Cooperative Diversity Routing in Wireless Networks

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What is the Problem?

energy efficiency in wireless networks is critical

- significant progress at physical layer
  - energy-efficient multi-antenna systems
  - distributed multi-antenna → cooperative communication

- extensive work on energy-efficient routing
  - wireless network → a graph of point-to-point links
  - oblivious to specific physical layer characteristics → e.g., multi-point-to-point cooperative links

- Our work: *joint optimization* of physical-layer cooperation and network-layer routing
Contributions

- minimum energy cooperative routing
  - only knowledge of channel statistics
  - optimal power allocation to form links
  - opportunistic routing to select links
  - simple heuristic algorithms

- benefits:
  - 60% more energy savings compared to routing along the shortest path
  - 20% more energy savings compared to equal power allocation
Outline

- model and assumptions
- cooperative link formation
- optimal route selection
- simulation examples
- summary
Channel Model

- slotted channel

$$y_j = \sqrt{\frac{p_i}{d_{ij}^\alpha}} h_{ij} x_i + n_j$$

- $y_j$: signal received at node $j$
- $x_i$: signal transmitted by node $i$
- $n_j$: noise at node $j$
- $h_{ij}$: complex channel gain between nodes $i$ and $j$
- $p_i$: transmit power at node $i$
- $d_{ij}$: distance between nodes $i$ and $j$
- $\alpha$: path-loss exponent
Cooperation Model

- multiple transmitters to multiple receivers
  - cooperative transmission $\Rightarrow$ diversity gain
  - individual reception $\Rightarrow$ cooperative reception is difficult
  - special cases: point-to-point and broadcast

received power at node $r_j$

$$P_j = \sum_{t_i} \left( \frac{|h_{ij}|^2}{d_{ij}^\alpha} \right) p_i$$
Routing Model

- cooperative link $\ell_k$
  - between sets $T_k$ and $R_k$
  - $C(T_k, R_k)$: cost of link $\ell_k$
- cooperative path $\ell$
  - sequence of cooperative links $\{\ell_1, \ldots, \ell_K\}$

**Minimum Energy Routing Formulation**

$$\min_{\ell} \sum_{\ell_k \in \ell} C(T_k, R_k)$$

s.t. $\rho(\ell) \geq \rho_0$

- path throughput
- target average throughput
Cooperative Link Cost

(1) What is the cost of forming a cooperative link for given $T$ and $R$?

We are interested in minimizing link cost

$$C(T_k, R_k) = \min_p \sum_{t_i \in T_k} p_i$$

s.t. $\exists \lambda : \min_{r_j \in R_k} \rho_j(\lambda) = \rho_0$

$$\rho_j(\lambda) = \lambda(1 - \phi_j(\lambda))$$

average throughput at $r_j$ subject to transmission rate $\lambda$
Example: Rayleigh Fading

at receiver $r_j$

- SNR due to transmitter $t_i$
  \[ \gamma_{ij} = \frac{1}{d_{ij}^\alpha} \frac{p_i}{P_n} | h_{ij} |^2 \rightarrow \text{Exponentially distributed} \]

- SNR due to transmitting set $T$
  \[ \gamma_j = \sum_{t_i} \gamma_{ij} \rightarrow \text{Sum of Exponentials} \]

- Outage at receiver $r_j$
  \[ \varphi_j(\lambda) = \Pr(\gamma_j < 2^\lambda - 1) \rightarrow \text{minimum rate} \]

check the paper for a closed-form expression!
Optimal Link Selection

(2) How to choose $T$ and $R$ at every step?

- $T = \{\text{all nodes that previously received data}\}$
  - power allocation algorithm optimally selects transmitting nodes

- $R$: subset of nodes that have not received data yet
  - selected by Opportunistic Bellman-Ford

$$
\pi(T) = \min_{R \subseteq T} \left\{ C(T, R) + \sum_{R_0 \subseteq R} \pi(T \cup R_0) \cdot (1 - \delta(R_0)) \right\}
$$

- cost to reach destination from set $T$
- set of receivers not in outage
Heuristic Cooperative Routing

optimal routing has exponential complexity

1. limited cooperation by limiting the set of transmitters or receivers

2. cooperation along the shortest non-cooperative path

3. local cooperation with optimal power allocation
Simulation Environment

- randomly distributed nodes
- node density = 2
- max node power = 1
- path-loss exponent = 2
- path throughput = 0.2
Energy Cost Comparison

ONCR: non-cooperative
CASP: along the shortest path
DSTC: equal power allocation
CASPO: proposed algorithm

![Graph showing energy cost comparison for different algorithms. The x-axis represents network dimension (D), and the y-axis represents energy cost. The graph compares ONCR, CASP, DSTC, and CASPO with different markers and line styles.]
Optimal v.s. Heuristic Cooperative Routes

Cooperation Along the Shortest Path

CASP

1-OPT

Optimal Selection of Next Node

12% more energy savings
Optimal v.s. Equal Power Allocation

**DSTC:**
distributed equal power allocation

**DCASP:** proposed distributed optimal power allocation
Limited Cooperation

Limited Transmitters

Limited Receivers
Summary

- optimal cooperative diversity routing
  - only statistical knowledge about fading

  - optimal power allocation
    (20% more energy savings that equal power allocation)

  - opportunistic cooperation
    (60% more energy savings that no-cooperation)

- open problem: distributed implementation
Thank you.