Cooperative Diversity Routing in Wireless Networks

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joint work with
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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

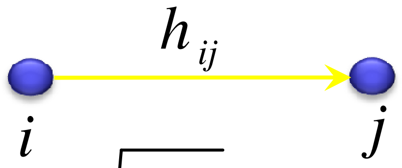
- benefits:
  - 60% more energy savings
    compared to routing along the shortest path
  - 20% more energy savings
    compared to equal power allocation

Outline

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

Channel Model

- slotted channel

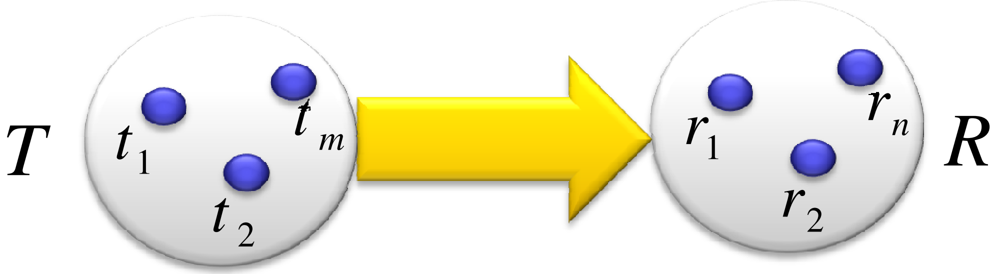


$$y_j = \sqrt{\frac{p_i}{d_{ij}^{\alpha}}} h_{ij} x_i + n_j$$

- 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
- α : path-loss exponent

Cooperation Model

- multiple transmitters to multiple receivers
  - cooperative transmission → diversity gain
  - individual reception → 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 ℓ_k
  - between sets T_k and R_k
  - $C(T_k, R_k)$: cost of link ℓ_k
- cooperative path ℓ
  - sequence of cooperative links $\{\ell_1, \ldots, \ell_K\}$

Minimum Energy Routing Formulation

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

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

target average throughput

path 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

$$C(T_k, R_k) = \min_{\mathbf{p}} \sum_{t_i \in T_k} p_i$$

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

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

average throughput at r_j subject to transmission rate λ

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

$$\gamma_j = \sum_{t_i} \gamma_{ij} \rightarrow \text{Sum of Exponentials}$$

check the paper for a closed-form expression!

- Outage at receiver r_j

$$\wp_j(\lambda) = \Pr(\gamma_j < 2^{\lambda} - 1)$$

minimum rate

Optimal Link Selection

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

- T = {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

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

cost to reach destination
from set T

set of receivers
not in outage

Heuristic Cooperative Routing

optimal routing has exponential complexity

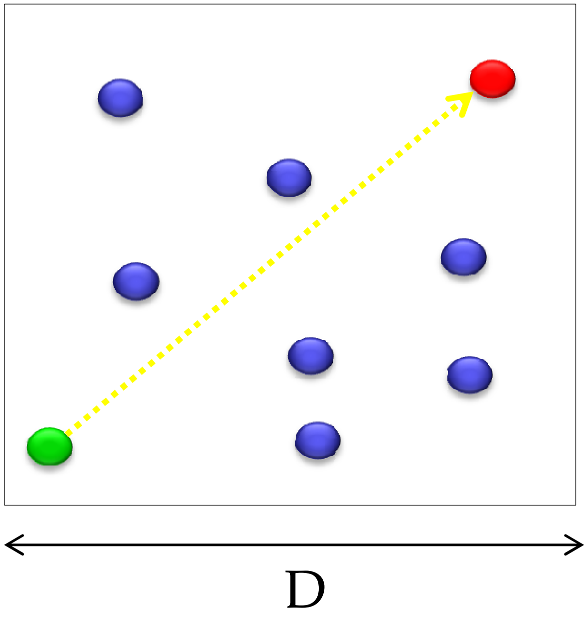
1. limited cooperation by limiting the set of transmitters or receivers

2. cooperation along the shortest non-cooperative path

3. local cooperation with optimal power allocation

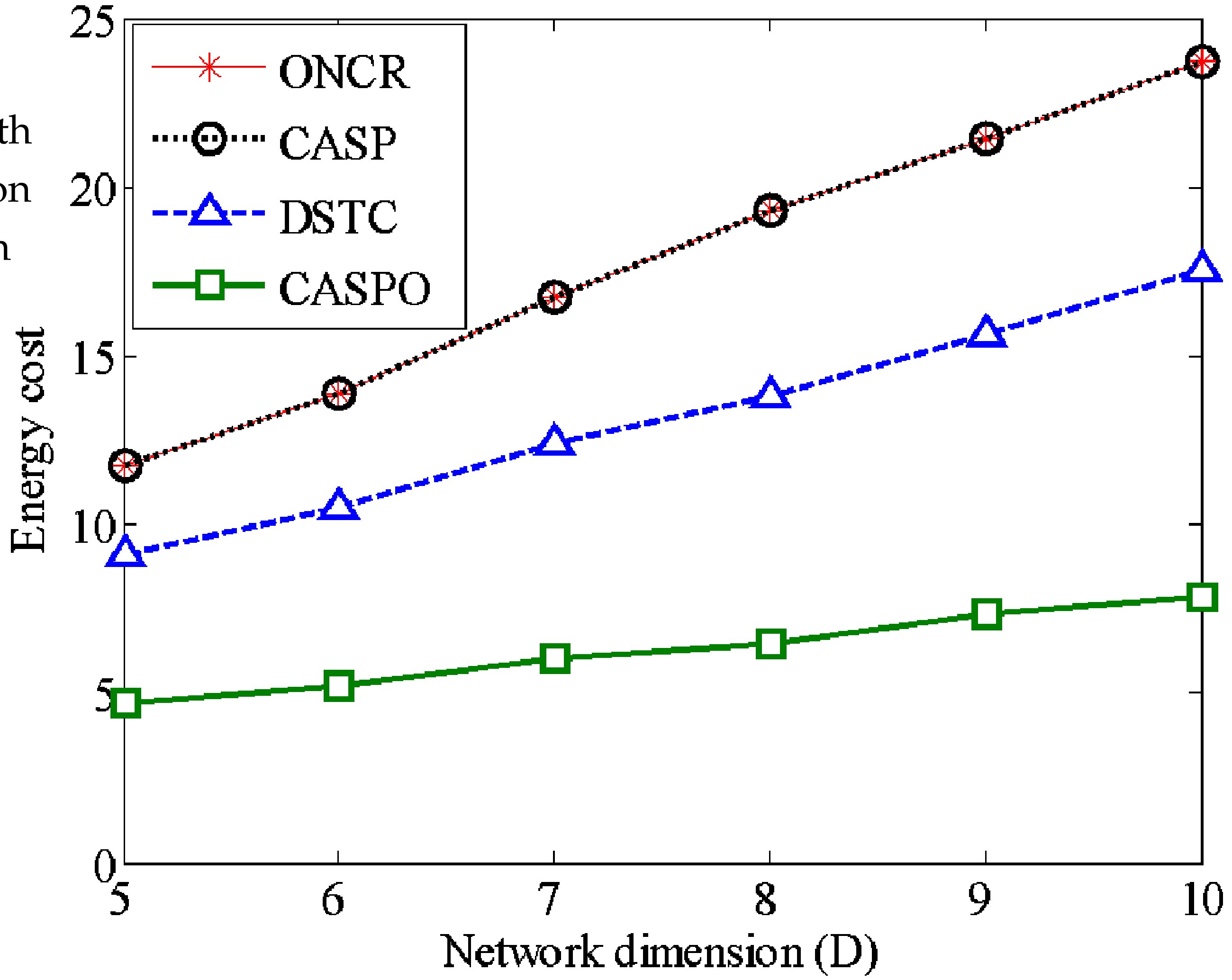
Simulation Environment

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

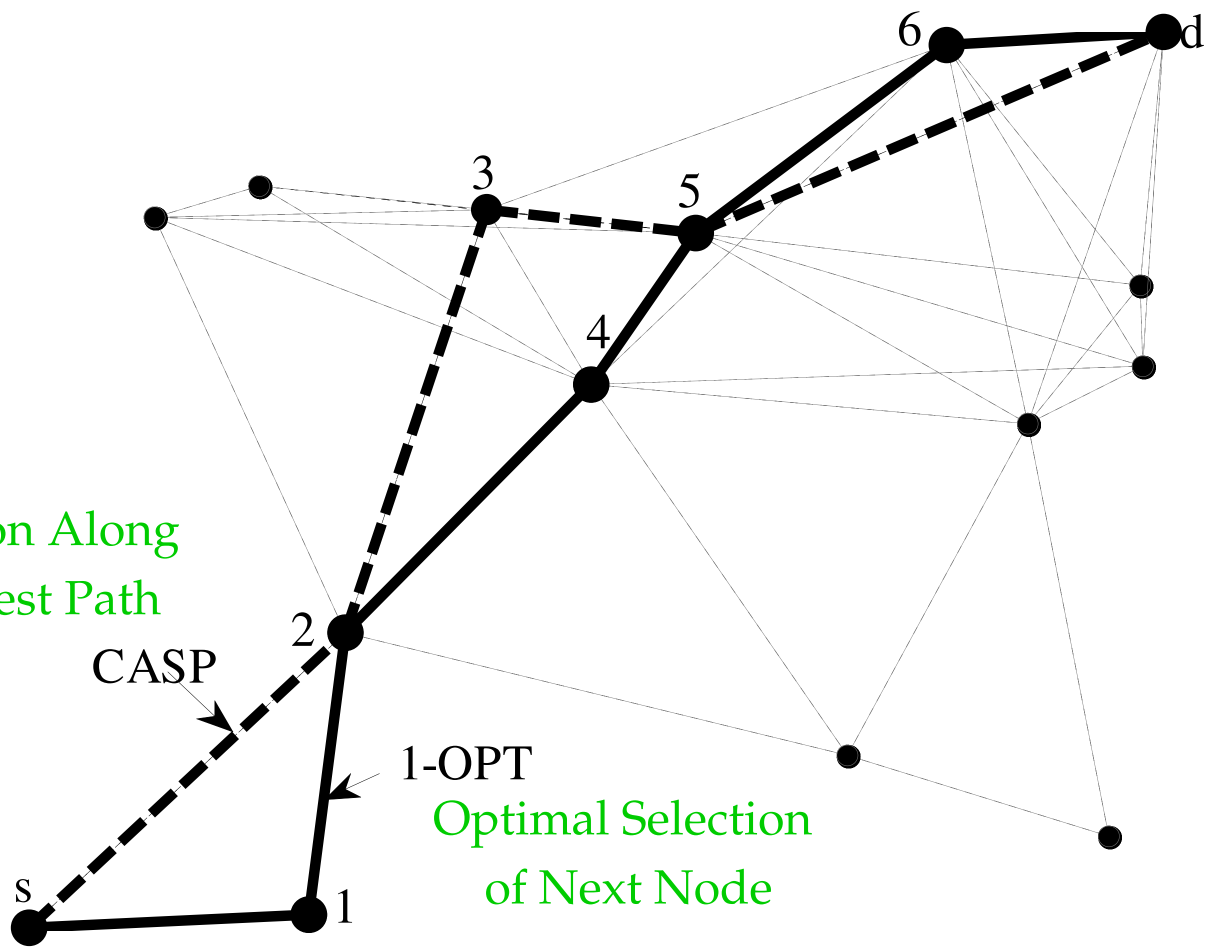


Energy Cost Comparison

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



Optimal v.s. Heuristic Cooperative Routes



Cooperation Along
the Shortest Path

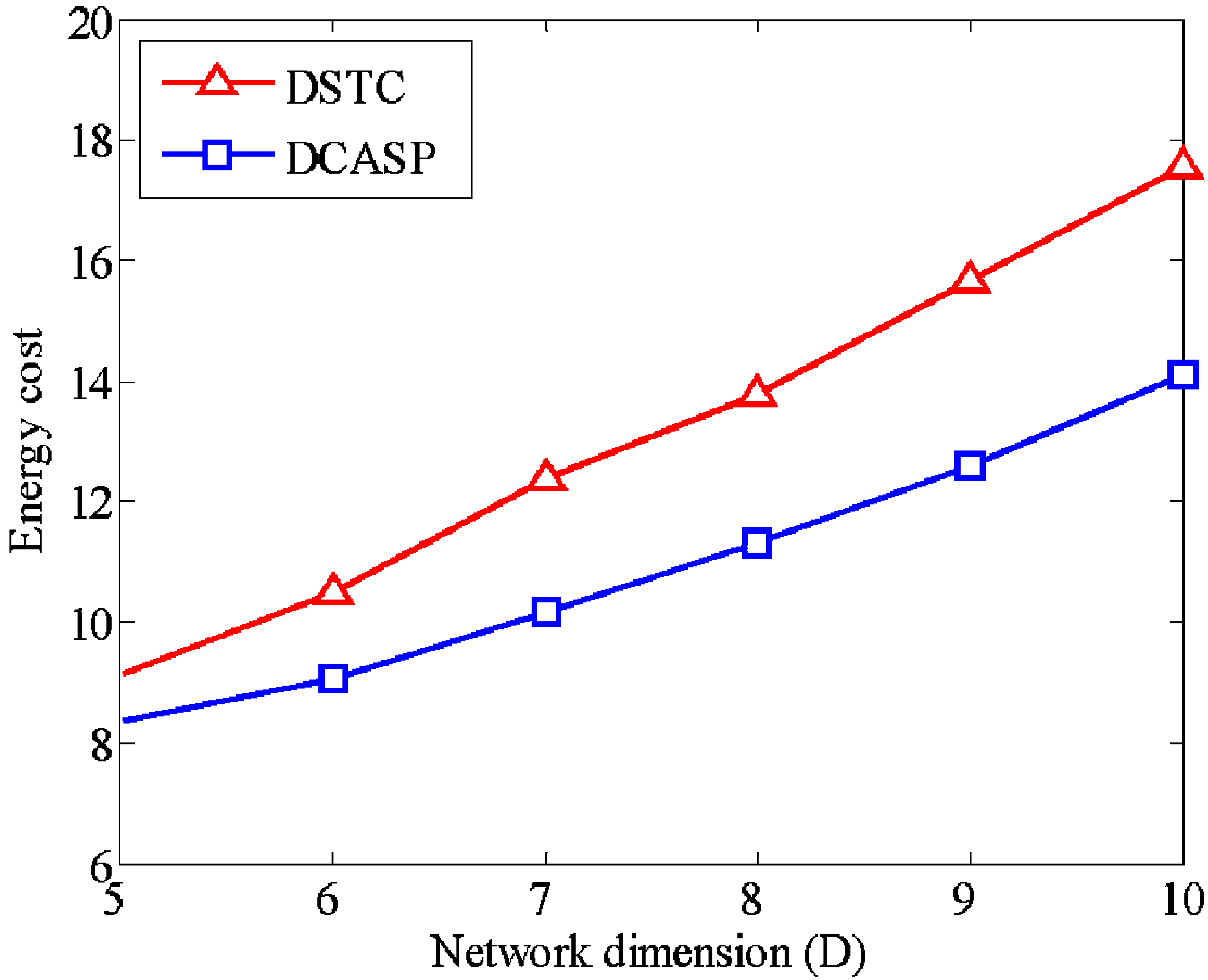
Optimal Selection
of Next Node

12% more energy savings

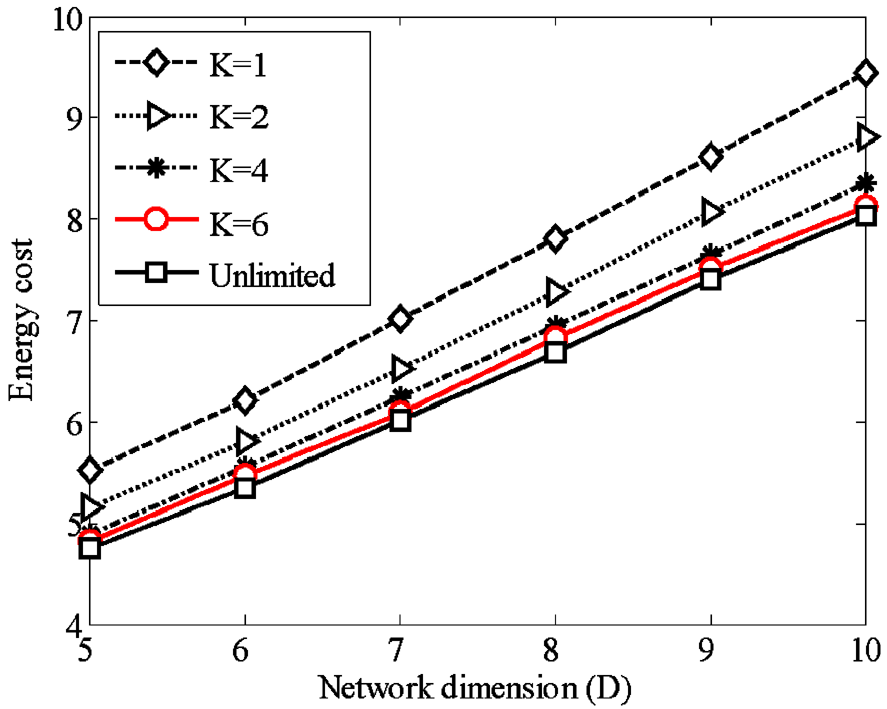
Optimal v.s. Equal Power Allocation

DSTC:
distributed equal
power allocation

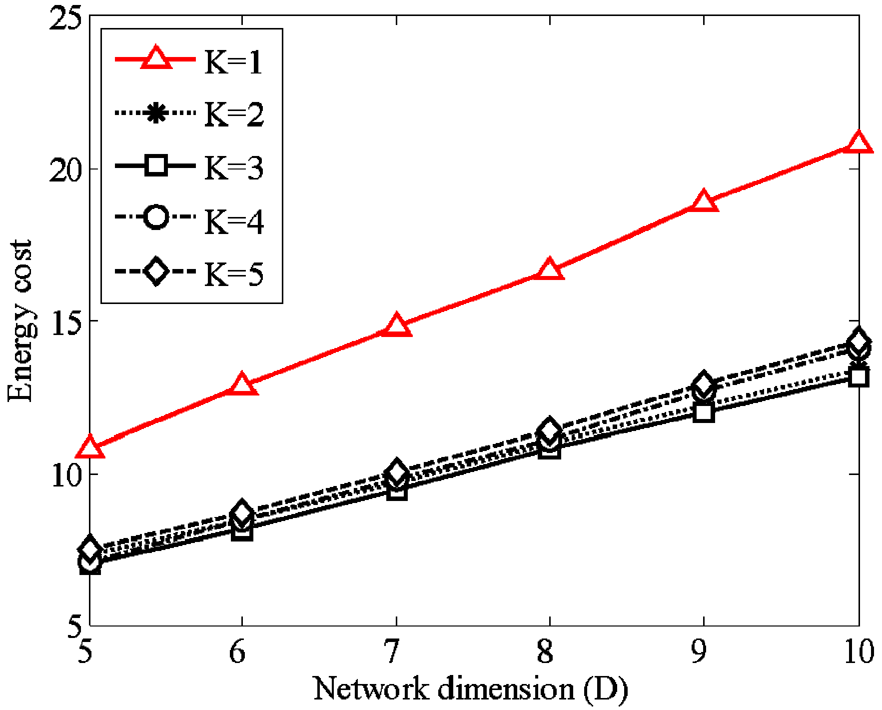
DCASP: proposed
distributed optimal
power allocation



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.