Bargain-based Stimulation Mechanism for Selfish Mobile Nodes in Participatory Sensing Network

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INTRODUCTION

- This work centers on the Participatory Sensing Network (PSN)
  - PSN consists of mobile devices to enable public and professional users to gather, analyze and share local knowledge
- Several well-known sensing tasks of PSN

Neighborhood Walkability task

Personal Environmental Impact Report (PEIR)

Diet Sense task

INTRODUCTION

- The participants in PSN can be either voluntary or stimulated by certain reward programs.
  - We focus on the latter in this research
- The objective of this work is to design an efficient scheme for selfish nodes to maximize their reward.
- Assumption: node is rational and doesn’t cheat

Network Architecture

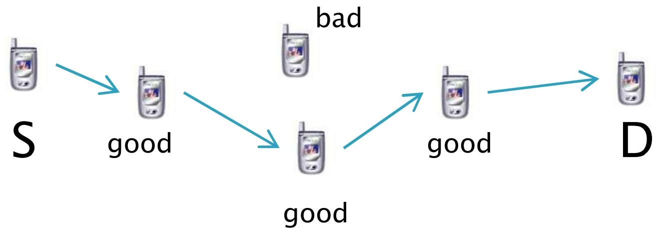
- A PSN consists of mobile sensors and sinks
  - Low power radio is employed.
  - The connectivity of PSN is low and intermittent, like the delay tolerant network (DTN).
  - Sinks deliver data to end users.
- A PSN can support various sensing tasks
  - Each sensing task consists of a sink node and multiple mobile nodes
- Each task has a unique message type, and its sink node is identified by this message type
  - One mobile node can participate in multiple sensing tasks simultaneously
- Each data message has two information fields:
  - Message type
  - Message sequence number

Network Architecture

- Sink accepts data messages from mobile nodes, if:
  - The message matches sink's type
  - The message sequence number indicated that this message has not been received before
- sink node rewards the mobile node with one credit unit if it receive one message from mobile node
  - The mobile node that delivers the message to the sink is the only beneficiary of the reward, even it is not the message generator
- The mobile node has limited buffer size
  - We assume all messages have approximately the same size.
- Transmission of a message costs one unit of energy.

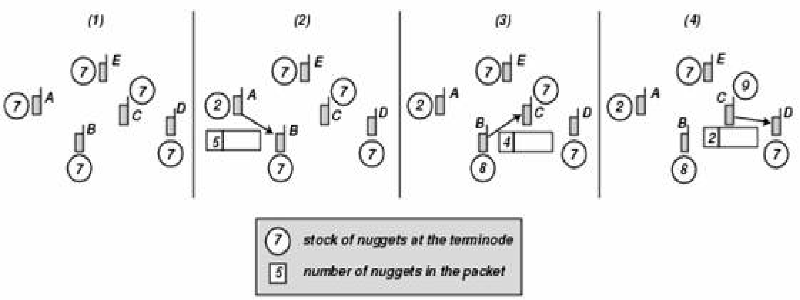
Related Work and Challenges

- Two types of stimulation schemes for selfish ad hoc networks
  - Reputation-based scheme

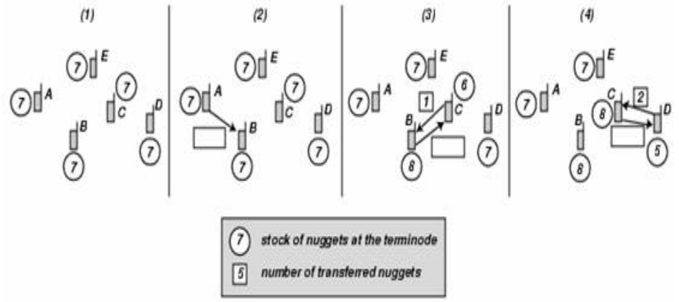


  - Credit-based scheme

Packet purse scheme



Packet trade scheme

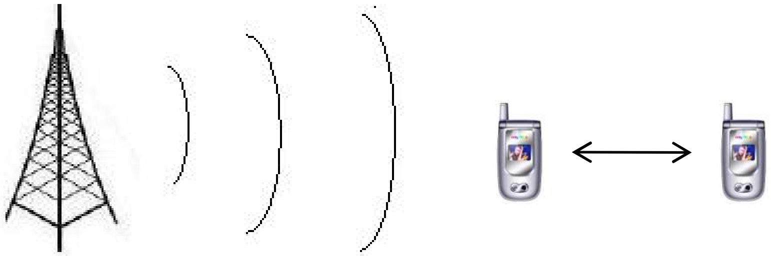


Related Work and Challenges

- Challenges
  - reputation-based scheme
    - Unrealistic for a node to monitor reputations of its neighbor nodes due to the intermittent connection
  - packet purse approach
    - Difficult for the source node to estimate the number of intermediate nodes
  - Packet trade approach
    - Intermediate nodes cannot accurately determine the value of the data packets since sender usually still keeps a copy of the data in PSN, a DTN-like network

Related Work and Challenges

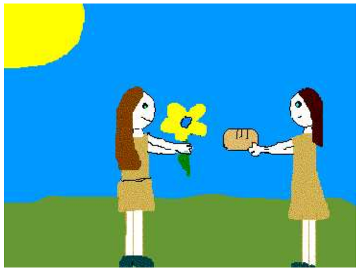
- Barter-based stimulation scheme for selfish DTN
  - A stationary source node broadcasts messages without repetition
  - Message types: primary message, secondary message
  - If a node misses any primary message from the source node, it can barter its secondary messages for primary messages with an encountered node
  - Considers downlink broadcasting scenario in DTN, instead of the more common scenario of transmissions from various mobile nodes to one or multiple sink nodes



Contributions

- A bargain-based stimulation mechanism is proposed for PSN
  - Credit is adopted for stimulating cooperation

  - Intermediate nodes exchange messages based on the estimated values of data messages



  - A game theory model is developed to address the bargain process

PRELIMINARIES

- $\mathcal{P}_i(r)$ Node i's **contact probability** with the sink node of type r

$$\mathcal{P}_i(r) = \begin{cases} \alpha[\mathcal{P}_i(r)] + (1-\alpha), & \mathit{at\ contact\ time} \\ \alpha[\mathcal{P}_i(r)], & \mathit{no\ contact\ in}\ \Delta \end{cases}$$

- $\mathcal{A}_i^m(r)$ **Message appraisal** of message m (type r) at node i
  - Ranges from 0 to 1
  - Indicates the probability that nodes except node i have not delivered any copy of this message m to the sink node r.

$$\begin{cases} \mathcal{A}_i^m(r) = [\mathcal{A}_i^m(r)](1-\mathcal{P}_j(r)) & \mathit{sender} \\ \mathcal{A}_j^m(r) = [\mathcal{A}_i^m(r)](1-\mathcal{P}_i(r)) & \mathit{receiver} \end{cases}$$

- $\mathcal{R}_i^m(r)$ **Expected credit reward** of delivering message m to type r sink by node i

$$\mathcal{R}_i^m(r) = \mathcal{A}_i^m(r) \times \mathcal{P}_i(r)$$

PRELIMINARIES

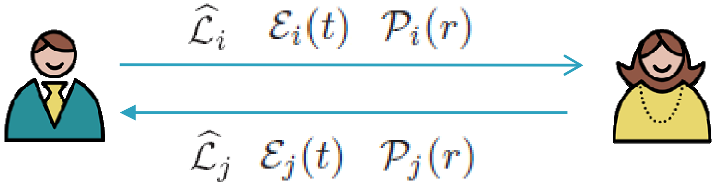
- $\mathcal{S}_i$ Utility Function of node i

$$\begin{aligned} \max \quad & \mathcal{S}_i = \sum_{r=1}^{R} \Big(\sum_{m \in \phi(r)} \mathcal{R}_i^m(r) - \sum_{m \in \psi(r)} \mathcal{R}_i^m(r) \Big) \\ w.r.t. \quad & 0 \leq l \leq \mathcal{E}_i(t), \end{aligned}$$

  - Node i wants to maximize its utility function should message exchange happen
  - R is the total number of message types
  - $\phi(r)$ and $\psi(r)$ are sets of type r messages after and before exchange, respectively
  - l is the number of messages sent by node i
  - $\mathcal{E}_i(t)$ is the total energy of node i at time t before exchange

BARGAIN-BASED STIMULATION MECHANISM

- Exchange control information, including complete list $\widehat{\mathcal{L}}_i$, $\widehat{\mathcal{L}}_j$

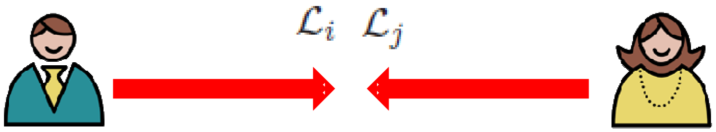


- Generate candidate list

$$\widetilde{\mathcal{L}}_i = \widehat{\mathcal{L}}_j - (\widehat{\mathcal{L}}_i \bigcap \widehat{\mathcal{L}}_j) \qquad \widetilde{\mathcal{L}}_j = \widehat{\mathcal{L}}_i - (\widehat{\mathcal{L}}_i \bigcap \widehat{\mathcal{L}}_j)$$

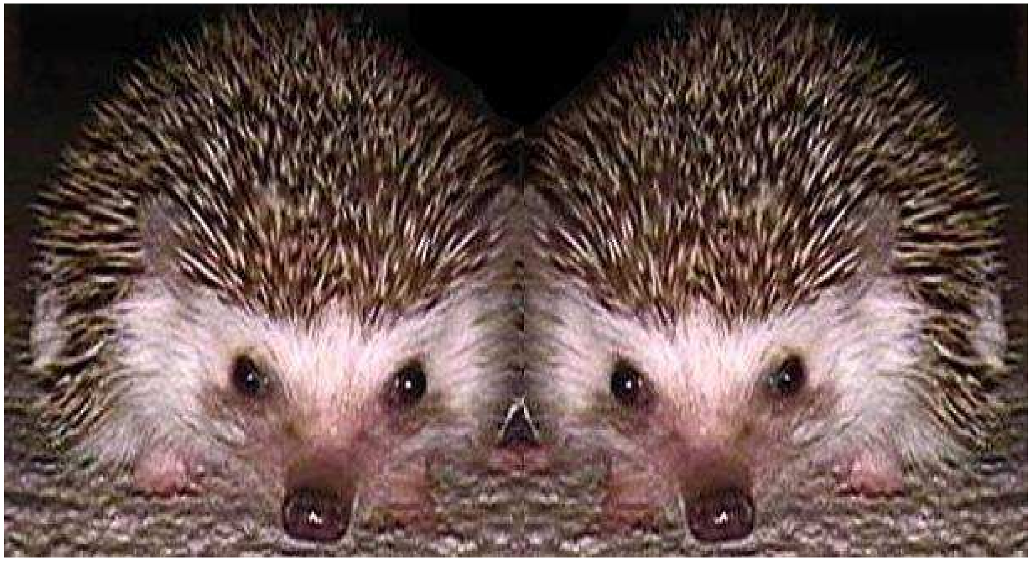
  - Optional action: node i removes messages of type r from $\widetilde{\mathcal{L}}_i$ if Pi(r) < Pj(r); similarly node j removes messages of type r from $\widetilde{\mathcal{L}}_j$ if Pj(r) < Pi(r).
  - With optional action: conservative scheme, O/W: aggressive scheme

- Bargain process is formulated as two-person cooperative game, the bargain solution (final list $\mathcal{L}_i$, $\mathcal{L}_j$) is determined by Nash Theorem



Necessary Condition for Feasible Transaction

- Theorem 1. *Necessary Condition for Feasible Transaction.* Node i has a type r message, and node j has a type s message. If both nodes i and j find it beneficial to exchange this message pair, then $\mathcal{P}_i(r) + \mathcal{P}_j(s) < 1$ must be true.
- Intuitive explanation: two hedgehogs who try to warm each other may hurt each other if they stay too close.



Scenario 1: Feasible

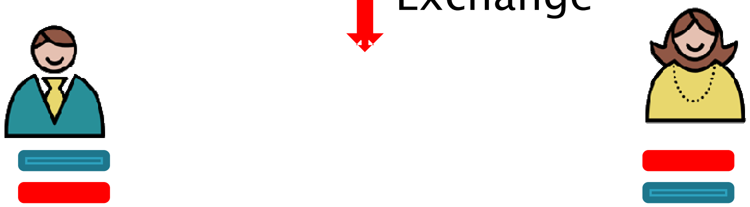
Pi(r)=0.1
Pi(s)=0.9

Pj(r)=0.8
Pj(s)=0.3

Type r msg [Ai(r)] =1
[Ri]= [Ai(r)]*Pi(r) =0.1

Type s msg [Aj(s)] =1
[Rj]= [Aj(s)]*Pj(s) =0.3

Exchange



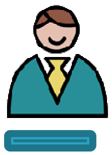
Type r msg Ai(r) =[Ai(r)]*(1-Pj(r)) =0.2
Type s msg Ai(s) =[Aj(s)]*(1-Pj(s)) =0.7
Ri= Ai(r)*Pi(r) + Ai(s)*Pi(s)
=0.02+0.63 = 0.65
Si = Ri - [Ri] = 0.55

Type s msg Aj(r) =[Aj(r)]*(1-Pi(r)) =0.9
Type r msg Aj(s) =[Ai(s)]*(1-Pi(s)) =0.1
Rj= Aj(s)*Pj(s) + Aj(r)*Pj(r)
=0.03+0.72 = 0.75
Si = Rj - [Rj] = 0.45

Pi(r) + Pj(s) = 0.1 + 0.3 < 1

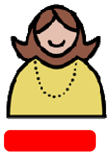
Scenario 2: Not Feasible

Pi(r)=0.5
Pi(s)=0.9



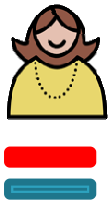
Type r msg [Ai(r)] =1
[Ri]= [Ai(r)]*Pi(r) =0.5

Pj(r)=0.8
Pj(s)=0.7



Type s msg [Aj(s)] =1
[Rj]= [Aj(s)]*Pj(s) =0.7

Exchange



Type r msg Ai(r) =[Ai(r)]*(1-Pj(r)) =0.2
Type s msg Ai(s) =[Aj(s)]*(1-Pj(s)) =0.3
Ri= Ai(r)*Pi(r) + Ai(s)*Pi(s)
=0.01+0.27 = 0.28
Si = Ri - [Ri] = -0.22

Type s msg Aj(r) =[Aj(r)]*(1-Pi(r)) =0.5
Type r msg Aj(s) =[Ai(s)]*(1-Pi(s)) =0.1
Rj= Aj(s)*Pj(s) + Aj(r)*Pj(r)
=0.4+0.07= 0.47
Si = Rj - [Rj] = - 0.23

Pi(r) + Pj(s) = 0.5 + 0.7 > 1 ✗

GAME THEORY MODEL FOR BARGAIN PROCESS

- Two-Person Cooperative Games
  - Consists of two rational and selfish players that cooperate with each other but have conflict interests
  - Two players reach binding agreement which benefits both persons

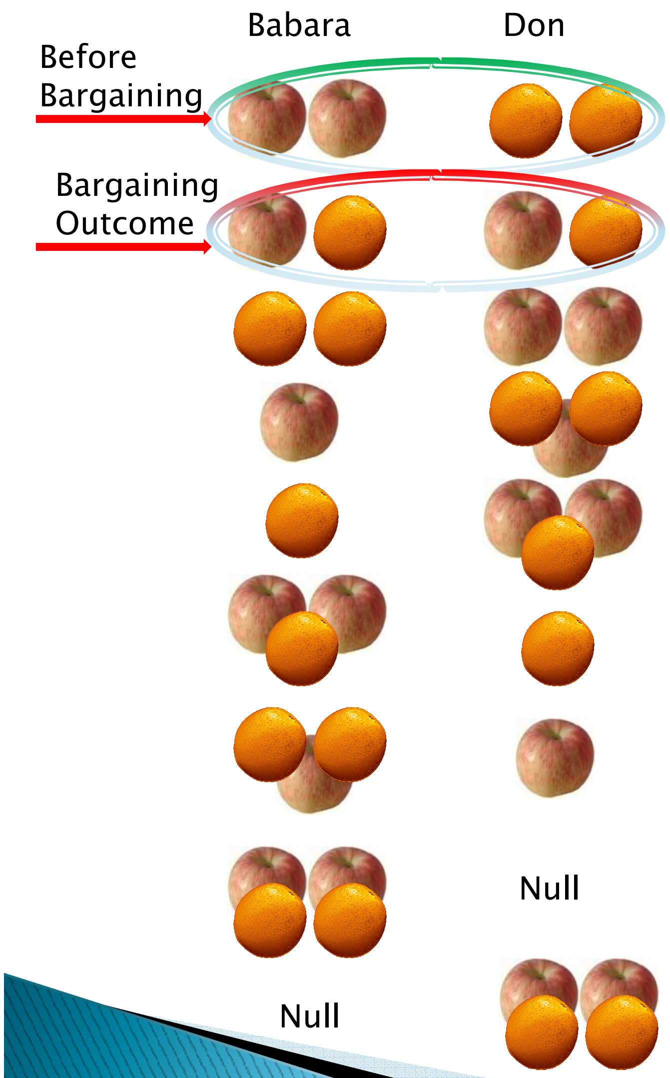
Nash Theorem

- The solution for two-person cooperative game, which satisfies four axioms: invariance, symmetry, independence and Pareto optimality, is given by

$$(\hat{s_1}, \hat{s_2}) = \arg \max_{(s_1,s_2)\in S} (s_1 - d_1) \times (s_2 - d_2)$$

(s_1, s_2) forms utility gain space S; (d_1, d_2) is the status quo point in space S, usually defined as the utility gain of no cooperation

Nash Theorem: A Simple Example

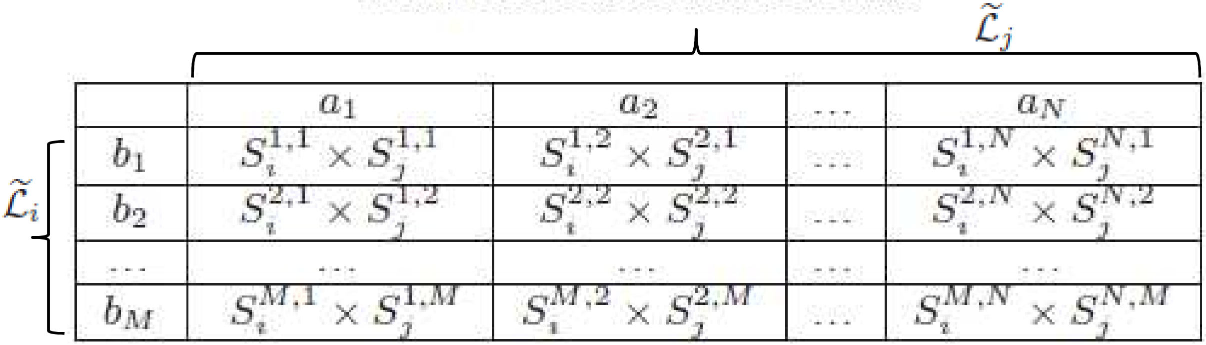


s_1	$s_1 - d_1$	s_2	$s_2 - d_2$	$(s_1 - d_1)*(s_2 - d_2)$
10	0	15	0	0
14	4	25	10	40
12	2	11	-4	-8
4	-6	36	21	-126
6	-4	35	20	-80
16	6	8	-7	-42
20	10	10	-5	-50
21	11	5	-10	-110
0	-10	37	22	-220

Greedy Algorithm for Game Solution

- Nash Theorem points out what the optimal solution is, but does not show how to reach the optimal solution.
- A greedy algorithm is proposed to divide bargain process into a finite sequence of steps, and each step corresponds to the exchange of a message pair between nodes i and j.
    - Unrealistic to adopt the brute forth manner to deplete all the possible patterns looking for Nash Solution due to the exponential complexity
- Nash product table

NASH PRODUCT OF MESSAGE PAIR

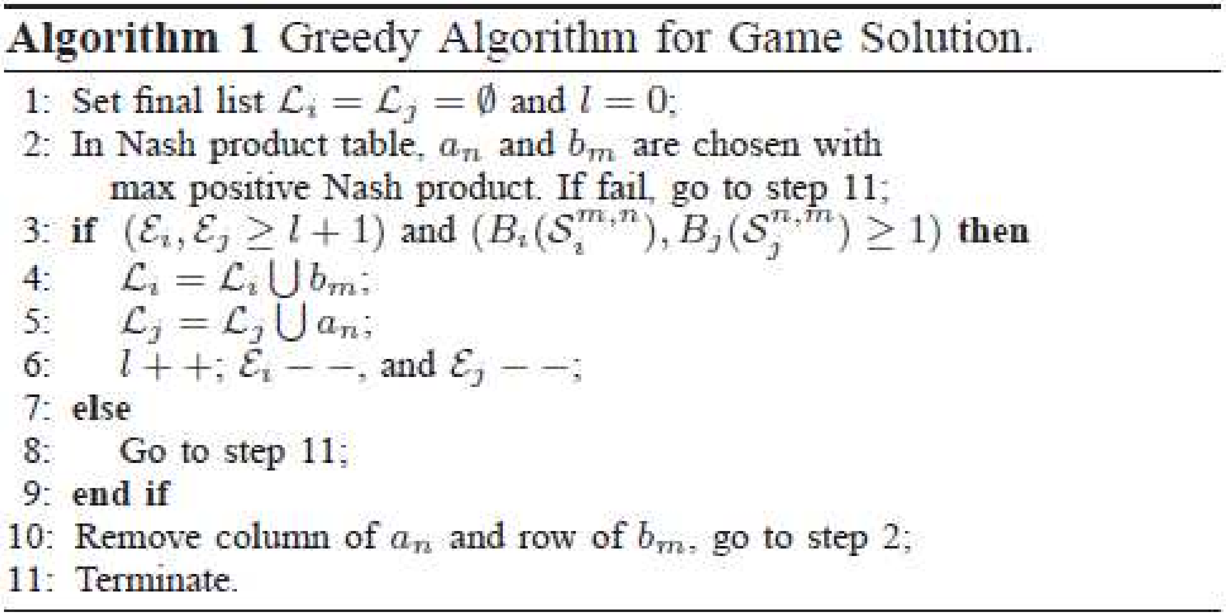


	a_1	a_2	...	a_N
b_1	$S_i^{1,1} \times S_j^{1,1}$	$S_i^{1,2} \times S_j^{2,1}$	...	$S_i^{1,N} \times S_j^{N,1}$
b_2	$S_i^{2,1} \times S_j^{1,2}$	$S_i^{2,2} \times S_j^{2,2}$	...	$S_i^{2,N} \times S_j^{N,2}$
...	...	...	...	...
b_M	$S_i^{M,1} \times S_j^{1,M}$	$S_i^{M,2} \times S_j^{2,M}$	...	$S_i^{M,N} \times S_j^{N,M}$

$$\begin{cases} \mathcal{C}_i^{b_m} = \mathcal{R}_i^{b_m}(T^{b_m}), \quad \mathcal{D}_i^{a_n} = [\mathcal{R}_i^{a_n}(T^{a_n})] - \mathcal{R}_i^{a_n}(T^{a_n}) \\ \mathcal{S}_i^{m,n} = \mathcal{C}_i^{b_m} - \mathcal{D}_i^{a_n} \\ \mathcal{C}_j^{a_n} = \mathcal{R}_j^{a_n}(T^{a_n}), \quad \mathcal{D}_j^{b_m} = [\mathcal{R}_j^{b_m}(T^{b_m})] - \mathcal{R}_j^{b_m}(T^{b_m}) \\ \mathcal{S}_j^{n,m} = \mathcal{C}_j^{a_n} - \mathcal{D}_j^{b_m}, \end{cases}$$

where C, D, S stand for credit, debit, utility gain

Greedy Algorithm for Game Solution



Algorithm 1 Greedy Algorithm for Game Solution.

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1: Set final list $\mathcal{L}_i = \mathcal{L}_j = \emptyset$ and $l = 0$;
2: In Nash product table, $a_n$ and $b_m$ are chosen with
      max positive Nash product. If fail, go to step 11;
3: if $(\mathcal{E}_i, \mathcal{E}_j \geq l + 1)$ and $(B_i(\mathcal{S}_i^{m,n}), B_j(\mathcal{S}_j^{n,m}) \geq 1)$ then
4:     $\mathcal{L}_i = \mathcal{L}_i \bigcup b_m$;
5:     $\mathcal{L}_j = \mathcal{L}_j \bigcup a_n$;
6:     $l++$; $\mathcal{E}_i--$, and $\mathcal{E}_j--$;
7: else
8:     Go to step 11;
9: end if
10: Remove column of $a_n$ and row of $b_m$, go to step 2;
11: Terminate.
```

$B_i(x)$ denotes the number of messages in node i with credit value less than x. Message a_n and b_m can be exchanged only when $B_i(S^{m,n}{}_i) \geq 1$ and $B_j(S^{n,m}{}_j) \geq 1$

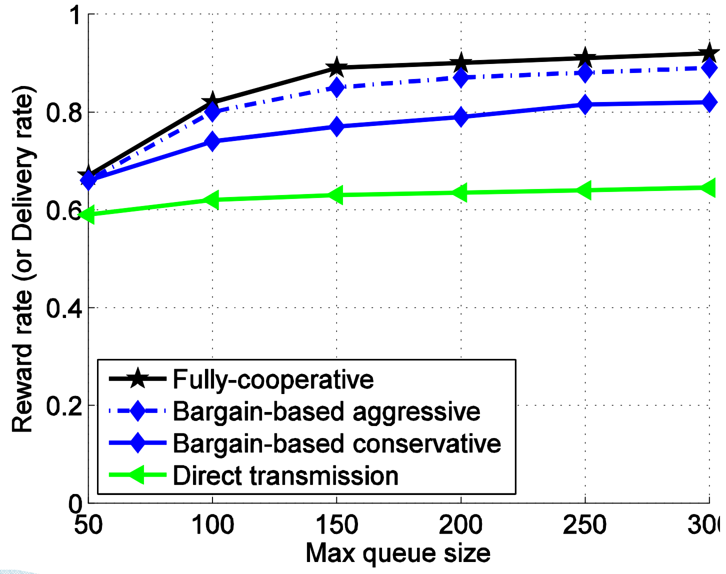
Simulation

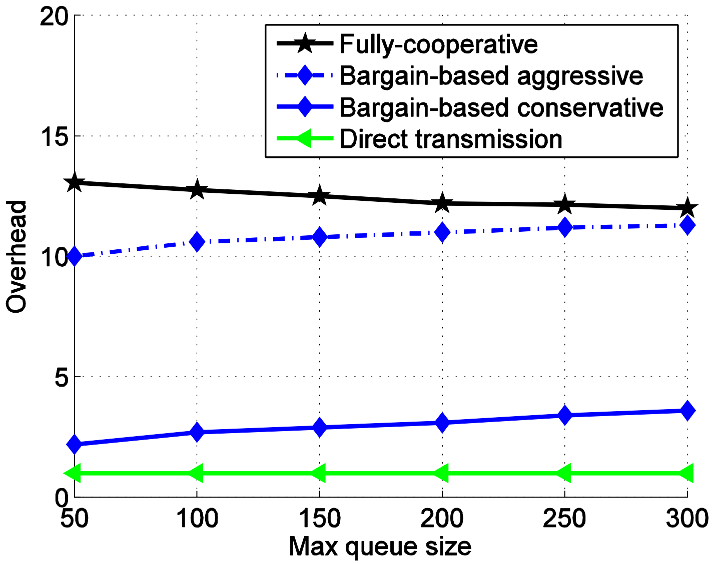
- Our simulations are based on real mobility traces available at CRAWDAD
- Two type of trace data
  - Position-based trace
    - Record GPS positions of nodes at fixed time intervals
  - Contact-based trace
    - No position info, only contact information
- Performance Metrics
  - Reward rate (delivery rate)
  - Network overhead
  - Fairness $f(x_1, x_2, ..., x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2}$, x_i *: node i's overhead*
- We compare our work with direct transmission and fully-cooperative scheme in DTN[1].

[1]Y. Wang and H. Wu, "DFT-MSN: The Delay Fault Tolerant Mobile Sensor Network for Pervasive Information Gathering," in Proc. of IEEE Conference on Computer Communications (INFOCOM), 2006, pp. 1-12

Position-based trace

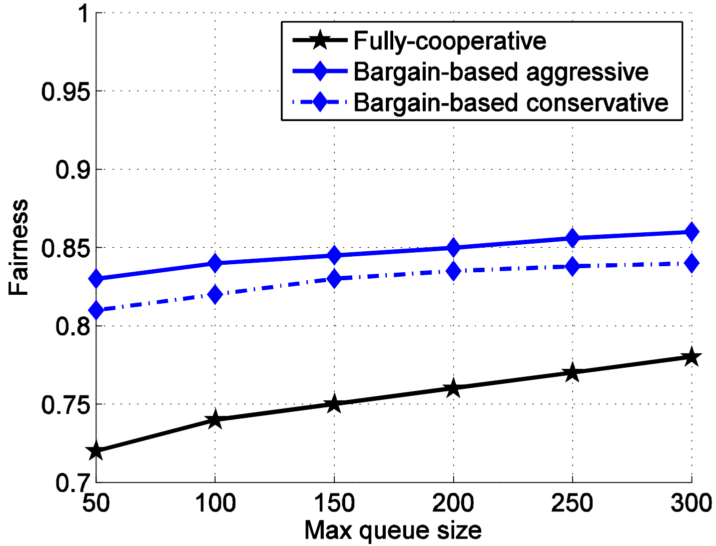
- Trace data of ZebraNet project is used in our simulations.
- Bargain-based scheme is effective in promoting nodal cooperation and improving network throughput.
  - The aggressive scheme is only 3% less than fully cooperative scheme in reward rate, while the conservative scheme is 10% less.
  - The overhead of bargain-based scheme is less than fully-cooperative scheme

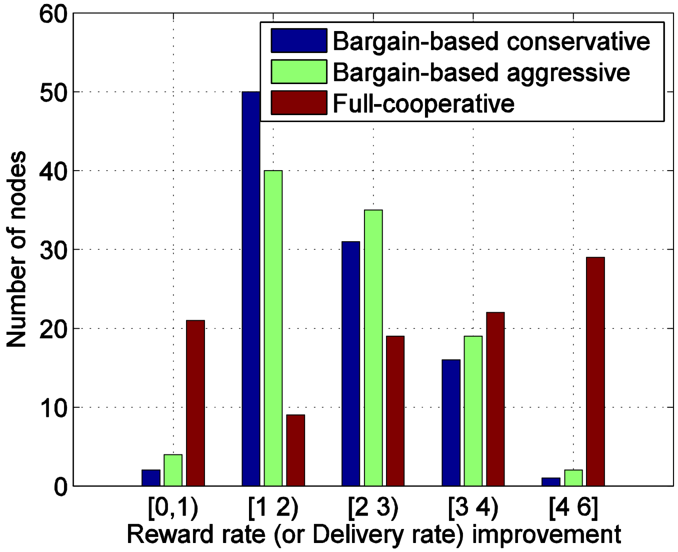




Position-based trace

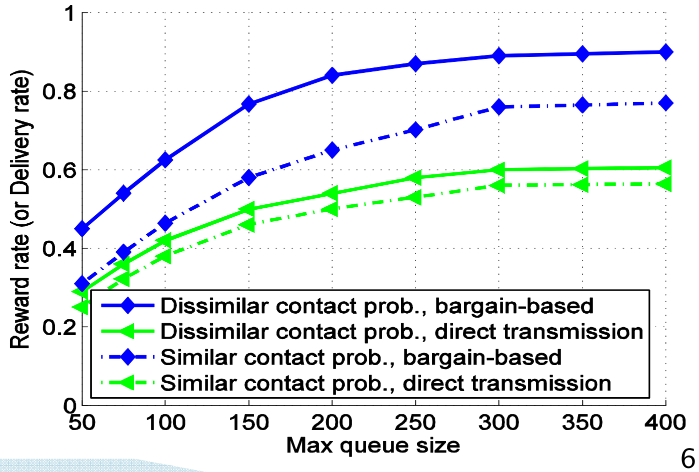
- Bargain-based schemes have much better fairness than fully-cooperative scheme
  - Bargain process allows each node to balance its individual interest with its contribution to network.
  - Compared to direct transmission, fully-cooperative scheme has more than 20% nodes experience worse performance, while 95% nodes enjoy more rewards under both aggressive and conservative scheme.





Contact-based trace

- Trace data of Cambridge Haggle project is used
  - In Haggle project, mobile nodes called iMotes were distributed to 50 people attending IEEE InfoCom workshop during three days.
  - 2 sinks and 2 message types
- Similar contact probability vs dissimilar contact probability
  - Similar contact probability: all nodes have Pi[1], Pi[2] uniformly distributed in [0, 1]
  - Dissimilar contact probability: half of nodes have Pi[1], Pi[2] uniformly distributed in [0, 0.4], [0.6,1], the other half of nodes have Pi[1], Pi[2] uniformly distributed in [0.6, 1], [0,0.4]
- Bargain-based mechanism achieves more gain when nodes have complementary sets of contact probabilities
  - Reward rate enhancement is 50% in scenario of dissimilar contact probability, compared to 35% enhancement in scenario of similar contact probability



Conclusion

- A novel bargain-based stimulation mechanism is proposed to encourage cooperation in selfish participatory sensing networks.
- The paper reveals necessary condition for feasible transaction of message exchange.
- The final message exchange list is determined in a bargain process, which is formulated as a two-person cooperative game.
- A greedy algorithm is proposed to resolve the game and find out optimal solution.
- The results show that our bargain-based stimulation schemes are fair and have comparable performance with fully-cooperative scheme with less overhead.

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