Resource Allocation in Energy-constrained Cooperative Wireless Networks

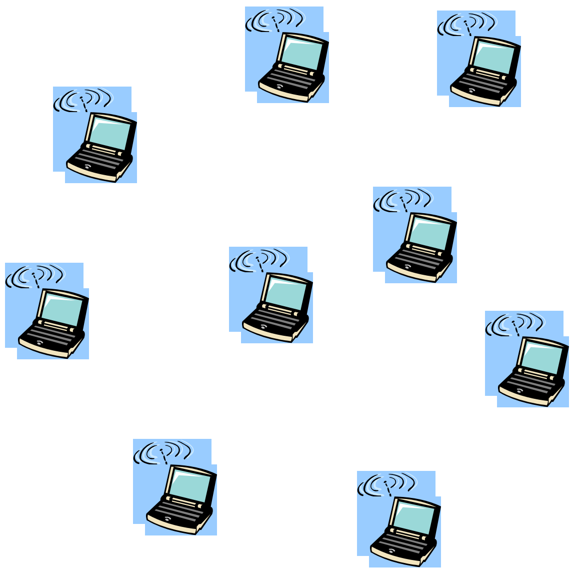
Lin Dai

City University of Hong Kong

Outline

- Resource Allocation in Wireless Networks
  - Tradeoff between Fairness and Throughput
- Fairness and Throughput in Energy-constrained Cooperative Networks
- Optimal Resource Allocation in Energy-constrained Cooperative Networks

Wireless Network



- Medium – electromagnetic wave
  - fading channel
  - shared spectrum
- Terminal – cellphone, PDA, laptop, …
  - portable
  - not so "smart"

- Increasing demand for a large variety of services
  - Voice, data, video, …

Resource ⇔ Allocation

- Limited resources
  - Bandwidth, power, processing capability…

Optimal Resource Allocation

Maximize $\sum_{k=1}^{K} T_k(\cdot)$

Subject to $S_k(\cdot) < q_k, \quad k = 1, \ldots, K$

Single User

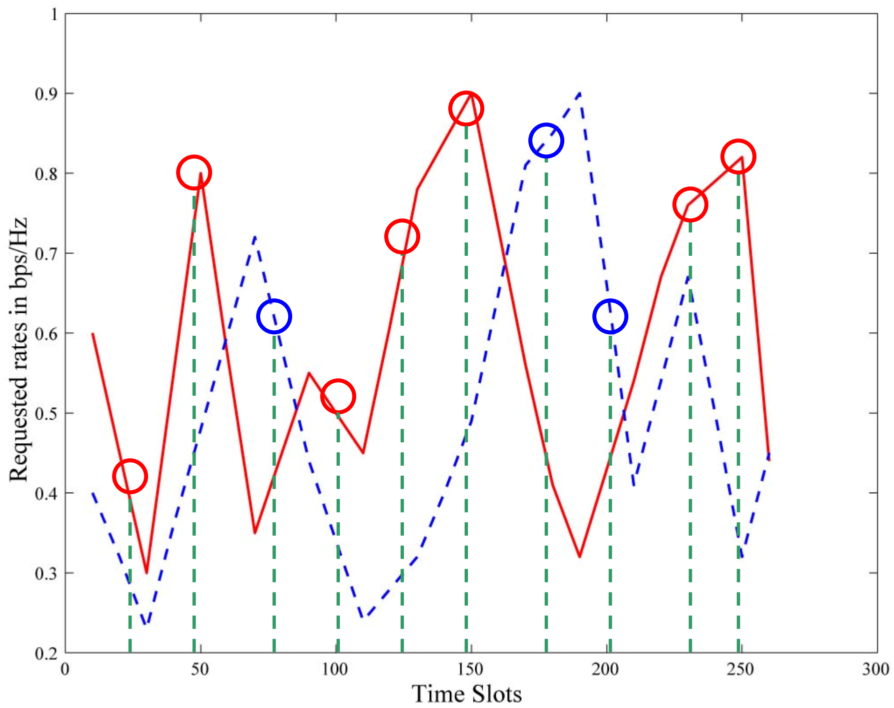
- Power allocation
- Antenna selection
- Subcarrier allocation
- ……

K-User

- Throughput maximization vs. Fairness
  - ✓ Effort fairness:
    Fairness in allocating the resources
  - ✓ Outcome fairness:
    Fairness in utilizing the resources

Example: Opportunistic Transmission

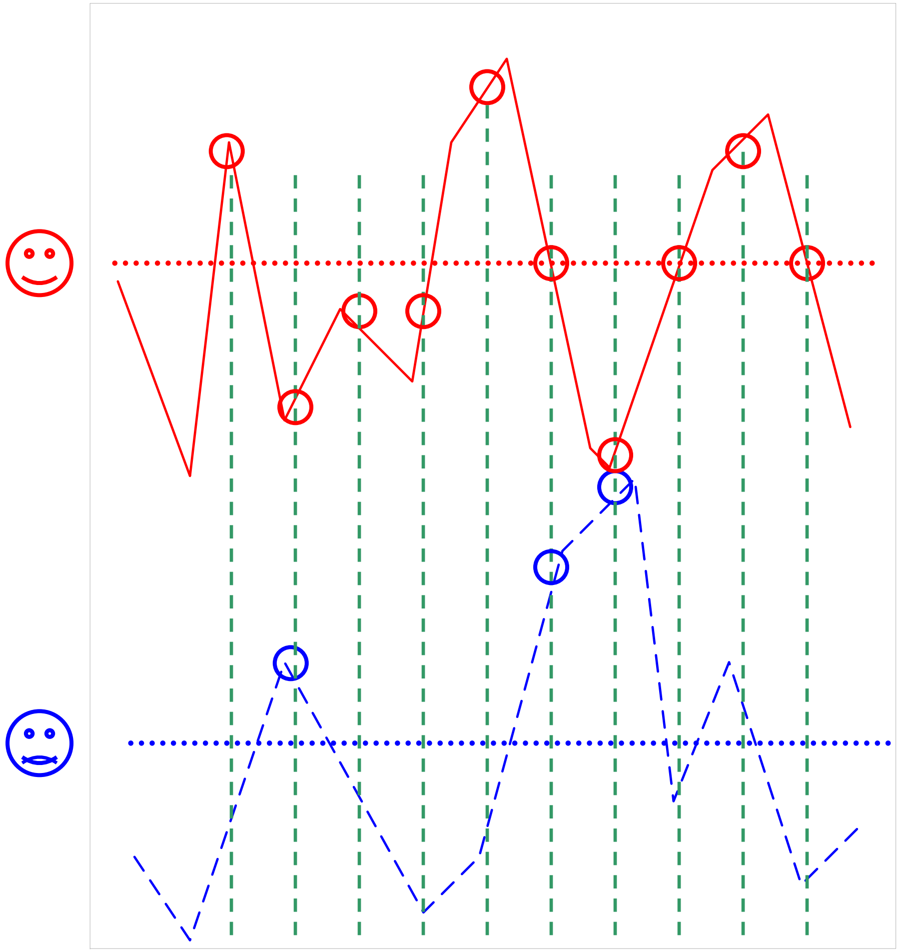
- Allocate different time slots to different users.
- Objective: Maximize $\sum_{k=1}^{K} T_k(\cdot)$



- Total throughput can be maximized by always serving the user with the strongest channel.
- The more users, the higher throughput.

Multiuser Diversity

Opportunistic Transmission with Fairness Constraint



- Help the "poor" -- a disadvantaged user is scheduled when its instantaneous channel quality is high relative to its own average channel condition.

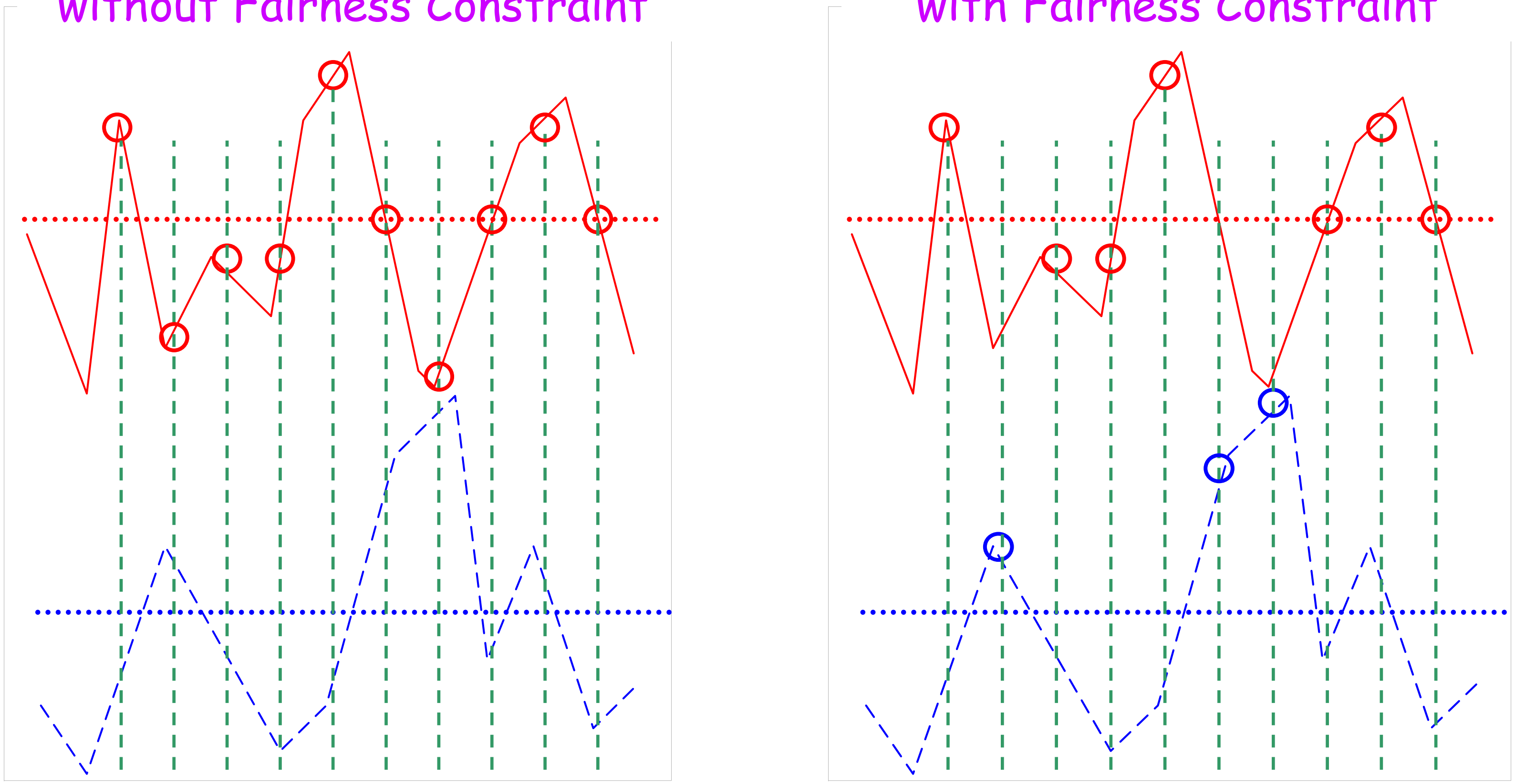
⇩

Maximize $\sum_{k=1}^{K} \log(T_k(\cdot))$

Tradeoff between Throughput and Fairness

Opportunistic Transmission without Fairness Constraint

Opportunistic Transmission with Fairness Constraint



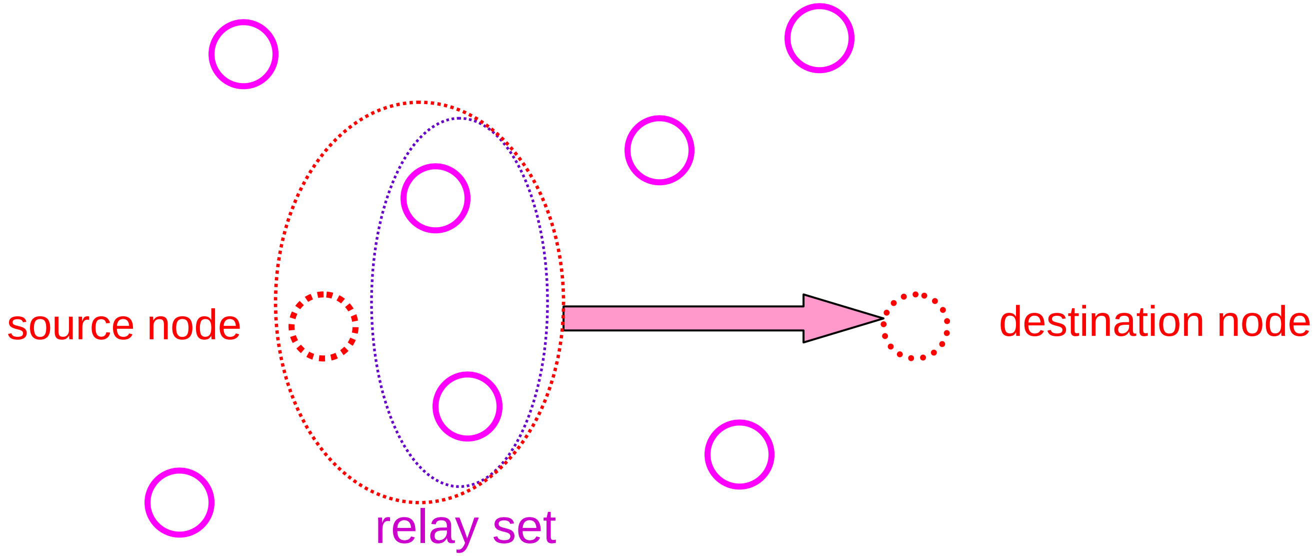
There is always a tradeoff between fairness and throughput.

Outline

- Resource Allocation in Wireless Networks
  - Tradeoff between Fairness and Throughput
- Fairness and Throughput in Energy-constrained Cooperative Networks
- Optimal Resource Allocation in Energy-constrained Cooperative Networks

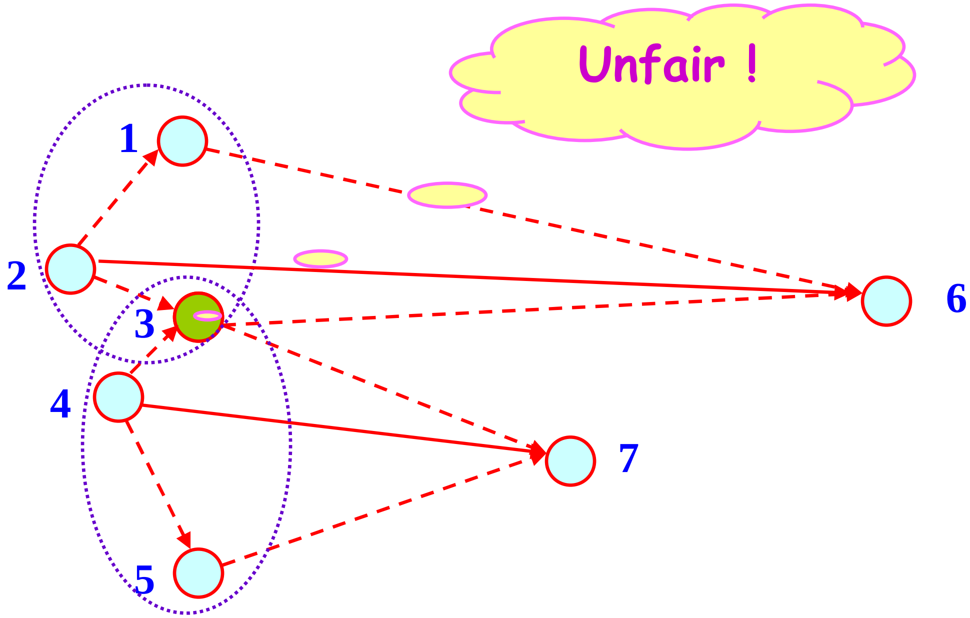
Cooperative Networks

- Diversity gain: $p_e \sim SNR^{-L}$
- How to achieve diversity gain in wireless ad-hoc networks?

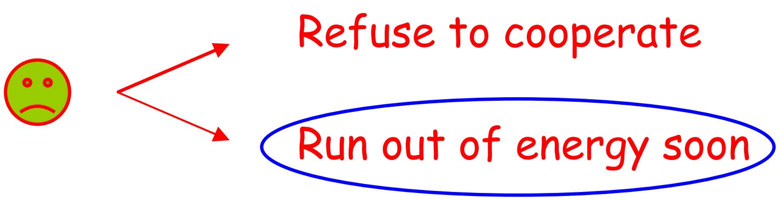


Node cooperation: more relay nodes, higher cooperative diversity gain.

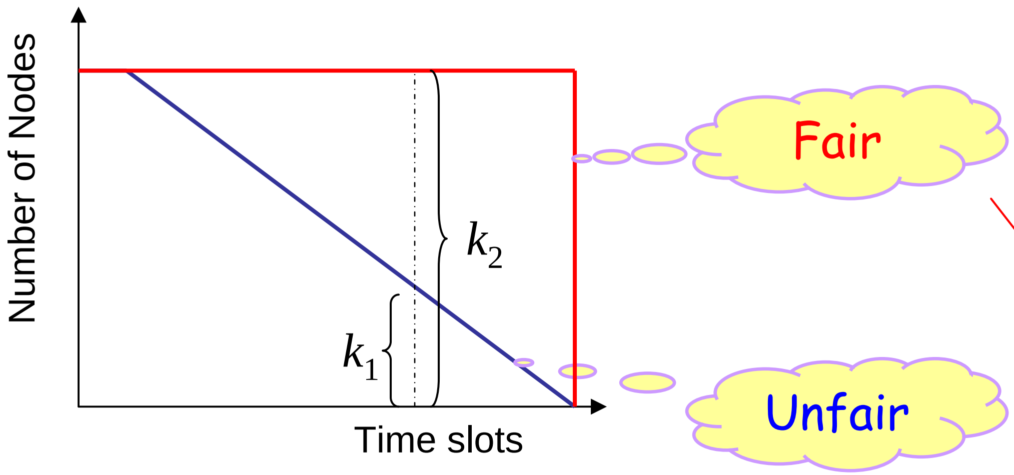
Multiuser Cooperative Protocol



- Some node may have more chances to be relays.



Fairness and Throughput in Energy-constrained Cooperative Networks



Effort fairness: equal lifetime

$k_1 \leq k_2$ at any time slot t

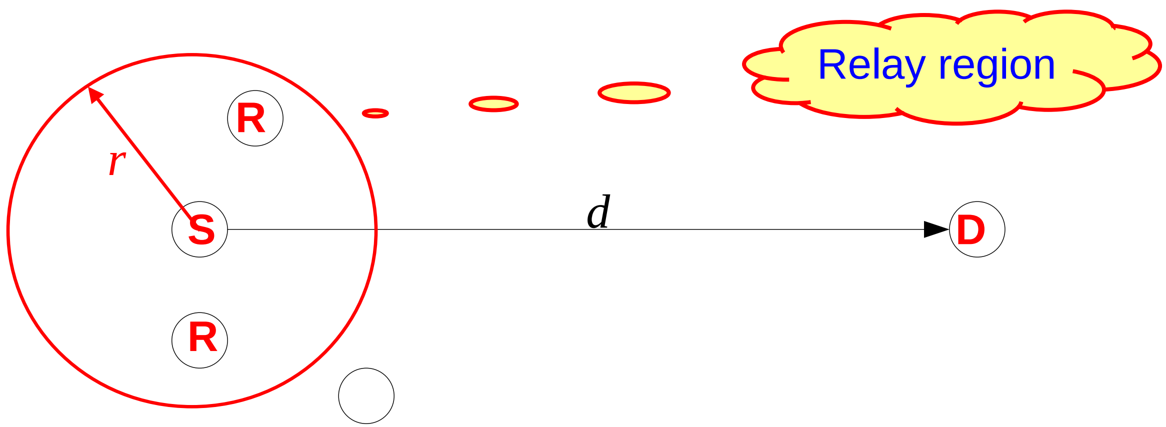
More nodes:
- higher cooperative diversity gain
- higher multiuser diversity gain

→ Higher throughput !

Improved fairness may lead to throughput gains in energy-constrained cooperative networks.

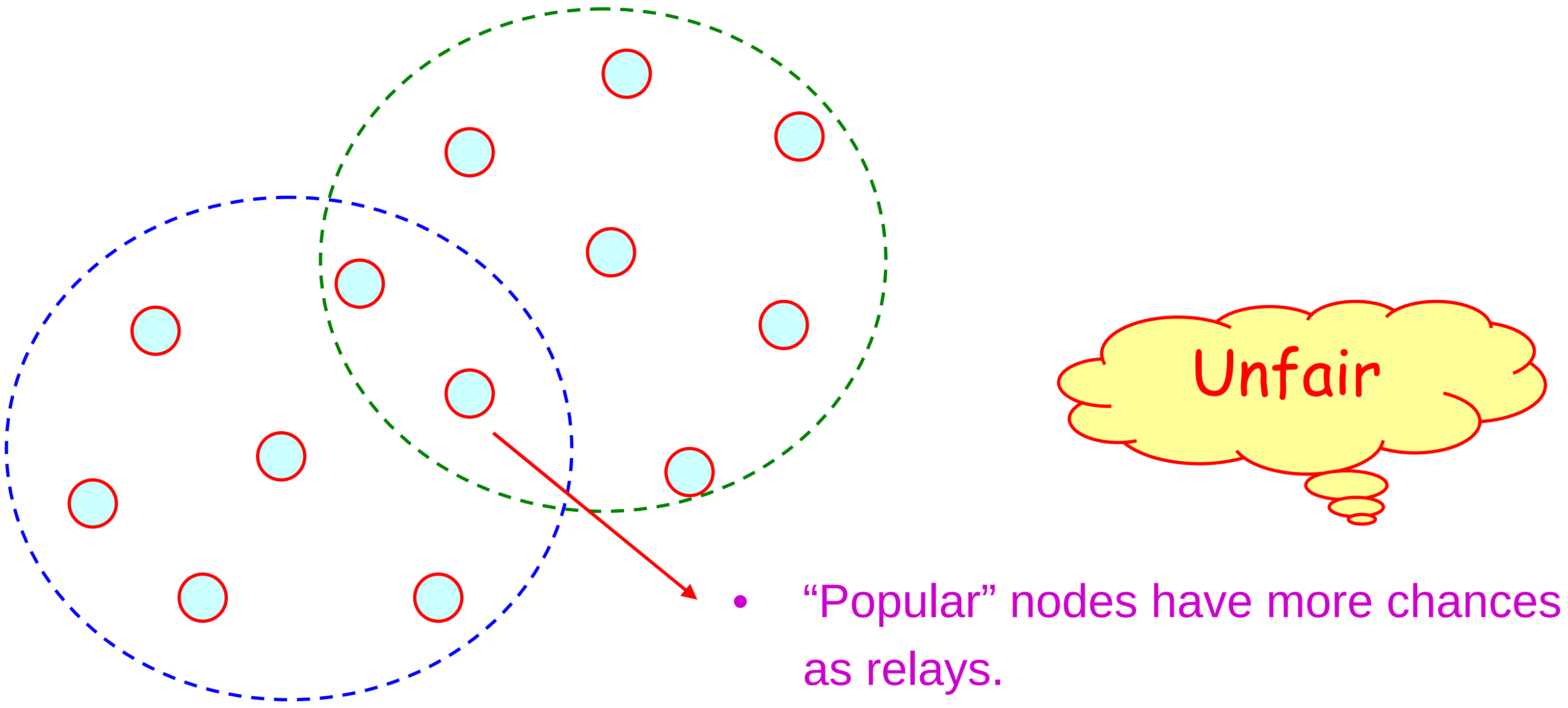
Network Model

- A wireless ad-hoc network with K nodes
- Each node with an energy constraint of E



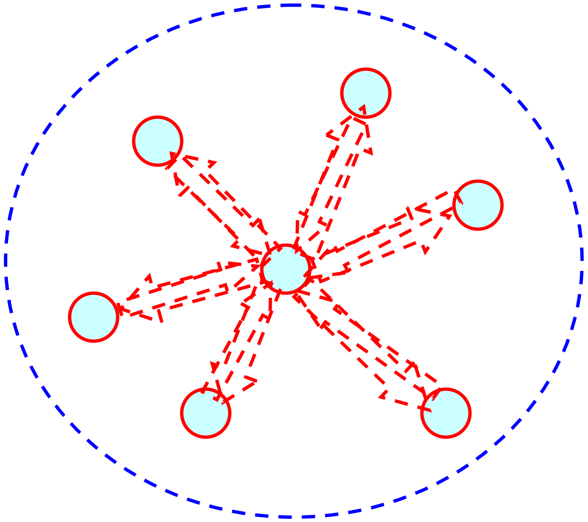
- Opportunistic transmission

Full Cooperative Protocol



- “Popular” nodes have more chances of acting as relays.
- They will run out of energy much faster than others.

How to Improve Fairness?



Resources required by each node should be no more than what it contributes to other nodes.

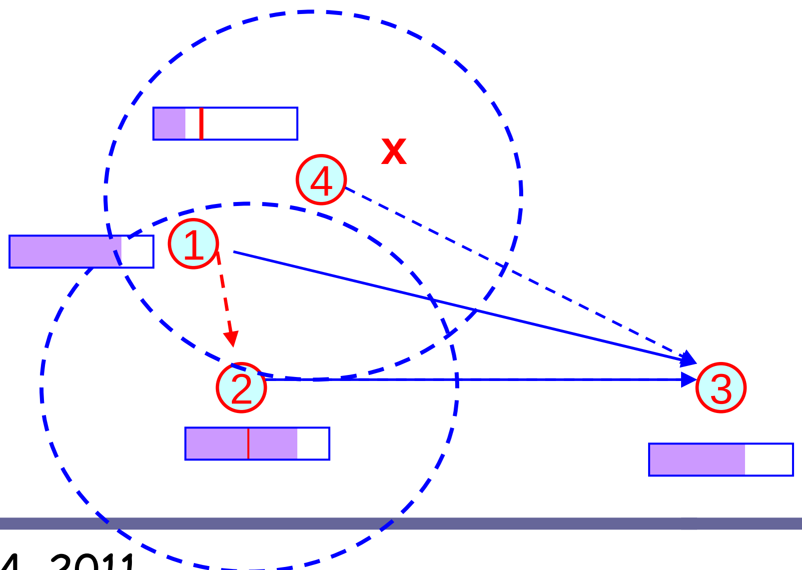
- Power Reward – adopted by each node to evaluate the power contributed to and by other nodes.

$$W_k \rightarrow W_k + P_k^j \qquad W_k \rightarrow W_k - \Psi_k \qquad \Psi_k = \sum_{j \in R_k} P_j^k$$

Power reward increases when node *k* acts as a relay
Power reward decreases when node *k* employs other nodes as relays

Fair Cooperative Protocol

- For each pair $(k, D(k))$, compare W_k and the sum relay power $\Psi_k = \sum_{j \in R_k} P_j^k$
  - If $W_k \geq \Psi_k$, use relays for cooperation
  - Else, no cooperation.
  - Compute the possible throughput.
- Compare the throughput of all the pairs and select the maximal one.
- Update the power reward.



With a power reward:

- Nodes cannot continuously employ relays;
- Nodes will not continuously act as a relay.

Fairness Indicator

- Fairness Indicator: $\xi = \dfrac{T_{\min}}{T_{\max}}$

$$T_{\min} = \min\{T_1, T_2, ..., T_K\}$$
$$T_{\max} = \max\{T_1, T_2, ..., T_K\}$$

  - ✓ Equal lifetime: $\xi = 1$

- Let ξ_d denote the fairness indicator of direct transmission
  - ξ_f full cooperative protocol
  - ξ_a fair cooperative protocol

  - ✓ $\xi_d \le \xi_f \le K^{v-1}, \quad 0 < v < 1$
  - ✓ $\xi_a \to \dfrac{\mathrm{E}[M_k]}{K}, \quad \text{as } K \to \infty$

Performance Comparison I: Fairness Indicator

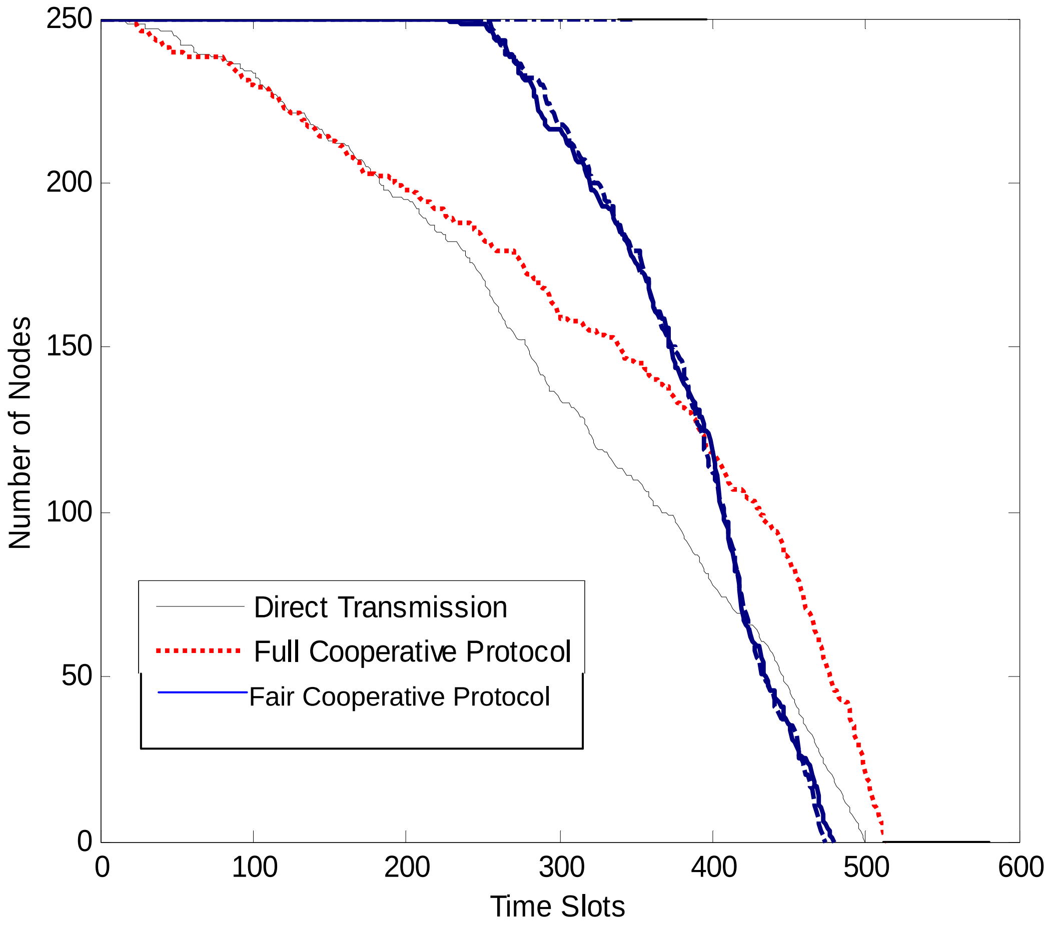
K	20	50	100	150	200	250
Direct transmission ξ_d	0.2	0.11	0.08	0.06	0.05	0.03
Full Cooperation ξ_f	0.16	0.14	0.07	0.04	0.04	0.04
Fair Cooperation ξ_a	0.31	0.34	0.35	0.41	0.48	0.48

$\mathrm{E}[M_k]/K = 0.5$

$\mathrm{E}[M_k]/K$	0.3	0.4	0.5	0.6	0.9
Fair Cooperation ξ_a	0.32	0.45	0.48	0.66	0.87

$K = 250$

Performance Comparison II: Lifetime



Aggregate Throughput

- Theorem 3 [Dai'09]: The aggregate throughput of an energy-constrained cooperative ad-hoc network with opportunistic transmission is given by

$$C = \mu_1 \int_0^{T_{\max}} \log_2 a(t)dt + \int_0^{T_{\max}} \log_2 b(t)dt + \xi T_{\max} + (\log_2 K - 1)T_{\max} + \upsilon T_{\max}$$

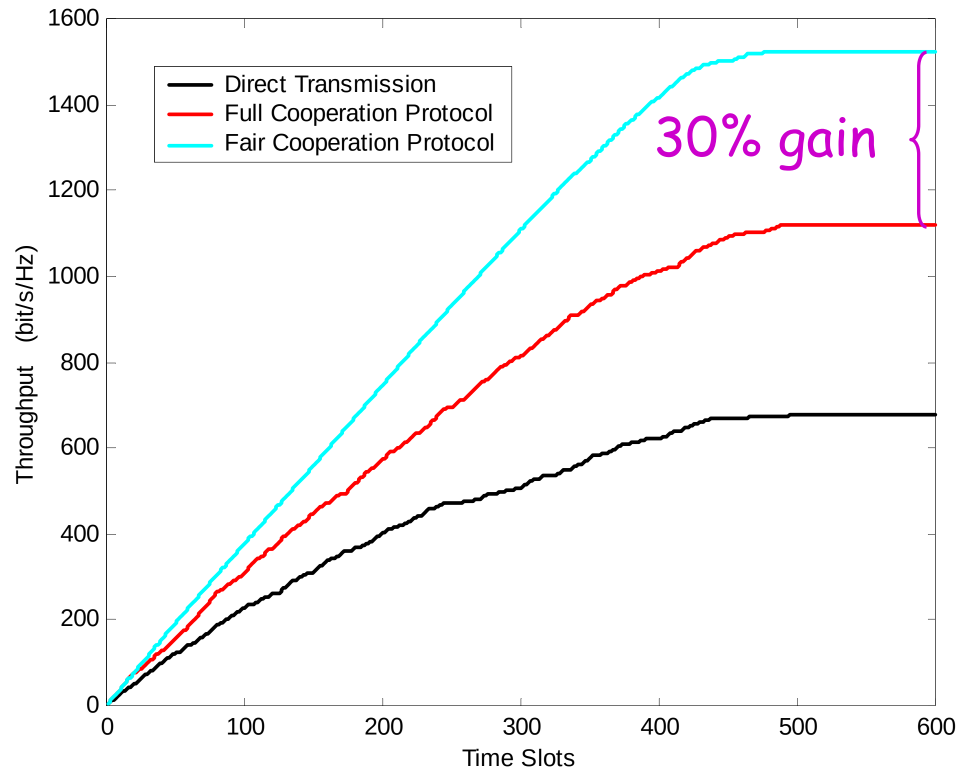
$a(t)$: proportion of nodes competing for the channel
$b(t)$: proportion of nodes acting as relays in the relay region
$\mu_1 << 1$

✓ Full cooperation: $C_f \approx \xi_f T_{\max} + (\log_2 K - 1)T_{\max} + \upsilon T_{\max}$

✓ Fair cooperation: $C_a \approx \xi_a T_{\max} + (\log_2 K - 1)T_{\max} + \upsilon T_{\max}$

$C_a > C_f$
because $\xi_a > \xi_f$

Performance Comparison III: Aggregate Throughput



• Lin Dai, Wei Chen, Leonard J. Cimini, Jr. and Khaled B. Letaief, "Fairness Improves Throughput in Energy-Constrained Cooperative Ad-hoc Networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3679-3691, July 2009.

Outline

- Resource Allocation in Wireless Networks
  - Tradeoff between Fairness and Throughput
- Fairness and Throughput in Energy-constrained Cooperative Networks
- Optimal Resource Allocation in Energy-constrained Cooperative Networks

Optimal Resource Allocation

- Resources: energy & time slots
- Objective
  - Maximizing the total throughput
  - Fairness: equal lifetime & energy fairness
- How to allocate?
  - Energy allocation
  - Time-slots allocation

Energy Fairness

E_j^i denotes the energy that node j consumed in transmitting/relaying signals of node i .

$$\begin{bmatrix} E_1^1 & E_1^2 & \cdots & E_1^K \\ E_2^1 & E_2^2 & \cdots & E_2^K \\ \vdots & \vdots & \ddots & \vdots \\ E_K^1 & E_K^2 & \cdots & E_K^K \end{bmatrix}$$

Σ (row) the total energy consumed by node 1:

$$e_1^C = \sum_{j=1}^{K} E_1^j$$

Σ (column) the total energy allocated to node 1: $e_1^A = \sum_{j=1}^{K} E_j^1$

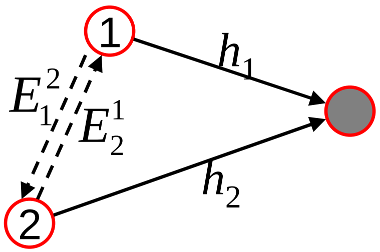
✓ Energy fairness:

$$e_i^A = e_i^C = E_{total} \Rightarrow \sum_{\substack{j=1 \\ j \neq i}}^{K} E_i^j = \sum_{\substack{j=1 \\ j \neq i}}^{K} E_j^i$$

$$i = 1, \ldots, K$$

Contribute more, gain more

Example: Two-node Cooperation



$$\begin{bmatrix} E_1^1 & E_1^2 \\ E_2^1 & E_2^2 \end{bmatrix}$$

- Energy fairness requires: $E_1^1 + E_2^1 = E_1^2 + E_2^2$, $E_1^1 + E_1^2 = E_2^1 + E_2^2$ $\Rightarrow E_1^2 = E_2^1$
- Suppose $|h_1| > |h_2|$. $E_2^1 > E_1^2$

How to guarantee energy fairness?

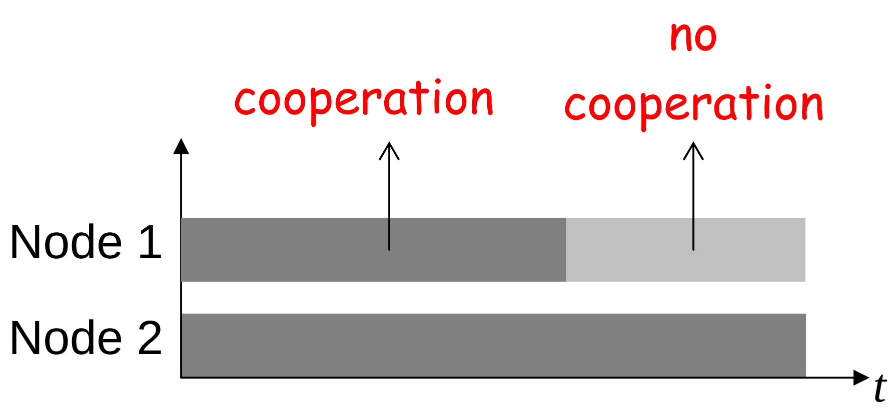
To Cooperate or Not to Cooperate?

Node 1:

- State 1: Node 2 helps node 1;
- State 2: Node 1 transmits alone.

Node 2:

- Node 1 always helps node 2.



Multi-state Cooperation

- Define a cooperation Matrix **A** with $a_{ij} = \frac{E_i^j}{e_j^A}$ $\Rightarrow$ $e_i^C = \sum_{j=1}^K E_i^j = \sum_{j=1}^K a_{ij} e_j^A$

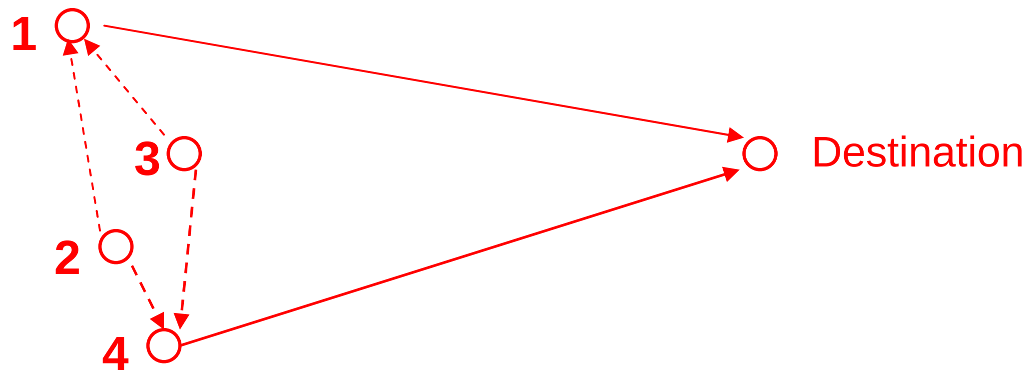
$$\begin{bmatrix} e_1^C \\ e_2^C \\ \vdots \\ e_K^C \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1K} \\ a_{21} & a_{22} & \cdots & a_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ a_{K1} & a_{K2} & \cdots & a_{KK} \end{bmatrix} \cdot \begin{bmatrix} e_1^A \\ e_2^A \\ \vdots \\ e_K^A \end{bmatrix}$$

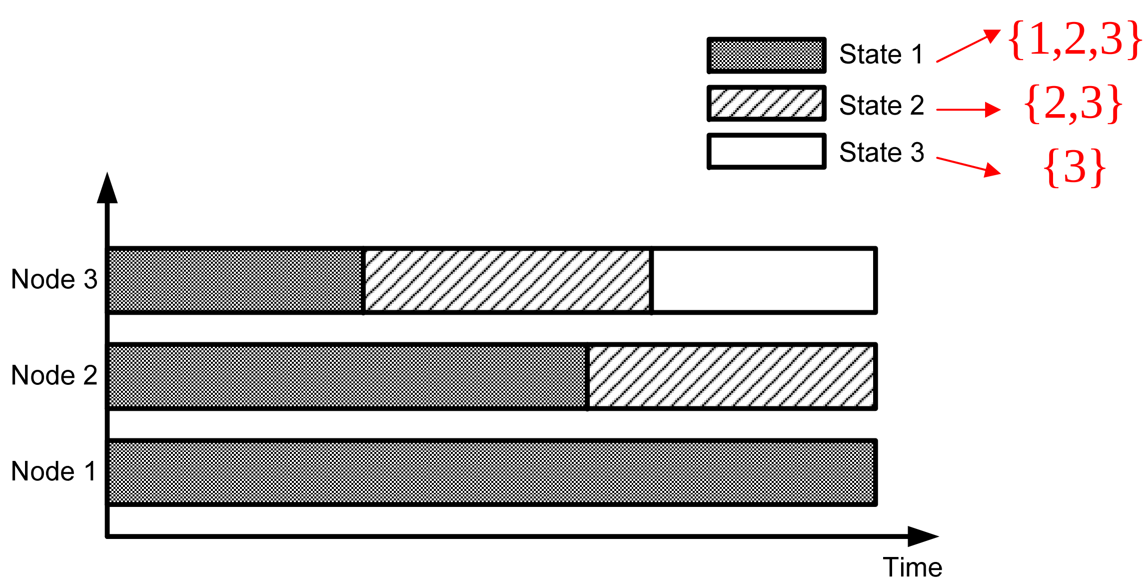
A should be a doubly-stochastic matrix!

- Divide cooperation into multiple states;
- At cooperation state n=1,…,N, choose a relay set such that A(n) is a doubly-stochastic matrix.

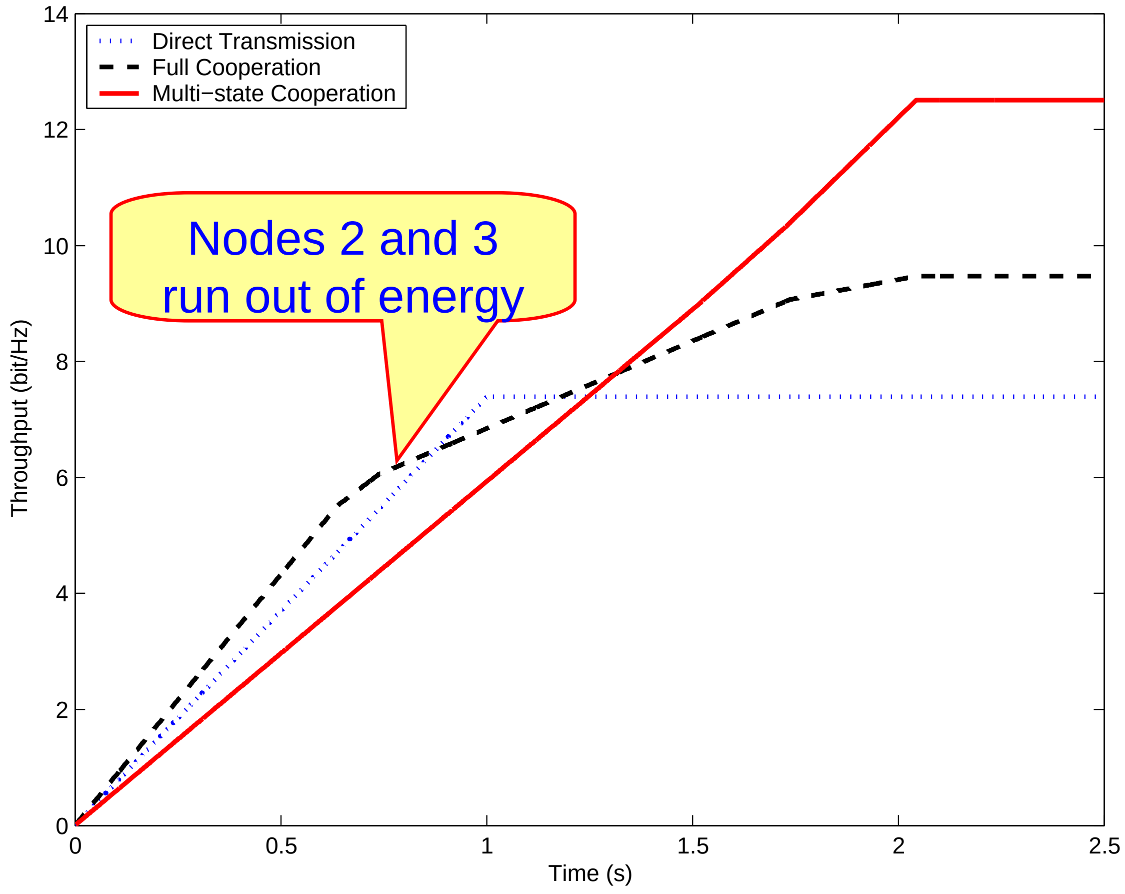
$$\begin{cases} \sum_{n=1}^N \mathbf{e}^C(n) = \sum_{n=1}^N \mathbf{A}(n)\mathbf{e}^A(n) = E_{total}\mathbf{1} \\ \sum_{n=1}^N \mathbf{e}^A(n) = E_{total}\mathbf{1} \end{cases}$$

Multi-state Cooperation





Performance Comparison I: Aggregate Throughput



Performance Comparison II: Fairness Performance

Compared to Direct Transmission

		Node 1	Node 2	Node 3	Node 4	
Increase in lifetime	Full	104%	-36%	-26%	74%	Effort fairness
	Multi-state	104%	104%	104%	104%	
Increase in throughput	Full	144%	-38%	-22%	90%	Outcome fairness
	Multi-state	87%	55%	67%	76%	

• Wei Chen, Lin Dai, Khaled B. Letaief and Zhigang Cao, "A Unified Cross-Layer Framework for Resource Allocation in Cooperative Networks," *IEEE Trans. Wireless Commun*., July 2008.
(won the 2009 IEEE Marconi Prize Paper Award)

Open Issues

- Distributed implementation
  - Power reward + distributed access
- Generalization to multi-hop cooperative networks
  - Optimal framework
  - Routing and access protocol design

Thank you!

Any Questions?