Data Gathering
Chapter 4

ETH
Eidgenössische Technische Hochschule Zürich
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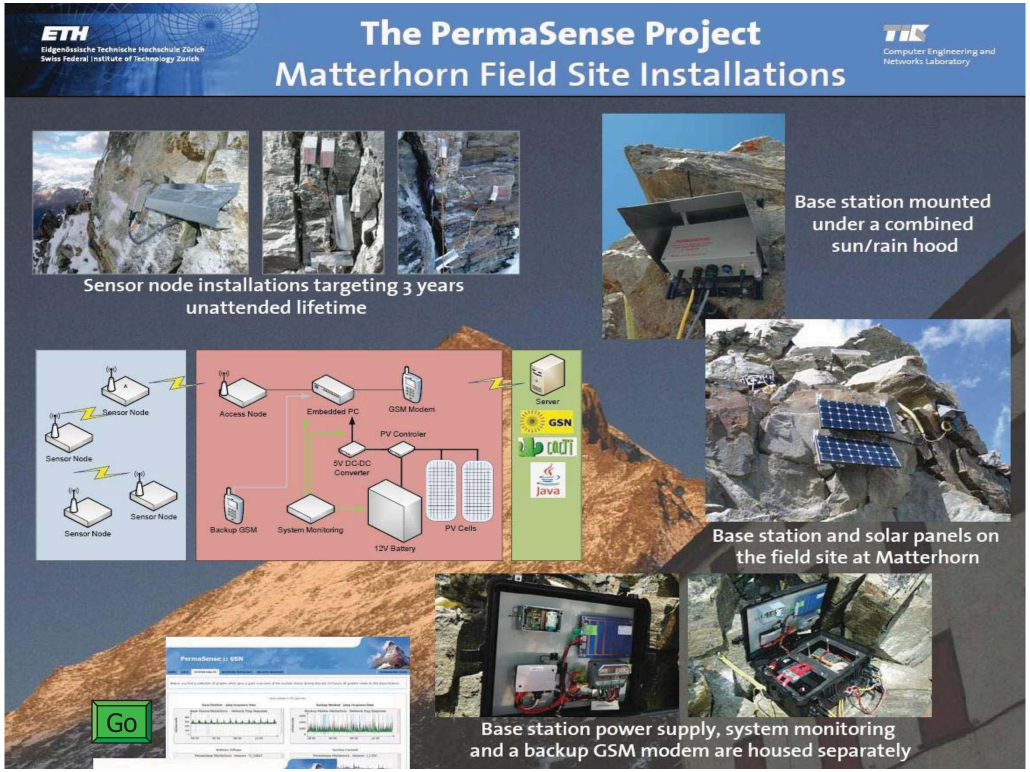


Rating

- Area maturity

  First steps — Text book

- Practical importance

  No apps — Mission critical

- Theoretical importance

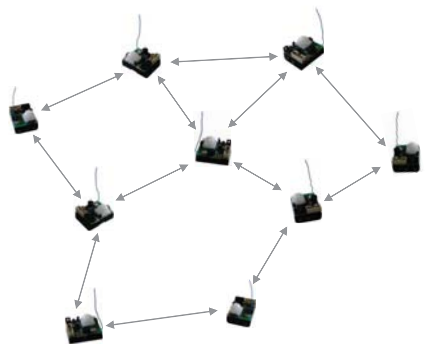
  Not really — Must have

Overview

- Motivation
- Data gathering
  - Max, Min, Average, Median, …
- Universal data gathering tree
- Energy-efficient data gathering: Dozer

Sensor networks

- Sensor nodes
  - Processor & memory
  - Short-range radio
  - Battery powered
- Requirements
  - Monitoring geographic region
  - Unattended operation
  - Long lifetime



What kind of traffic patterns may occur in a sensor network?

Data Gathering

- Different traffic demands require different solutions
- Continuous data collection
  - Every node sends a sensor reading once every two minutes
- Database-like network queries
  - “Which sensors measure a temperature higher than 21°C?”
- Event notifications
  - A sensor sends an emergency message in case of fire detection.

Sensor Network as a Database

- Use paradigms familiar from relational databases to simplify the “programming” interface for the application developer.

```
SELECT roomno, AVERAGE(light), AVERAGE(volume)
FROM sensors
GROUP BY roomno
HAVING AVERAGE(light) > l AND AVERAGE(volume) > v
EPOCH DURATION 5min
```

- TinyDB is a service that supports SQL-like queries on a sensor network.
  - Flooding/echo communication
  - Uses in-network aggregation to speed up result propagation.

```
SELECT <aggregates>, <attributes>
[FROM {sensors | <buffer>}]
[WHERE <predicates>]
[GROUP BY <exprs>]
[SAMPLE PERIOD <const> | ONCE]
[INTO <buffer>]
[TRIGGER ACTION <command>]
```


Distributed Aggregation

- Growing interest in distributed aggregation
  - Sensor networks, distributed databases...
- Aggregation functions?
  - *Distributive* (max, min, sum, count)
  - *Algebraic* (plus, minus, average)
  - *Holistic* (median, k^th smallest/largest value)
- *Combinations* of these functions enable complex queries.
  - „What is the average of the 10% largest values?“

What cannot be computed using these functions?

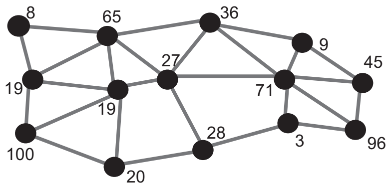
Aggregation Model

- How difficult is it to compute these aggregation primitives?

Can be generalized to an arbitrary number of elements!

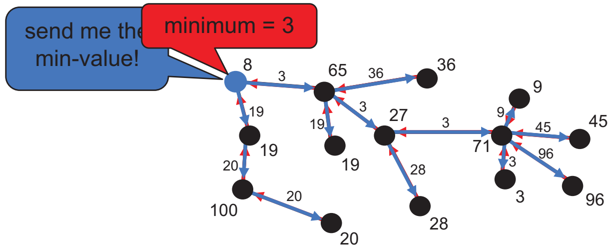
- Model:
  - All nodes hold a single element.
  - A spanning tree is available (diameter D).
  - Messages can only contain 1 or 2 elements.

O(1)



Computing the Minimum Value…

- Use a simple *flooding-echo* procedure → convergecast



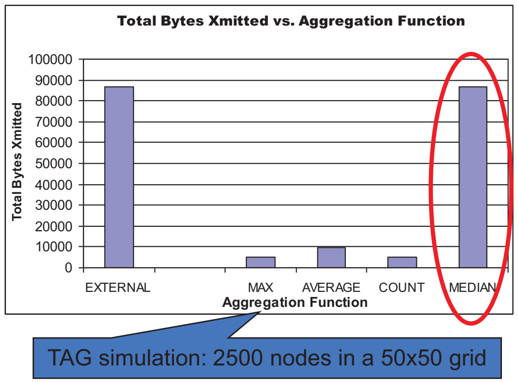
- Time complexity: $\Theta(D)$
- Number of messages: $\Theta(n)$

Distributive & Algebraic Functions

How do you compute the sum of all values?
... what about the average?
... what about a random value?
... or even the median?

Holistic Functions

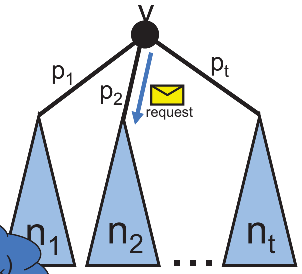
- It is widely believed that holistic functions are hard to compute using in-network aggregation.
  - Example: TAG is an aggregation service for sensor networks. It is fast for other aggregates, but not for the MEDIAN aggregate.



„Thus, we have shown that (...) in network aggregation can reduce communication costs by an order of magnitude over centralized approaches, and that, even in the worst case (such as with MEDIAN), it provides performance equal to the centralized approach.“

Randomized Algorithm

- Choosing elements uniformly at random is a good idea...
  - How is this done?



- Assuming that all nodes know the sizes $n_1,\ldots,n_t$ of the subtrees rooted at their children $v_1,\ldots,v_t$, the request is forwarded to node v_i with probability: $p_i := n_i / (1+ \Sigma_k n_k)$.

With probability $1 / (1+ \Sigma_k n_k)$ node v chooses itself.

- Key observation: Choosing an element randomly requires O(D) time!
  - Use pipe-lining to select several random elements!

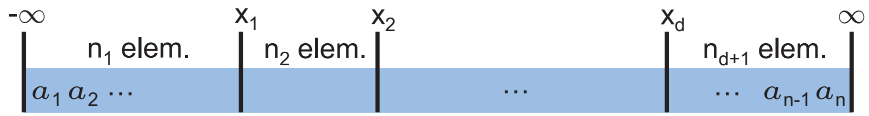
D elements in O(D) time!

Randomized Algorithm

- The algorithm operates in phases
  - A candidate is a node whose element is possibly the solution.
  - The set of candidates decreases in each phase.
- A phase of the randomized algorithm:

1. Count the number of candidates in all subtrees
2. Pick O(D) elements $x_1,\ldots,x_d$ uniformly at random
3. For all those elements, count the number of smaller elements!

Each step can be performed in O(D) time!



Randomized Algorithm

- Using these counts, the number of candidates can be reduced by a factor of D in a constant number of phases with high probability.

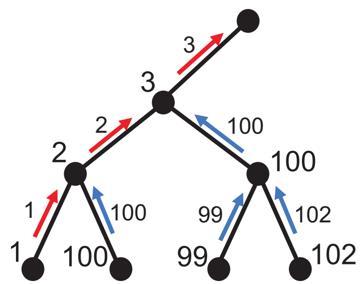
➡ The time complexity of is $O(D \cdot \log_D n)$ w.h.p.

With probability at least $1-1/n^c$ for a constant $c \geq 1$.

- It can be shown that $\Omega(D \cdot \log_D n)$ is a lower bound for distributed k-selection.
  - This simple randomized algorithm is asymptotically optimal.
- The only remaining question: What can we do deterministically?

Deterministic Algorithm

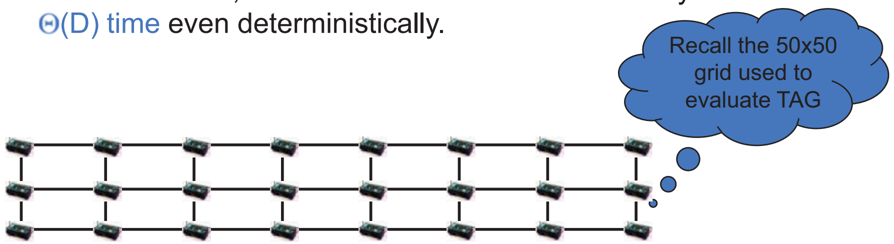
- Why is it difficult to find a good deterministic algorithm?
  - Finding a good selection of elements that provably reduces the set of candidates is hard.
- Idea: Always propagate the median of all received values.
- Problem: In one phase, only the h^{th} smallest element is found if h is the height of the tree...
  - Time complexity: $O(n/h)$



One could do a lot better!!! (Not shown in this course.)

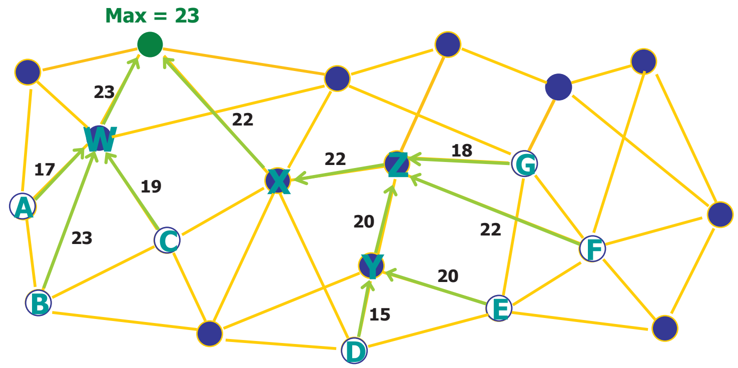
Median Summary

- Simple randomized algorithm with time complexity $O(D \cdot \log_D n)$ w.h.p.
  - Easy to understand, easy to implement…
  - Asymptotically optimal. Lower bound shows that no algorithm can be significantly faster.
- Deterministic algorithm with time complexity $O(D \cdot \log_D^2 n)$.
  - If $\exists c \leq 1$: $D = n^c$, k-selection can be solved efficiently in $\Theta(D)$ time even deterministically.



Sensor Network as a Database

- We do not always require information from all sensor nodes.
  - SELECT MAX(temp) FROM sensors WHERE node_id < "H".



Selective data aggregation

- In sensor network applications
  - Queries can be frequent
  - Sensor groups are time-varying
  - Events happen in a dynamic fashion
- Option 1: Construct aggregation trees for each group
  - Setting up a good tree incurs communication overhead
- Option 2: Construct a single spanning tree
  - When given a sensor group, simply use the induced tree

Group-Independent (a.k.a. Universal) Spanning Tree

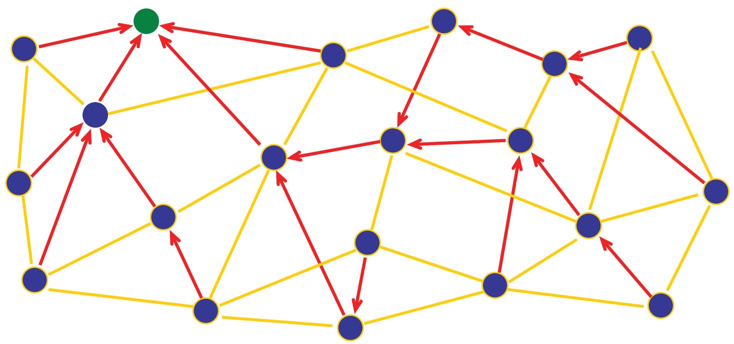
- Given
  - A set of nodes V in the Euclidean plane (or forming a metric space)
  - A root node $r \in V$
  - Define stretch of a universal spanning tree T to be

$$\max_{S \subseteq V} \frac{\text{cost(induced tree of } S+r \text{ on } T)}{\text{cost(minimum Steiner tree of } S+r)}.$$

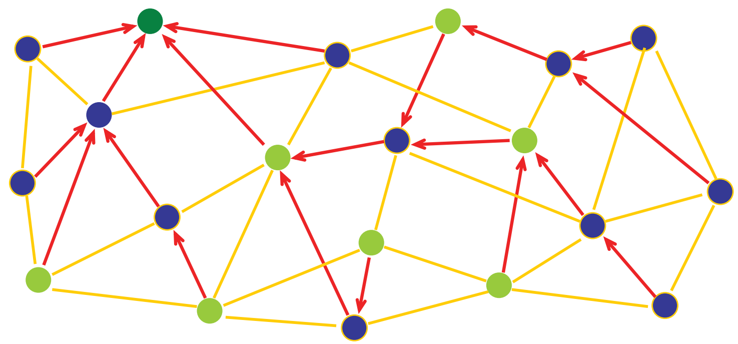
- We're looking for a spanning tree T on V with minimum stretch.

Example

- The red tree is the universal spanning tree. All links cost 1.

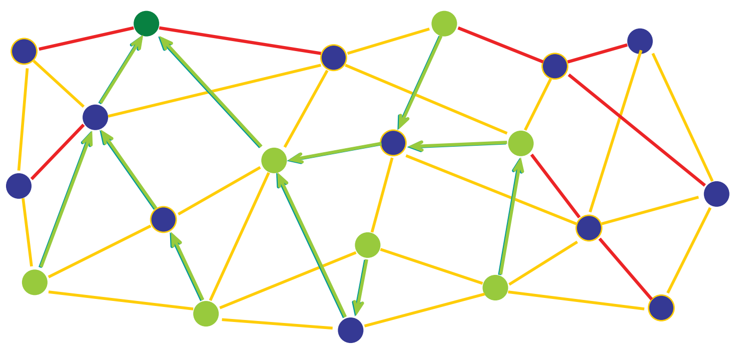


Given the lime subset…



Induced Subtree

- The cost of the induced subtree for this set S is 11. The optimal was 8.



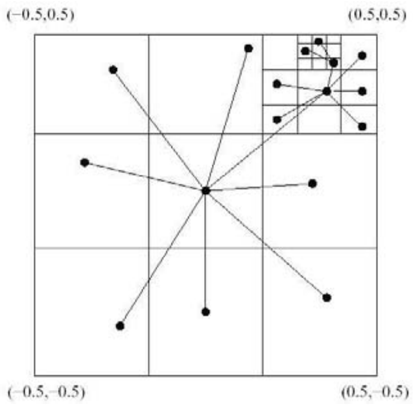
Main results

- [Jia, Lin, Noubir, Rajaraman and Sundaram, STOC 2005]
- Theorem 1: (Upper bound)
  For the minimum UST problem on Euclidean plane, an approximation of O(log n) can be achieved within polynomial time.
- Theorem 2: (Lower bound)
  No polynomial time algorithm can approximate the minimum UST problem with stretch better than Ω(log n / log log n).
- Proofs: Not in this lecture.

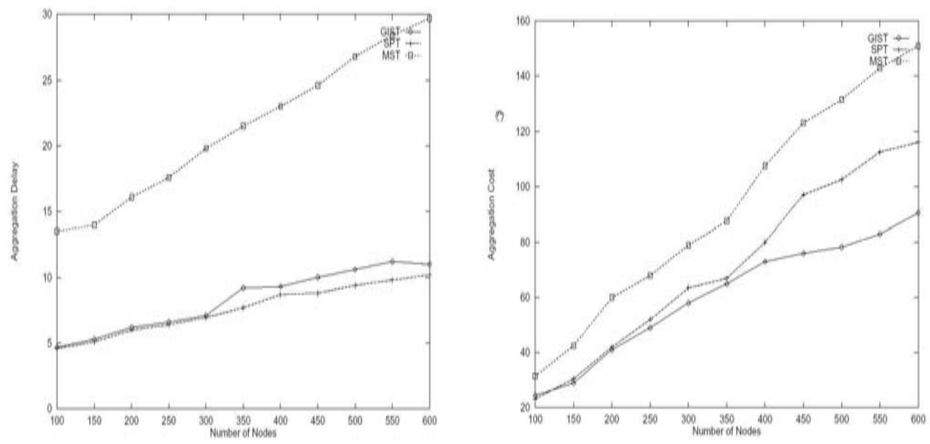
Algorithm sketch

- For the simplest Euclidean case:
- Recursively divide the plane and select random node.

- Results: The induced tree has logarithmic overhead. The aggregation delay is also constant.



Simulation with random node distribution & random events



Continuous Data Gathering

- Long-term measurements
- Unattended operation
- Low data rates
- Battery powered
- ~~Network latency~~
- ~~Dynamic bandwidth demands~~

Energy conservation is crucial to prolong network lifetime

Energy-Efficient Protocol Design

- Communication subsystem is the main energy consumer
  - Power down radio as much as possible

TinyNode	Power Consumption
uC sleep, radio off	0.015 mW
Radio idle, RX, TX	30 – 40 mW

- Issue is tackled at various layers
  - MAC
  - Topology control / clustering
  - Routing

➡ Orchestration of the whole network stack to achieve radio duty cycles of ~1‰

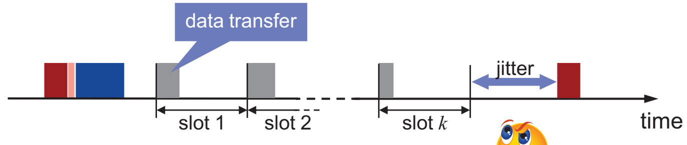
Dozer System

- Tree based routing towards data sink
  - No energy wastage due to multiple paths
  - Current strategy: Shortest Path Tree
- "TDMA based" link scheduling
  - Each node has two independent schedules
  - No global time synchronization

- The parent initiates each TDMA round with a beacon
  - Enables integration of disconnected nodes
  - Children tune in to their parent's schedule

Dozer System

- Parent decides on its children data upload times
  - Each interval is divided into upload slots of equal length
  - Upon connecting each child gets its own slot
  - Data transmissions are always acknowledged
- No traditional MAC layer
  - Transmissions happen at exactly predetermined point in time
  - Collisions are explicitly accepted
  - Random jitter resolves schedule collisions



Dozer System

- Lightweight backchannel
  - Beacon messages comprise commands
- Bootstrap
  - Scan for a full interval
  - Suspend mode during network downtime

periodic channel activity check

- Potential parents
  - Avoid costly bootstrap mode on link failure
  - Periodically refresh the list

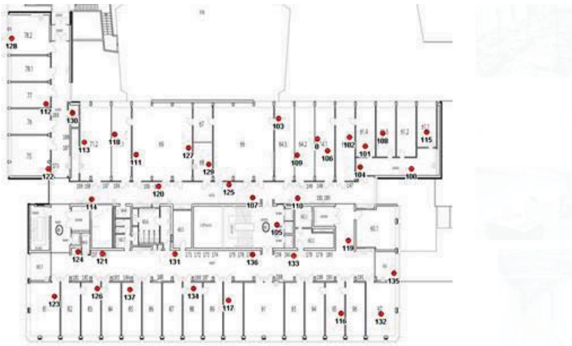
Dozer System

- Clock drift compensation
  - Dynamic adaptation to clock drift of the parent node

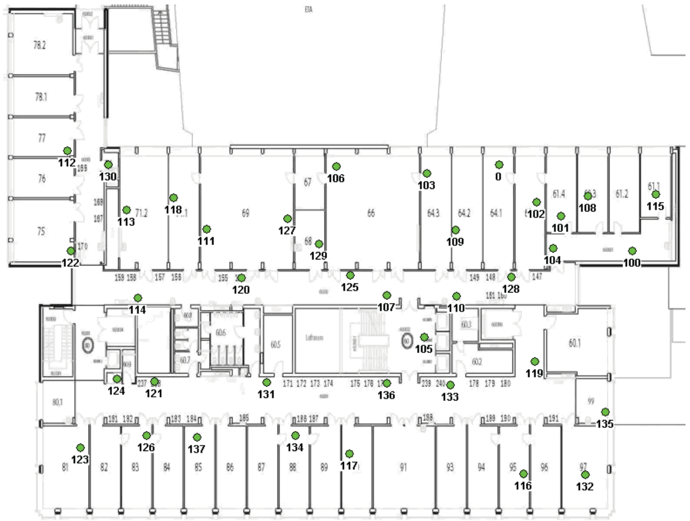
- Application scheduling
  - Make sure no computation is blocking the network stack
  - TDMA is highly time critical
- Queuing strategy
  - Fixed size buffers

Evaluation

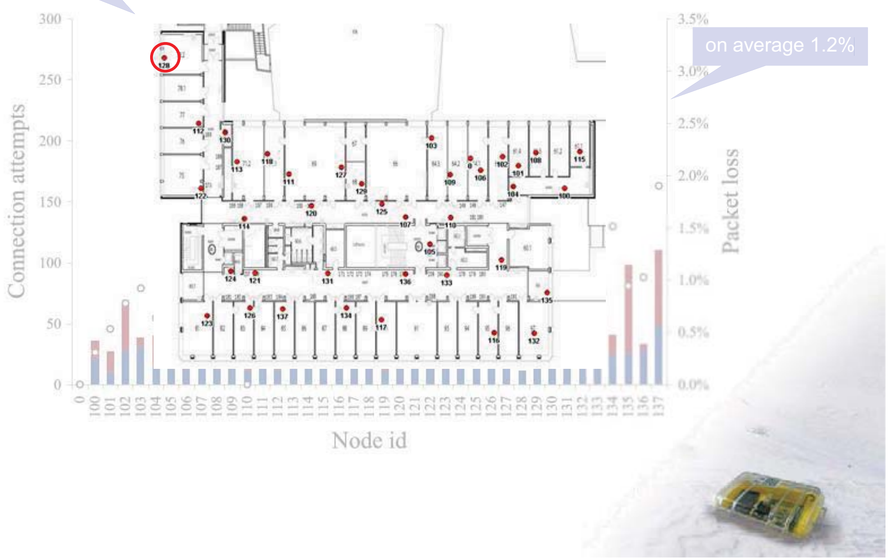
- Platform
  - TinyNode
    - MSP 430
    - Semtech XE1205
  - TinyOS 1.x
- Testbed
  - 40 Nodes
  - Indoor deployment
  - > 1 month uptime
  - 30 sec beacon interval
  - 2 min data sampling interval



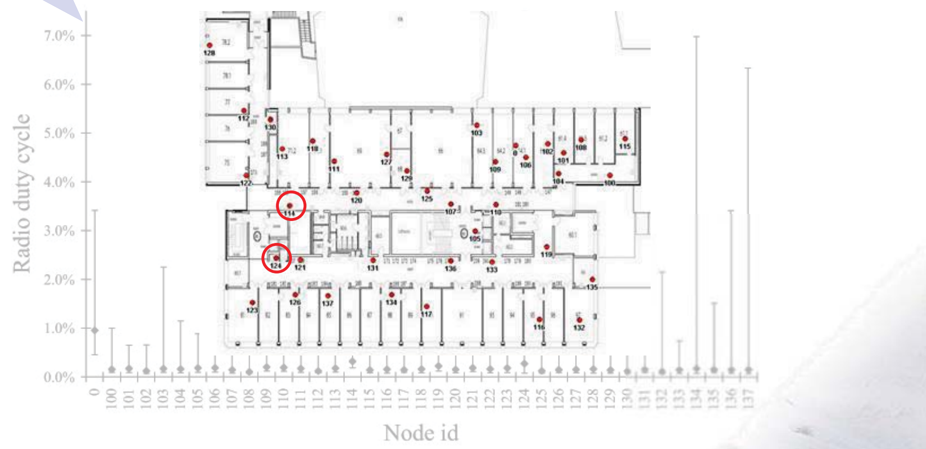
Dozer in Action



Tree Maintenance

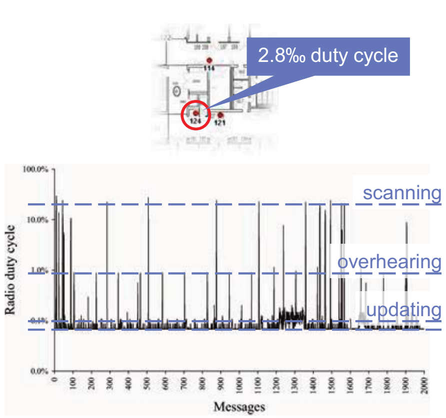


Energy Consumption

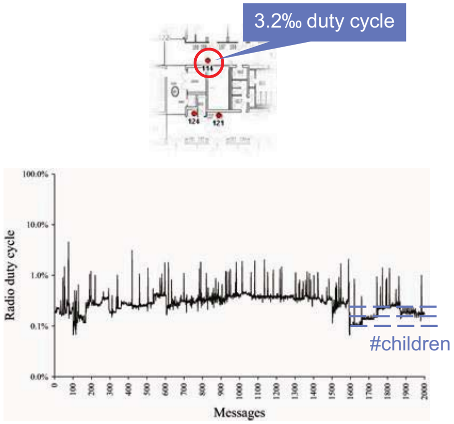


➡ Mean energy consumption of 0.082 mW

Energy Consumption



- Leaf node
- Few neighbors
- Short disruptions



- Relay node
- No scanning

More than one sink?

- Use the anycast approach and send to the closest sink.
- In the simplest case, a source wants to minimize the number of hops. To make anycast work, we only need to implement the regular distance-vector routing algorithm.
- However, one can imagine more complicated schemes where e.g. sink load is balanced, or even intermediate load is balanced.

Dozer Conclusions & Possible Future Work

- Conclusions
  - Dozer achieves duty cycles in the magnitude of 1‰.
  - Abandoning collision avoidance was the right thing to do.
- Possible Future work
  - Optimize delivery latency of sampled sensor data.
  - Make use of multiple frequencies to further reduce collisions.

Open problem

- Continuous data gathering is somewhat well understood, both practically and theoretically, in contrast to the two other paradigms, event detection and query processing.
- One possible open question is about event detection. Assume that you have a battery-operated sensor network, both sensing and having your radio turned on costs energy. How can you build a network that raises an alarm quickly if some large-scale event (many nodes will notice the event if sensors are turned on) happens? What if nodes often sense false positives (nodes often sense something even if there is no large-scale event)?