Cooperation and Interference Management in Wireless Networks

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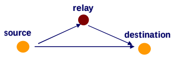
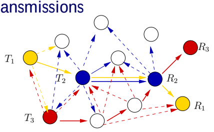
Introduction

- In relay networks:
- Relays forward data for a single source-destination pair
- Cooperative strategies are well developed and known to bring gains
- Cooperative strategies exploit the broadcast nature of wireless medium



- In networks with multiple sources:
- The center issue is coping with interference created by simultaneous transmissions



Motivation

- Relaying in network with multiple sources has aspects not present in the relay networks:

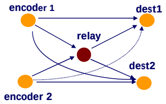
1. Relaying messages to one destination increases interference to others
2. Relays can jointly encode messages from multiple sources
   - There are many relevant encoding strategies

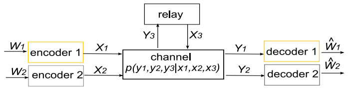
- Encoding strategies for networks with multiple sources are not well understood and developed
- Current approach: multihop routing
  - Time shares between data streams (no joint encoding)
  - Does not exploit broadcast or interference

- Networks with multiple sources contain broadcast, multicast, relay and interference channel elements as their building blocks

Channel Model

- We consider smallest network that captures relaying for multiple sources: *the interference channel with a relay*





- Two messages: $W_t \in \{1,\dots,M_t\}$
- Rates: $R_t = \log_2 M_t / N$
- Encoding: $X_1^n = f_1(W_1)$, $X_2^n = f_2(W_2)$, $X_{3,i} = f_{3,i}(Y_3^{i-1})$
- Decoding: $\hat{W}_1 = g_1(Y_1^n)$, $\hat{W}_2 = g_2(Y_2^n)$

- We present new relaying strategy: interference forwarding
- Previous work:
- *Sridharan, Vishwanath, Jafar and Shamai [ISIT, 2008]*
- Rates and degrees of freedom when the relay is cognitive
- *Sahin and Erkip [Asilomar 2007, CTW 2008]*

Achievable Rates

- Theorem: Any rate pair (R_1,R_2) that satisfies

$$
\begin{aligned}
R_1 &\le I(X_1,X_3;Y_1|U_2,X_2)\\
R_2 &\le I(X_2,X_3;Y_2|U_1,X_1)\\
R_1+R_2 &\le I(X_1,X_2,X_3;Y_1)\\
R_1+R_2 &\le I(X_1,X_2,X_3;Y_2) \qquad (1)\\
R_1 &\le I(X_1;Y_3|X_2,X_3)\\
R_2 &\le I(X_2;Y_3|X_1,X_3)\\
R_1+R_2 &\le I(X_1,X_2;Y_3|X_3)
\end{aligned}
$$

for any distribution

$$p(u_1)p(x_1|u_1)p(x_2|u_2)f(x_3|u_1,u_2)p(y_1,y_2|x_1,x_2,x_3)$$

are achievable.

- Rates in the Thm. are achieved by:
- Decode-and-forward at the encoders
- Joint encoding at the relay
- Joint decoding at the receivers

Capacity Result in Strong Interference

- We define *strong interference conditions* as:

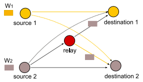
$$
\begin{aligned}
I(X_1,X_3;Y_1|X_2) &\le I(X_1,X_3;Y_2|X_2) \qquad (2)\\
I(X_2,X_3;Y_2|X_1) &\le I(X_2,X_3;Y_1|X_1)
\end{aligned}
$$

satisfied for any distribution $p(x_1)p(x_2)p(x_3|x_1x_2)p(y_1,y_2|x_1,x_2,x_3)$

- Conditions (2) imply that the flow of information from each source to the non-intended receiver is better than to the intended receiver
- Consequently, receivers can decode the undesired messages for 'free'

- The channel *degradedness*: $p(y_1,y_2|y_3,x_3,x_2) = p(y_1,y_2|y_3,x_3)$ (3)

- Theorem: When (2)-(3) hold, rates (1) are the capacity region.
  - In strong interference, decoding both messages is optimal



- The relay can 'push' a receiver into the strong interference regime where decoding the interfering message is optimal

- We evaluated these results for Gaussian channels:

$$
\begin{aligned}
Y_1 &= X_1 + h_{12}X_2 + h_{13}X_3 + Z_1\\
Y_2 &= h_{21}X_1 + X_2 + h_{23}X_3 + Z_2\\
Y_3 &= h_{31}X_1 + h_{23}X_2 + Z_3
\end{aligned}
$$

Noise: $Z_1 \sim [0,1]$

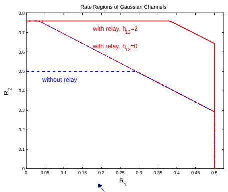
Powers $E[X_t^2] \le P_t$

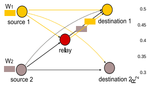
- To illustrate gains from interference forwarding, we consider special cases:

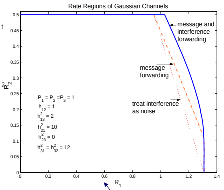
1)The relay cannot observe signal sent from source 1
   - It can only forward W_2. For receiver 1: interference forwarding
   - Can relay help also receiver 1?

2) Relay cannot communicate to receiver 2. Should it forward W_2?

Interference Forwarding Improves Rates





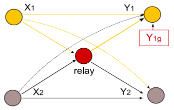


- Without the relay: IC in strong interference
- Relay, h_{13}=0: no interference forwarding
- Relay, h_{13}>0: interference forwarding
- Interference forwarding enlarges the rate region
- It facilitates interference cancellation

- Relay power split between forwarding message and interference

A New Sum-Rate Outer Bound

- Use the approach developed for Gaussian interference channels by *[G. Kramer 2004]*
- A genie gives to a receiver *minimum* information needed for decoding *both* messages



$$Y_{1g} = d_1X_1 + d_2X_2 + d_3X_3 + d_4Z_1 + d_5Z_1'$$

- Receiver 1 can form an estimate:

$$
\begin{aligned}
\hat{Y}_1 &= h_{21}X_1 + X_2 + h_{23}X_3 + Z_e\\
Y_2 &= h_{21}X_1 + X_2 + h_{23}X_3 + Z_2
\end{aligned}
$$

-> When $var(Z_e) < var(Z_2)$ receiver 1 can decode (W_1,W_2)

A New Sum-Rate Outer Bound

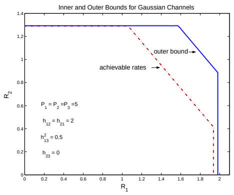
- We choose parameters so that receiver 1 gets less noisy observation about W_2 than receiver2
- One can show that $R_1 + R_2 \le I(X_1,X_2,X_3;Y_1,Y_{1g})$
- Maximized by jointly Gaussian inputs

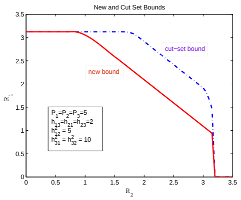
- The sum-rate is upper bounded by

$$R_1 + R_2 \le \min_{d_1,\dots d_5} \max I(X_1,X_2,X_3;Y_1,Y_{1g})$$

for parameter values for which receiver1 can decode W_2

- Comparisons:





Summary

- Derived an achievable rate region
- Developed a sum-rate outer bound
- Derived strong interference conditions under which forwarding messages and interference achieves capacity

- Interference forwarding:
- Achieves capacity in strong interference
- It 'pushes' receiver in strong interference regime where the receiver can decode both messages
- We determined conditions under which decoding interference is optimal

- Interference forwarding outperforms rate splitting (no relaying) when

$I(X_2;Y_2|X_1) \le I(X_3;Y_1)$ strong relay-rcvr1 link

$I(X_2;Y_2|X_1) \le I(X_2;Y_3|X_3)$ strong source2-relay link

for any distribution $p(x_1)p(x_2,x_3)p(y_1,y_2|x_1,x_2,x_3)$

Conclusions and Future Work

- Demonstrated gains from interference forwarding
- How it works:
- The relay forwards an unwanted message, thus increasing interference at the receiver. This allows the receiver to decode and cancel interference
- Can improve the performance through interference cancellation
- Can hurt the receiver by increasing interference

- Interference forwarding can be:
- Realized through decode, compress -and-forward
- Combined with other encoding schemes

Insights:

When relaying for multiple sources:

- Jointly encode messages (network coding approach)
- Exploit broadcast
- Forward messages and interference

Future work:

- Develop and evaluate more general transmission strategies
- Apply and analyze interference forwarding and the outer bound in larger networks