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

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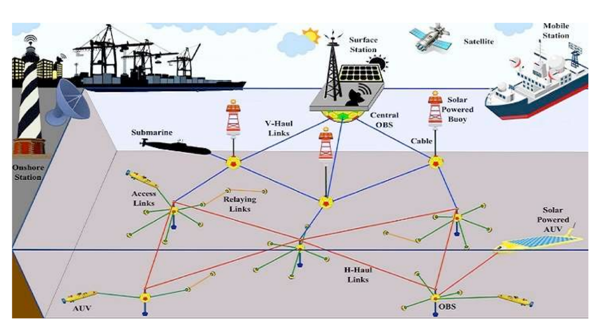
Abstract:

- 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.

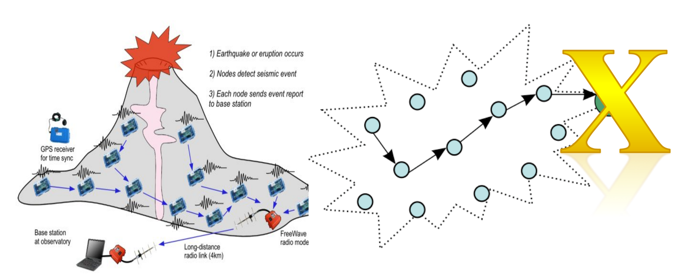
Base Station-less Sensor Networks (BSNs):

- Sensing applications developed inaccessible and remote area
  - Underwater exploration, volcano eruption



Source: phys.org

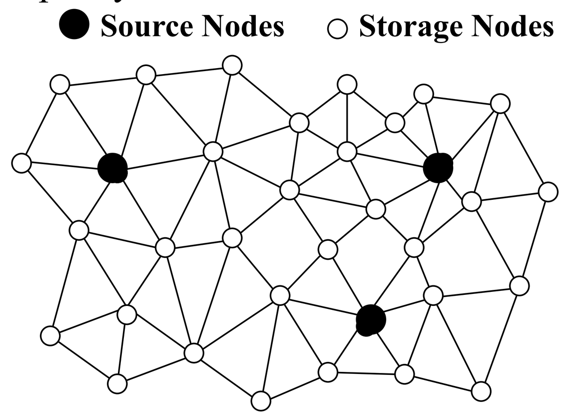
- Not feasible to install base station in field
- Sensory data are stored in the network, periodically uploaded to basestation via robots or AUVs



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

Data Preservation in BSNs:

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



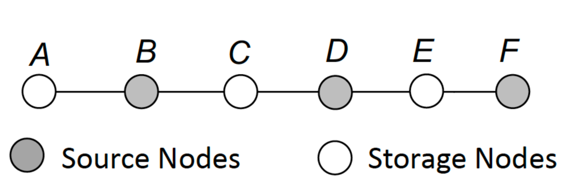
- Data Preservation: overflow data is offloaded from source nodes to storage nodes
- *Node u* sends a packet of R bits to *v* over $l_{u,v}$

$$E_r(R) = E_{elec} \times R$$

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

- Data Preservation Problem in BSNs

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



Why Game Theory?

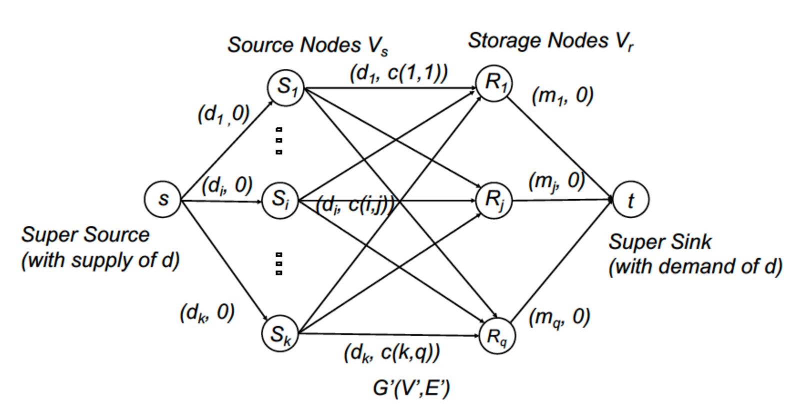
- Sensor nodes become intelligent, could perceive, learn, and reason on top of sensing, computation, and communication
- Sensor networks are distributed in nature and sensor nodes could under different controls
- Sensor nodes have limited battery and processing power
- Nash Equilibrium (NE): Game-theoretical 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?
- Performance Metrics of Data Preservation Nash Equilibrium (DP-NE)

a. Price of Anarchy (PoA): ratio of total preservation cost of worst DP- NE and the socially optimal : Performance upper bound

b. Price of Stability (PoS): ratio of the total preservation cost of the best DP-NE and the socially optimal: Performance lower bound

c. Rate of Efficiency Loss (REL): ratio of total preservation cost of any DP-NE and the socially optimal: Able to quantity any DP-NE

Research Results:



❖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

Algorithm 1: The Node-based Greedy Algo.

1. In each iteration, one source node offloads its overflow data packets to its closest storage nodes with available spaces

2. Theorem 2: The Node-Based Greedy Algorithm reaches a NE with a *PoA = H(d), where H(d) = $2^{d-1} + 2^{d-2} + ... + 2^0$, where d is total number of data packets*

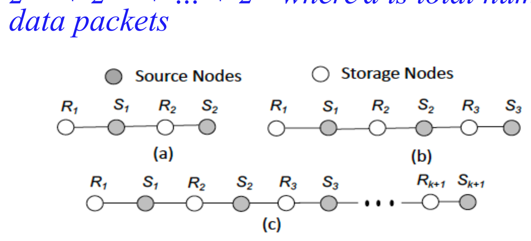


Fig. 3. Illustrating PoA = $H(d)$ for NEs resulted from Algo. 1.

Algorithm 1: The Node-based Greedy Algorithm.
Input: A BSN graph $G(V, E)$;
Output: Data preservation paths $f : D \rightarrow V_r$;
Notations: l_i: number of un-offloaded data packets at S_i;
h_j: number of available storage spaces at R_j;
1. **for** $(1 \le i \le k)$ // current data packets at S_i
2. $l_i = d_i$;
3. **for** $(1 \le j \le q)$ // current storage space at R_j
4. $h_j = m_j$;
5. **for** $(1 \le i \le k)$ // each source node S_i
6. **while** $(l_i > 0)$
7. Find the storage node in V_r closest to S_i that still has available spaces, say R_j;
8. Offload $\min(l_i, h_j)$ packets to R_j along the the preservation path between S_i and R_j;
9. $l_i = l_i - \min(l_i, h_j)$, $h_j = h_j - \min(l_i, h_j)$;
10. **end while;**
11. **end for;**
12. **RETURN** $f : D \rightarrow V_r$.

Algorithm 2: The Distance-based Greedy Algo.

1. In each iteration, it finds a source and storage node pair with the minimum preservation cost

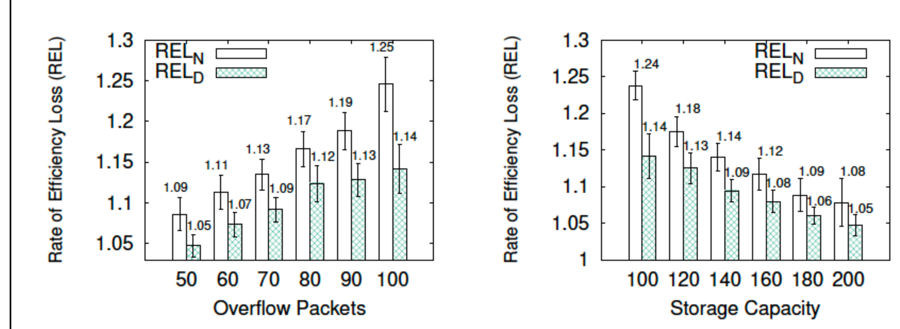
2. Theorem 3: The Distance-Based Greedy Algorithm reaches a NE with a PoA < 3

Theorem 4: There exists a greedy algorithm for DPP that reaches NE with PoS = PoA = 1

Algorithm 2: The Distance-base Greedy Algorithm.
Input: A BSN graph $G(V, E)$;
Output: Data preservation paths $f : D \rightarrow V_r$;
Notations: l_i: number of un-offloaded data packets at S_i;
h_j: number of available storage spaces at R_j;
1. **for** $(1 \le i \le k)$ // current data packets at S_i
$l_i = d_i$;
2. **for** $(1 \le j \le q)$ // current storage space at R_j
$h_j = m_j$;
3. Find the shortest distance between all the (S_i, R_j) pairs;
4. Sort the pairs in the non-descending order of their distances and denote it as L;
5. **while** (L is not empty)
6. Let (S_i, R_j) be the first pair in L;
7. **if** $(l_i > 0 \wedge h_j > 0)$
8. Offload $\min(l_i, h_j)$ packets from S_i to R_j along the the data preservation path between S_i and R_j;
9. **end if;**
10. $l_i = l_i - \min(l_i, h_j)$, $h_j = h_j - \min(l_i, h_j)$;
11. **if** $(l_i == 0 \vee h_j == 0)$
12. Remove (R_i, S_j) from L;
13. **end if;**
14. **end while;**
15. **RETURN** $f : D \rightarrow V_r$.

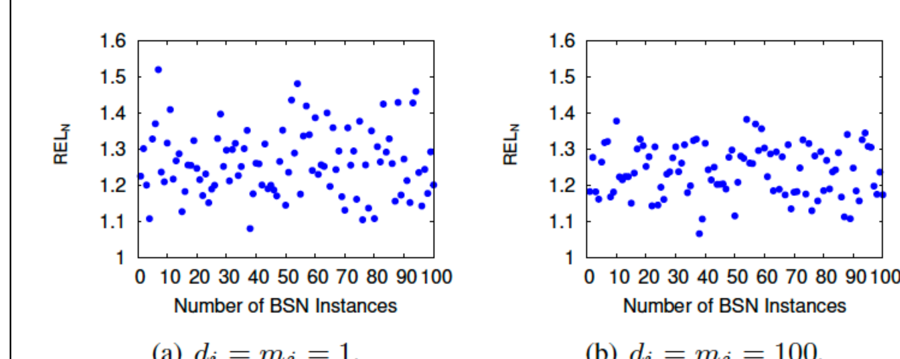
Performance Evaluation:

- BSN sensor field
  - 50 nodes in 2000m×2000m network, Tr = 200m, Each packet is 512 Bytes
  - 75 randomly selected as source node, rest storage nodes
  - Number of packets at each source node d_i= 100, storage capacity m_j= 100
- Algorithms
  - Minimum cost flow (**MCF**), Node-based greedy (**Greedy-N**), Distance-based greedy (**Greedy-D**)
  - Rate of Efficiency Loss (REL)
  - Each data point is an average of 20 runs



(a) Varying d_i with $m_j = 100$. (b) Varying m_j with $d_i = 100$.

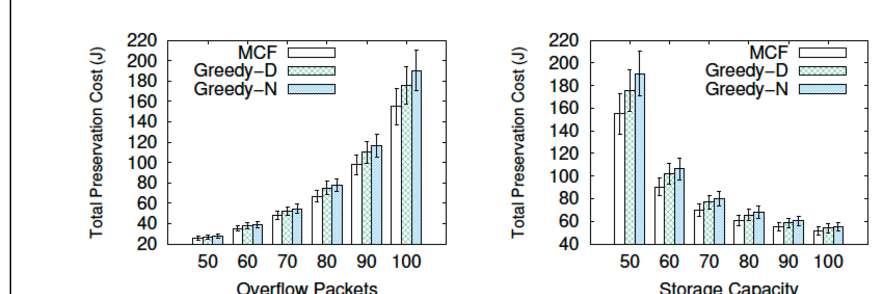
- Greedy-D has a less NE efficiency loss than Greedy-N
- More data packets aggravate NE efficiency loss while more storage spaces alleviate NE efficiency loss
- With infinite social resources, no efficiency loss for any NEs



(a) $d_i = m_j = 1$. (b) $d_i = m_j = 100$.

- 100 random instances
- REL_N = [1.08, 1.52] for $d_i = m_j = 1$
- REL_N = [1.05, 1.25] for $d_i = m_j = 100$
- Empirical results much better than theoretical results
  - $PoA = 2^{d-1} + 2^{d-2} + ... + 2^0$

Fig. 6. Investigating the PoAs of Greedy-N.



(a) Varying d_i with $m_j = 100$. (b) Varying m_j with $d_i = 100$.

- 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

Fig. 8. Total preservation costs of different algorithms.

Conclusions and Future Work:

- Study the NE performances of data preservation algorithms in BSNs
- Minimum cost flow-based algorithm achieves NE with PoS = 1
- There always exists an efficient greedy algorithm that produces NEs with PoS = 1
- Consider the different data packets have different values

References:

- 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.

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