Trust Degree Based Beamforming for Multi-Antenna Cooperative Communication Systems

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Mobile/Social Networks - Motivation

A salient characteristic of mobile data networks: person behind each device

- Mobile Data Networks
  - Physical coupling between mobile devices
  - Virtual coupling among the users behind these devices

Virtual ties, in many ways, shape the data traffic flows and quality-of-service (QoS) requirements in the physical domain.

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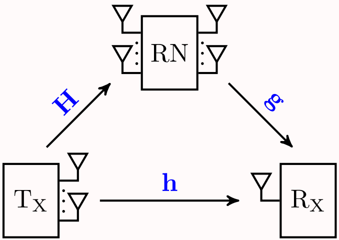
Key questions

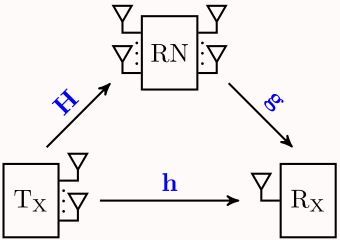
- How can we model/quantify social-physical interactions in communication networks?
  - Trust degrees
- How can we exploit social connections to improve physical communication performance?
  - cooperation among nodes to increase rate, security, access, etc.

System Model



physical connections

System Model



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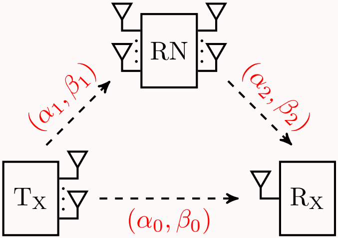

virtual (social) connections

Node	# antenna
source (S)	N_s
relay (R)	N_r
destination (D)	1

- channel state information (CSI) is known at the transmitters

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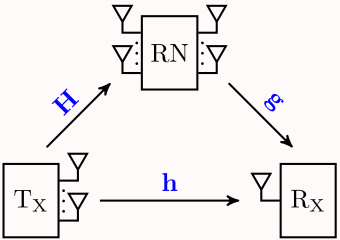

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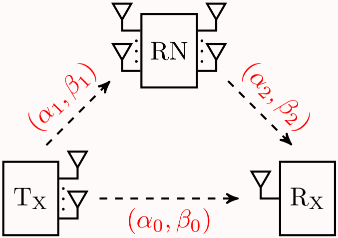

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Node	# antenna
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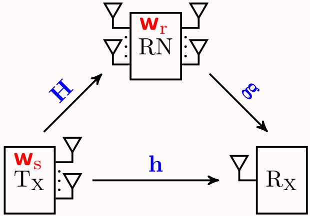
- social system is modeled by *trust degree*
- trust degree is a level of belief that one node can help the other node for relaying

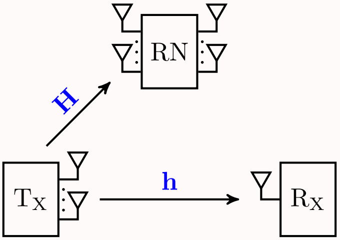
System Model



Why beamforming?
To improve signal-to-noise ratio (SNR)
signal-to-interference-plus-noise ratio (SINR)

An optimal beamformer aims to balance between the direct link and the cooperating link as well as respecting the trust degree.

Physical Channel



physical connections
(a two-hop relay)

symbol x_s is first multiplied by a beamforming vector $\mathbf{w}_s$ before being transmitted at S

- Source Transmission:
  received signal at D and R

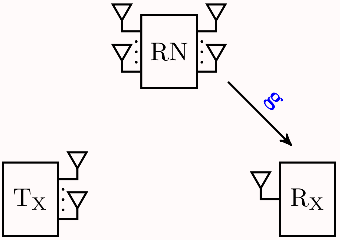
$$y_{SD} = \mathbf{h}^t \mathbf{w}_s x_s + n_{SD},$$
$$\mathbf{y}_{SR} = \mathbf{H}^t \mathbf{w}_s x_s + \mathbf{n}_{SR},$$

-$n_{SD} \sim \mathcal{CN}(0,1)$, $\mathbf{n}_{SR} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$
are complex Gaussian noise
-$\mathbf{w}_s$ is beamforming vector
received SNRs at D and R

$$\gamma_{SD} = |\mathbf{h}^t \mathbf{w}_s|^2 P_s,$$
$$\gamma_{SR} = \|\mathbf{H}^t \mathbf{w}_s\|^2 P_s,$$

and
$$C_{SD} = \log_2(1+\gamma_{SD}),$$
$$C_{SR} = \log_2(1+\gamma_{SR}).$$

Physical Channel



physical connections
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decode-and-forward (DF) relaying

- Relay Transmission:

$$y_{\mathrm{RD}} = \mathbf{g}^t \mathbf{w}_{\mathrm{r}} x_{\mathrm{r}} + n_{\mathrm{RD}},$$

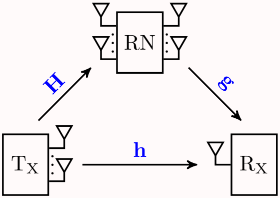
where $n_{\mathrm{RD}} \sim \mathcal{CN}(0,1)$.
- received SNR at D

$$\gamma_{\mathrm{RD}} = |\mathbf{g}^t \mathbf{w}_{\mathrm{r}}|^2 P_{\mathrm{r}}.$$

-D can combine the signal received from S and R

$$\mathcal{C}_{\mathrm{D}} = \log_2(1 + \gamma_{\mathrm{SD}} + \gamma_{\mathrm{RD}}).$$

Physical Channel



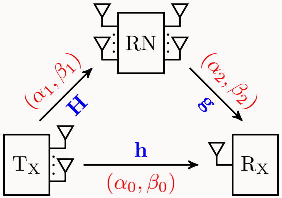
- Relay may work in the full-duplex of half-duplex mod
- Half-duplex case is more practical but more involved (see [Vaezi et al.'17])

- DF Achievable Rate: An achievable rate for full-duplex DF relay system is given by [Host-Madsen-Zhang'05]

$$\mathcal{C}_{\rm DF} = \min\{\mathcal{C}_{\rm SR}, \mathcal{C}_{\rm D}\}$$
$$= \min\left\{\log_2(1+\gamma_{\rm SR}), \log_2(1+\gamma_{\rm SD}+\gamma_{\rm RD})\right\}.$$

- Beamforming design: is extensively studied [Tang-Hua'07],[Ryu-Choi'08],[Xiong et al.'14]

Social-Physical Cooperation



- For each link i, (α_i, β_i) represents a virtual (social) tie [Ryu-Lee-Quek'15]
- α_i: the probability of cooperation
- β_i: the fraction of power a node uses for relaying

- Physical-Virtual Cooperation Achievable Rate: the expected trust degree based rate

$$\begin{aligned}\mathcal{R}_{\mathrm{T}} &= \alpha_1 \mathcal{C}_{\mathrm{DF}} + (1-\alpha_1)\mathcal{C}_{\mathrm{SD}} \\ &= \alpha_1 \min\left\{ \log_2(1+\gamma_{\mathrm{SR}}), \log_2(1+\gamma_{\mathrm{SD}}+\gamma_{\mathrm{RD}}) \right\} \\ &\quad + \bar{\alpha}_1 \log_2(1+\gamma_{\mathrm{SD}}) \qquad (1)\end{aligned}$$

- Optimal beamforming is open in general

A New Problem Formulation

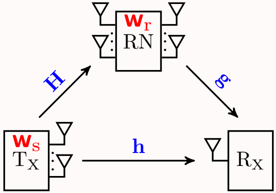
Our goal is to jointly optimize the beamforming vectors $\mathbf{w}_{\rm s}$ and $\mathbf{w}_{\rm r}$ as well as α to maximize $\mathcal{R}_{\rm T}$, i.e.,

$$\begin{aligned} \max_{\mathbf{w}_{\rm s},\mathbf{w}_{\rm r},\alpha} \quad & \mathcal{R}_{\rm T} \\ \text{s.t.} \quad & \|\mathbf{w}_{\rm s}\|^2 \leq 1, \\ & \|\mathbf{w}_{\rm r}\|^2 \leq 1, \\ & 0 \leq \alpha \leq \alpha_1, \end{aligned} \tag{2}$$

where $\mathcal{R}_{\rm T}$ is defined in (1).

- This optimization problem is non-convex
- $\alpha = 1 \implies$ MIMO DF realy
- MISO case ($N_{\rm r} = 1$) with $\alpha = \alpha_1$ [Ryu-Lee-Quek'15]

This Talk



Question

find optimal $\mathbf{w}_s$, $\mathbf{w}_s$, and α

Our observations and contribution

- $\alpha = \alpha_1$ is not necessarily optimal; we find optimal α
- Maximal ratio transmission (MRT) beamformer is optimal at relay, i.e., $\mathbf{w}_r = \frac{\mathbf{g}^*}{\|\mathbf{g}\|}$
- Optimal $\mathbf{w}_s$ is found either in closed-form or heuristically
- The same approach is applicable to the half-duplex case

Optimal Trust Degree and $\mathbf{w}_{\mathrm{r}}$

Lemma 1: Maximal ratio transmission (MRT) beamformer is optimal at the relay, i.e., $\mathbf{w}_{\mathrm{r}} = \frac{\mathbf{g}^*}{\|\mathbf{g}\|}$.

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Proof: $\mathcal{R}_{\mathrm{T}}$ is linear with α. Thus, its maximum happens in either of the ends.

Lemma 3: For $\alpha = 0$, MRT is optimal at the source ($\mathbf{w}_{\mathrm{s}} = \frac{\mathbf{h}^*}{\|\mathbf{h}\|}$).

Proof: For $\alpha = 0$ direct transmission is optimal and $\mathcal{R}_{\mathrm{T}}$ is linear with α. Thus, its maximum happens in either of the ends

Solving the New Problem

- The only case left is to find $\mathbf{w}_{\rm s}$ for $\alpha = 1$. Thus, the optimization problem is reduced to

$$\max_{\mathbf{w}_{\rm s}} \quad \mathcal{R}_{\rm T}$$
$$\text{s.t.} \quad \|\mathbf{w}_{\rm s}\|^2 \leq 1$$

where

$$\mathcal{R}_{\rm T} = \alpha_1 \min\left\{\log_2(1+\gamma_{\rm SR}), \log_2(1+\gamma_{\rm SD}+\gamma^{\star}_{\rm RD})\right\} + \bar{\alpha}_1 \log_2(1+\gamma_{\rm SD})$$

An optimal beamformer must balance between the direct link ($\gamma_{\rm SD}$) and the cooperating link ($\gamma_{\rm SR}$).

Precoding and Power Allocation

- $\mathbf{w}_{\rm s}$ depends on $\gamma_{\rm SD}$ and $\gamma_{\rm SR}$ which are functions of $\mathbf{h}$ and $\mathbf{H}$
- Let $\mathbf{w}_{\rm s} = c\mathbf{h} + \sum_{i=1}^{N_{\rm r}} c_i \mathbf{h}_i$, where $\mathbf{h}_i$ is the ith column of $\mathbf{H}$
- Intractable! as $\mathbf{h}$ and the $\mathbf{h}_i$'s are not orthogonal

We compute the following orthogonal vectors

$$\mathbf{w} \triangleq \frac{\mathbf{h}}{\|\mathbf{h}\|}$$
$$\mathbf{w}_i \triangleq \frac{\bar{\mathbf{h}}_i}{\|\bar{\mathbf{h}}_i\|}, \quad i \in \{1, \ldots, N_{\rm r}\}.$$

By definition, we have $\mathbf{w} \perp \mathbf{w}_i^{\perp}$, i.e., $\mathbf{w}^{\dagger}.\mathbf{w}_i^{\perp} = 0 \; \forall i \in \{1, \ldots, N_{\rm r}\}$.

Special Cases

Theorem

The transmit beamformer that maximizes the achievable rate can be represented as

$$\mathbf{w}_{\mathrm{s}} = \sqrt{\gamma_0}\mathbf{w} + \sum_{i=1}^{N_{\mathrm{r}}} \sqrt{\gamma_i}\mathbf{w}_i$$

in which $\mathbf{w}$ *and the* $\mathbf{w}_i$*'s are orthonormal bases spanning the column space of* $\mathbf{h}$ *and* $\mathbf{H}$*, and* $\gamma_0 + \gamma_1 + \ldots + \gamma_{N_{\mathrm{r}}} = 1$*.*

Proof.

We prove this Theorem by contradiction. □

Special Cases

Remark 1: We only need to find N_{r} real numbers whereas in the original problem we needed to find N_{s} complex numbers. Usually $N_{\mathrm{s}} \gg N_{\mathrm{r}}$ and N_{r} as relay nodes are assumed to be network users.

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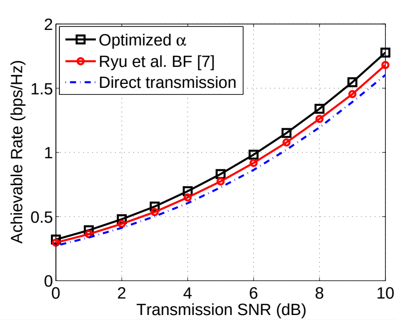
Remark 2: For the MISO case ($N_\mathrm{r} = 1$), $\mathbf{w}^{\perp} = \mathbf{w}_1$. Then, to find $\mathbf{w}_\mathrm{s}$, we only need to find. γ_0.

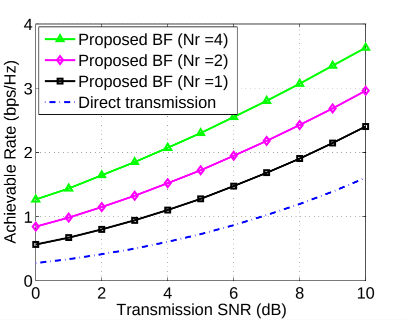
Remark 3: Ignoring social connection ($\alpha_1 = 0$), the system and solution reduces to those of DF relay.

Simulation Results



$N_s = 4,\ N_r = 1,\ \alpha_1 = 0.7$

$(\sigma^2_{\mathbf{h}}, \sigma^2_{\mathbf{H}}, \sigma^2_{\mathbf{g}}) = (-5, -4, 10)\mathrm{dB}$



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Conclusions

Summary

- Design communication systems with consideration of social links beside physical connection
- Cooperative communication can largely benefit from social connections modeled by trust degree
- The underlying problem in non-convex and hard to solve
- Linear beamforming is designed to maximize achievable rate

Future Work

- This kind of approaches does not scale with network nodes
- Can we use machine learning for this purpose?

Thank you!