Energy Efficiency in Wireless Sensor Networks

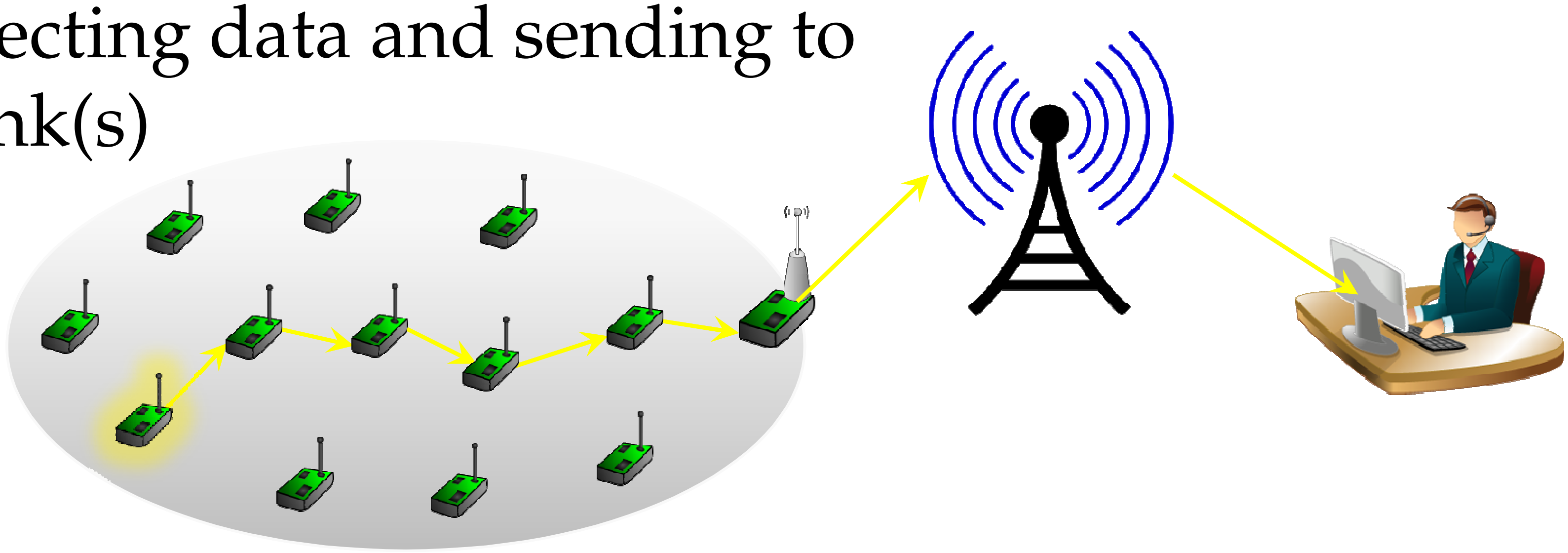
Majid Ghaderi
Department of Computer Science
University of Calgary
mghaderi@ucalgary.ca

Outline

- wireless sensor networks
- energy efficiency challenge
- compression and cooperation
- cooperative routing
- open problems

What is a Wireless Sensor Network?

- network of typically small, battery-powered, wireless devices:
  - on-board processing
  - wireless communication
  - sensing capabilities
- collecting data and sending to a sink(s)



What is the Networking Challenge?

- power, power, power, …
- life time with 2 AA batteries $\approx$ 20 days
- processing and memory limitations are temporary
  - processing capacity doubles every 2 years
- power limitation is fundamental
  - battery capacity doubles every 35 years!

What is the Networking Challenge?

- wireless communication is power hungry:
  - energy to transmit 1 Kbit over 100 m
    ≈ executing 3 million instructions
- energy efficient communication is critical
  - duty cycling sensors, efficient MAC protocols
  - …

our work:

1. compression: minimize transmitted data
2. cooperation: minimize transmission energy

Minimize Data Volume

- take advantage of redundant sensor data
  - sensors are densely deployed
  - nearby readings might be correlated
  - correlated data can be compressed
- decades of research/innovation in data compression
  - entropy achieving compression
  - distributed compression (Slepian-Wolf coding)
- how can it be applied in sensor networks?

Minimize Data Volume

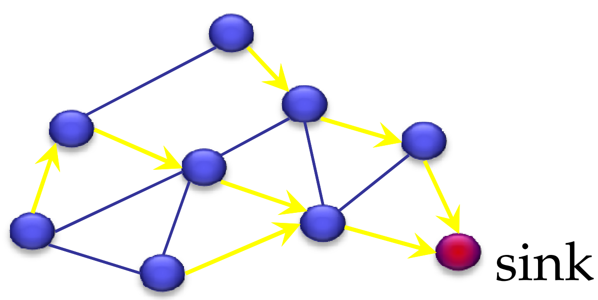
- our work: *hierarchical routing*
  - nearby sensors form a *cluster*
  - each cluster has a cluster *head*
  - cluster head *aggregates* cluster data
- challenges:
  - how to form clusters?
  - what is the optimal size of clusters?
  - NP-hard problem
  - approximate and heuristic techniques

Minimize Transmission Energy

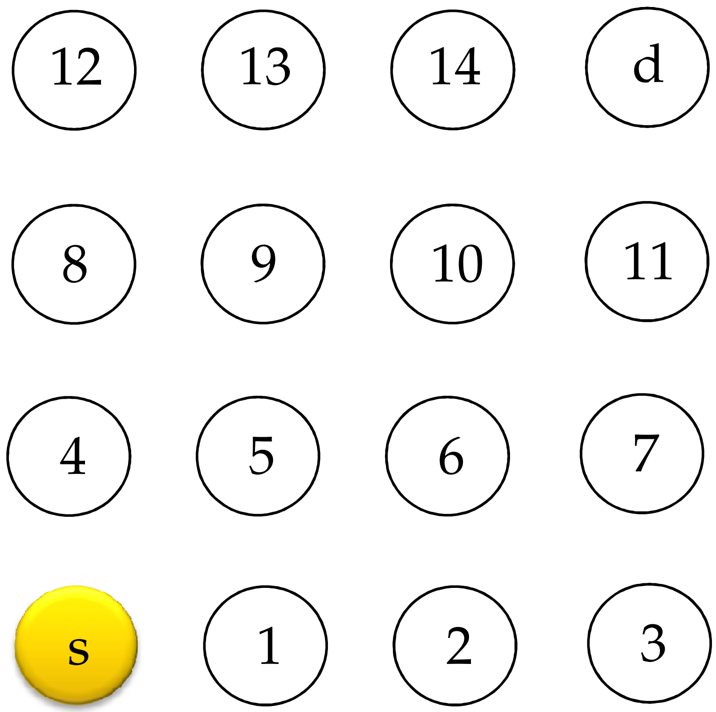
- significant advances at physical layer
  - efficient communication techniques, such as *cooperative communications*
  - caveat: not much impact at network layer
- **our goal:**
  - design network protocols to take advantage of cooperation
  - how? *cross-layer* design, specifically *routing* → *joint optimization* of cooperation and routing

Routing in Sensor Networks

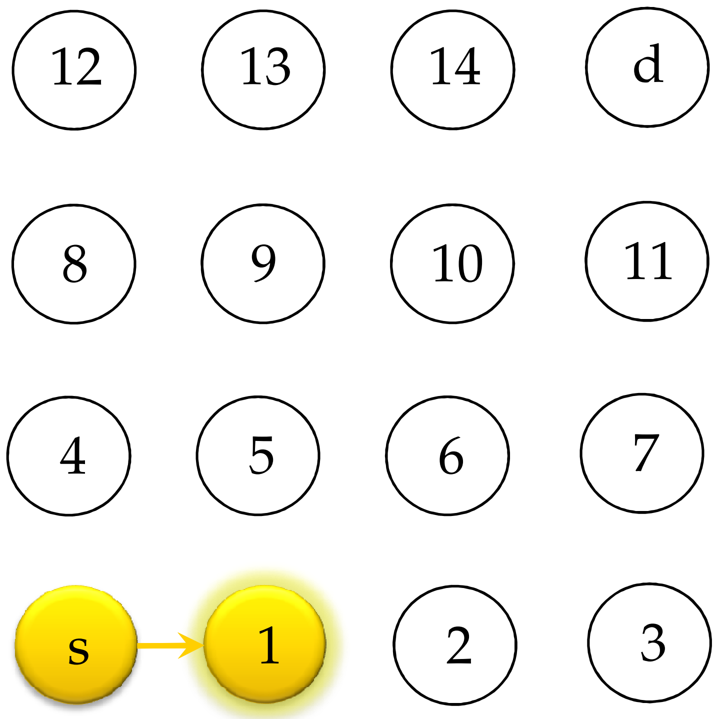
- *link* abstraction between *two* nodes
  - a functional link originates from a single node
  - simultaneous transmissions result in collision
- shortest path routing
  - network is a graph of point-to-point links
  - link cost is transmission energy



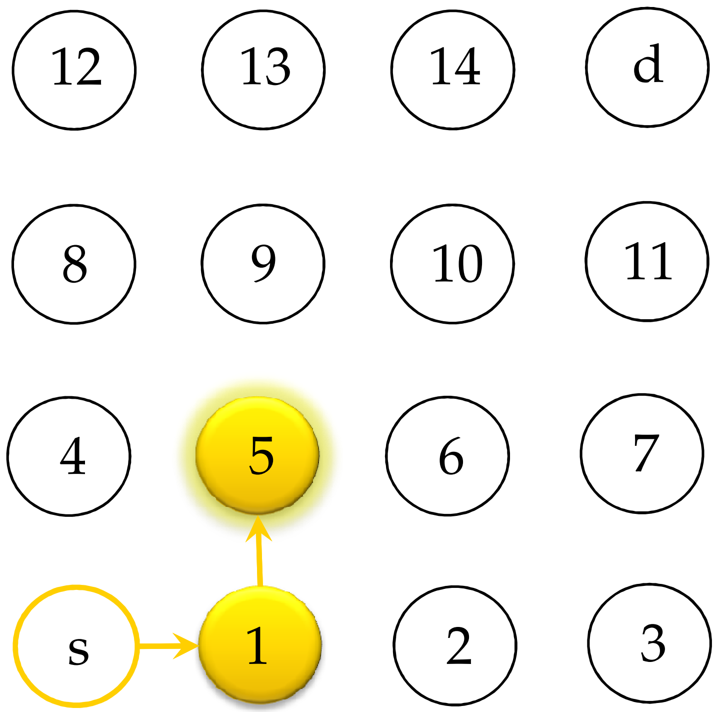
Routing Example



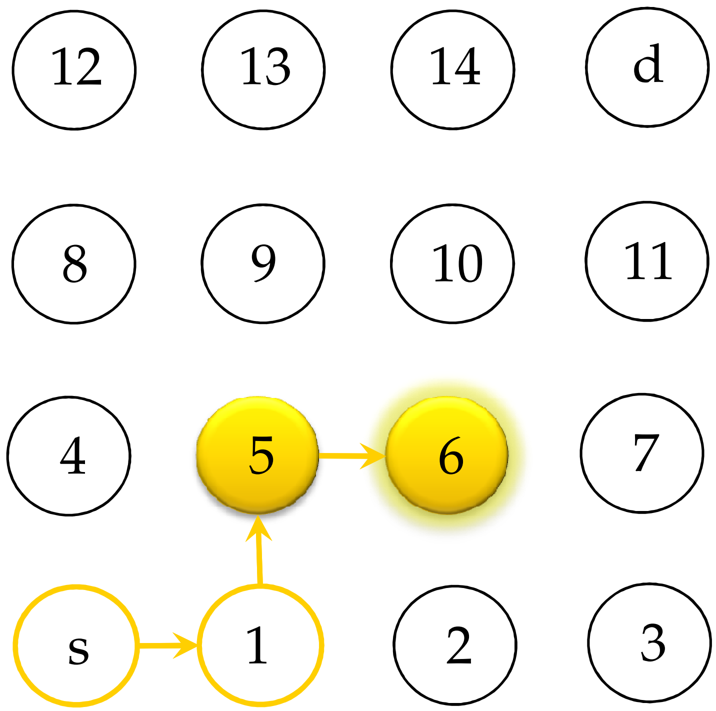
Routing Example



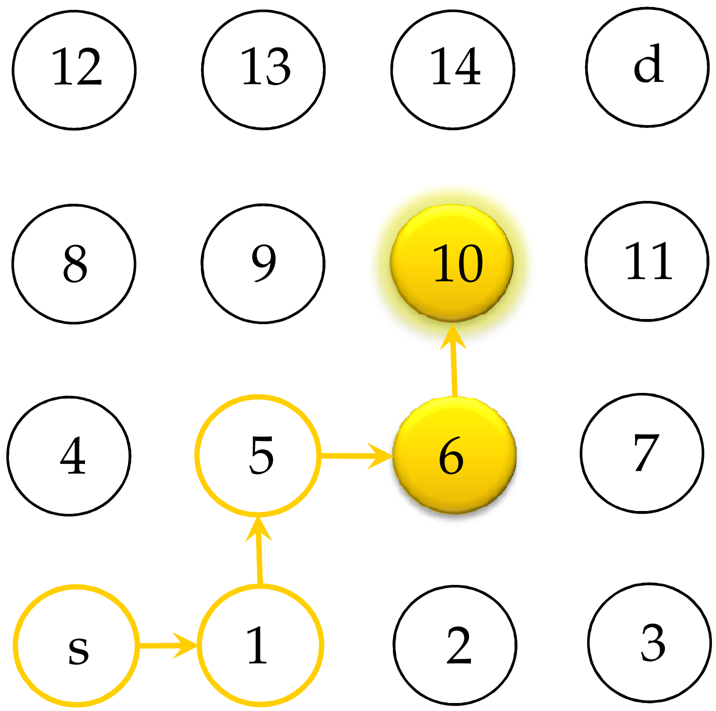
Routing Example



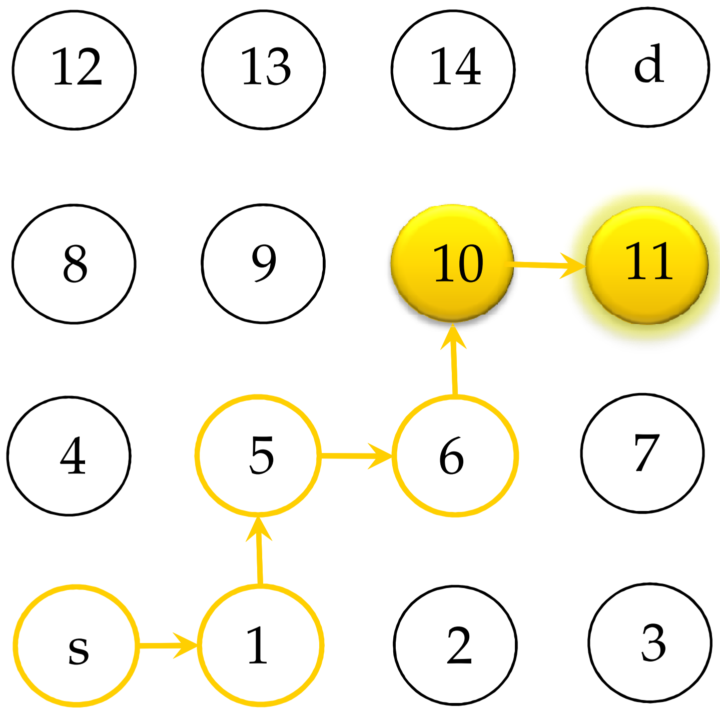
Routing Example



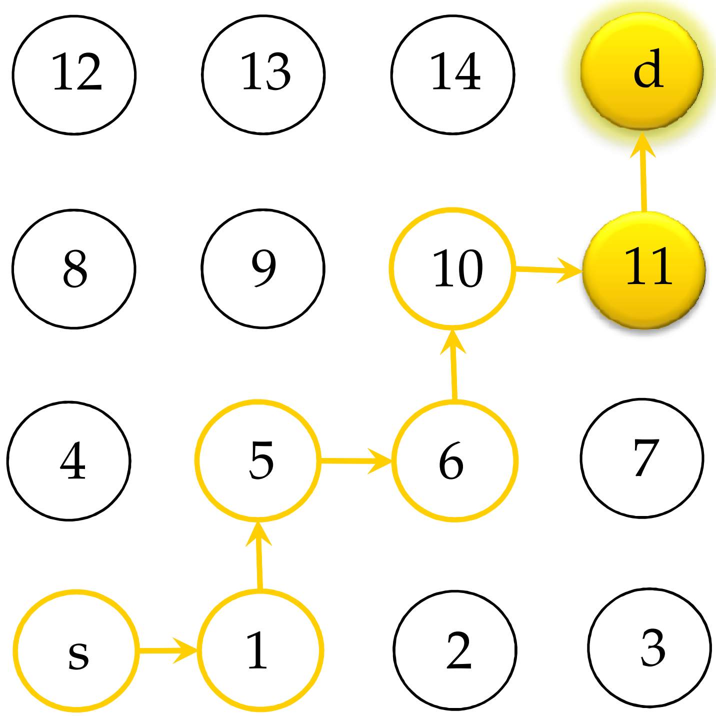
Routing Example



Routing Example

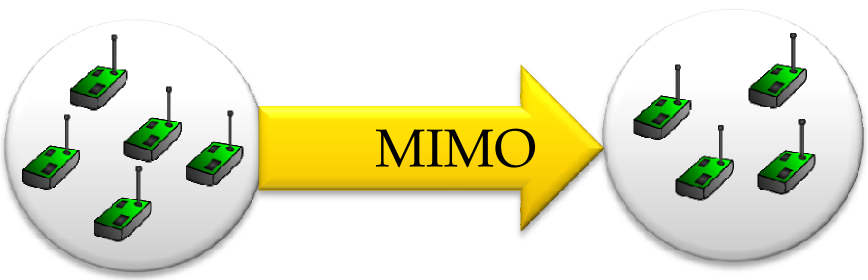


Routing Example



Cooperative Communication

- single antenna nodes create a distributed multiple antenna system
  - virtual MIMO (multiple-input multiple-output)

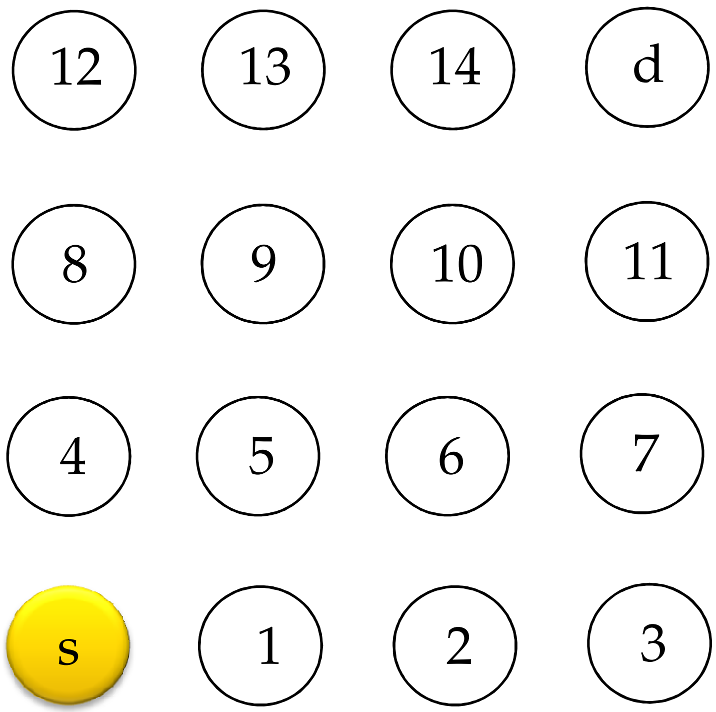


- benefits?
  - less transmission energy
  - more reliable *links* →longer transmission range

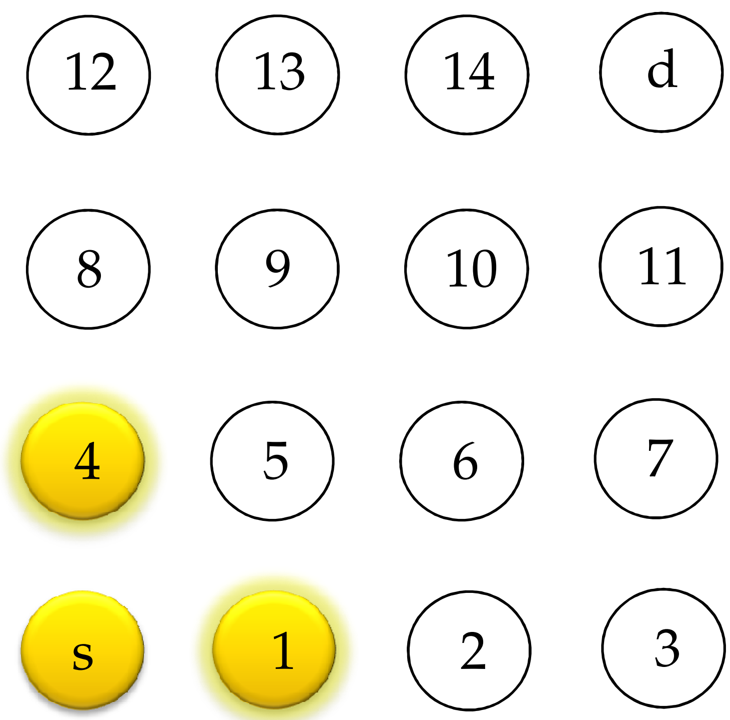
Cooperative Routing

- simple graph representation is not adequate
  - notion of a link is *vague* → no fixed links
  - changing cooperative nodes changes links!
  - non-adjacent nodes may communicate cooperatively
- **our** cooperative routing:
  - multi-hop routing
  - in each step, a set of transmitters send to a set of receivers cooperatively

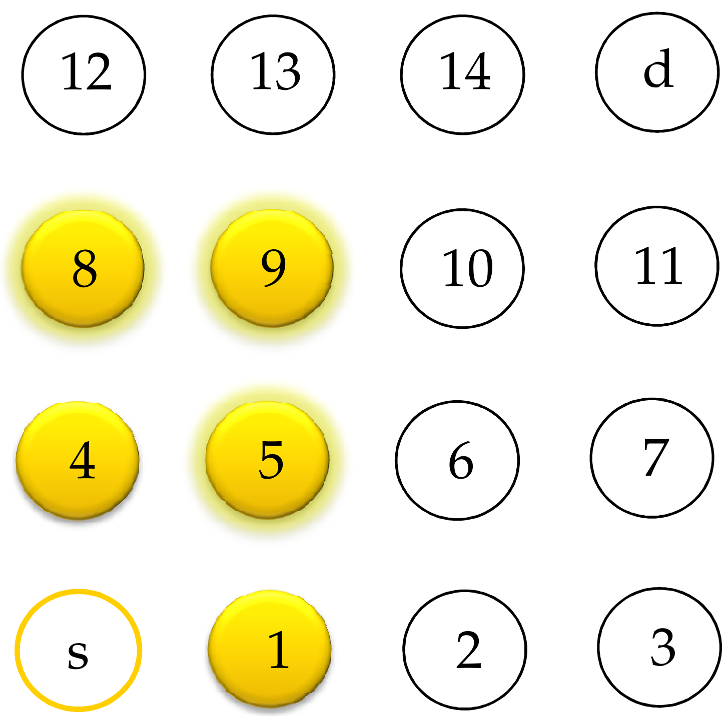
Routing Example



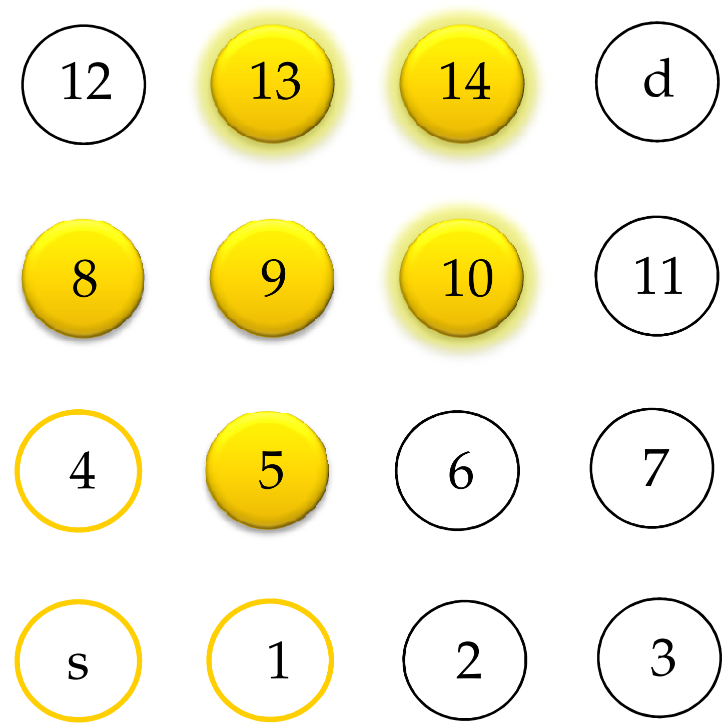
Routing Example



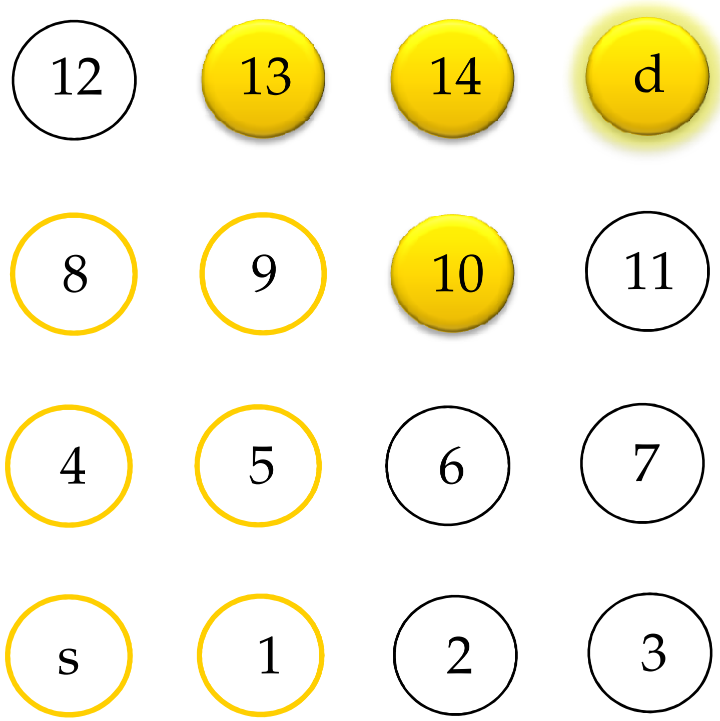
Routing Example



Routing Example



Routing Example



Cooperative Routing

- how to choose transmitting and receiving sets in each step?
  - minimize end-to-end path cost

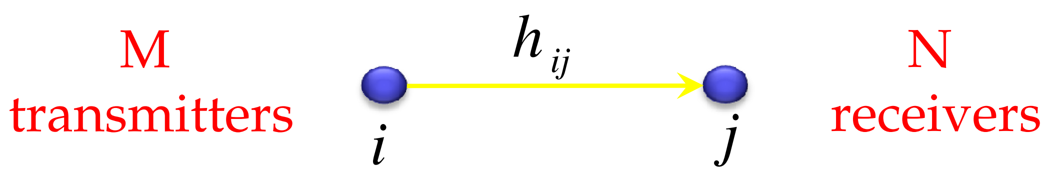
$$\text{Path Cost} = \sum_k \text{LC}(S_k, T_k)$$

$$\text{LC}(S_k, T_k): \text{link cost from } S_k \text{ to } T_k$$

  - form a super graph of all possible transmitting/receiving sets
  - find the shortest path in the super graph

Link Cost Formulation

- channel model



$$y_j[t] = \sum_{i=1}^{M} h_{ij}[t] x_i[t] + \eta_j[t]$$

- $y_j[t]$: signal received at node j
- $x_i[t]$: signal sent by node i
- $\eta_j[t]$: noise at node j

Link Cost Formulation

- $P_{\max}$: power constraint at transmitters
- $\mathrm{SNR}_{\min}$: decoding constraint at receivers
- w_i : transmit power at node *i*

$$\text{Link Cost (LC)} = \sum_{i=1}^{M} w_i^2$$

$$\sum_{i=1}^{M} h_{ij} w_i \geq \sqrt{\mathrm{SNR}_{\min} P_{\eta_j}} \qquad \text{for all receiver } j$$

$$w_i \leq \sqrt{P_{\max}} \qquad \text{for all transmitter } i$$

Link Cost Formulation

we are interested in minimizing link cost, i.e. minimizing transmit power

$$\min \sum_{i=1}^{M} w_i^2$$

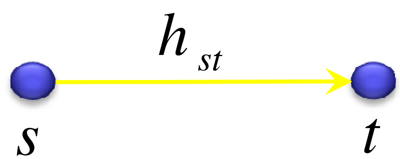
subject to:

$$\sum_{i=1}^{M} h_{ij} w_i \geq \sqrt{\mathrm{SNR}_{\min} P_{\eta_j}} \qquad \text{for all receiver } j$$

$$w_i \leq \sqrt{P_{\max}} \qquad \text{for all transmitter } i$$

Link Cost Formulation

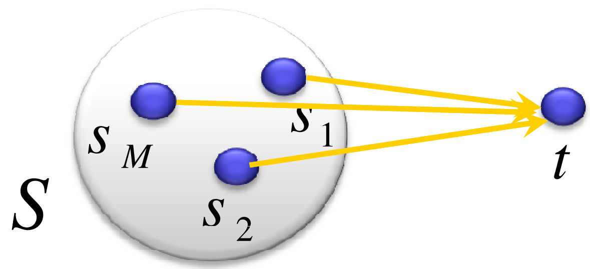
SISO: single-input single-output



$$\mathrm{LC}(s,t) = \frac{\mathrm{SNR}_{\min} P_{\eta_t}}{h_{st}^2}$$

Link Cost Formulation

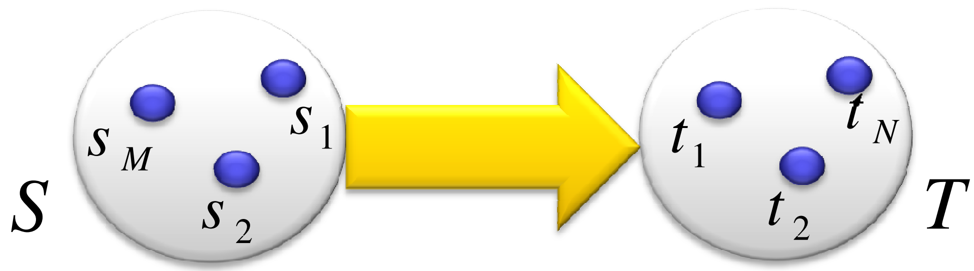
MISO: multiple-input single-output



$$\mathrm{LC}(S,t)=\frac{1}{\sum_{i=1}^{M}\frac{h_{it}^2}{\mathrm{SNR}_{\min}P_{\eta_t}}}=\frac{1}{\frac{1}{\mathrm{LC}(s_1,t)}+\cdots+\frac{1}{\mathrm{LC}(s_M,t)}}$$

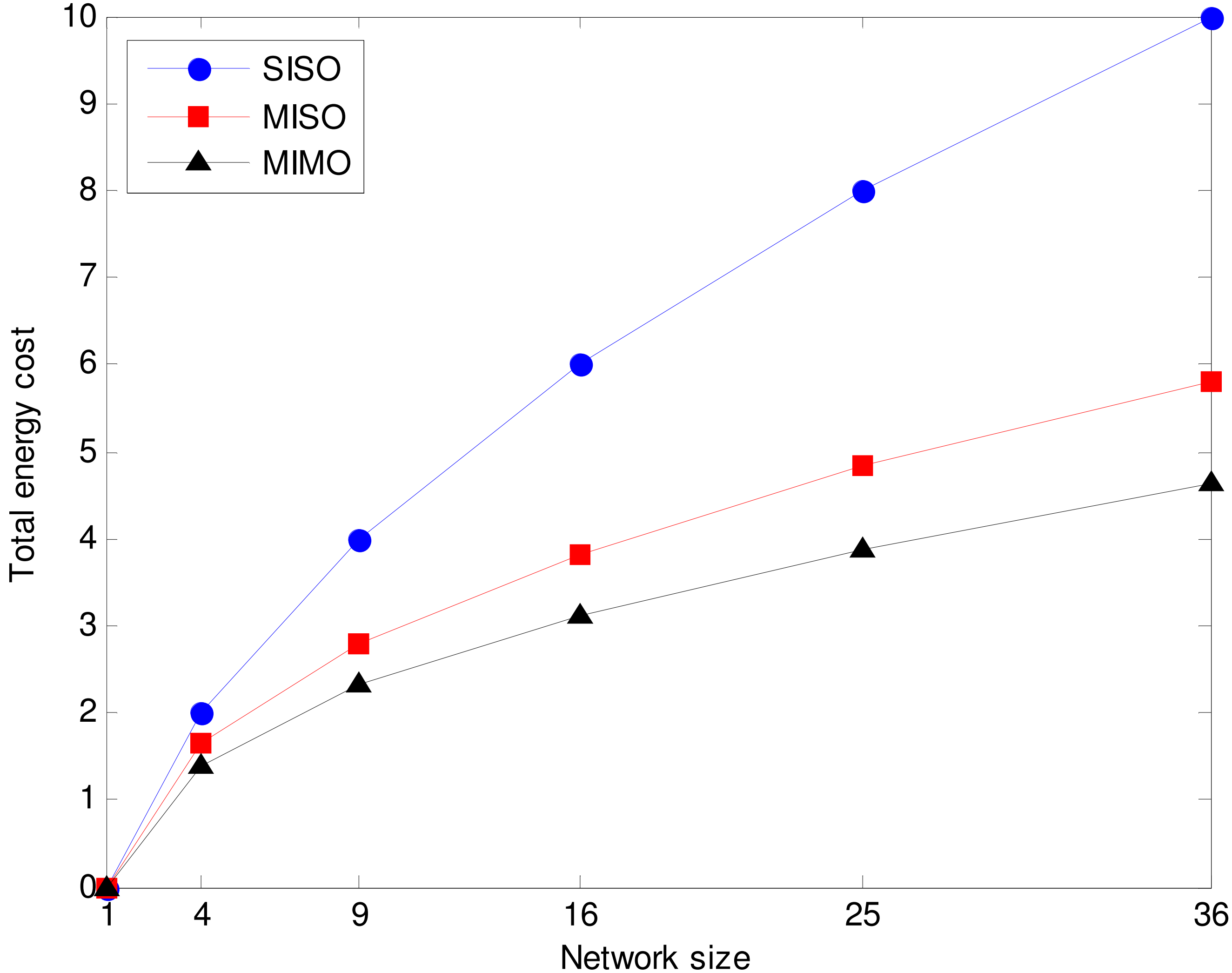
Link Cost Formulation

MIMO: multiple-input multiple-output



- no exact closed-form solution
  → *approximate as a MISO link*
  - convert T to a single super node t
  - noise power at super node: $P_{\eta_t} = \max_{1 \le j \le N} P_{\eta j}$
  - channel gains: $h_{it} = \min_{1 \le j \le N} h_{ij}$

Simulation Results



Energy comparison of routing algorithms.

Open Problems

- how about throughput in multi-flow networks?
  - interference increases due to cooperation
  - transmission range increases due to cooperation
- protocol design
  - optimal routing is NP-hard
  - heuristic routing algorithms
  - distributed implementation

Thank you.

For more information, please go to
http://www.ucalgary.ca/~mghaderi/research.html

M. Dehghan and M. Ghaderi, ``**Energy efficient cooperative routing in wireless networks**,"
Tech. Report 2009-930-09, Department of Computer Science, University of Calgary, June 2009.