Collaborative Research: CISE-MSI: RCBP-RF: CNS: Truthful and Optimal Data Preservation in Base Station-less Sensor Networks: An Integrated Game Theory and Network Flow Approach Award No. CNS- 2131309

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Outline

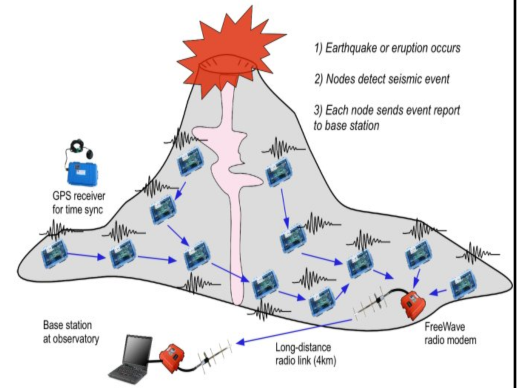
- Introduction of this project
- Research results
- Student engagement

Project Introduction

Project Abstract

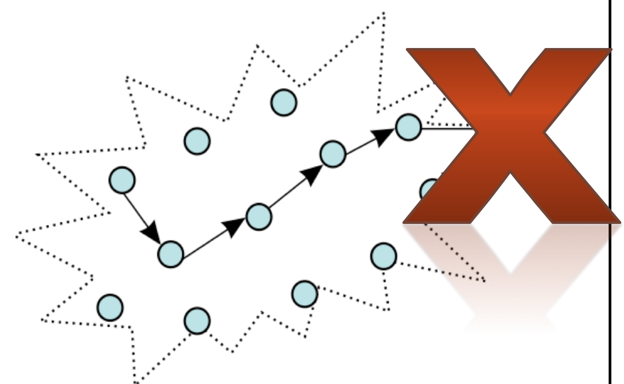
- The overarching goal of the project is to create a truthful and optimal resource allocation framework for emerging *base station-less sensor networks* (BSNs).
- As BSNs are deployed in challenging environments (e.g., underwater exploration), there is no data-collecting base station available in the BSN. The paramount task of the BSN is to preserve large amounts of generated data inside the BSN before uploading opportunities become available.
- Previous research designed a sequence of cooperative data preservation techniques based on classic network flows (e.g., maximum (weighted) flow and minimum cost flow).
- In a distributed setting and under different control, however, the sensor nodes with limited resources (i.e., energy power and storage spaces) could behave selfishly in order to save their own resources and maximize their own benefits.
- The tension between node-centric selfishness and data-centric data preservation in our unique BSN model gives rise to new challenge that calls for integrated study of game theory and network flows in the same problem space.

Base Station-less Sensor Networks (BSNs)



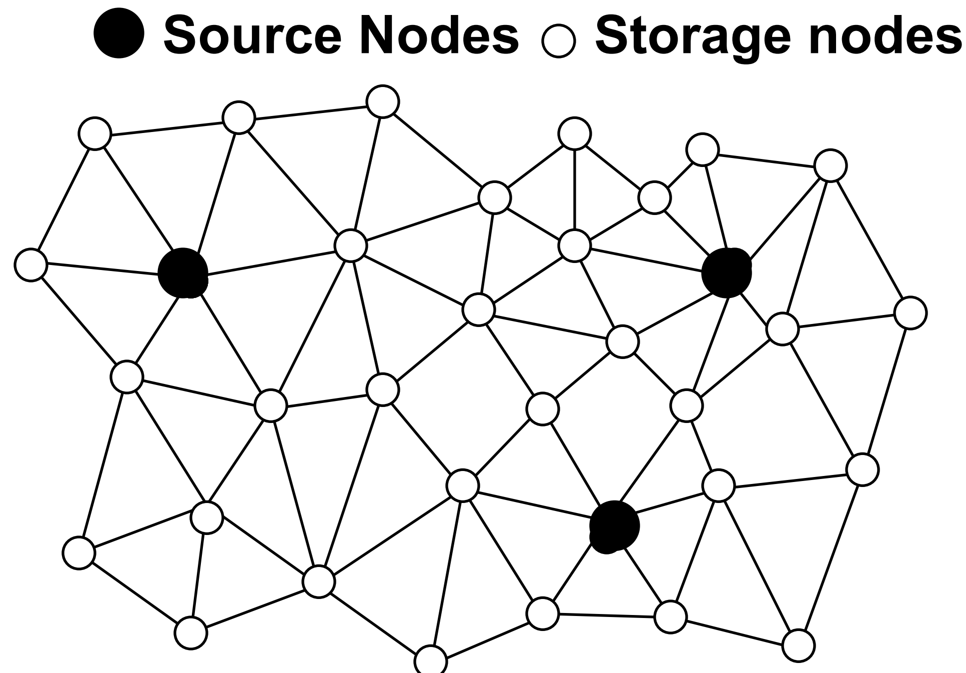
Source: http://fiji.eecs.harvard.edu/Volcano

- Sensing applications developed inaccessible and remote area
  - Underwater exploration, volcano eruption
- Not feasible to install base station in field
- Sensory data are stored in the network, periodically uploaded via robots or AUVs



Data Preservation in BSNs

- Non-uniform data generation and limited storage capacity
- Source nodes
  - Storage-depleted
  - Overflow data packets
- Storage nodes
  - Available storage spaces



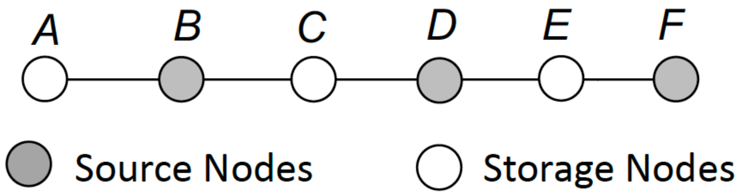
- Data Preservation: overflow data is offloaded from source nodes to storage nodes
- *Node u* sends a packet of R bits to *v* over $l_{u,v}$

$$E_r(R) = E_{elec} \times R$$
$$E_t(R, l_{u,v}) = E_{elec} \times R + \epsilon_{amp} \times R \times l_{u,v}^2$$

Data Preservation Problem (DPP)

- Goal: How to find a data preservation that minimizes the energy consumption (total preservation cost)

- An Example



  - B, D, F are source nodes (with one packet each)
  - A, C, E are storage nodes (each has one storage capacity)
  - Energy cost on each edge is one
  - Optimal solution: B to A, D to C, and F to E, with total cost of 3

Why Game Theory?

- Sensor nodes become intelligent, could perceive, learn, and reason on top of sensing, computation, and communication
- Sensor networks are distributed in nature and sensor nodes could under different controls
- Sensor nodes are resource-constrained in battery and processing power
- Game-theoretical solution (such Nash Equilibrium, that characterizes selfish players' optimal strategies in non-cooperative games

Research Results

On the Performance of Nash Equilibria for Data Preservation in Base Station-less Sensor Networks

Giovanni Rivera, Yutian Chen, and Bin Tang, IEEE International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS 2023)

Nash Equilibrium (NE) in Data Preservation

- Game-theoretical solution that characterizes selfish players' optimal strategies in non-cooperative games

- Not socially optimal due to selfish players, needs to study performance degradation in NE

- Question: Can we design data preservation algorithms that achieve NE with performance guarantees?

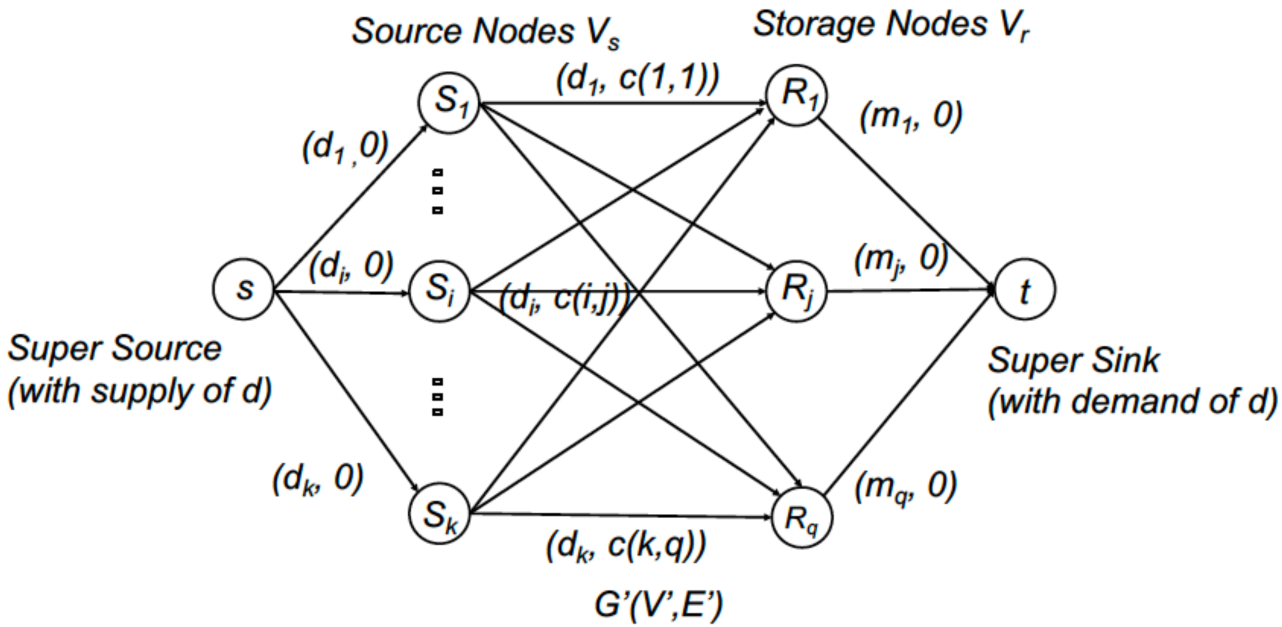
Data Preservation Game

- Players: k source nodes $\{S_1, S_2, \ldots, S_k\}$
  - Source node S_i compensates all other nodes involved in the preservation of its data
  - S_i has a set of data preservation strategies A_i: how many of its packets are offloaded to which storage nodes
- *Data preservation strategy profile:* $A = A_1 \times A_2 \ldots \times A_k$
- *Utility of S_i under A: $u_i = - c_i$, the preservation cost of S_i's packets*
  - *S_i aims to maximize u_i*
- $s^* = \{s_i^*, s_{-i}^*\} \in A$, *s. t.* $u_i(s_i^*, s_{-i}^*) \geq u_i(s_i, s_{-i}^*)$ for all $s_i \in A_i$
  - Data Preservation NE (DP-NE)

Performance Metrics

- Price of Anarchy (PoA): ratio of total preservation cost of worst DP-NE and the socially optimal
  - Performance upper bound
- Price of Stability (PoS): ratio of the total preservation cost of the best DP-NE and the socially optimal
  - Performance lower bound
- Rate of Efficiency Loss (REL): ratio of total preservation cost of any DP-NE and the socially optimal
  - Able to quantity any DP-NE

Minimum Cost Flow (MCF)



- DPP in BSN graph is equivalent to MCF in above flow network
- Theorem 1: The MCF-based data preservation algorithm gives a NE with optimal total preservation cost; its PoA = PoS = 1

The PoS of Greedy Algorithm

- Theorem 4: There exists a greedy algorithm for DPP that reaches NE with PoS = PoA = 1
  - Proof by Induction
  - Socially optimal outcome for any network involves at least one overflow data preserved via its minimum-cost path

- Successive shortest path algorithm for minimum cost flow problem

Preservation cost

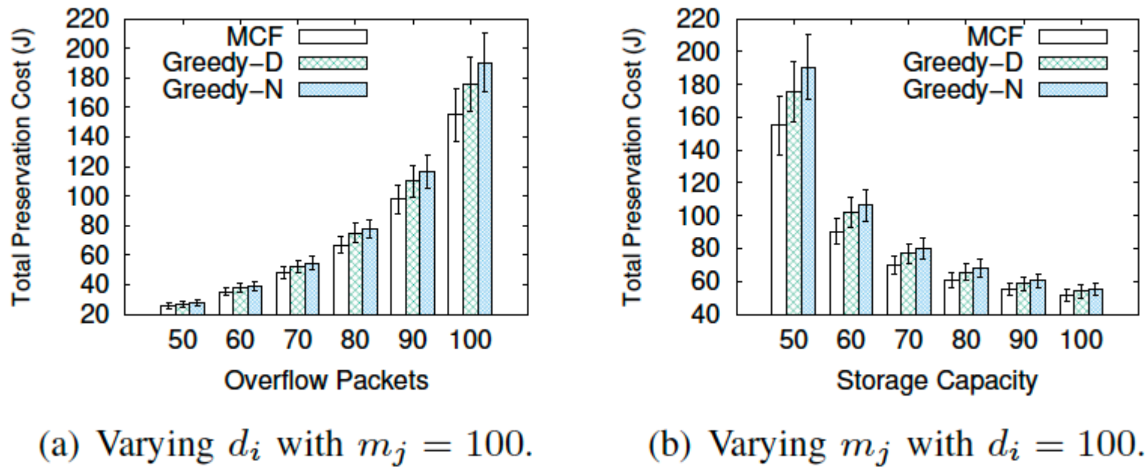


Fig. 8. Total preservation costs of different algorithms.

- MCF < Greedy-D < Greedy-N

- Performance difference are smaller when data preservation is less challenging

- Economic interpretation: more resources results in less performance degradation of NEs

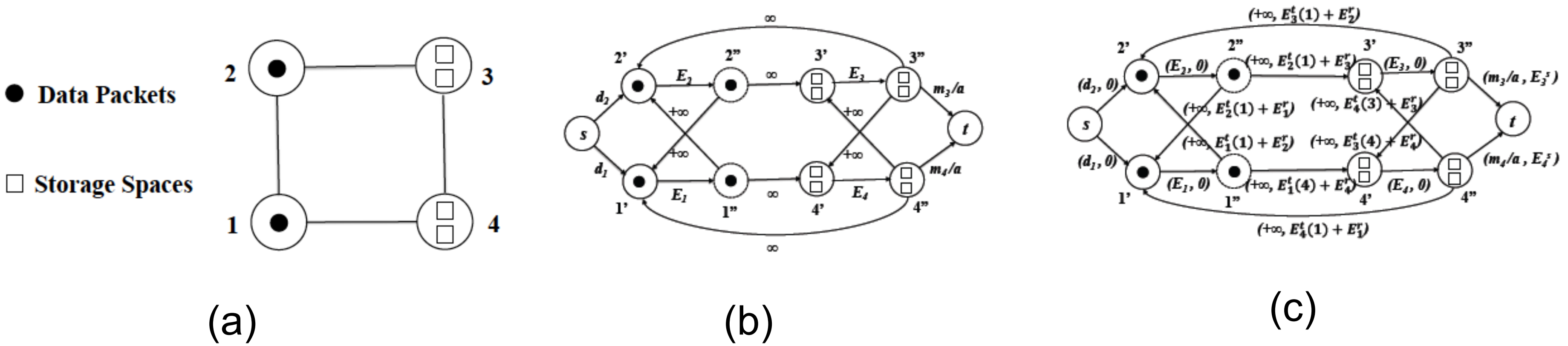
Truthful and Optimal Data Preservation in Base Station-less Sensor Networks: An Integrated Game Theory and Network Flow Approach

YuningYu, Shangli Hsu, Andre Chen,Yutian Chen, Bin Tang. ACM Transactions on Sensor Networks, 2023,Volume 20, Issue 1, , pp 1–40.

- Integrates algorithmic mechanism design (AMD) and minimum cost flow-based data preservation solution.
- Data preservation games that yields dominant strategies for sensor nodes and delivers truthful and optimal data preservation.
- When nodes have limited battery power, the games fail to achieve truthful and optimal data
- Utilizing packet-level flow observation of sensor node behaviors computed by minimum cost flow and ILP, uncover the cause of the failure.

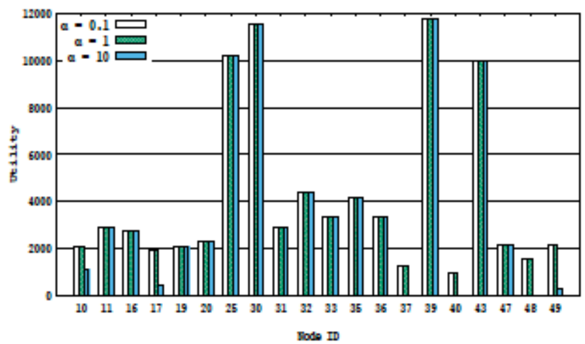
Network Flow Approach

- Solve Data Preservation Problem by designing an integer linear programming (ILP)-based optimal solution considering energy constraint and selfishness

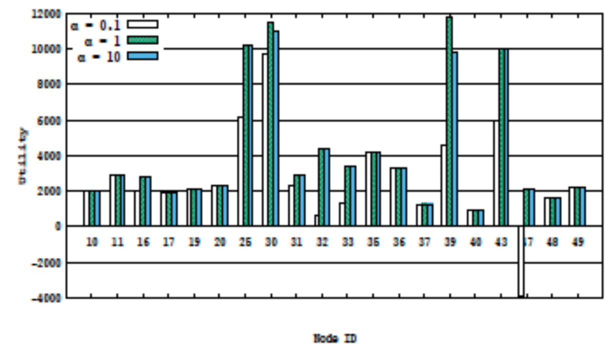


Algorithmic Mechanism Design

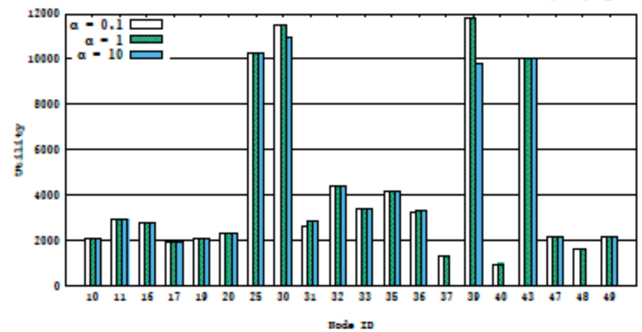
- Data preservation games that yields dominant strategies for sensor nodes and delivers truthful and optimal data preservation.



(a) Lying ε^{s}



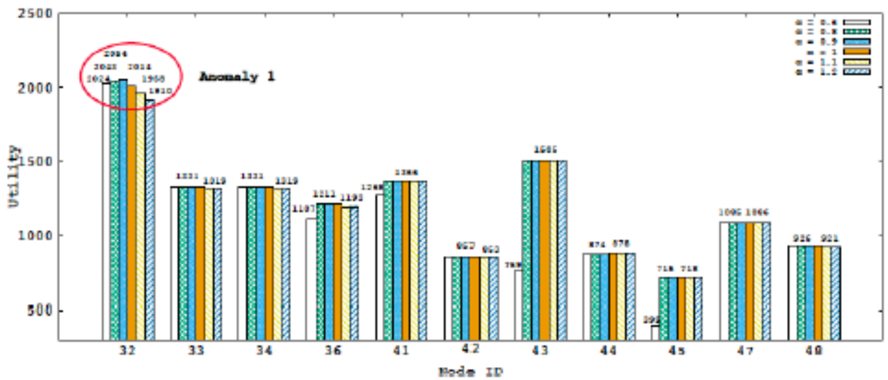
(b) Lying ε^{a}



(c) Lying ε^{e}

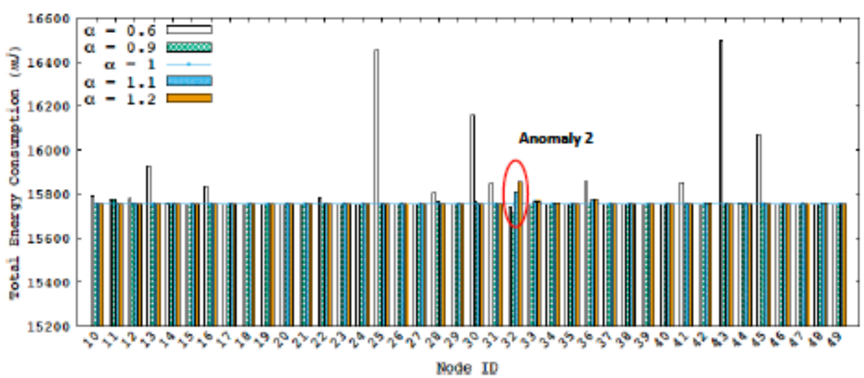
Algorithmic Mechanism Design

- When nodes have limited battery power, the games fail to achieve truthful and optimal data



(a)

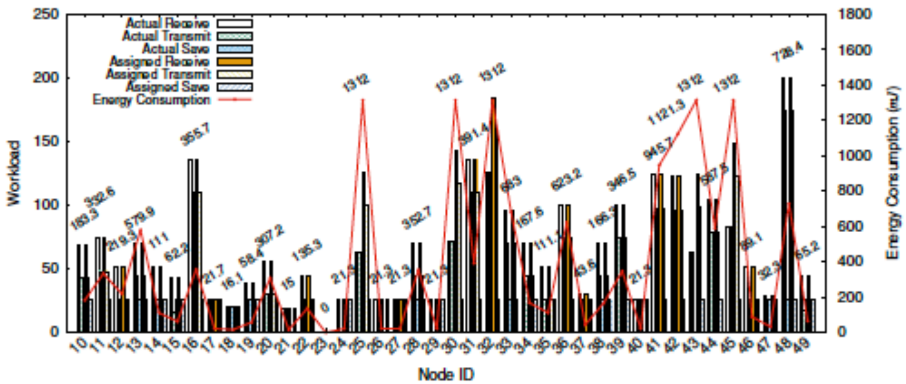
(a) Node 32's lying utility is larger that its truth-telling.



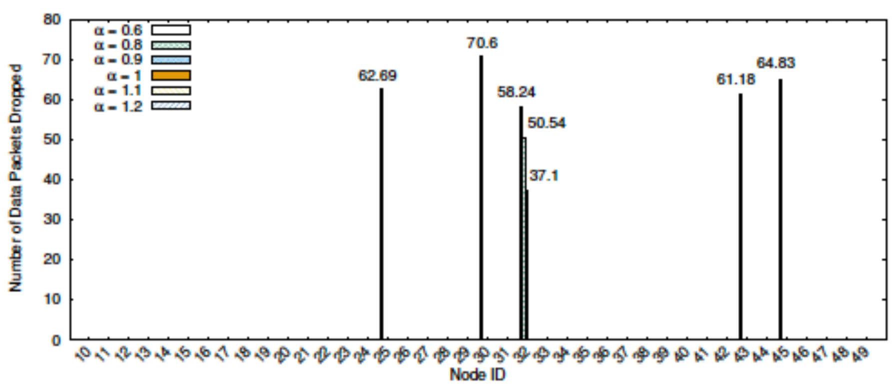
(b)

(b) Total energy consumption (i.e., total preservation cost) resulted from node 32's lying is lower than the optimal total preservation cost when it is truth-telling.

Microscopic View from Network Flow Computation



(a)



(b)

(a) Each storage node's assigned (and actual) receive, transmit, and save, as well as energy consumption when α = 0.6.

(b) Number of dropped data packets by lying storage nodes.

Data Loss Inhibiting Mechanism

- When nodes have limited battery power, the games fail to achieve truthful and optimal data

Data: A BSN graph $G(V, E)$.
Result: Detect if data loss occurs at storage node i.
Transform $G(V, E)$ to a flow network $G'''(V''', E''')$ following Transformation III in Section 4.2.2;
Apply ILP (B) on $G'''(V''', E''')$ to compute the assigned load, assigned relay, and assigned save;
if *assigned load* $> \lfloor \frac{m_i}{a} \rfloor$, *where* $\lfloor \frac{m_i}{a} \rfloor$ *is node i's storage capacity* **then**
  actual save = assigned save = $\lfloor \frac{m_i}{a} \rfloor$;
  assigned relay = assigned load $- \lfloor \frac{m_i}{a} \rfloor$;
  actual relay = 0;
  Sort the packets in the assigned relay in the non-descending order of their transmission energy;
  Let E^i_{curr} be the remaining energy of node i after receiving the assigned load amount of data packets following ILP (B);
  // In the assigned relay, relays those incurring minimum transmission energy until i's energy power is depleted;
  while $E^i_{curr} > 0$ **do**
    $E^i_{curr} = E^i_{curr} - \lfloor \frac{m_i}{a} \rfloor \cdot a \cdot \epsilon^s_i$; //compute the remaining energy after saving data packets;
    Relay the packet in the assigned reply with minimum transmission energy;
    Update E^i_{curr};
    actual relay = actual relay + 1;
  end
else
  actual save = assigned load;
  actual relay = 0;
end
actual load = actual save + actual relay;
data loss = assigned load - actual load;
Return data loss;

Algorithm 1: Finding data loss at storage node i.

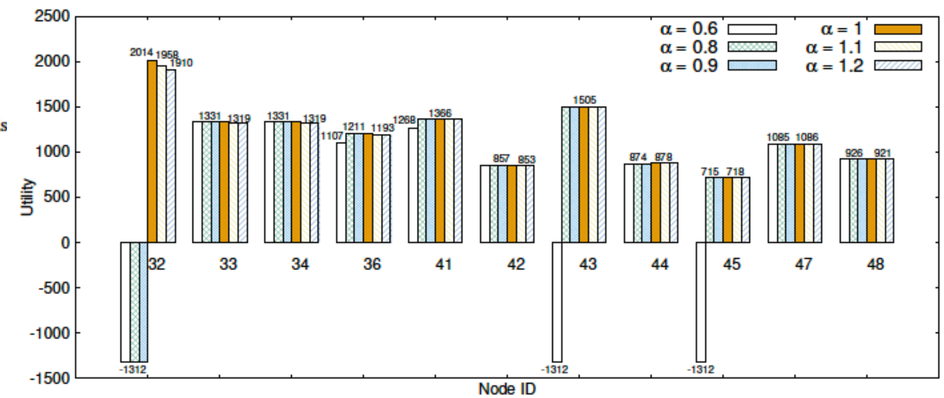


Fig. 19. Utilities of nodes 32-49 in DPG-2 with data loss inhibiting mechanism. E_i = 1312 mJ and m_i = 26.

Student Engagement

Where did they go after graduation?

- Five undergraduate students, five graduate students
  - Rachel Varghese, Justin Gamoras, Grace Huang (CSULB Economics Undergraduate Students)
  - Jose Chavez, Brian Rios (CSULB Economics Graduate Students)
  - Giovanni Rivera, Jennifer Ly (CSUDH CS Undergraduate Students)
  - Chris Gonzalez, Ryan Steubs, Yuning Yu, Shangli Hsu (CSUDH CS Graduate Students)

- Justin Gamoras has started his graduate MBA degree at UC Irvine School of Business
- Grace Huang will purse graduate degree in Public Policy at George Washing University, starting Fall 2024
- Giovanni Rivera will purse Ph.D. in Computer Science in University of California Riverside, starting Fall 2024

Student presentation from this grant

- **Justin Gamoras,** Application of Economic Game Theory and Nash-Q Reinforcement Learning in Studying Data Preservation Sensor Nodes, **First Place Winner** at 36th Annual CSULB Student Research Competition, Virtual, May 9, 2024.

- **Grace Huamg,** A Correlated Equilibrium Q-Learning for Data Preservation in Base Station-less Sensor Network, 98th Annual Western Economic Association International (WEAI), July 2nd-6th, *2023,* San Diego, California.

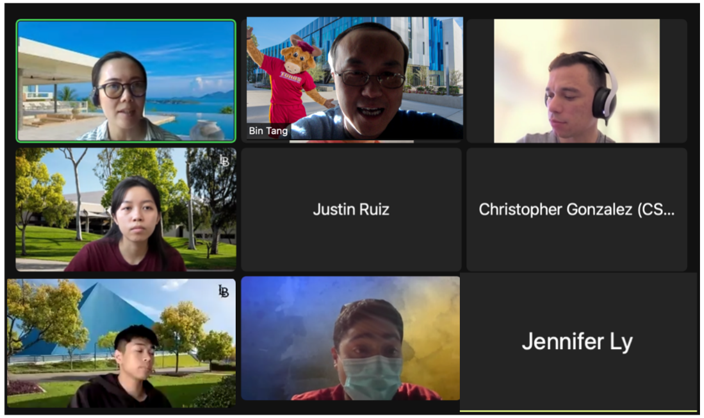
- **Giovanni Rivera,** Nash Equilibria of Data Preservation in Base Station-less Sensor Networks, Third Computer Science Conference for CSU Undergraduates (CSCSU 2023), Virtual, April 13, 2023

- **Giovanni Rivera,** California State University, Dominguez Hills Computer Science Presentation Title: Achieving Data Resilience in Wireless Sensor Networks Under Severe Storage and Energy Constraints, Edison STEM-NET Student Research Symposium, virtual, 4/9/2024

Student Publication from this grant

- ***On the Performance of Nash Equilibria for Data Preservation in Base Station-less Sensor Networks*, Giovanni Rivera,** Yutian Chen, and Bin Tang, Proceedings of the **IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS 2023)**.
- **Truthful and Optimal Data Preservation in Base Station-less Sensor Networks: An Integrated Game Theory and Network Flow Approach** , **Yuning Yu, Shangli Hsu, Andre Chen,** Yutian Chen, Bin Tang. **ACM Transactions on Sensor Networks**, 2023, Volume 20, Issue 1, , pp 1–40.
- ***Data-VCG: A Data Preservation Game for Base Station-less Sensor Networks with Performance Guarantee* Jennifer Ly** and Yutian Chen and Bin Tang, 3rd International Workshop on Time-Sensitive and Deterministic Networking (TENSOR), IFIP Networking 2023.
- ***Voluntary Data Preservation Mechanism in Base Station-less Sensor Networks***, Yutian Chen, **Jennifer Ly**, Bin Tang , Proceedings of the 12th EAI International Conference on Game Theory for Networks (GameNets 2022).
- ***DRE*^{2}*: Achieving Data Resilience in Wireless Sensor Networks: A Quadratic Programming Approach*, Shanglin Hsu, Yuning Yu,** and Bin Tang, Proceedings of the IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS 2020).
- **A Truthful and Efficient Auction Mechanism for Data Preservation in Base Station-less Sensor Networks**, **Ryan Steubs**, Yutian Chen, and Bin Tang, Submitted

Lesson we learned



- Be flexible
- Start early, start small
- Small and well-thought project

Thank you NSF!