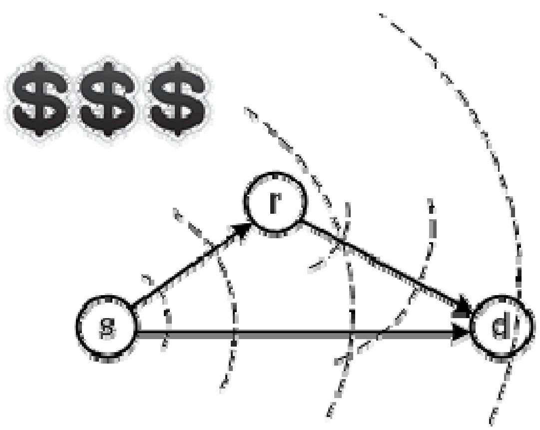
Resource Allocation in Cooperative Networks: The Rule of Games



Guoliang Xue
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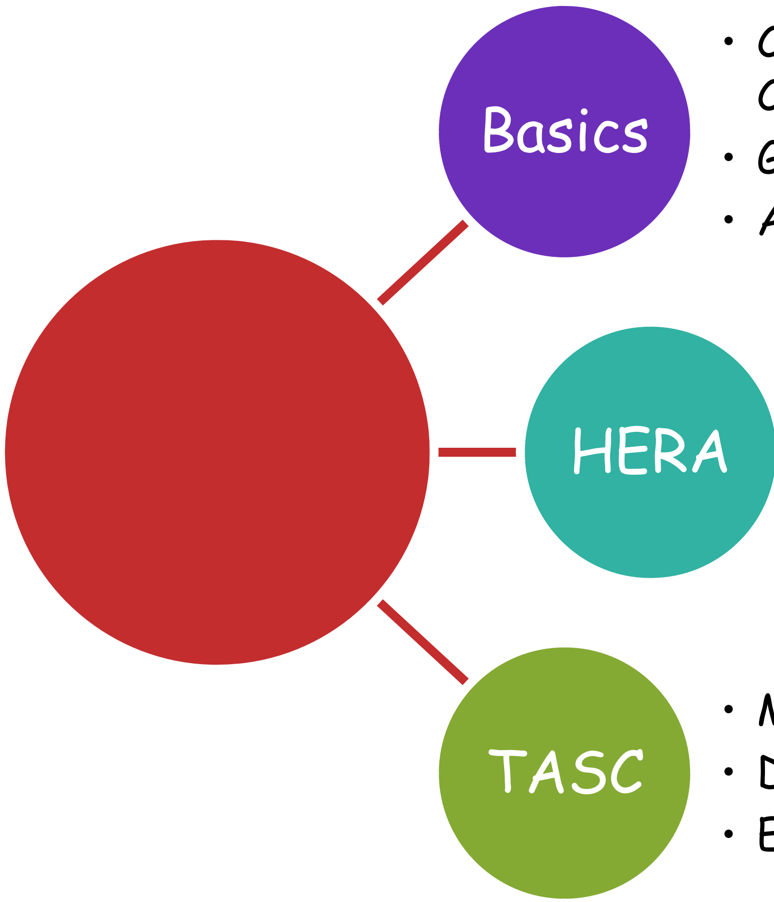
IEEE LCN'2011 Keynote
10/06/2011, Bonn, Germany

ARIZONA STATE UNIVERSITY

Outline



- Cooperative Communication
- Game Theory
- Auction Theory

- Motivation
- Optimal Assignment
- Payment of the Source Nodes
- Payment to the Relay Nodes

- Motivation
- Design
- Example

Outline

Basics
- Cooperative Communication
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HERA
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TASC
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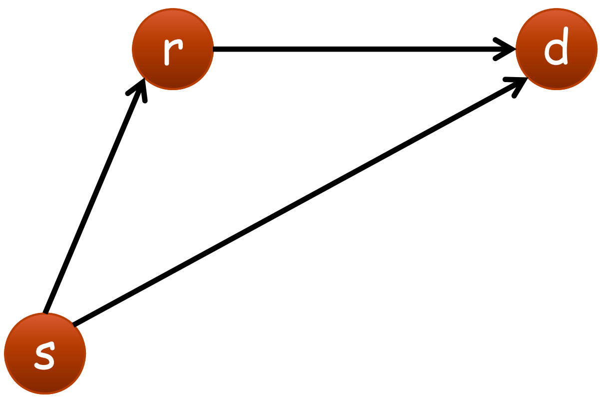
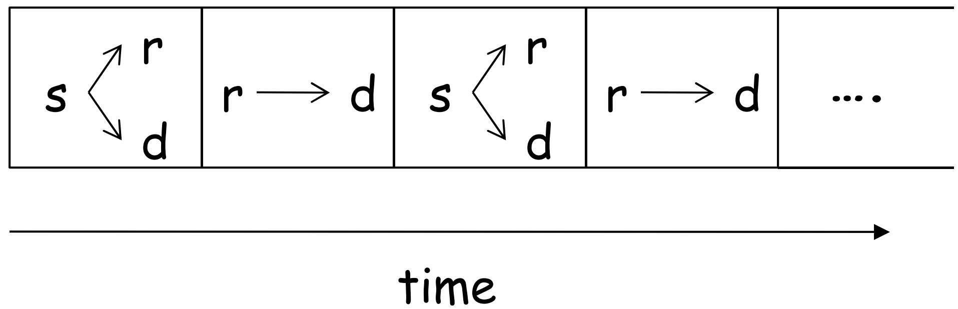
Cooperative Communication





$$C_R = f(s, r, d)$$

(x_r, y_r) and P_r

J.N. Laneman

D. Tse

G.W. Wornell

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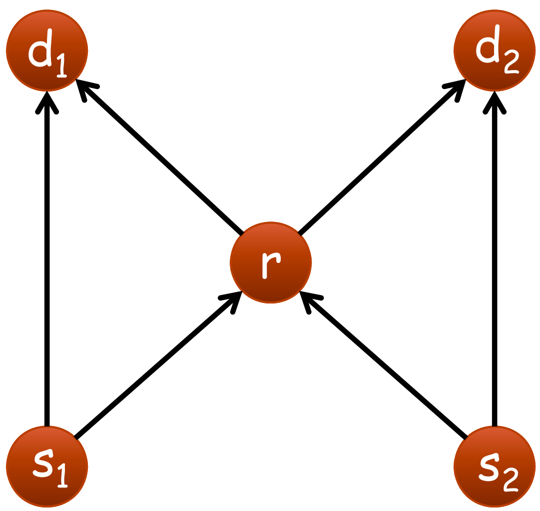
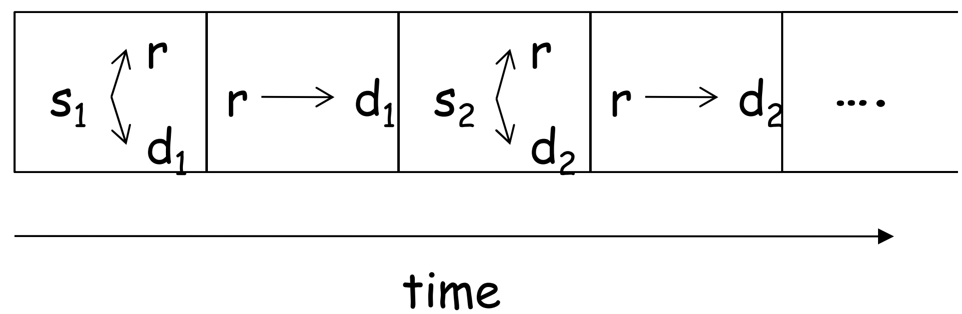
Multi-Source Cooperative Communication





$$C(s_i, r_j) = \frac{C_R(s_i, r_j)}{n_j}$$

r_j is the relay node assigned to source s_i,
n_j is the number of source nodes sharing relay node r_j

Game Theory

Player	• Entities in the game
Strategy	• Actions taken by players
Utility	• Valuation of players on the outcome of the game

Game Theory

Best Response

- The strategy which maximizes the player's utility, when other players' strategies are given

Nash Equilibrium

- Every player is playing its best response.

Strongly Dominant Strategy

- Every player is playing a strategy which produces a larger utility than any other strategy, regardless of other players' strategies

Auction Theory

Buyer	• Bidder buying service
Seller	• Bidder selling service
Bid	• Price provided by a buyer
Ask	• Price provided by a seller
Valuation	• True price that a bidder wants to bid or ask

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System Model

- *n* source-destination pairs, denoted by *S*
- *m* relay nodes, denote by *R*
- Each source-destination pair is assigned at most ONE relay node [Zhao et al. ISIT'06]
- Single radio
- Half duplex
- Interference: enough orthogonal channels

Challenges

System Performance

- Capacity depends on the relay assignment

Selfishness

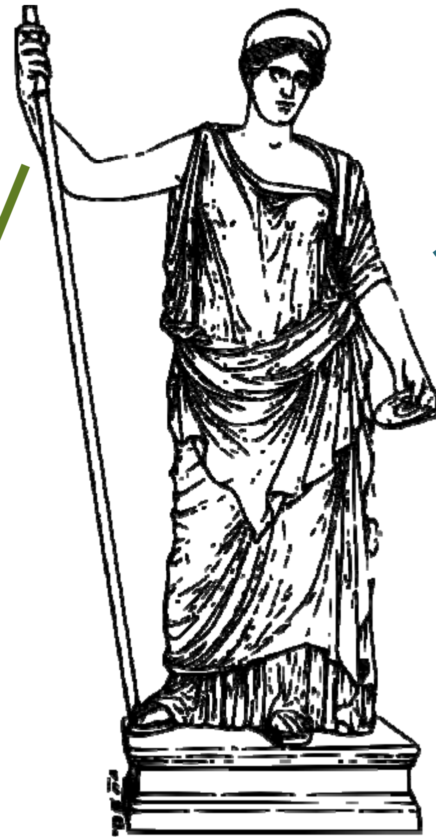
- Wireless devices belong to independent entities
- Source nodes select relays solely to maximize their own utility

Cheating

- Relay assignment is based on the reported power from relay nodes
- Relay nodes can rig the assignment

HERA: An Integrated Optimal Relay Assignment Scheme

Selfish users converging to the optimal assignment



HERA

Selfish users being honest

Budget-balanced

Dejun Yang, Xi Fang, and Guoliang Xue; HERA: An Optimal Relay Assignment Scheme for Cooperative Networks; accepted for publication in *IEEE Journal on Selected Areas in Communications* , 2011

Related Work

- Relay assignment to maximize the minimum capacity [Shi *et al.* Mobihoc'08]
  - **A different objective**
  - **A constrained model**
- Relay assignment to maximize the total capacity [Zhang *et al.* WCNC'09]
  - **The same objective**
  - **A constrained model**

Related Work

- Resource trade between source nodes and relay nodes [Wang *et al.* TMC’09, Huang *et al.* JSAC’08, and Zhang *et al.* ETRI’09]
  - No system performance guarantee
  - Only consider selfish behavior, not cheating behavior

Motivating Example

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	10	7	6	6	8
r_2	4	8	4	10	9

Total Capacity = 17

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	10	7	6	6	8
r_2	4	8	4	10	9

Total Capacity = 20

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	10	7	6	6	8
r_2	4	8	4	10	9

Total Capacity = 22.5

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	10	7	6	6	8
r_2	4	8	4	10	9

Total Capacity = 24

Local Optimum vs. Global Optimum

Local Optimum

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	10	7	6	6	8
r_2	4	8	4	10	9

Total Capacity = 24

vs.

Global Optimum

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	10	7	6	6	8
r_2	4	8	4	10	9

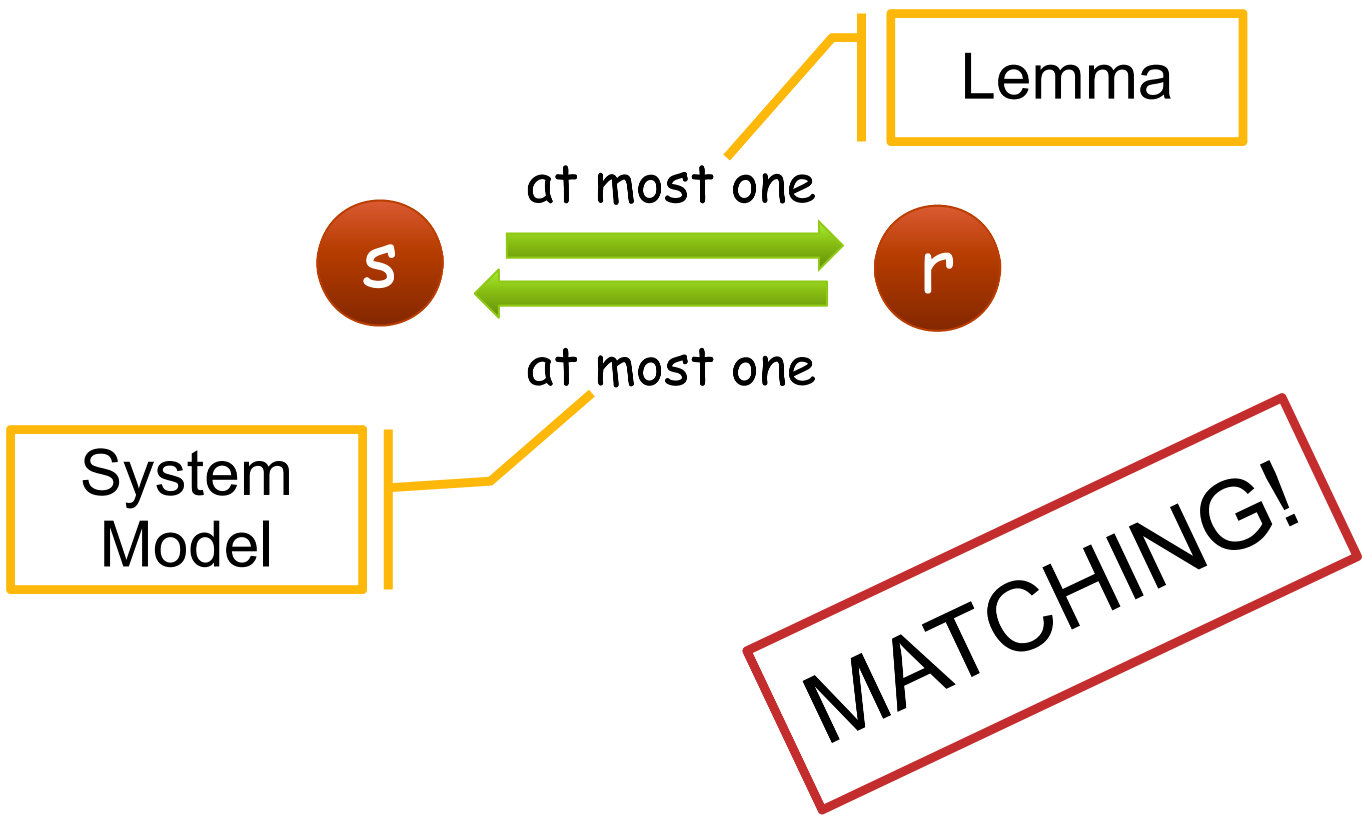
Total Capacity = 25

Key Observation

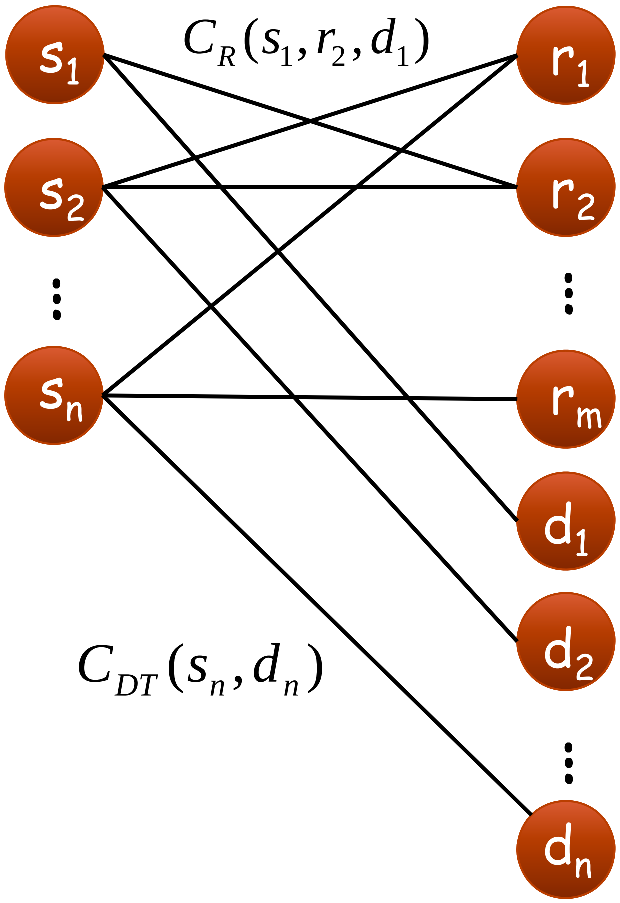
LEMMA: If a relay node is shared by multiple source nodes, let s_i be the source node with the minimum capacity. Making s_i transmit to d_i directly can

increase the total capacity.

What the Lemma Implies



Optimal Relay Assignment



- Construct a bipartite graph
- Construct nodes corresponding to source nodes
- Construct nodes corresponding to relay nodes
- Construct nodes corresponding to destination nodes
- Set weight on the source-relay edge as the achievable capacity of CC
- Set weight on the source-dest edge as the capacity of DT
- Find the maximum weighted matching
- Assign relays according to the matching

Source Nodes Are Selfish

Global Optimum

	s_1	s_2	s_3	s_4	s_5
r_0	**4**	**2**	**1**	3	1
r_1	10	7	6	6	**8**
r_2	4	8	4	**10**	9

Total Capacity = 25

	s_1	s_2	s_3	s_4	s_5
r_0	4	**2**	**1**	3	1
r_1	**10**	7	6	6	**8**
r_2	4	8	4	**10**	9

Total Capacity = 22

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	**1**	3	1
r_1	**10**	7	6	6	**8**
r_2	4	**8**	4	**10**	9

Total Capacity = 19

Nash Equilibrium

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	**10**	7	**6**	6	8
r_2	4	**8**	4	**10**	**9**

Total Capacity = 17

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	**10**	7	**6**	6	8
r_2	4	**8**	4	**10**	**9**

Total Capacity = 17

	s_1	s_2	s_3	s_4	s_5
r_0	4	2	1	3	1
r_1	**10**	7	**6**	6	**8**
r_2	4	**8**	4	**10**	9

Total Capacity = 17

How Bad is Selfish Selection

	s_1	s_2	s_3	•••	s_{n-1}	s_n
r_0	1	1	1	•••	1	1
r_1	10	1	1	•••	1	5
r_2	5	10	1	•••	1	1
r_3	1	5	10	•••	1	1
r_4	1	1	5	•••	1	1
⋮	⋮	⋮	⋮	•	⋮	⋮
r_{n-1}	1	1	1	5	10	1
r_n	1	1	1	•••	5	10

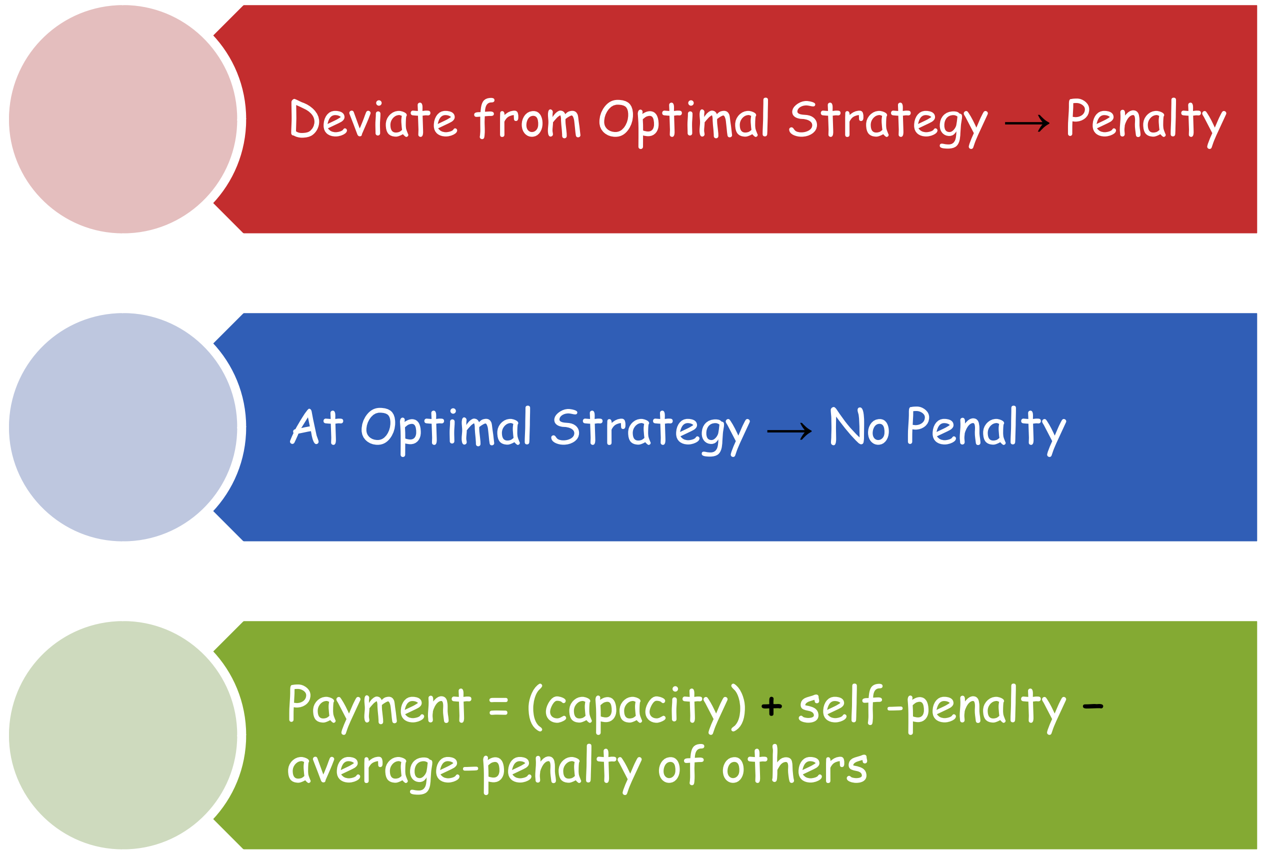
NE

	s_1	s_2	s_3	•••	s_{n-1}	s_n
r_0	1	1	1	•••	1	1
r_1	10	1	1	•••	1	5
r_2	5	10	1	•••	1	1
r_3	1	5	10	•••	1	1
r_4	1	1	5	•••	1	1
⋮	⋮	⋮	⋮	•	⋮	⋮
r_{n-1}	1	1	1	5	10	1
r_n	1	1	1	•••	5	10

OPT

$$\frac{C(NE)}{C(OPT)} = \frac{5n}{10n} = \frac{1}{2}$$

Mechanism to Induce the Selfish Players



Payment of the Source Nodes

$$p_i^s = \begin{cases} C(s_i, \gamma_i) + \left(g(\gamma_i, \gamma_i^*) - \frac{1}{n-1} \sum_{k \neq i} g(\gamma_k, \gamma_k^*) \right), & \text{if } \gamma_i \neq r_0, \\ g(\gamma_i, \gamma_i^*) - \frac{1}{n-1} \sum_{k \neq i} g(\gamma_k, \gamma_k^*), & \text{if } \gamma_i = r_0, \end{cases}$$

$$g(\gamma_i, \gamma_i^*) = l \cdot |x - y|,$$

where $\gamma_i = r_x, \gamma_i^* = r_y, l = \max_{s_i \in S} C_{DT}(s_i) + \varepsilon$, and $\varepsilon > 0$.

Convergence to the Optimal Assignment

THEOREM: The optimal relay assignment **IS** the unique Strongly Dominate Strategy Equilibrium (SDSE)

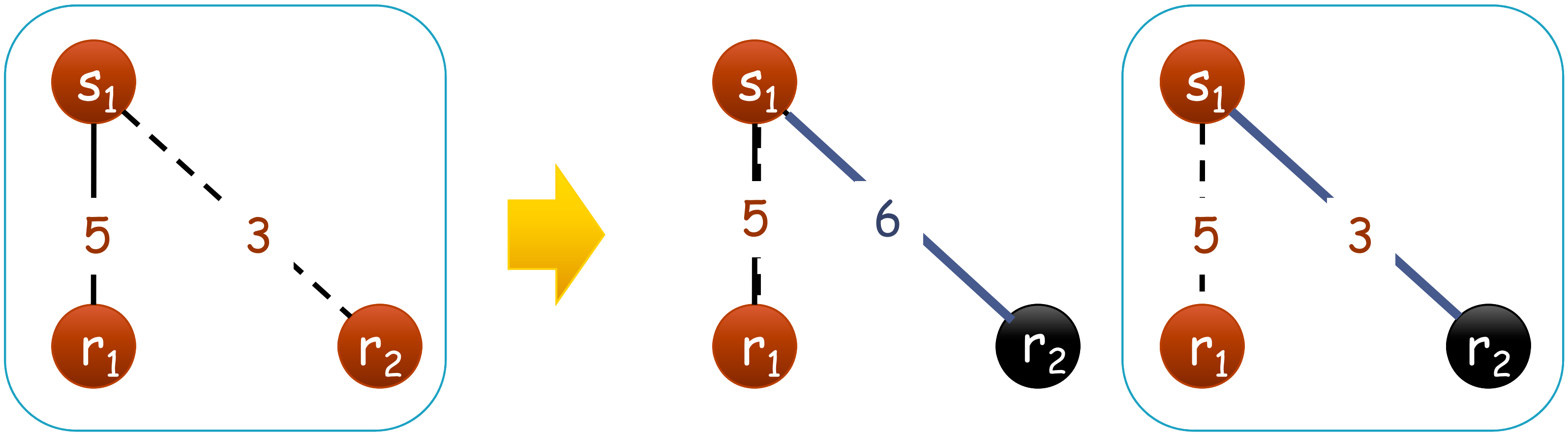
Incentive for Relay Nodes

Problem: Relay Nodes relay data at the cost of their own resource

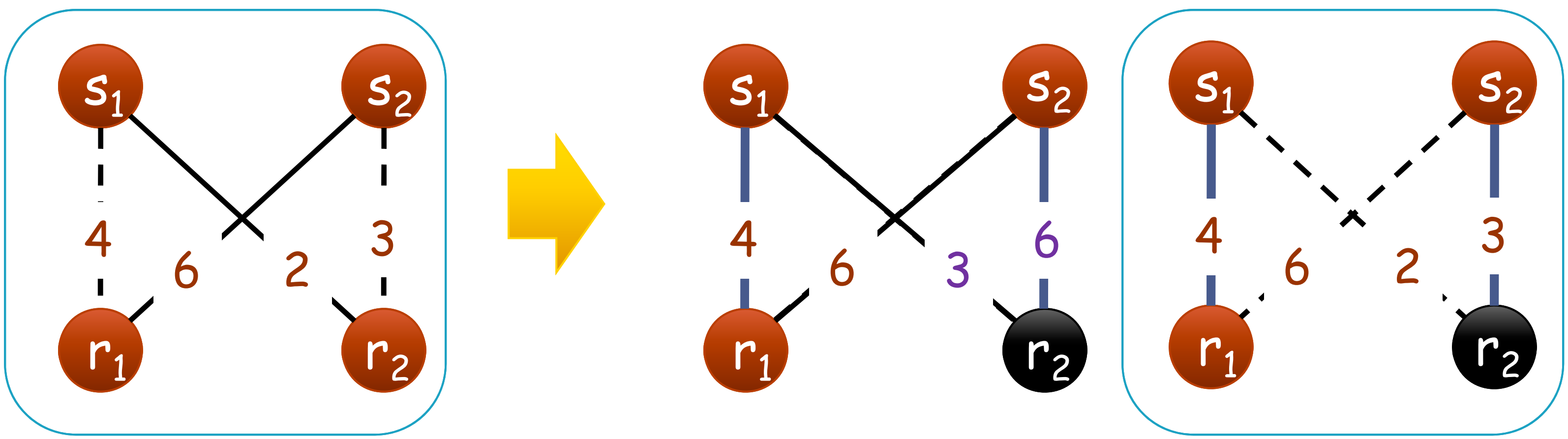
A simple solution: Pay them the amount of the achieved capacity by cooperative communication

Not work! Relay nodes can cheat!

Why Cheating Matters



The actual total capacity decreases from 5 to 3



The actual total capacity decreases from 8 to 7

Mechanism to Ensure Truthfulness

VCG-based payment: Each winning bidder receives the payment, which is equal to the actual achievable capacity subtracted by the *opportunity cost* that its presence introduces to all the other bidders.

Payment to the Relay Nodes

$$p_j^r = \begin{cases} 0, & \sigma_{\mathrm{j}} = s_0, \\ C(\sigma_{\mathrm{j}}, r_j) - \left(\Psi(S, R \setminus \{r_j\}) - \Psi(S \setminus \{\sigma_{\mathrm{j}}\}, R \setminus \{r_j\})\right), & \text{otherwise} \end{cases}$$

where σ_j is the source node r_j is assigned to, and $\Psi(S, R)$ is the system capacity of the network consisting of S and R.

HERA

Relay nodes report their power

↓

Source nodes select relay nodes

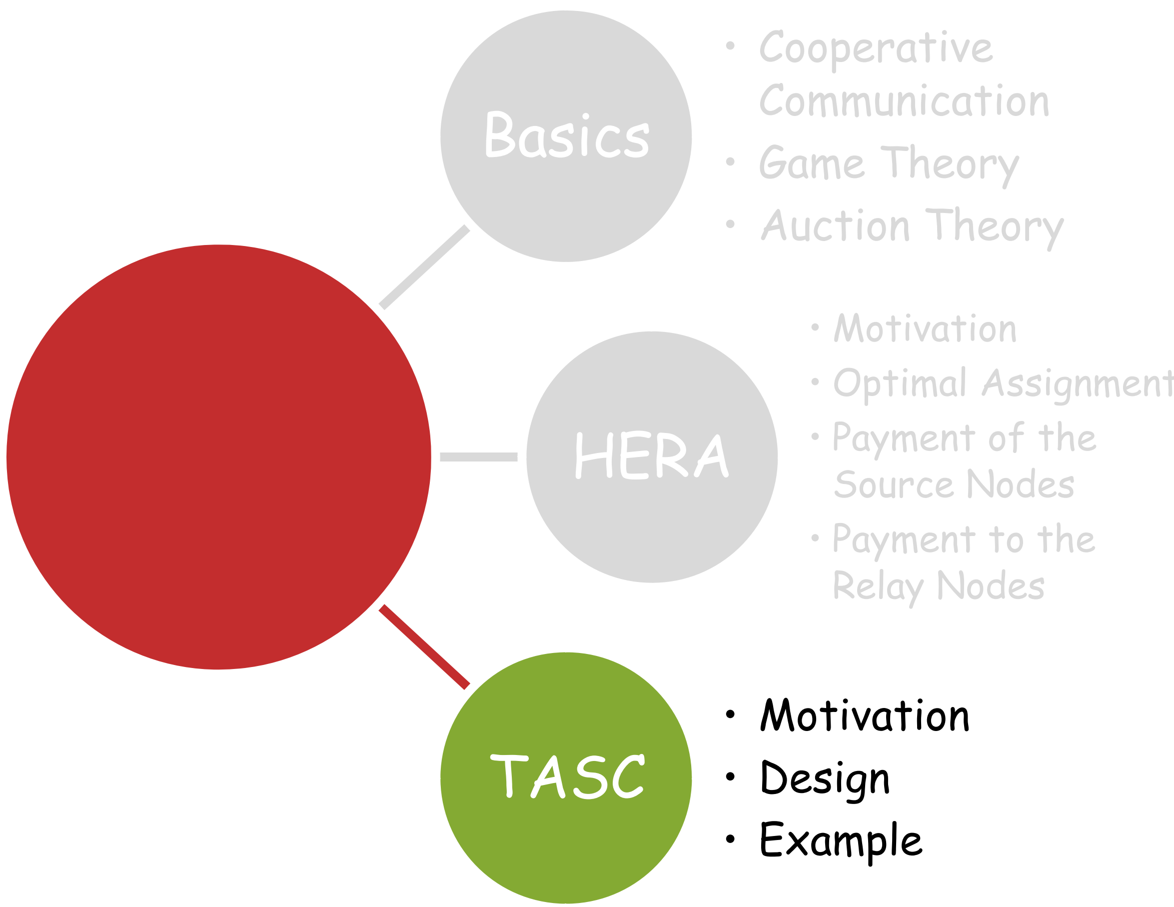
↓

Administrator charges source nodes and pays relay nodes

Wrap Up of Part II

- We designed HERA, an integrated optimal relay assignment scheme
- HERA induces selfish source nodes to converge to the optimal assignment
- HERA prevents relay nodes from cheating on their power
- HERA is budget-balanced

Outline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Motivation

Capacity demand continually grows in wireless networks

- E.g. Cellular networks

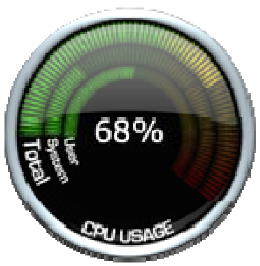
A significant amount of money has been spent on capacity enhancement

- E.g. AT&T spent approximately 19 billion dollars in 2010

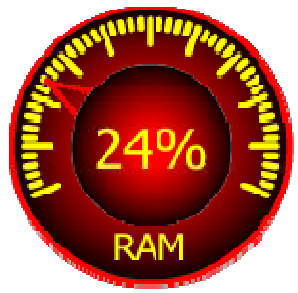
Motivation

Why Auction

Relay node consumes its own resources.



CPU



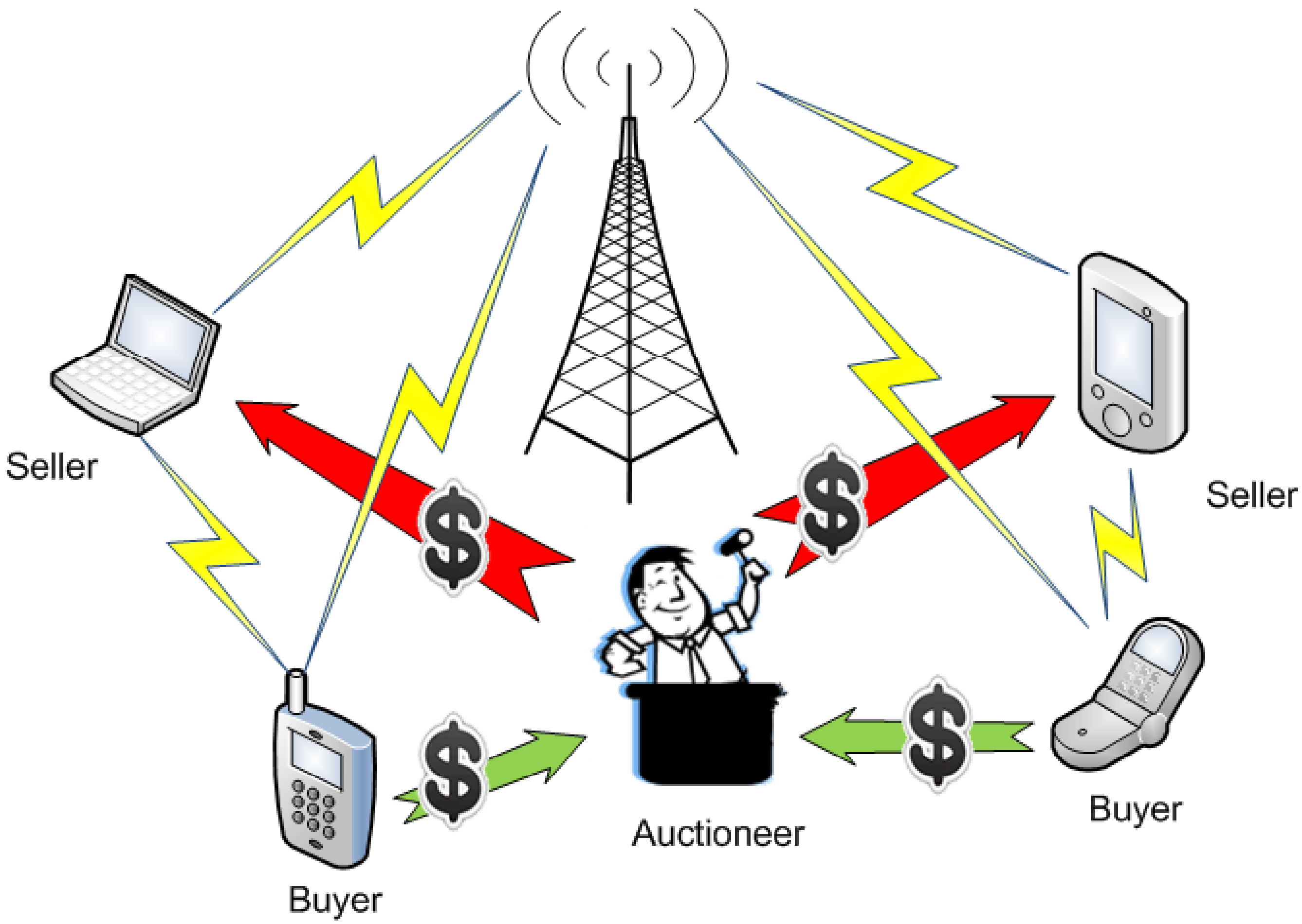
Memory

Power

What is Auction

- WIKIPEDIA The Free Encyclopedia : An auction is a process of buying and selling goods or services by offering them up for bid, taking bids, and then selling the item to the highest bidder. In economic theory, an auction may refer to any mechanism or set of trading rules for exchange.

Cooperative Communication Auction



Auction Formulation

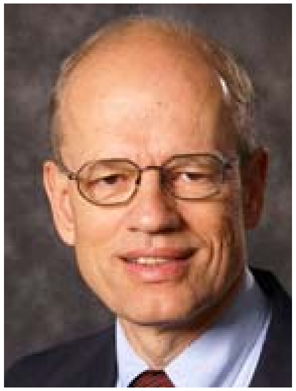
	Source Node	Relay Node
Bidder	Buyer	Seller
Private Type	Achievable Capacity (V_{ij})	Resource Consumption (C_j)
Utility	$V_{ij} - P_i^b$	$P_j^s - C_j$

Desirable Economic Properties

- Individual Rationality
- Budget Balance
- Truthfulness
- System Efficiency

Impossible to satisfy **ALL** four properties.

R. Myerson



M. Satterthwaite

TASC

Truthful

Auction

Scheme for

Cooperative Communications

- Individual rational, budget balanced and truthful
- Allow the auctioneer to choose different allocation algorithms

Dejun Yang, Xi Fang, and Guoliang Xue; Truthful Auction for Cooperative Communications; ACM MOBIHOC 2011.

Challenges of Designing a Cooperative Communication Auction

Double auction

- Consider both buyers and sellers

Multiple heterogeneous items

- Each buyer has preference on different sellers

Little theoretical support

- Neither Computer Science society nor Economic society
- VCG double auction does not work

Existing Work

Existing Work	Heterogeneous Item	Double Auction	Truthful
Demange et al. *Journal of Political Economy 1986*	✓	✗	✓
Plott and Gray *Journal of Economic Behavior & Organization 1990*	✗	✓	✗
McAfee *Journal of Economic Theory 1992*	✗	✓	✓
Babaioff and Nisan *EC 2001*	✗	✓	✓
Parkes et al. *IJCAI 2001*	✓	✓	✗
Deshmukh et al. *ESA 2002*	✓	✓	✗
Huang et al. *Computational Intelligence 2002*	✗	✓	✓
Ausubel *The American Economic Review 2006*	✓	✗	–
Mishra and Garg *Journal of Mathematical Economics 2006*	✓	✗	–
TASC	✓	✓	✓

TASC: Overview

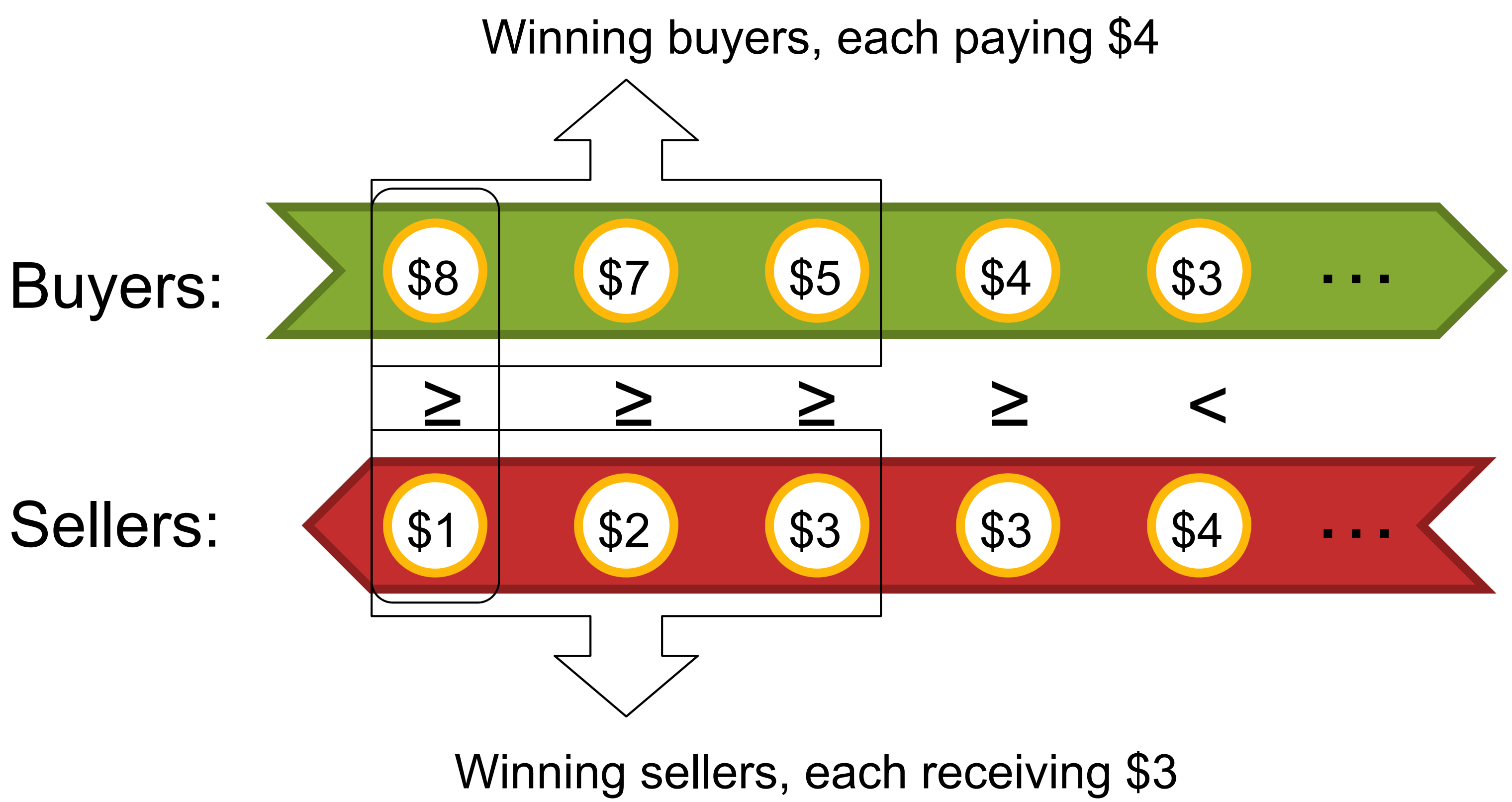
Bid/Ask-independent assignment

- Achieve the truthfulness

Based on McAfee double auction

- Achieve all three economic properties while enabling multi-item auction

McAfee Double Auction



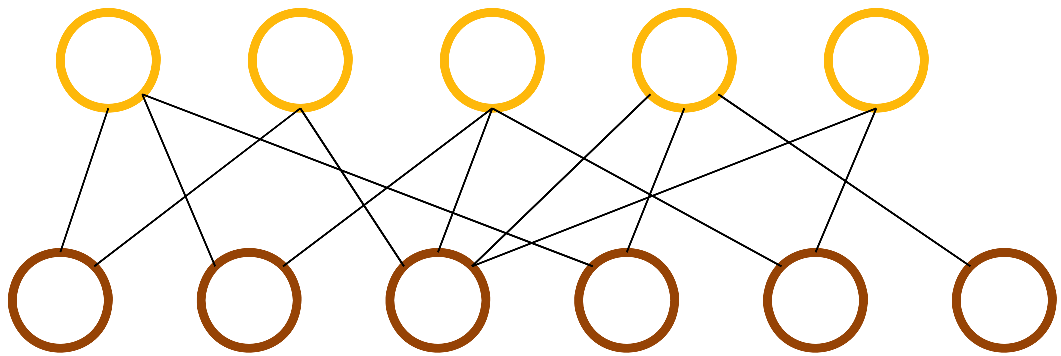
TASC: Design

Relay Assignment

Winner Determination

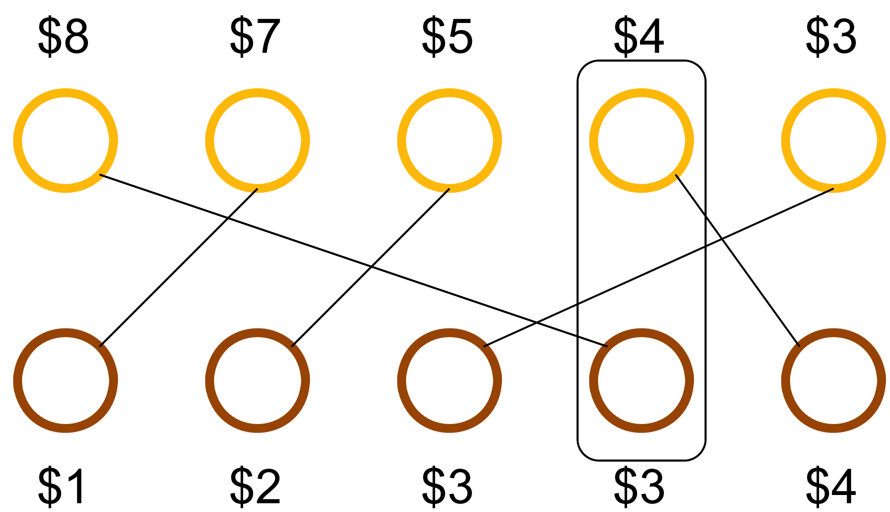
Pricing

- Construct the bipartite graph
- Apply bid/ask-independent relay assignment algorithms



TASC: Design

- Apply McAfee auction



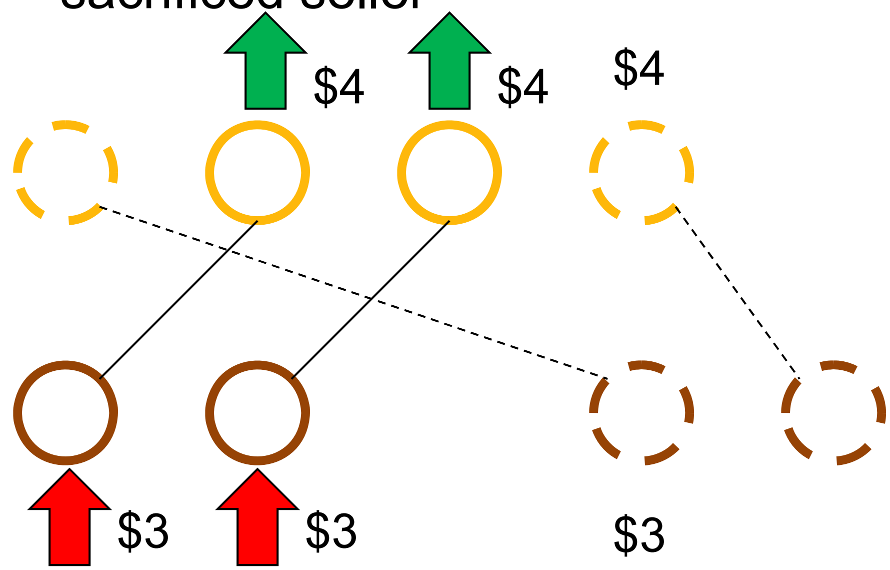
TASC: Design

Relay Assignment

Winner Determination

Pricing

- Charge the buyers the bid of the sacrificed buyer
- Pay the sellers the ask of the sacrificed seller



TASC: Example

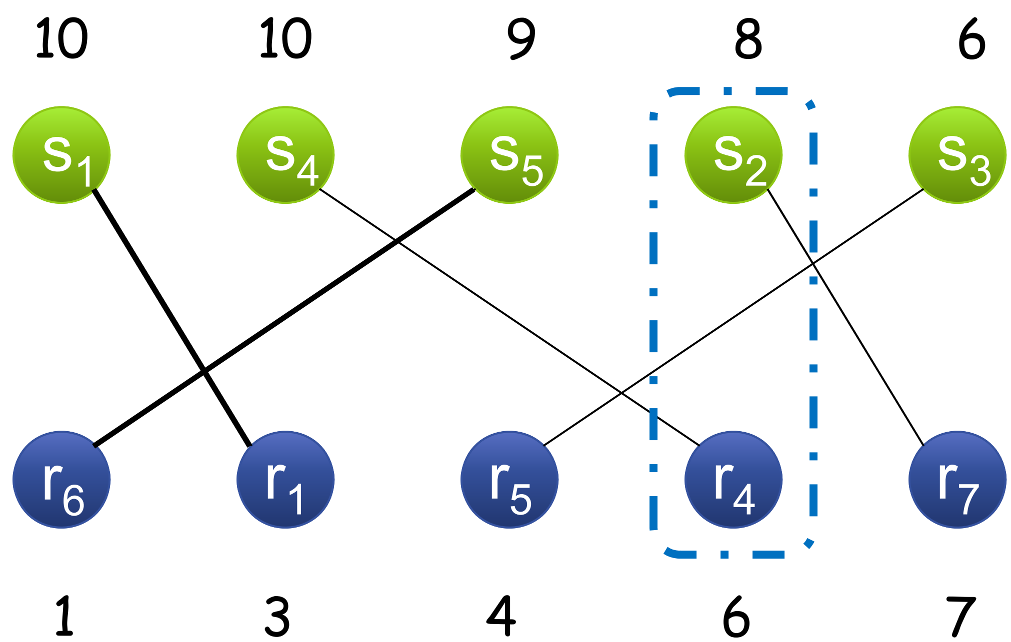
	r_1	r_2	r_3	r_4	r_5	r_6	r_7
s_1	10	4	4	0	0	0	0
s_2	0	0	7	3	4	0	8
s_3	7	0	0	4	6	0	0
s_4	0	6	0	10	4	6	0
s_5	0	0	8	0	0	9	4

Capacity (Bid)

seller	r_1	r_2	r_3	r_4	r_5	r_6	r_7
ask	3	2	5	6	4	1	7

Ask

TASC: Example



- Winning buyer-seller pairs: (s_1, r_1) and (s_5, r_6)
- Each Winning buyer pays 8 and each winning sellers receives 6
- Auctioneer’s profit is 2*(8-6) = 4

Properties of TASC

TASC is individual rational

TASC is truthful

TASC is budget-balanced

Any bid-independent allocation algorithm can be applied

Conclusions

Game theory is an appropriate tool to analyze the network with independent individuals belonging to different entities

Game theory helps with the resource allocation in cooperative networks

Auction theory provides incentives to the individuals to participate in cooperative communication

Acknowledgment

- Results presented are joint work with my students:
  - Dejun Yang
  - Xi Fang

Challenges

- Utility function selection
- Existence and uniqueness of NE
- Computation of NE
- Efficiency of NE
- System efficiency in mechanism design

Q&A