DAO^2: Overcoming Overall Storage Overflow in Intermittently Connected Sensor Networks

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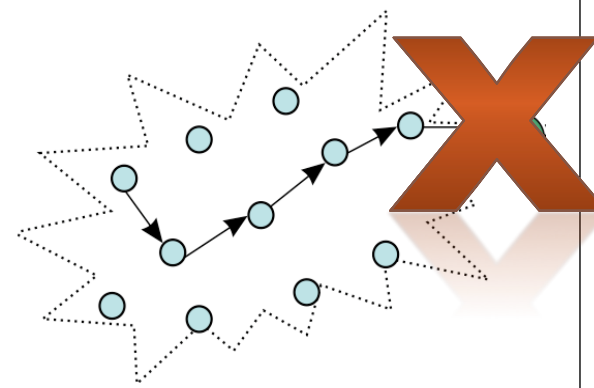
Outline

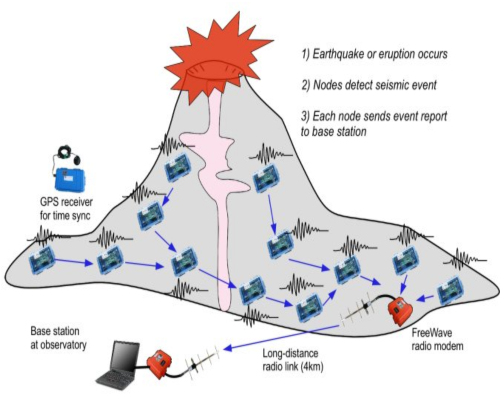
- ICSN and its overall storage overflow problem
- DAO^2 (Data Aggregation for Overall Storage Overflow)
- MTSW (Multiple Traveling Salesman Walks)
- Distributed DAO^2 algorithm
- Simulation results
- Conclusion and future work

Intermittently Connected Sensor Networks (ICSN)

- Deepwater sensor networks for tactical surveillance, volcano eruption/glacial melting monitoring



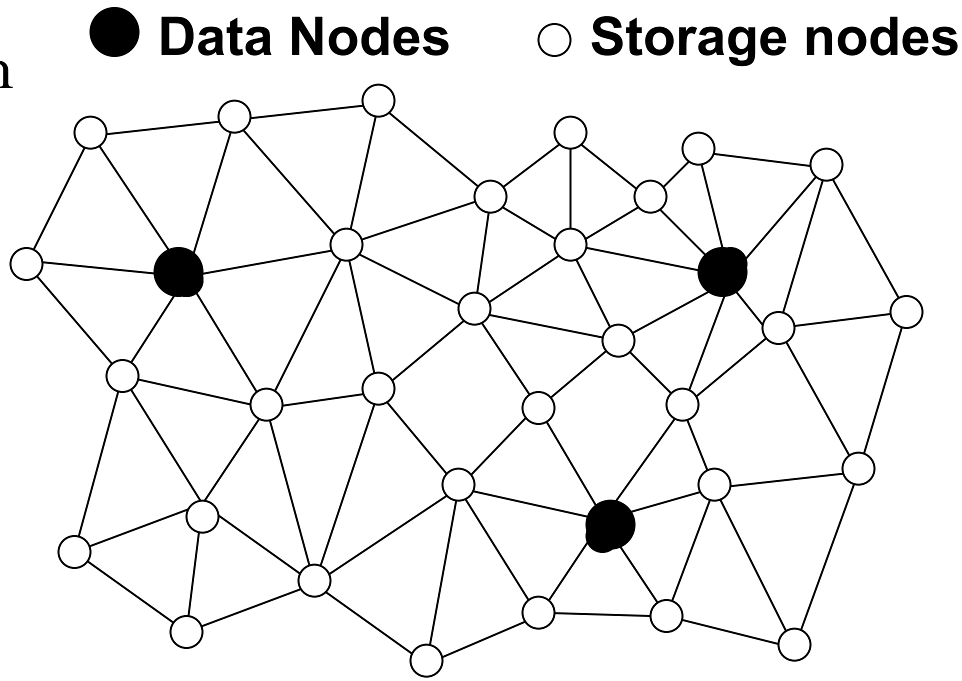
- Not feasible to install base station in field
- Data generated and stored in the network, periodically uploaded via data mules or satellite links
- Data uploading opportunities are intermittently available



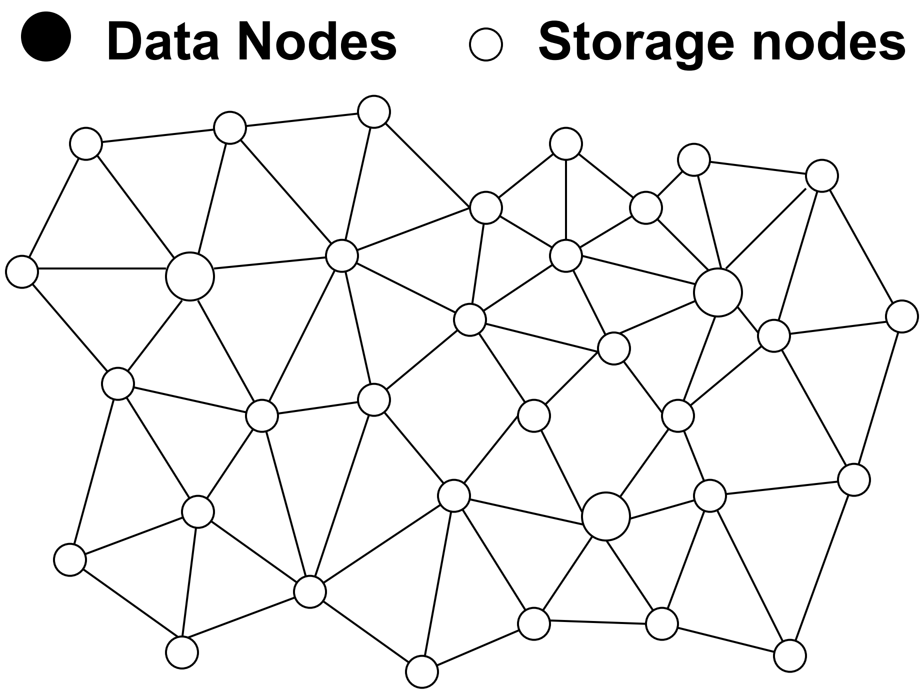
Source: http://fiji.eecs.harvard.edu/Volcano

Data Preservation in ICSN

- Non-uniform data generation and limited storage capacity
- Data nodes
  - Storage-depleted
  - Overflow data
- Storage nodes
  - Available storage spaces
- Data preservation: offload overflow data from data node to storage nodes



Overall Storage Overflow In Data Preservation

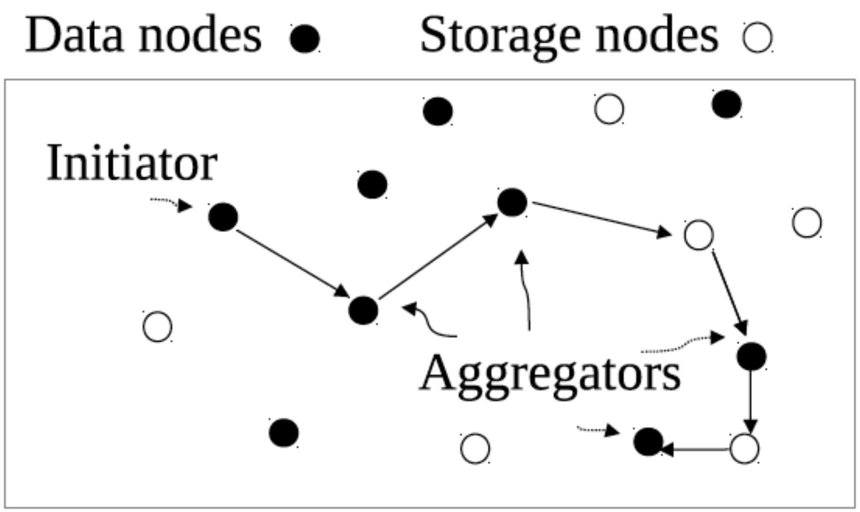


- When total size of overflow data exceeds the total available storage in the network

Overall storage overflow

Solution - DAO^2 (Data Aggregation for Overall Storage Overflow)

- Spatial correlation among sensory data
- Two stages: 1) data aggregation, 2) data offloading



- Challenge: energy efficient data aggregation

Problem Formulation of DAO[2]

- Undirected weighted graph $G(V, E)$
- p data nodes, each has R bits of overflow data
  - when a data node receives data information from at least another data node, it becomes an aggregator, and
  - it reduces the size of its overflow data from R *to* r, $0 \leq r < R$
- $|V| - p$ storage nodes, each has m bits of storage space
- Due to overall storage overflow: $p \times R > (|V| - p) \times m$

$$\frac{|V|m}{m+R} < p \leq \lfloor \frac{|V|m - R + r}{m+r} \rfloor$$

Problem Formulation of DAO²

- *q*: number of aggregators,

$$q = \lceil \frac{p \times (R + m) - |V| \times m}{R - r} \rceil$$

- Therefore, at most *p-q* sensor nodes can be initiators

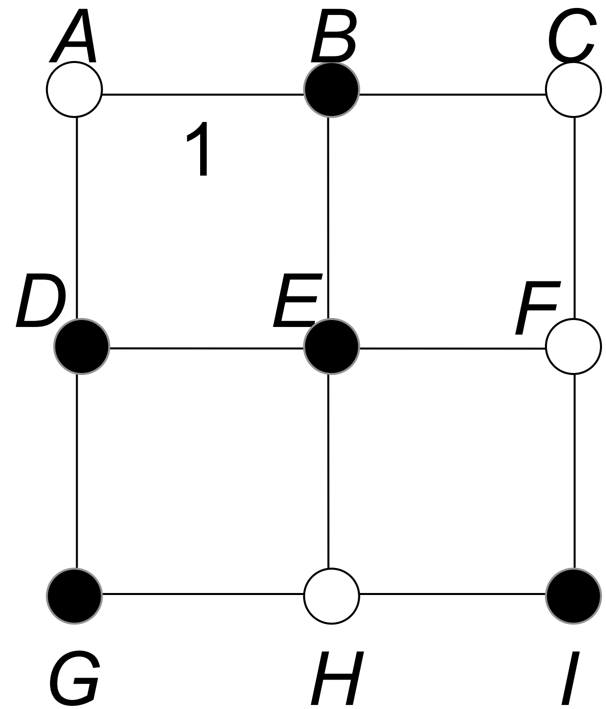
- Energy model - *u* sends *R*-bit data to *v* over $l_{u,v}$

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

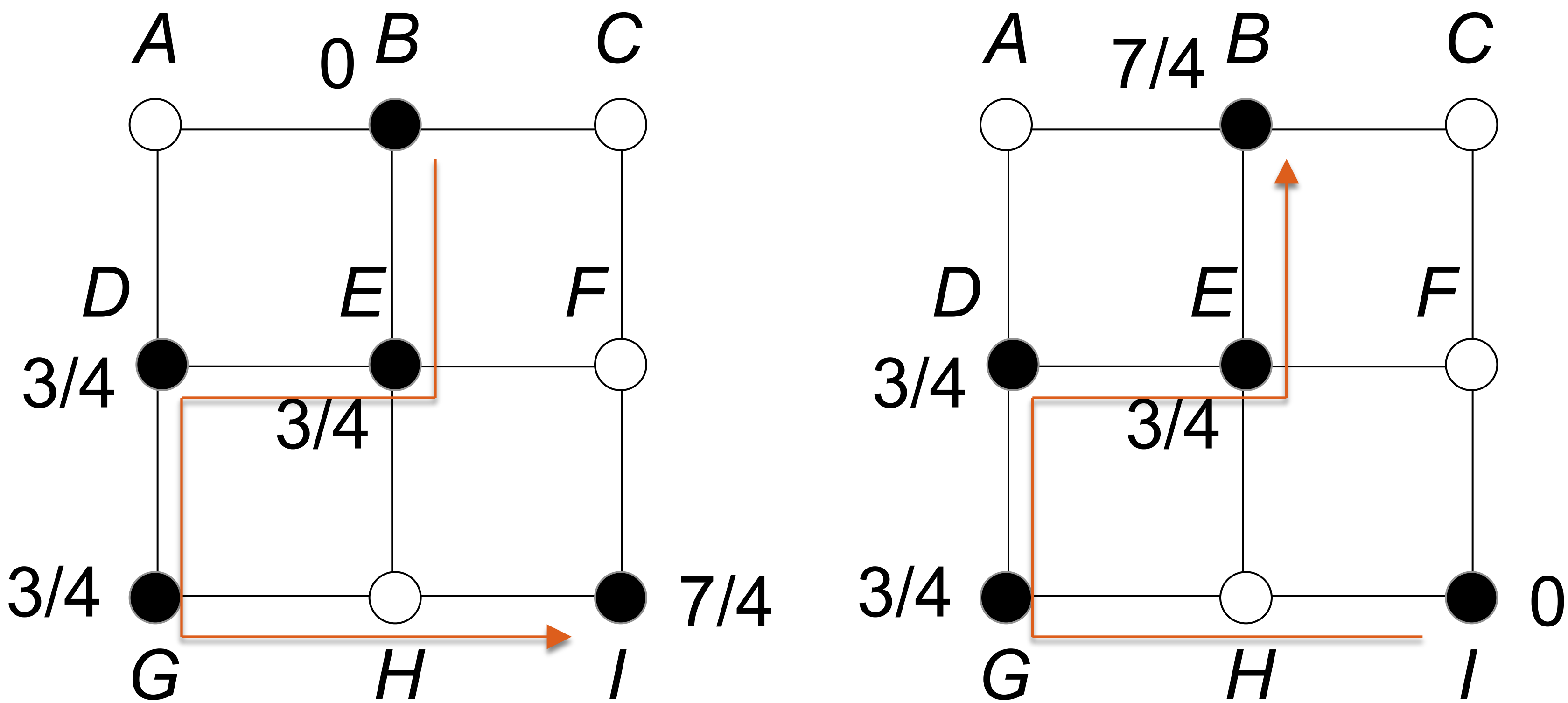
- Goal: select a set of *b* (1 ≤ *b* ≤ *p-q*) initiators, each visiting some data nodes (aggregators) following a walk, *s.t.* total *q* distinct aggregators are visited with minimum total energy cost

An Example of DAO²

- Data nodes: *B, D, E, G, I*
- Storage nodes: *A, C, F, H*
- $R = m = 1$ ➡ overall storage overflow!
- $r = ¾$, number of aggregators $q = 4$, leaving one data node to be initiator
- Edge weight = *1*
- Decide: which data node to be initiator and which path it visits?



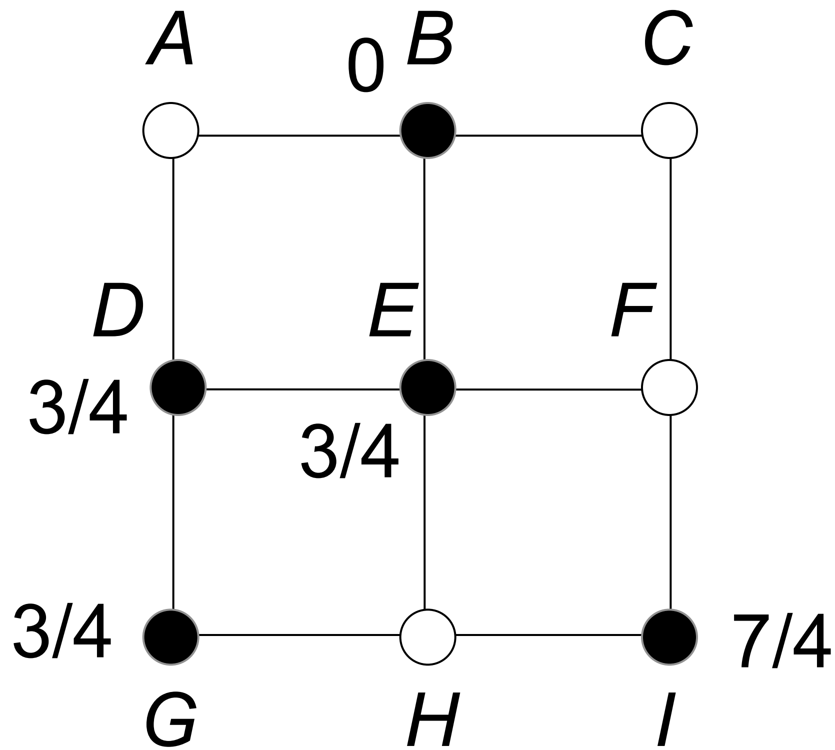
Two Optimal Solutions: cost=5



(a) B is initiator

(b) I is initiator

Next, data offloading…



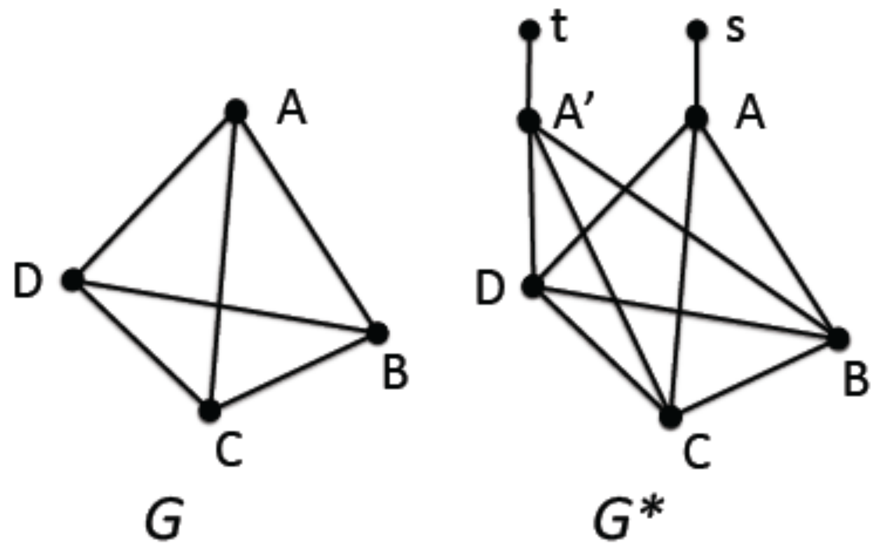
Equivalent to minimum cost flow problem
(Tang et al. TOSN 2013)

Multiple Traveling Salesman Walks (MTSW)

- Input: An undirected weighted graph G(V,E) and a number q
- Output: Finds at most $|V|$ - q starting nodes, each visiting some other nodes following a walk, *s.t.*
- Goal: total q nodes are visited while the total cost of the walks is minimized

MTSW is NP-hard

- Traveling salesman path problem (TSPP) is a special case of MTSW, with q=|V|-1
- Prove TSPP is NP-hard, reduced from traveling salesman problem (TSP)



Approximation Algo. for MTSW

Algorithm 1: Approximation Algorithm for MTSW.

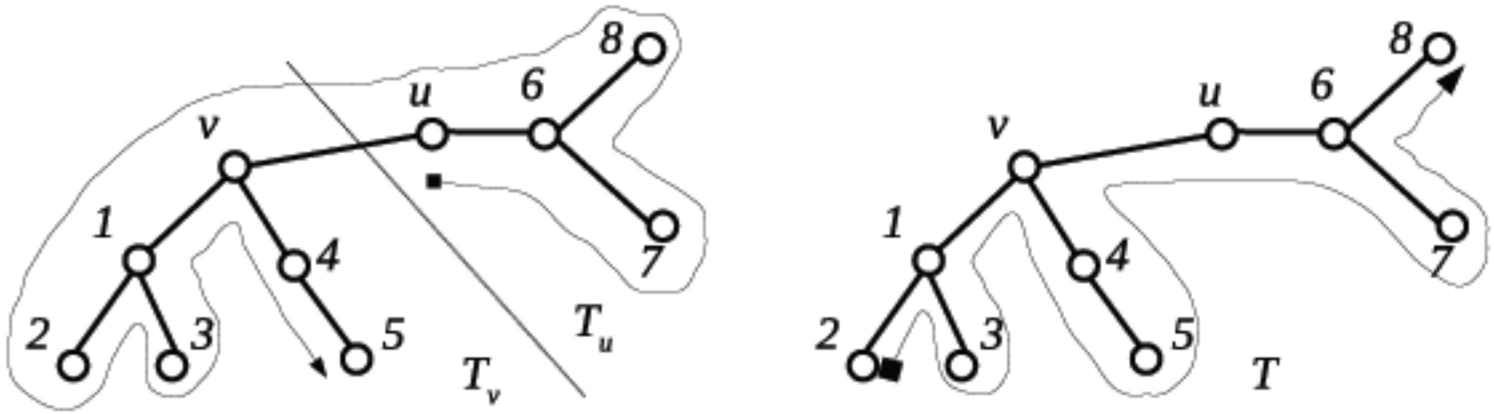
Input: $G(V, E)$ and number of nodes to visit q;

Output: a walks: $W_1, W_2, ..., W_a$, and $\sum_{1 \leq j \in a} c(W_j)$;

0. **Notations:**
   E_q: set of q cycleless edges;
   $G[E_q]$: a q-edge forest;
   $C(G[E_q])$: set of connected components in $G[E_q]$;
   C_j: the j^{th} connected component in $C(G[E_q])$;
1. Let $w(e_1) \leq w(e_2) \leq ... \leq w(e_{|E|})$;
2. $E_q = \phi$ (empty set), $i = j = k = 1$;
3. **while** $(k \leq q)$
4.   **if** (e_i is a cycleless edge w.r.t. E_q)
5         $E_q = E_q \cup \{e_i\}$;
6. $k++$;
7.   **end if;**
8. $i++$;
9. **end while;**
10. Let $|C(G[E_q])| = a$; /*a connected components*/
11. **for** $(1 \leq j \leq a)$
12.   **if** (C_j is linear) Start from one end node of C_j and visit the rest nodes in C_j once;
13.   **if** (C_j is a tree) Do a B-walk on C_j;
14.   Let the resulted walk (or path) be W_j;
15. **end for;**
16. **RETURN** $W_1, W_2, ..., W_a$, and $\sum_{1 \leq j \in a} c(W_j)$.

- Find the q smallest cycleless edges, referred to as q-edge forest
- Traverse each tree in the forest using a B-walk
- Works alike and generalizes Kruskal's MST algo.
- $O(|E| \log |E|)$

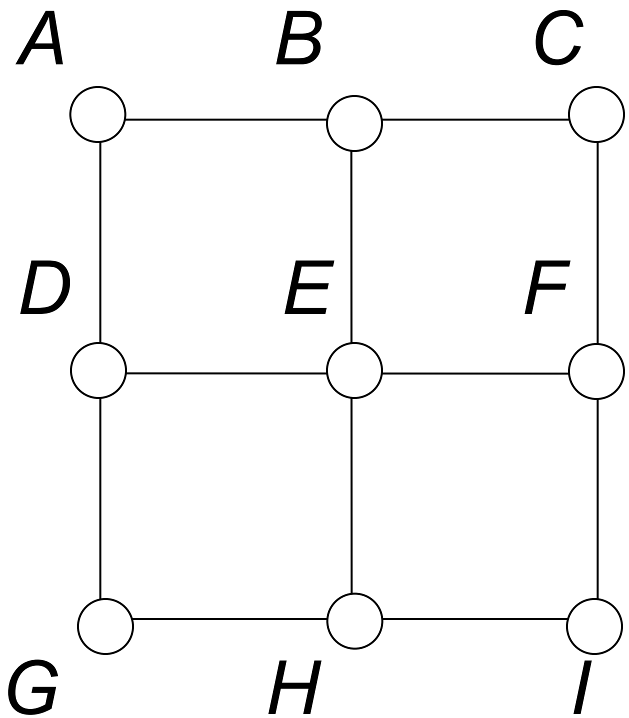
Binary Walk (B-Walk) and Longest-Path Walk (LP-Walk)



(a) B-Walk. (b) LP-Walk.

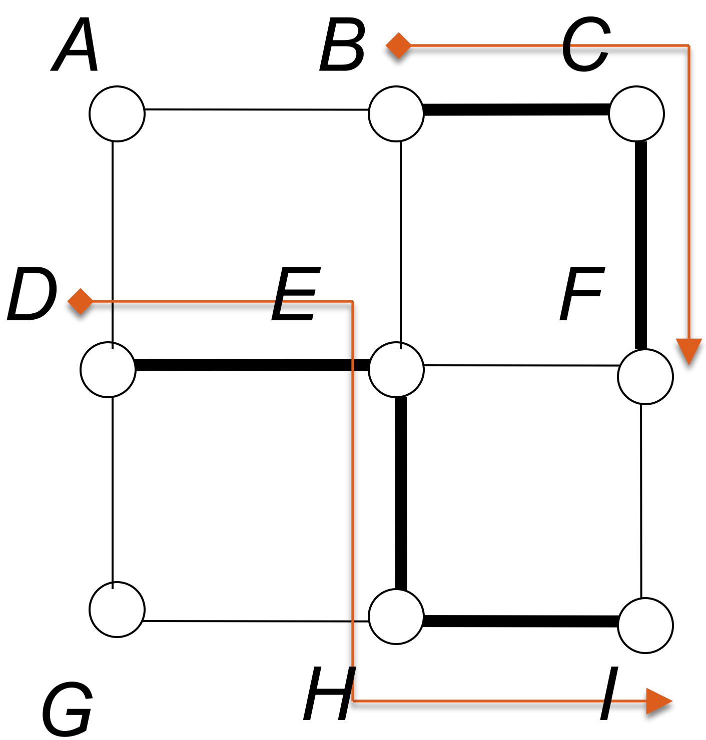
$$c(W) \leq \left(2 - \frac{1}{|T|}\right) \times c(T)$$

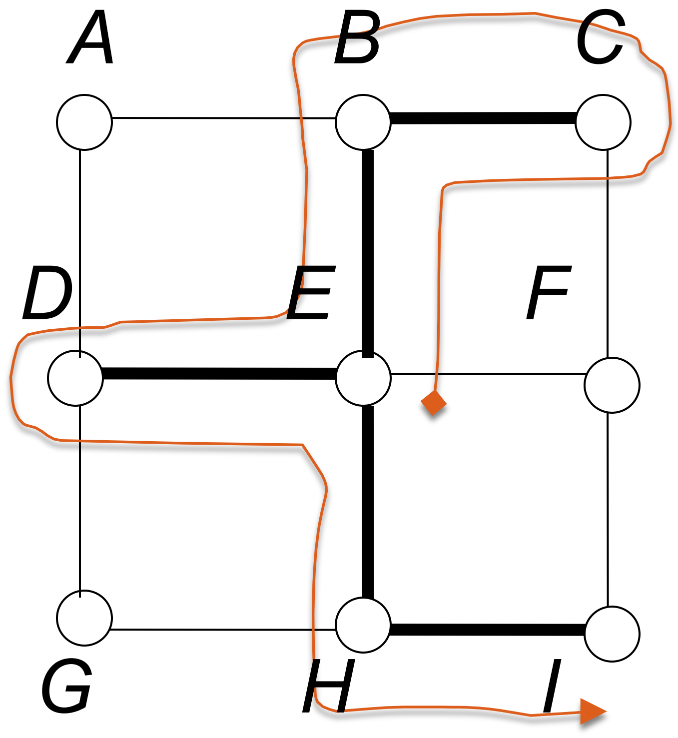
An Example of Algo. 1 (q=5)



- Edge weight = *1*
- How to visit 5 nodes energy efficiently?

Many solutions…





- B, D are starting nodes
- C, F, E, H, I are visited
- Cost = 5

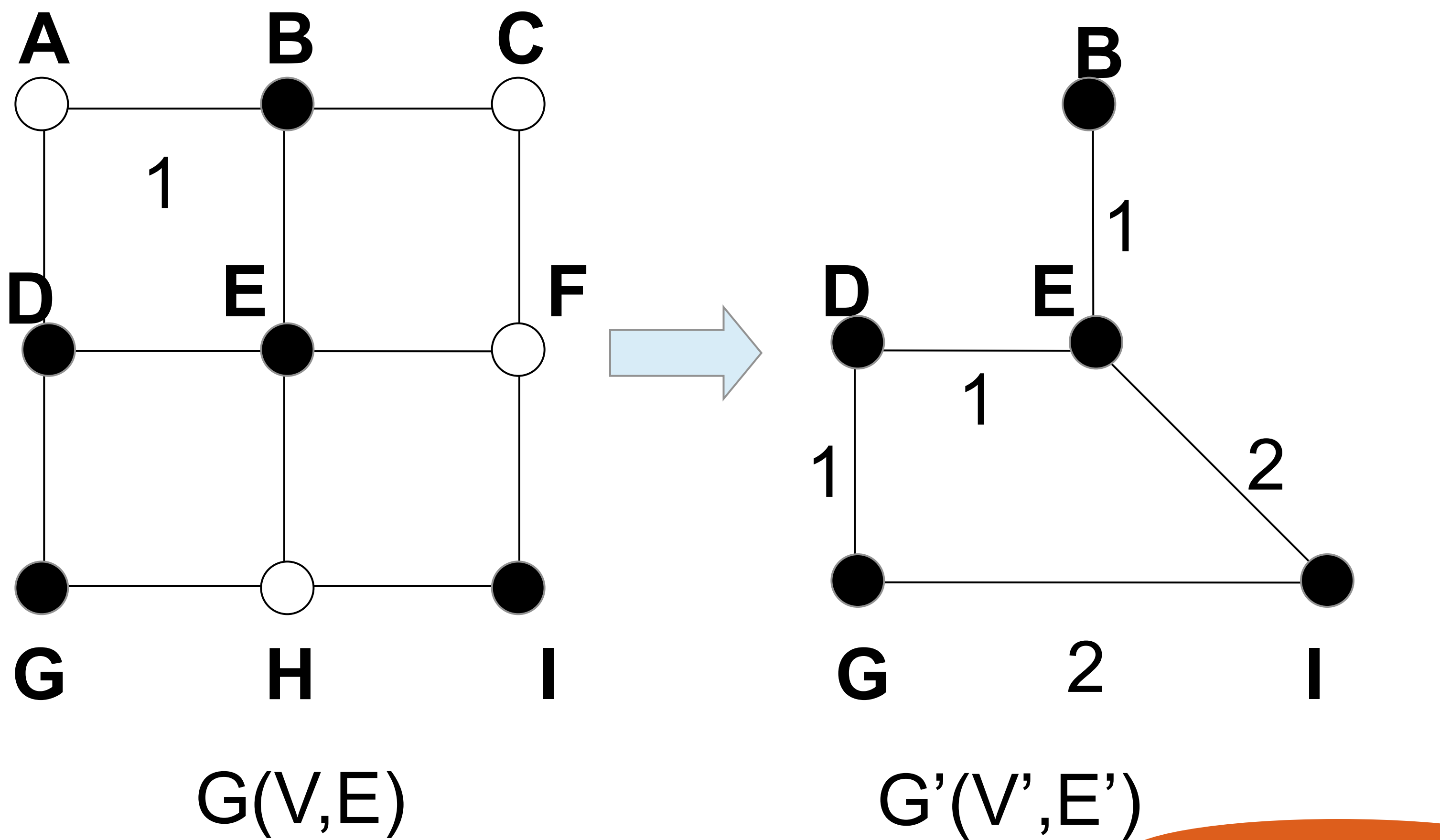
- E is starting node
- B, C, D, H, I are visited
- Cost = 8

Analysis of Algo. 1

- Lemma 1: Its resulted q-edge forest is a minimum q-edge forest
- Lemma 2: The cost of the minimum q-edge forest is a lower bound of the optimal MTSW cost
- Theorem: Algorithm 1 is a (2-1/q) approximation algorithm

Equivalency b/t MTSW and DAO^2

Theorem: DAO^2 in sensor network G(V,E) is equivalent to MTSW in aggregation network G'(V',E')



Distributed DAO^2 Algorithm

Based on distributed minimum spanning tree algorithm by Gallager, Humblet, and Spira

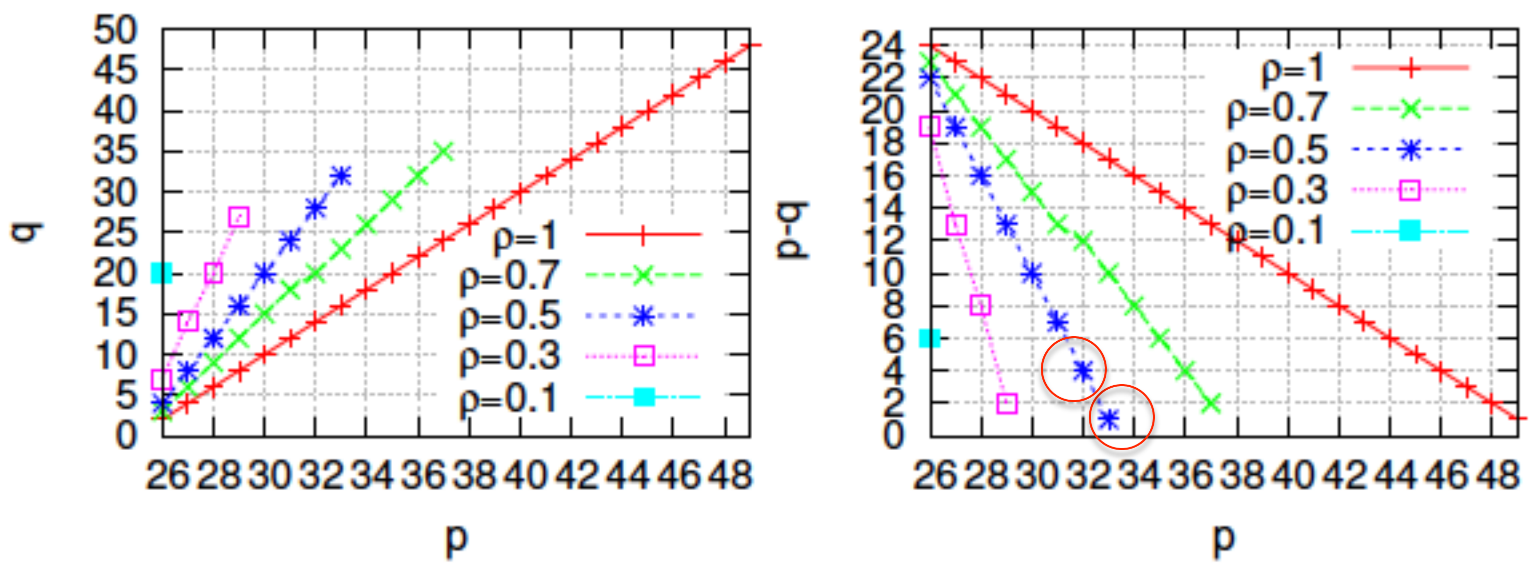
1. Starts with each node being considered as a fragment, with level value 0
2. Each level 0 node
   1) Chooses its minimum-weight incident edge and mark that edge as a branch edge.
   2) Sends a message via the branch edge to notify the node on the other side.
   3) Waits for a message from the other end of the edge.
3. The edge chosen by both nodes it connects becomes the core with level 1.
4. For a non-zero level fragment, the execution takes three stages: broadcast, convergecast, and change core
5. **while** (number of branch edges $< q$)
   1) Each fragment finds its minimum weight outgoing edge
   2) Uses it to combine with other fragments, using two operations: merge and absorb

end while

It runs in O(NlogN) time and uses O(NlogN+E) messages.

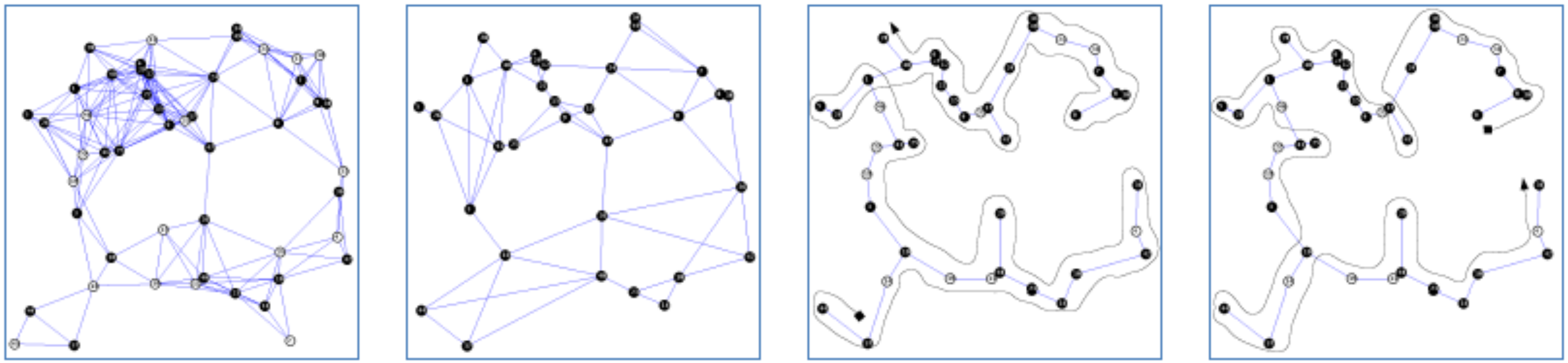
Performance Evaluation

- **Visual Performance Comparison**
  - 50 nodes in 1000m×1000m network, Tr = 250m
  - R=m=512MB, $\rho = 1 - r/R$



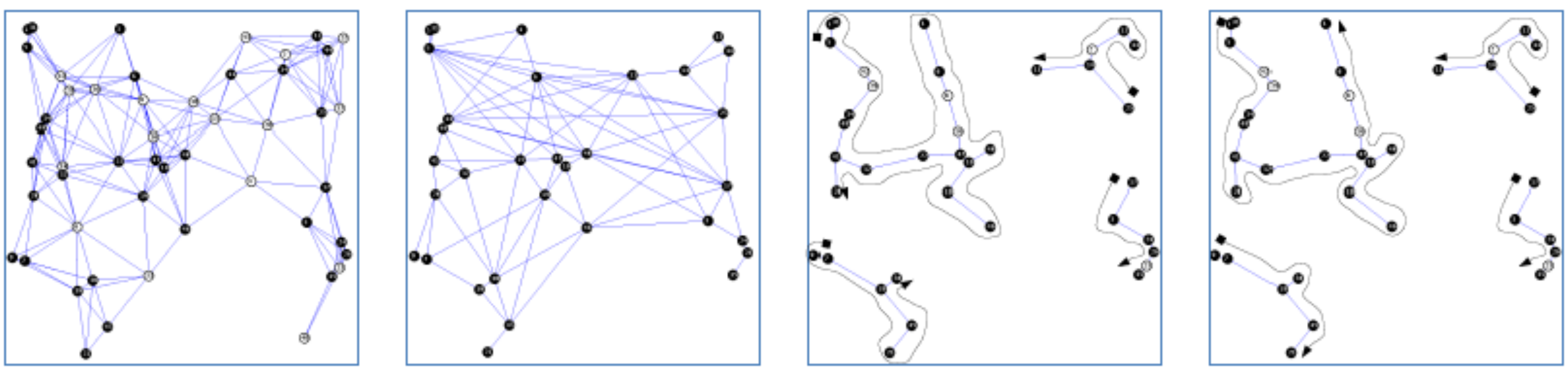
(a) q vs. p. (b) $p - q$ vs. p.

Fig. 6. Valid range of p while varying ρ ($R = m$).



(a) Sensor network graph. (b) Aggregation graph. (c) B-Walk (cost=381.2J). (d) LP-Walk (cost=290.6J).

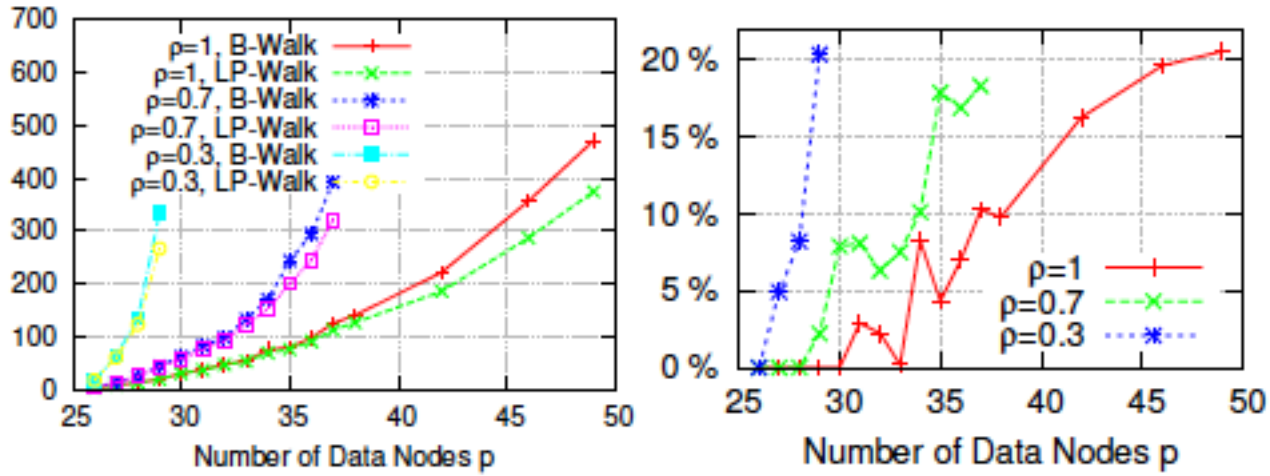
One initiator



(a) Sensor network graph. (b) Aggregation graph. (c) B-Walk (cost=255.9J). (d) LP-Walk (cost=203.0J).

Four initiators

Comparing B-Walk and LP-Walk



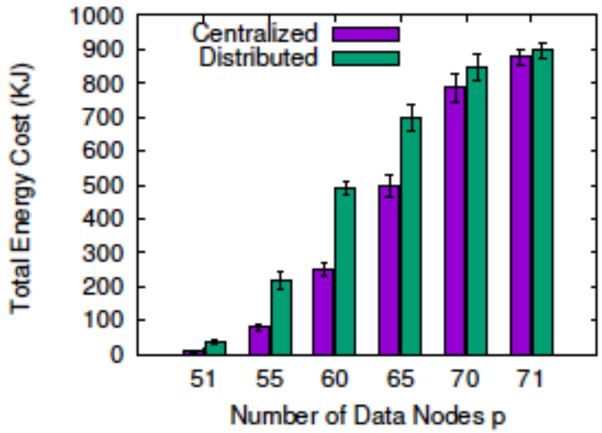
(a) Total aggregation cost (KJ). (b) Performance improvement.

Fig. 9. Comparing B-Walk with LP-Walk by varying p and ρ.

Distributed DAO^2 Algorithm

p	55	60	65	70	71
q	17	34	50	67	70
Number of Initiators	38	26	15	3	1
Centralized (KJ)	78.79	251.76	494.12	787.07	876.29
Distributed (KJ)	209.52	479.12	680.93	827.76	876.29

TABLE II
AGGREGATION COSTS IN CENTRALIZED AND DISTRIBUTED ALGORITHMS.



- Implemented in DistAlgo (Liu et al. OOPSLA 2012)
- 100 nodes in 2000m×2000m senor network, Tr = 250m
- R=m=512MB, overhead message = 20B

Conclusions and Future Works

- DAO^2 is an architectural and algorithmic framework to tackle overall storage overflow
- A new multiple traveling salesman walk problem
- Energy-efficient optimal, approximation, heuristic, and distributed algorithm
- Techniques applicable for any application where data correlation and resource constraints coexist
- Varying overflow data size and storage capacity
- Integrate data aggregation and data offloading