scaling laws
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How to cooperate?
Cooperative Gains

- Capacity
- Energy efficiency
- Extended coverage
- Cooperative diversity
- Improved scaling laws

How to cooperate?
How to Cooperate?
How to Cooperate?

Multi-Hop

- Store-and-forward packets
How to Cooperate?

Multi-Hop

- Store-and-forward packets
- Network viewed as a set of point-to-point links
  - Does not capture broadcast
  - Avoids interference by orthogonalizing transmissions
Relaying Strategies

- Decode, compress, amplify -and-forward
- Capture broadcast
- Introduce block Markov encoding
Relaying Strategies

- Decode, compress, amplify -and-forward
- Capture broadcast
- Introduce block Markov encoding

Decode-and-forward
- Performs well when the relay is close to the source
  - Source and relay act as two transmit antennas
Antenna-Clustering Capacity \cite{Gastpar, Kramer and Gupta, 2005}

- Generalizes to multiple relays
- DF relays act as a multiple-transmit antenna
Antenna-Clustering Capacity

- CF relays act as a multiple-receive antenna
Antenna-Clustering Capacity

- Two closely spaced clusters: DF and CF
- Achieves optimal scaling behavior
Scaling Capacity [Ozgur, Leveque and Tse, 2007]

- Dense network with $n$ pairs
- Form node clusters
- Sources in cluster cooperate
- MIMO long-range transmissions
- Destinations in cluster cooperate
- $O(\sqrt{n}) \rightarrow O(n)$
Successes

For small networks

- Higher rates
- Diversity-multiplexing gains

For large networks

- Scaling $\mathcal{O}(\sqrt{n}) \to \mathcal{O}(n)$

[Gastpar, Kramer, Gupta, 05]
Wireless Challenge: Interference

- Suboptimal approach: orthogonalize transmissions
Interference Channel

\[ W_1 \quad \text{source 1} \quad \hat{W}_1 \quad \text{destination 1} \]

\[ W_2 \quad \text{source 2} \quad \hat{W}_2 \quad \text{destination 2} \]
Interference Channel

- Capacity unknown
Rate-Splitting \cite{Carleial1978, HanKobayashi1981}  

- Highest achievable rates  
- Facilitates partial decoding of interference
Gaussian Interference Channel

\[ Y_1 = X_1 + h_{12} X_2 + Z_1 \]
\[ Y_2 = h_{21} X_1 + X_2 + Z_2 \]
Gaussian Interference Channel

\[ Y_1 = X_1 + h_{12} X_2 + Z_1 \]
\[ Y_2 = h_{21} X_1 + X_2 + Z_2 \]

Recent results:

- Capacity within-a-bit [Etkin, Tse and Wang, 2007]
- Sum-capacity in weak interference
  [Shang, Kramer and Chen], [Annapureddy and Veeravalli], [Motahari and Khandani], 2007
Differences when Relaying for Multiple Sources
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- Interference
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- Interference
- Relaying one message increases interference for other users
Differences when Relaying for Multiple Sources

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- Joint relaying of multiple data streams
Differences when Relaying for Multiple Sources

- Interference
- Relaying one message increases interference for other users
- Joint relaying of multiple data streams
- Smallest network: interference channel with a relay
Simple Approach: Multi-Hop

W1
source 1

relay

W1
destination 1

W2
source 2

destination 2
Simple Approach: Multi-Hop

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Simple Approach: Multi-Hop

- Relay time-shares in helping sources
- No combining of bits, symbols or packets at the relay
- On the other hand: network coding approach is a success
Analog Network Coding

- Amplify-and-forward/analog network coding outperforms any time-sharing approach

[Katti, Marić, Goldsmith, Médard, Katabi, 2007]
Analog Network Coding in Two-Way Relay Channel

![Diagram of the two-way relay channel with nodes X1, X2, Y3, and a relay node.]

- X1 and X2 are the transmitters.
- Y3 is the receiver.
- The figure shows the signaling paths between the nodes.

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**Throughput vs. SNR**

- **Throughput (b/s/Hz)** is plotted on the y-axis.
- **SNR (dB)** is plotted on the x-axis.
- Two lines are shown:
  - **Joint Relaying & Network Coding** (solid line)
  - **Routing** (dashed line)

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Exploiting Interference through Cooperation and Cognition
Techniques That Can be Used

▶ IT perspective: contains 30-year old open problems
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  - Decode, compress, amplify -and-forward, block Markov encoding, network coding
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  - Rate-splitting
Techniques That Can be Used

- IT perspective: contains 30-year old open problems
- Relay channel
  - Decode, compress, amplify -and-forward, block Markov encoding, network coding
- Interference channel
  - Rate-splitting
- Broadcast channel
  - Coding for channels with states [Gel’fand & Pinsker], Dirty paper coding [Costa]
- Evaluation is difficult
- Goal: develop strategies that can be applied to larger networks and bring gains
Strong Interference

- No rate-splitting
- Receivers decode both messages
- Optimal when [Costa & El Gamal, 1987]:

\[
I(X_1; Y_1|X_2) \leq I(X_1; Y_2|X_2) \\
I(X_2; Y_2|X_1) \leq I(X_2; Y_1|X_1)
\]

for all \( p(x_1)p(x_2) \)

- When interference is strong → decode it
Joint Encoding

- No rate-splitting at encoders

Relay:
- Decodes and jointly encodes messages
Joint Encoding

- No rate-splitting at encoders

Relay:
- Decodes and jointly encodes messages
- Forwards a message and interference
- Facilitates joint decoding of messages at receivers
Achievable Rates

Theorem

Any rate pair \((R_1, R_2)\) that satisfies

\[
R_1 \leq I(X_1, X_3; Y_1 | U_2, X_2) \quad R_1 \leq I(X_1; Y_3 | X_2, U_1, U_2)
\]

\[
R_2 \leq I(X_2, X_3; Y_2 | U_1, X_1) \quad R_2 \leq I(X_2; Y_3 | X_1, U_1, U_2)
\]

\[
R_1 + R_2 \leq I(X_1, X_2, X_3; Y_1) \quad R_1 + R_2 \leq I(X_1, X_2; Y_3 | U_1, U_2)
\]

\[
R_1 + R_2 \leq I(X_1, X_2, X_3; Y_2)
\]

for \(p(u_1)p(x_1 | u_1)p(u_2)p(x_2 | u_2)f(x_3 | u_1, u_2)p(y_1, y_2, y_3 | x_1, x_2, x_3)\)

is achievable.

▶ Insights?
▶ Capacity results?
Scenario: Relay Has no Information About $W_1$

- Relay can forward $W_2$
- Increases rate $R_2$ but increases interference at destination 1
- Can forwarding interference $W_2$ help both receivers?
Gaussian Channel

\[ Y_1 = X_1 + h_{12}X_2 + h_{13}X_3 + Z_1 \]
\[ Y_2 = h_{21}X_1 + X_2 + h_{23}X_3 + Z_2 \]
\[ Y_3 = h_{31}X_1 + h_{32}X_2 + Z_3 \]
No Relaying

- No relay: strong interference regime

\[ h_{12} = 1, \ h_{21}^2 = 2, \ h_{23}^2 = 0.15, \ h_{32}^2 = 12 \]
Relaying

- No relay: strong interference regime
- With relay, no interference forwarding

\[ h_{12} = 1, \ h_{21}^2 = 2, \ h_{23}^2 = 0.15, \ h_{32}^2 = 12 \]
Relaying and Interference Forwarding

- No relay: strong interference regime
- With relay, and interference forwarding

\[ R_2 \]

Rate Regions of Gaussian Channels

- with relay, \( h_{13} = 2 \)
- with relay, \( h_{13} = 0 \)
- without relay

\[ h_{12} = 1, \ h_{21}^2 = 2, \ h_{23}^2 = 0.15, \ h_{32}^2 = 12 \]
When Relay Can Forward Both

- Should a relay ever send the interference along (instead) of the desired message?
- Forwarding $W_2$ does not help the intended receiver
- Sending $W_2$ is only interference forwarding
- Should the relay ever forward $W_2$?
When Relay Can Forward Both

Interference forwarding can improve the rates

Relay splits power to forward desired and interfering message
Capacity in Strong Interference

The *strong interference* conditions:

\[
I(X_1, X_3; Y_1 | X_2) \leq I(X_1, X_3; Y_2 | X_2) \\
I(X_2, X_3; Y_2 | X_1) \leq I(X_2, X_3; Y_1 | X_1)
\]  

(1)

for every

\[
p(x_1)p(x_2)p(x_3 | x_1, x_2)p(y_1, y_2, y_3 | x_1, x_2, x_3)
\]

The channel *degradedness* condition:

\[
p(y_1, y_2 | y_3, x_3, x_1, x_2) = p(y_1, y_2 | y_3, x_3)
\]  

(2)

**Theorem**

*When (1)-(2) hold, the achievable rates are the capacity region.*
Interference Forwarding

- Can help decoders via interference cancelation
Interference Forwarding

- Can help decoders via interference cancelation
- The relay splits its power for forwarding the desired and interfering message
Interference Forwarding

- Can help decoders via interference cancelation
- The relay splits its power for forwarding the desired and interfering message
- Achieves capacity in strong interference
Interference Forwarding

- Can help decoders via interference cancelation
- The relay splits its power for forwarding the desired and interfering message
- Achieves capacity in strong interference
- Can be realized through decode, compress -and-forward
Large Networks

- Exploit broadcast (instead of treating it as interference)
- Jointly encode messages
- Relays forward messages and interference
- Exploit multiple antennas
Enabling Cooperation

Knowledge about messages can be obtained through:

1. Cooperative strategies
2. Dedicated orthogonal links (conferencing)
3. Feedback
4. Cognition
Cooperation in Cognitive Networks
Motivation: Bandwidth Gridlock

Current bandwidth allocation:
- Licensed spectrum
  - Crowded; not efficiently used
- Unlicensed spectrum
  - Users follow etiquette rules

New Kind of Users:
- Increase efficiency of the spectrum use
- Coexist with other users
- Do not disrupt others
- Aware of environment
- Use advanced wireless technology
Interweave (Opportunistic) Approach

- Dynamic spectrum access
- Sense the environment
- Transmit in a spectrum hole

From slides by B. Brodersen, BWRC cognitive radio workshop
Underlay Approach

- Share the bandwidth
- Constraint: created interference below a threshold
- For example, UWB
Awareness of environment $\rightarrow$ side information

Cognitive radio can utilize available side information about users in its vicinity

Interweave approach: use cognition for interference avoidance

Why not use obtained information for cooperation?
Cognition and Cooperation

- In cooperation: a helper needs knowledge about relayed message
  - Assistance of the source node
  - Listening to the channel

- Cognitive node can obtain similar information through cognition

- Overlay paradigm: share the band and compensate for interference by cooperation
How Can Side Information be Obtained?

- **Interweave:** users’ activity
  - Detection of spectrum holes
  - Holes common to the transmitter and receiver

- **Underlay:** channel gains
  - If there is a channel reciprocity or feedback

- **Overlay:** channel gains, codebooks and (partial) messages
  - Codebooks: through protocol
  - Messages via: retransmission; cooperation; listening to the channel; orthogonal links
Idealized Channel Model

Two messages: \( W_k \in \{1, \ldots, M_k\} \)

Encoding: \( X_1^n = f_1(W_1, W_2), X_2^n = f_2(W_2) \)

Decoding: \( \hat{W}_k = g_k(Y_k^n) \)

Rates: \( R_k = (\log_2 M_k)/n \)

What is the optimal cognitive strategy?
Related Work

- An achievable rate region [Devroye, Mitran and Tarokh, 2005]
- Capacity in strong interference [Marić, Yates and Kramer, 2006]
- Capacity in weak interference [Wu, Vishwanath and Arapostathis, 2006], [Jovićić and Viswanath, 2006]
- General rate region and outer bounds [Marić, Goldsmith, Kramer and Shamai, 2007], [Jiang and Xin, 2007]
- MIMO case [Sridharan and Viswanath, 2007]
- [Liang, Baruch, Poor, Shamai and Verdú, 2007]
- Capacity of a Z-interference channel class [Liu, Marić, Goldsmith and Shamai, 2009]
Elements of Cognitive Encoding Strategy

- Opportunistic approach: interference avoidance
Elements of Cognitive Encoding Strategy

- Opportunistic approach: *interference avoidance*

- Overlay approach:
Elements of Cognitive Encoding Strategy

- Opportunistic approach: interference avoidance

- Overlay approach:
  1. Cooperative strategies
Elements of Cognitive Encoding Strategy

- Opportunistic approach: interference avoidance

- Overlay approach:
  1. **Cooperative strategies**
     To increase rate at non-cognitive receiver
Elements of Cognitive Encoding Strategy

- Opportunistic approach: interference avoidance

- Overlay approach:
  1. Cooperative strategies
     To increase rate at non-cognitive receiver
  2. Rate-splitting
Elements of Cognitive Encoding Strategy

- Opportunistic approach: interference avoidance

- Overlay approach:
  1. Cooperative strategies
     To increase rate at non-cognitive receiver
  2. Rate-splitting
     To reduce interference at non-cognitive receiver
Elements of Cognitive Encoding Strategy

- Opportunistic approach: interference avoidance

- Overlay approach:
  1. Cooperative strategies
     To increase rate at non-cognitive receiver
  2. Rate-splitting
     To reduce interference at non-cognitive receiver
  3. Precoding against interference
Elements of Cognitive Encoding Strategy

- Opportunistic approach: **interference avoidance**

- Overlay approach:
  1. **Cooperative strategies**
     To increase rate at non-cognitive receiver
  2. **Rate-splitting**
     To reduce interference at non-cognitive receiver
  3. **Precoding against interference**
     To remove interference at cognitive receiver
Cooperation

- To increase rate for the oblivious receiver
- Cognitive radio acts as a relay

\[ X_1^n = f_1(W_1, W_2) \]

- Dedicates some power to transmit the other user’s message
- Increases interference to its own receiver
Rate-Splitting at Cognitive Encoder

- To reduce interference at non-cognitive decoder
- No cognition needed
Precoding against Interference

- Eliminate interference at the cognitive receiver
Precoding against Interference

- Eliminate interference at the cognitive receiver
- How?
Precoding against Interference

- Full cognition: MIMO broadcast channel
- Strategy: precoding against interference
  [Gel'fand and Pinsker, 1979]
- Gaussian channels: Dirty-paper coding (DPC) [Costa, 1981]
  - Achieves capacity [Weingarten, Steinberg and Shamai, 2004]
GP Setting vs. Cognitive Setting

GP Setting:

In Gaussian channel:

\[ C = 0.5 \log(1 + SNR) \]
GP Setting vs. Cognitive Setting

GP Setting:

In Gaussian channel:

\[ C = 0.5 \log(1 + SNR) \]

Cognitive settings:

codeword of other user is interference
Elements of Cognitive Encoding Strategy

1. **Cooperative strategies**
   To increase rate at oblivious receiver

![](cooperation.png)
Elements of Cognitive Encoding Strategy

1. **Cooperative strategies**
   To increase rate at oblivious receiver

2. **Rate-splitting**
   To partially remove interference at non-cognitive receiver
Elements of Cognitive Encoding Strategy

1. **Cooperative strategies**
   To increase rate at oblivious receiver

2. **Rate-splitting**
   To partially remove interference at non-cognitive receiver

3. **Precoding against interference**
   To remove interference at cognitive receiver
Elements of Cognitive Encoding Strategy

1. **Cooperative strategies**
   To increase rate at oblivious receiver

2. **Rate-splitting**
   To partially remove interference at non-cognitive receiver

3. **Precoding against interference**
   To remove interference at cognitive receiver

| rate-splitting | precoding | cooperation |
Achievable Rates and an Outer Bound

- Generalizes existing strategies

Achievable rate region and outer bound

\[ P_1 = P_2 = 6 \]
\[ a^2 = 0.3 \]
\[ b^2 = 2 \]

\[ R_1 \text{ [bits/channel use]} \]
\[ R_2 \text{ [bits/channel use]} \]

BC

outer bound

Thm 1 rates

X–J rates

cognitive radio

\( T_1 \)

\( R_1 \)

\( R_2 \)
Capacity Results for Gaussian Channels

\[ Y_1 = X_1 + aX_2 + Z_1 \]
\[ Y_2 = bX_1 + X_2 + Z_1 \]

- Regions for which capacity is known:
  - **Strong interference**, \( a > b > 1 \)
  - **Cooperation** achieves capacity
  - **Weak interference**, \( b \leq 1 \)
  - Precoding against interference and cooperation achieve capacity

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Exploiting Interference through Cooperation and Cognition
Impact of Power

- Changing power of cognitive user has a more drastic impact
Exploit the Structure of Interference

GP vs. cognitive setting:
precoding against interference vs. against a codebook
Exploit the Structure of Interference

- GP vs. cognitive setting:
  precoding against interference vs. against a codebook

- Number of interfering codewords $S^n$ is **exponentially smaller**
  - Number of $S^n$ in GP problem: $2^{nH(S)}$
  - Noncognitive user’s rate: $R_2 \leq H(S)$

- GP precoding can be outperformed when $R_2$ is small
  - Forward interference
Forwarding Interference Can Be Beneficial
Forwarding interference can outperform GP precoding when:

\[ R_2 < I(S; X_1, Y_1) \]
Impact of Delay

If cognitive user learns interference with a block delay:

- Precoding against interference brings no benefit
- Cooperation can still be used
If Cognitive User Can Decode Before the Block Ends

- But... interference is a codeword
- Cognitive user may decode the interference in fraction $kn$
  - When two transmitters are close to each other
- Apply precoding against interference in $\bar{kn}$
Unidirectional Cooperation

- Considered model captures unidirectional cooperation
  - Orthogonal links
  - Base station, more capable user
- Broadcast channel with a helper
- Generalizes to capture delay, partial message knowledge
Insights to System Design

- Current cognitive radio approach is **suboptimal**
  - Orthogonal transmissions
- Cognitive capabilities can be used for:
  - Cooperation
  - Canceling strong interference
  - Forwarding interference
  - Removing (precoding against) interference
- Capacity-achieving for
  - Strong and weak interference
  - Cognitive Z-channel with a noiseless link
- Depend on availability of side information
  - With block delay: precoding against interference cannot help
Impact

- Different spectrum regulations
  - Cognitive users should co-exist with primary users
- Different sensing approach
  - Current sensing:
    - Fast scanning
    - Detection of weak primary users
    - Collaborative sensing for better detection in fading
  - To enable cognitive strategies:
    - Detect strong primary users
    - Lock to channels of strong primary users
- Exploit interference
- Noncognitive users should be aware of cognitive users
- Best performance: all nodes cooperative and cognitive
Open Problems

- Information theoretic models
  - How much side information can a cognitive radio collect?
  - How useful side information can be?

- New paradigms to exploit cognition
  - Exploit structure (codewords) of interfering primary users
  - Feedback, multiple antennas

- Large networks
  - All of the above
  - Scaling laws
Exploiting Interference

Different interference regimes

- **Strong**: decode it
- **Weak**: treat it as noise
- **Medium**: partially decode

Relays can...

- Jointly encode
  - Network coding on phy layer
  - Further gains in multicast
- Change interference conditions
- Facilitate interference cancelation by forwarding interference
- Exploit multiple antennas
Outlook

Develop...

- Joint encoding strategies for large networks
- Relaying in presence of interference
  - Interference forwarding + rate-splitting?
Outlook

- Fundamental limits
Outlook

▶ Fundamental limits
Outlook

- Fundamental limits
- Many performance metrics of interest
  - Delay, energy efficiency, outage, security, stability
Outlook

- Fundamental limits
- Many performance metrics of interest
  - Delay, energy efficiency, outage, security, stability
- Interference and cooperation