

Coalition Games with Cooperative Transmission: A Cure for the Curse of Boundary Nodes in Selfish Packet-Forwarding Wireless Networks

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* Special thanks to Zhu Han for sending me his slides.

Outline

- Overview
- Coalition games
 - Stability
 - Fairness
- Proposed protocol
- Simulation results
- Conclusions
- Discussion

Wireless Networks

Overview



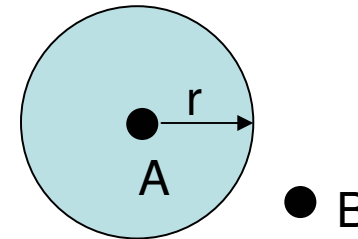
Main constraints:

(1) Limited Battery

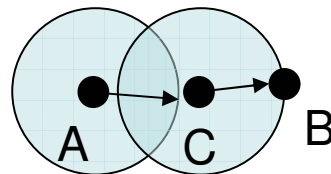


(2) Limited Transmission Range

Related Problem:
Lack of Connectivity



How to address it?
Packet Forwarding

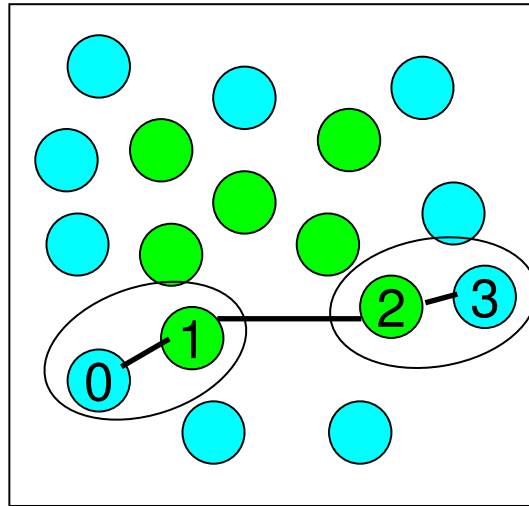


Packet Forwarding

Oblivious

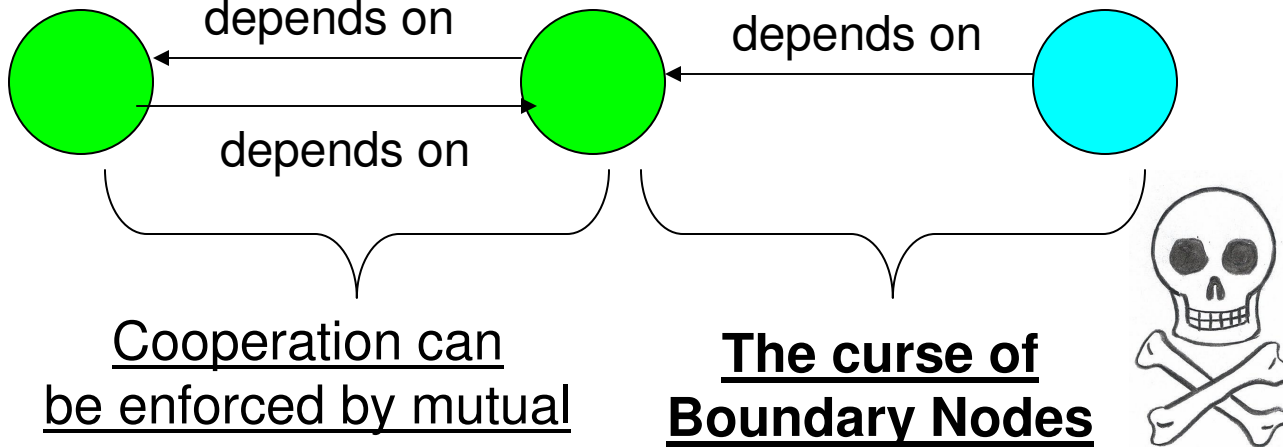
Selfishly

Game theoretical models



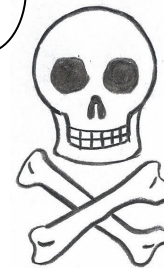
Backbone

Boundary

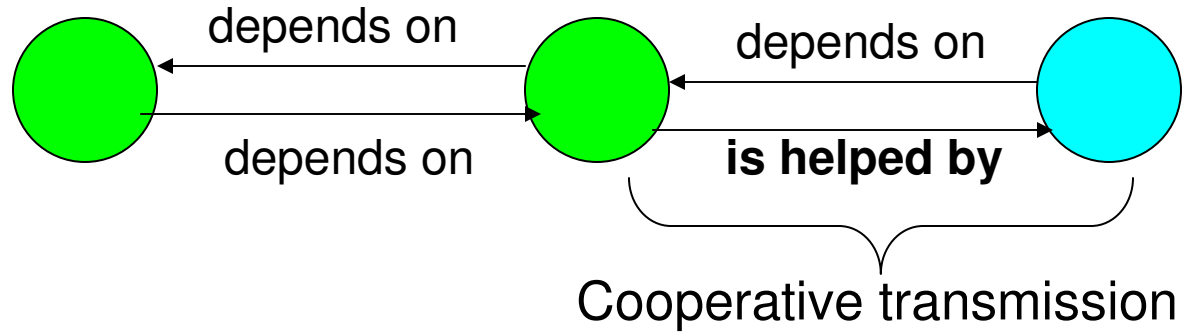


Cooperation can be enforced by mutual dependency

The curse of Boundary Nodes



How to incentivate a backbone node to forward boundary node's packets?



Key idea:



power saving



packets forwarded

Cooperative transmission System Model

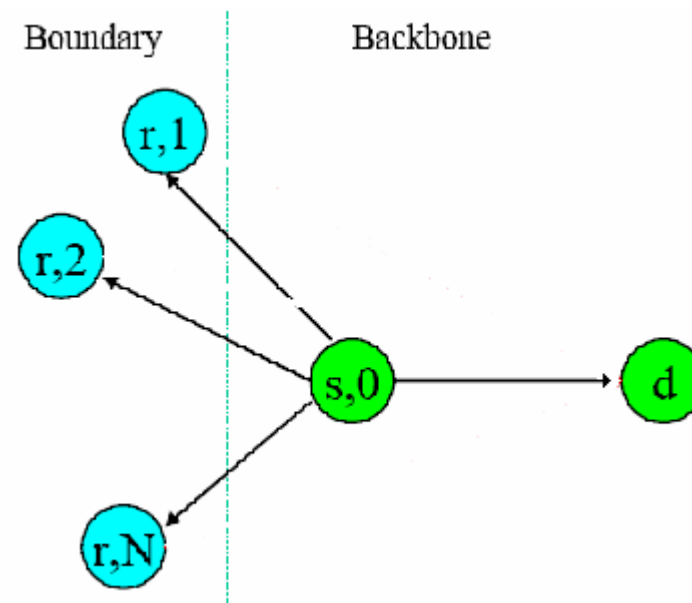
- Traditional direct transmission case

- Received SNR:

$$\Gamma_d = \frac{P_d h_{s,d}}{\sigma^2}$$

- For a successful transmission:

$$\Gamma_d > \gamma$$



Cooperative transmission System Model

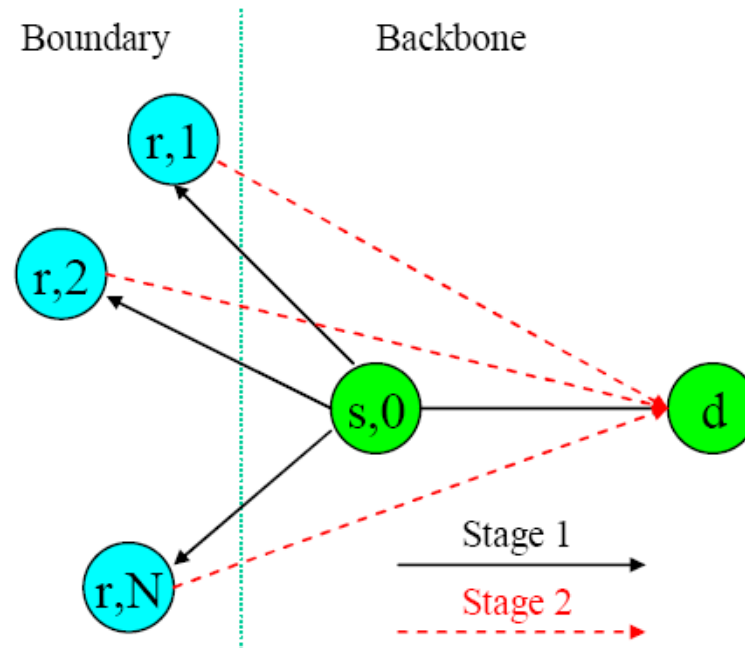
- 2-stage cooperative transmission

- Received SNR:

Assump.
$$\Gamma'_d = \Gamma_0 + \sum_{i=1}^N \Gamma_i$$

- For a successful transmission:



$$\Gamma'_d > \gamma$$



$$\Gamma'_d = \Gamma_d \quad \text{and} \quad \Gamma_i > 0 \quad \rightarrow \quad P_0 < P_d$$

Nodes will form **coalitions** to provide mutual benefits.

Measuring payoff

	Not in a coalition	In a coalition
	-P spent in direct tx.	-(P spent in coop. tx. + P spent in pkt fwd)
	$U_i = -\infty$	-P spent in coop. tx. p/ pkt forwarded

Coalition Games

- A **coalition** S is a subset of N formed by nodes which want to cooperate.
- A **coalition form of a game** is given by (N, v) , where

$$v : \{S_1, \dots, S_{2^N}\} \rightarrow \mathfrak{R}$$

is called **characteristic function** and have the following properties:

- i) $v(\{\}) = 0$
- ii) Super-additivity: if S and Z are disjoint coalitions, then

$$v(S) + v(Z) \leq v(S \cup Z)$$

- Consider that coalitions are formed by a backbone node 0 and a set of boundary nodes i , $1 \leq i \leq N$ (nodes are in each other's range)

$$v(\{0\}) = -P_d \qquad v(\{i\}) = -\infty$$

Payoff definition

- Payoff is measured in power spent per packet
- Then, the payoff can be computed by

$$U_0 = -\left(P_0 + \sum_{i=1}^N \alpha_i P_d\right)$$

$$U_i = -\frac{1}{\alpha_i} \times P_i$$

where

$$\frac{1}{\alpha_i} = \# \text{ packets coop. xmitted before being rewarded}$$

- Note that payoff allocation is determined by the vector α

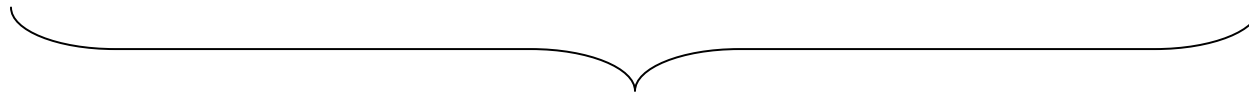
Desirable properties of the payoff allocation

Group Rational

$$\sum_{i=0}^N U_i = v(N)$$

Individually Rational

$$U_i \geq v(\{i\})$$



Imputation

Stability



Core

Fairness

Min-max using
Nucleolus

Average using
Shapley Function

Stability of an imputation

- We also want the payoff vector to be **stable** through each possible coalition, that is,

$$\sum_{i \in S} U_i \geq v(S) \quad \forall S \subseteq N$$

- The set of stable imputations is called the **core**.
- *Theorem:* The core is not empty if:

$$\sum_{i=1}^N \alpha_i \leq \frac{P_d - P_0}{P_d}$$

If the inequality holds, the **grand coalition** is formed. Why?

Min-Max fairness

- How do we choose fair values for $\alpha_i \geq 0$ according to a certain criterion?
- Let the **maximum excess** of player i over player j be defined as

$$s_{ij} = \max_S \{v(S) - \sum_{k \in S} U_k \mid S \subseteq N \setminus \{j\}, i \in S\}$$

This quantity represents the bargaining power of i over j .

- The **kernel** of v is the set of all allocations U such that either:
 - A pair of players (i,j) have the same bargaining power, or
 - Player i has more bargaining power than Player j , but $U_j = v(\{j\})$
Then Player j is immune to Player i 's threats.

Min-Max fairness

- **Nucleolus** of a game is the imputation U that minimizes the *maximum excess*.
 - Interesting properties:
 - It **always exists** and is **unique**.
 - If the core is not empty, then the nucleolus is **in the core** and **in the kernel**.
- *Theorem:* The maximal α_i to yield the nucleolus of the proposed coalition game is given by

$$\alpha_i = \frac{P_d - P_0(\mathbf{N})}{NP_d}$$

Average fairness using Shapley Function

- A Shapley function assigns to each possible characteristic function v a vector of real numbers:

$$\phi(v) = (\phi_0(v), \phi_1(v), \dots, \phi_N(v))$$

and satisfy:

- 1) *Efficiency Axiom*: $\sum_{i \in \mathbf{N}} \phi_i(v) = v(\mathbf{N})$.
- 2) *Symmetry Axiom*: If node i and node j are such that $v(S \cup \{i\}) = v(S \cup \{j\})$ for every coalition S not containing node i and node j , then $\phi_i(v) = \phi_j(v)$.
- 3) *Dummy Axiom*: If node i is such that $v(S) = v(S \cup \{i\})$ for every coalition S not containing i , then $\phi_i(v) = 0$.
- 4) *Additivity Axiom*: If u and v are characteristic functions, then $\phi(u + v) = \phi(v + u) = \phi(u) + \phi(v)$.

Average fairness using Shapley Function

- There is a unique function satisfying the Shapley axioms and it can be computed as

$$\phi_i(v) = \sum_{S \subset N-i} \frac{(|S|!(N-|S|)!}{(N+1)!} [v(S \cup \{i\}) - v(S)]$$

- Interpretation: the worth of this node.
- *Theorem:* The maximal α_i to satisfy the average fairness with the physical meaning of the Shapley function is given by

$$\alpha_i = \frac{P_i^s}{P_d}$$

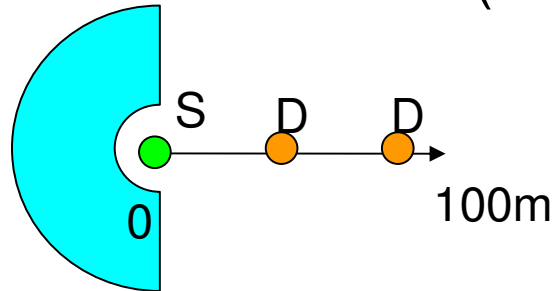
Where P_i^s is the average power saving with random entering order.

*Packet-Forwarding Protocol
using Repeated Games and
Coalition Games*

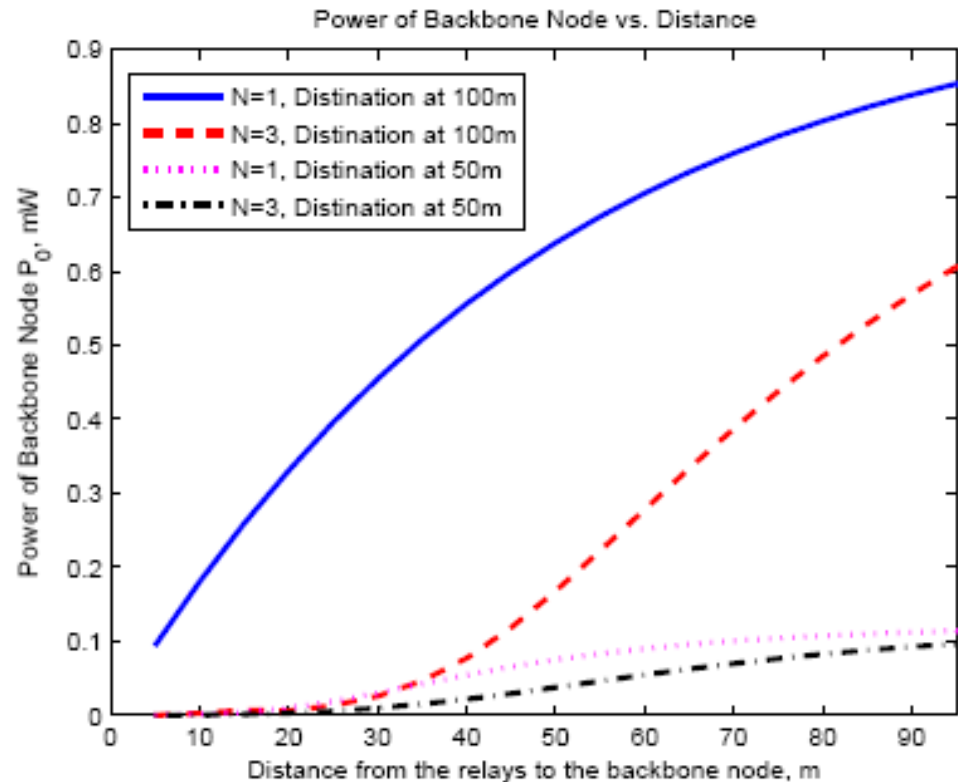
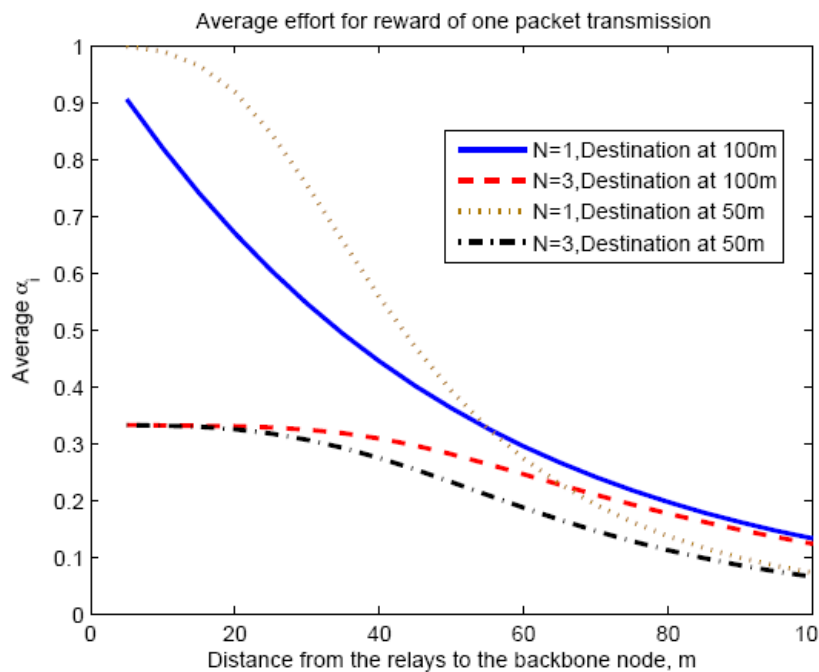
1. **Route discovery** for all nodes.
2. Packet-forwarding enforcement for the **backbone nodes**, using threat of future punishment in the **repeated games**.
3. **Neighbor discovery** for the boundary nodes.
4. **Coalition game formation**.
5. **Packet relay** for the backbone nodes with **cooperative transmission**.
6. Transmission of the boundary nodes' own packets to the backbone nodes for **forwarding**.

Simulation results (min-max fairness)

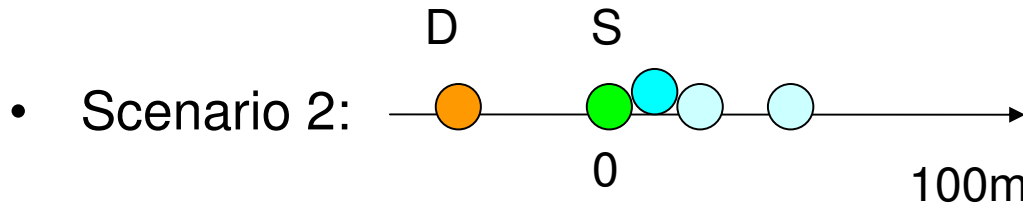
- Scenario 1:



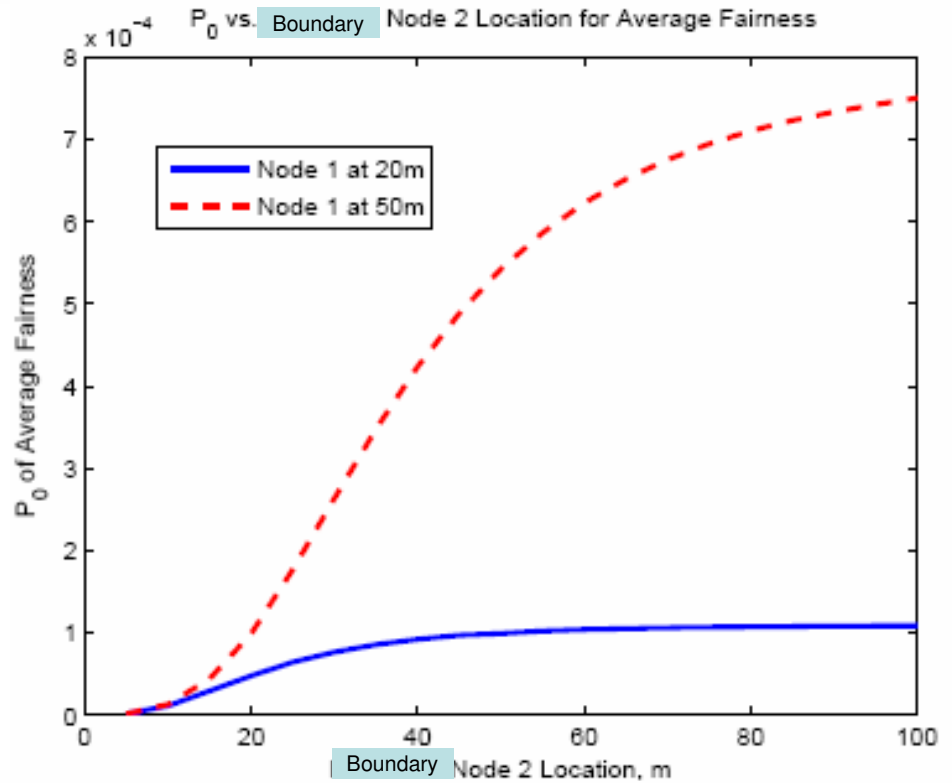
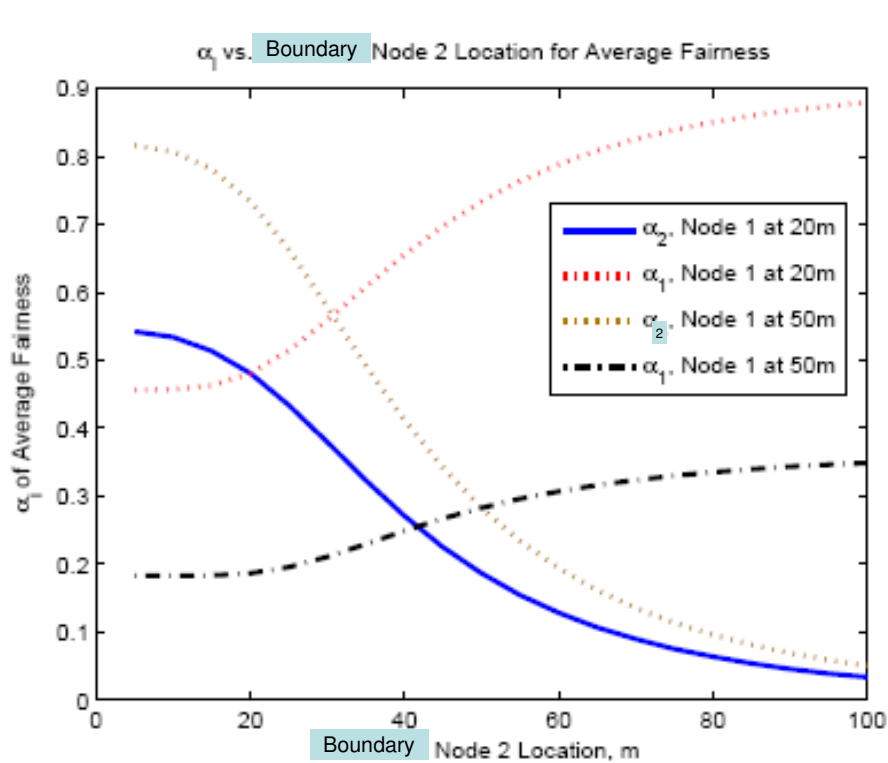
Longer the distance, less effective the boundary nodes to help backbone node, smaller α_i (more packets the boundary nodes need to transmit to get rewards).



Simulation results (average fairness)

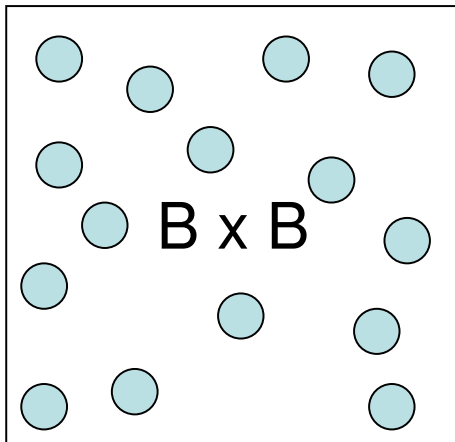


Due to different locations, the power saving by the nodes are different, so the rewards are different. (not like min-max case)

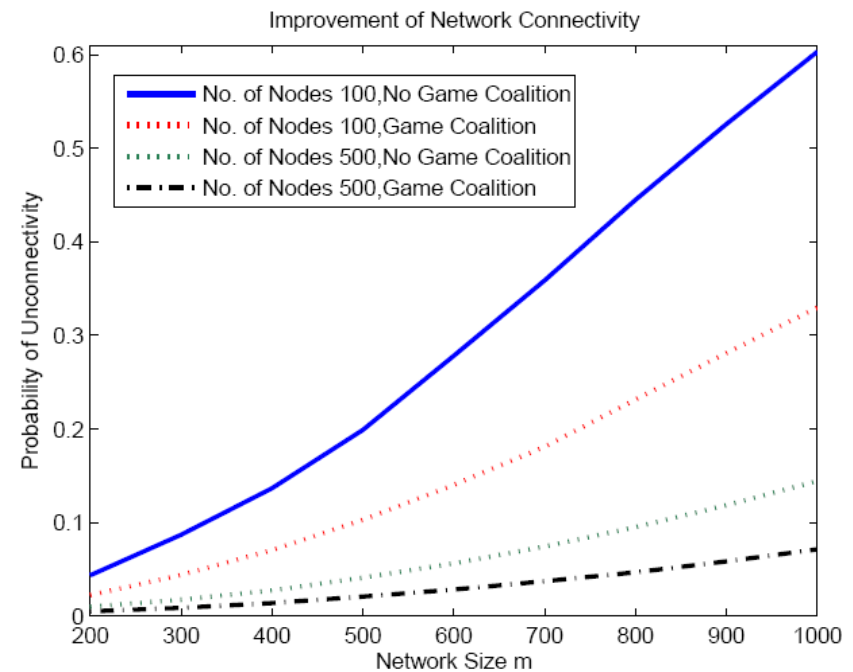


Simulation results (connectivity)

- Scenario 3:
 - $N = \{100, 500\}$



- Unconnectivity:



Conclusions

- Key idea: mutual benefit
 - Boundary nodes relay backbone node's packets to reduce the backbone node's transmission power
 - Backbone node forwards the boundary nodes' packets as rewards.
- Use of cooperative transmission
- Coalition formation is the cure for the curse of boundary nodes
- The coalitions formed by the proposed protocol are stable and fair
- Two fairness have been evaluated
 - Min-max fairness
 - Average fairness
- Network connectivity can be improved by about 50%

Discussion

1. Why not to use cooperative transmission also for forwarding boundary nodes' packets?
2. Practical issues have been left aside. How should a backbone node adaptatively adjust its transmission power? How should we compute the average power saving for adding a boundary node taking into account random entering order?
3. Will the boundary nodes run out of battery before the backbone nodes?
4. Why should a backbone to maximize α_i ?



Q&A

Backup Slides: Static Game Definition

- A **static game** $G = (P, S, U)$.
 - P is the set of **players**
 - S is the set of possible **strategies** for each player
 - U is the **utility** function for each player
 - E.g: The prisoner's dilemma

		Henry	
		Not Guilty	Guilty
Dave	Not Guilty	2 Years	5 Years, 1 Yr.
	Guilty	5 Years, 1 Yr.	3 Years

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Backup Slides: Repeated games

- **A repeated game**
 - **Payoff** is computed according to:

$$\sum_{t=1}^T \beta^{t-1} u_i(t)$$

- **Average payoff:**

$$u_i = (1 - \beta) \sum_{t=1}^T \beta^{t-1} u_i(t)$$

- The Folk Theorem