Can mobility improve WSN performance?

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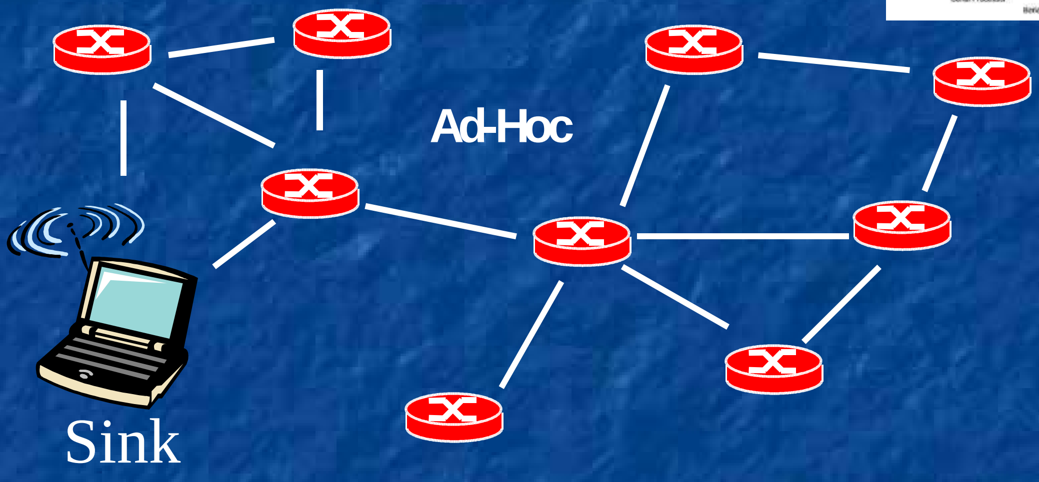
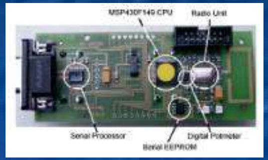
Wireless Sensor Networks

Traditional view



Sensor node

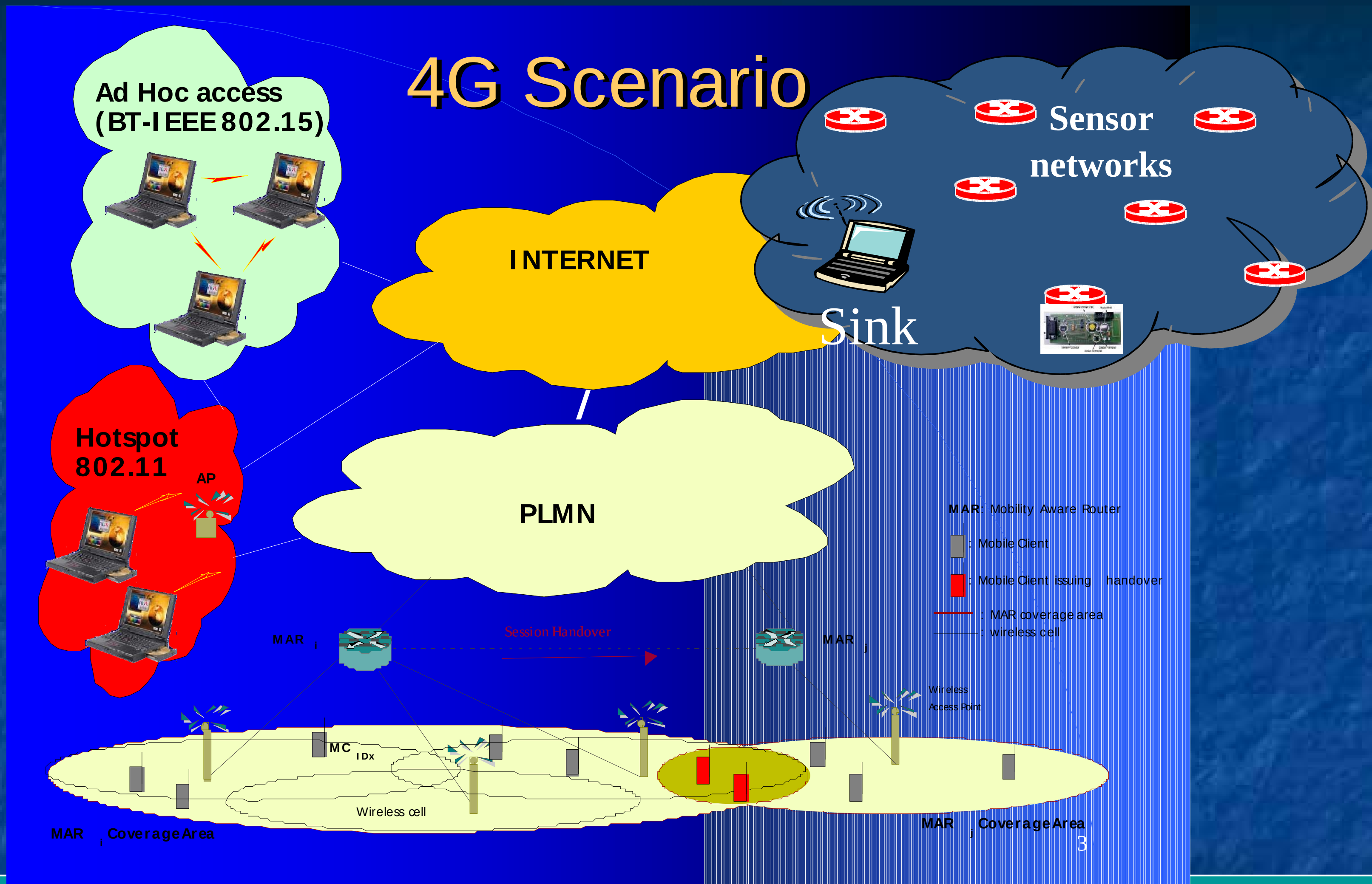


Traditional applications

-environmental monitoring
-precision agriculture
- structural integrity of buildings/bridges
- military applications
….

A sensor network is a network whose nodes have sensing, (actuating), (wireless) transmission capability. Nodes cooperate to perform monitoring of events of interest. Communication is via multi-hop paths to/from more resource-rich devices called sinks

Wireless Sensor Networks



A sensor network is a network of nodes which monitor events of interest to provide ambient intelligence. Such intelligence can be exploited by existing networks to provide value added services.

WSN: features and constraint

- Sensor nodes are very limited in terms of
  - *energy*, memory, computational power
- Are deployed in very large numbers in often hostile, inaccessible areas →batteries cannot be recharged/replaced
- Communication is from the sink to the sensor nodes (interest dissemination) and from the sensor nodes to the sink (convergecasting)
- Systems must be operational for long times (say years)
- Traffic maybe low
- Nodes and network elements are static (TRUE ??)

⬇

- Need to adopt simple, fully distributed, scalable, schemes

- Energy-efficiency really an issue for system implementation
  - key metric: network lifetime ← time till the system is fully operational)
  - key element: exploit the fact nodes transceiver can alternate between awake and asleep (low energy-consuming) modes

WSN: Where we are today

<u>A lot has been done already</u> on the design of energy-efficient protocols for WSNs…

- **Energy-efficient design of protocols at the PHY,MAC, routing layers**
- **Exploitation of data aggregation, awake-asleep scheduling**
- **Cross-layer optimizations to design an overall energy-efficent solution**
- **Homogenous networks usually assumed**

<u>Current hot topics</u>

- **Need of large-scale real-life testing, and of development of tools to enable extensive testing**
- **Mobility of some of the network elements is an emerging issue still to dealt with**
  - **As associated to some specific scenarios**
  - **<u>As able to improve performance (today's talk)</u>**
- **Scalability issues should be accounted for**

Why mobility in sensor networks?

- To allow communication between different connected components of the network → allowing also sparse networks to operate
- To reduce energy consumption
- To better load balance energy consumption among the nodes → increasing lifetime
- To improve placement (sensors mobility) and coverage

Different Architectures and mobility

Which network component is mobile?

Sensor Nodes

Sensor nodes are mobile (usually for better placement)

Sensors are attached to mobile devices (e.g. car, buses)

Mobile Agents

Communication to/from the sensor nodes only when the agent passes by → energy-latency trade-off

Sink

Allows improvements in performance. Communication can be multi-hop.

- Uncontrolled, unpredictable mobility
- Uncontrolled predictable mobility
- Controlled mobility

An example: Data Mules

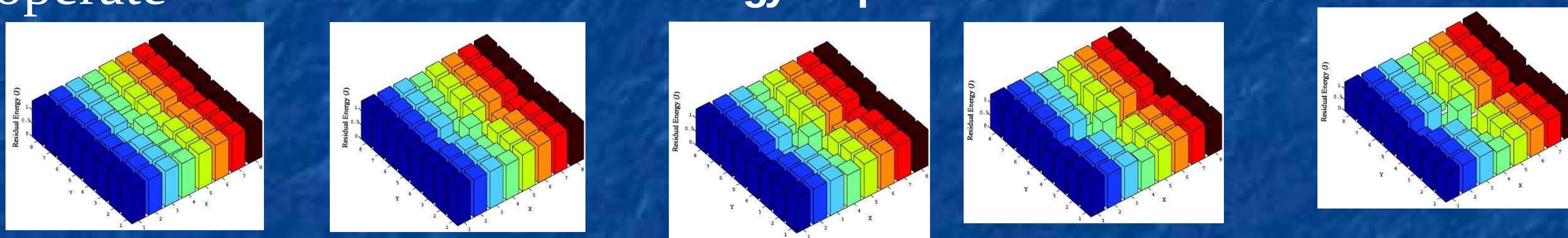
- Sensor nodes communicate data to MULEs when they pass by
- MULEs store the info they gather and delivery them to the sink when they pass by

low complexity & energy vs. latency

Our idea: controlled sink mobility

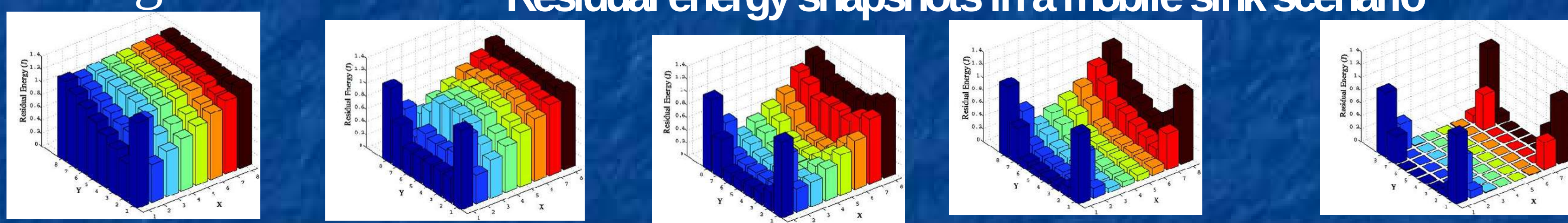
Idea: If the sink is static independently of the routing protocol adopted nodes close to the sink will fast deplete their energy and die → sink disconnection → the WSN can no longer operate

Residual energy snapshots in a static sink scenario



If the sink can move the energy consumption is more fairly balanced among nodes

Residual energy snapshots in a mobile sink scenario



If sink mobility can be controllable (e.g. the sink is a robot, an UV, or located over a moving object) then we can address how it should move to maximize lifetime (general multi-hop WSN scenario)

Problem Formulation

- *Given n wireless sensor nodes deployed in an area, and a set of sink sites S determine the initial site, the route to be followed by the sink as well as the sojourn times t_k at each site k in S so that the network lifetime is maximized.*
- Each sensor node i trasmits data periodically with a rate r_i, has a transmission range and energy model which depend on the sensor node prototype. All sensor nodes use the same routing protocol (e.g. shortest path-geographic).

Problem Formulation

- We assume that each time the sink reaches a new site it informs the nodes which perform route maintenance accordingly
- When the sink decides to move it also informs the nodes
  - generated or in transit packets are buffered till nodes are informed of the new sink site
  - → longer traveled distances result in more time the packets may have to be buffered → longer latencies

A MILP formulation

Given a routing protocol, and a set of sink sites, how can we determine the sink route and sink sojourn times at the different sink sites to maximize the network lifetime?

$$Max \sum_{k\in S} t_k$$

$$\sum_{k\in S} c_{ik} t_k + \sum_{k\in S} f_{ik} y_k \le e_0 \qquad i\in N$$

$$t_{MIN}\, y_k \le t_k \le M y_k \qquad k\in S$$

$$\sum_{k\in S} x_{0k} = 1$$

$$\sum_{k\in S} x_{k,q+1} = 1$$

$$\sum_{\substack{j\in S\cup\{0\}\\ (j,k)\in O\cup A}} x_{jk} = \sum_{\substack{j\in S\cup\{q+1\}\\ (k,j)\in A\cup D}} x_{kj} \qquad k\in S$$

$$\sum_{\substack{j\in S\cup\{0\}\\ (j,k)\in O\cup A}} x_{jk} = y_k \qquad k\in S$$

$$u_j - u_k + q x_{jk} \le q-1 \qquad (j,k)\in A$$

$$t_k, u_k \ge 0 \quad y_k \in\{0,1\} \quad x_{jk}\in\{0,1\}$$

Distinguished Features of the Model

- The model can be applied to a sensor network with any geometric shapes, e.g. squares or circles.
- The model is independent from the underlying sensor network topology, a grid or any arbitrary topology.
- The model can also work with any type of routing method, e.g., shortest path or geographic routing method.
- The model is not restricted with the transmission range or any physical parameters set up in the sensor nodes.
- The model accounts for the energy "costs" associated to changing the sink site.
- The model accounts for the extra latency induced during the sink movements
- The model is independent of the nodes density.
- *Partially controllable mobility and multi-sink scenarios can be easily accounted for*

A few notes on the model

- d_{max} to bound the packet latency
- t_{min} to control the effect of the sink mobility rate
- Routing-independent approach (the reasons why to use a given routing protocol can go beyond the lifetime only)
- Extensions:
  - Each site can be traversed h times instead of 1
  - The model can capture partially controllable mobility and a multi-sink scenario

Distributed Schemes: GMRE

- *We say the adjacent sites of a site are the sites within euclidean distance d_{max} from it*
- When the sink moves to a given site it also determines 'sentinels' for the adjacent sites k* (i.e. nodes in the tx range of k*)
- Every t_{min} the sink decides whether to move or stay
  - It contact each of the sentinels inquirying them about the residual energy around the associated site
  - Gather info on the sentinels
  - It moves drawn by the residual energies of the adjacent sites
    - If the current site is still the one with most residual energy it stays
    - Otherwise it move to the adjacent site with more residual energy
    - Residual energy= minimum residual energy of the nodes around the site

Distributed Schemes: RM

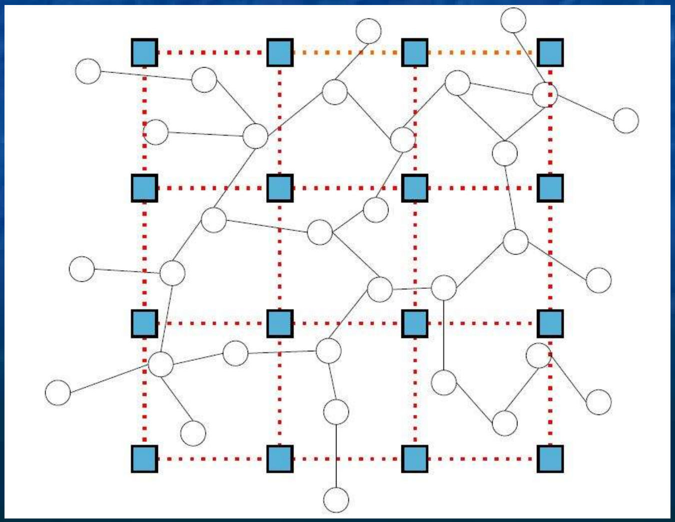
- Every t_{min} the sink moves randomly to one of the adjacent sites
  - Captures random mobility as in DATA MULES
  - Used for sake of benchmarking

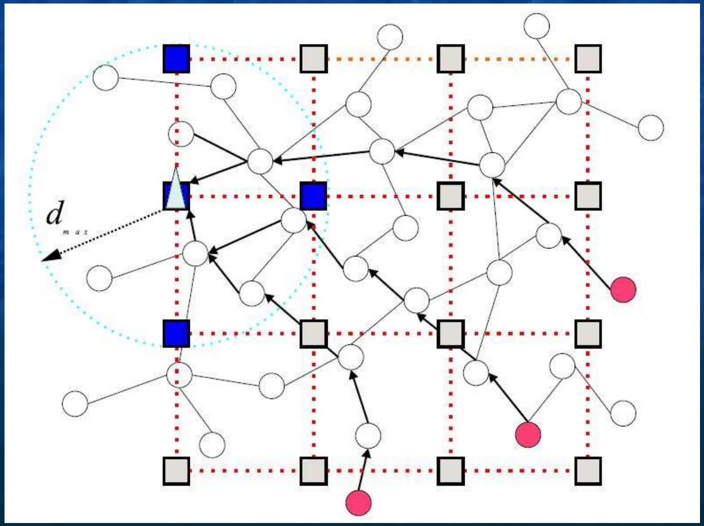
Simulation scenarios

- Ns-2 based
- Compared the performance of
  - Optimum sink mobility (MILP model) → OPT
  - Static sink optimally placed → STATIC
  - Random Mobility → RM
  - Greedy Maximum Residual Energy heuristic → GMRE
- Metrics of interest:
  - Network lifetime
  - Residual energy over time
  - Latency
  - Overhead
  - Sojourn times at the different sites

First experiments: Basic Scenario

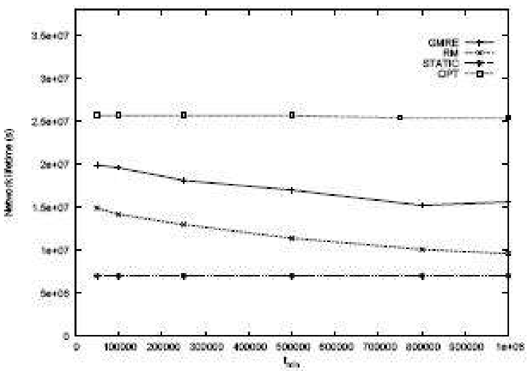
- Deployment area: 400mx400m square
- n = 400 nodes with 25m transmission range
- Sensor nodes initial energy 50J. Nodes equipped with TR1000 (14.8mW Tx, 12.5mW Rx)
- Data rate per node: 0.5bps, channel data rate: 250Kbps
- CSMA/CA MAC, "Shortest path like routing"
- Sink sites: 4x4,6x6,8x8 matrix
- Dmax=190m



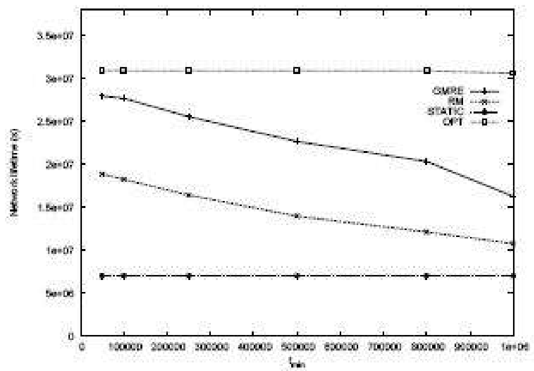


Basic Scenario: Results

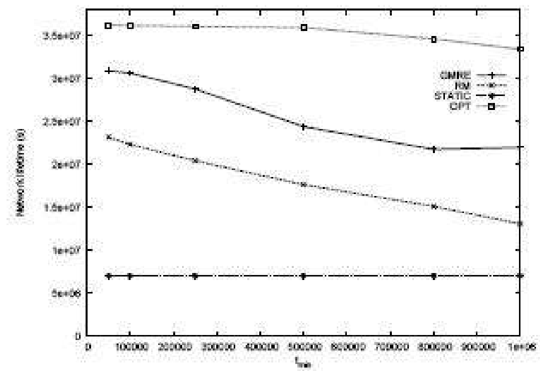
Network Lifetime



(a) 4 × 4 sink sites



(b) 6 × 6 sink sites

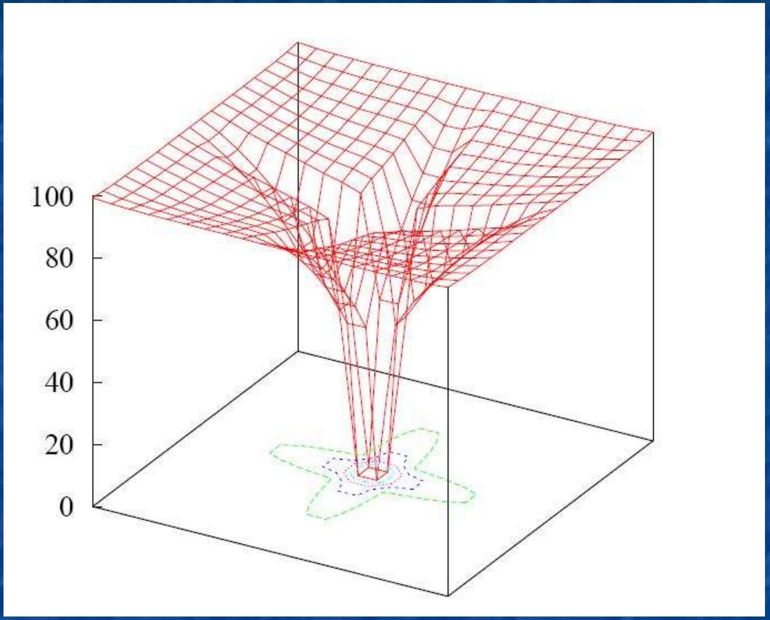


(c) 8 × 8 sink sites

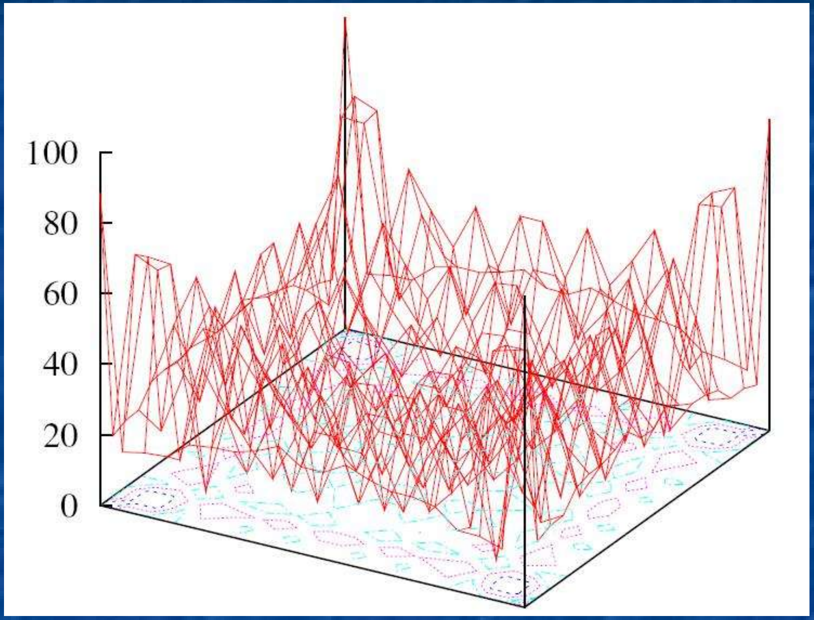
- GMRE:
  - 200-300% improvement over STATIC
  - 16-28% decrease wrt OPT lifetime
- RM:
  - 100-220% improvement over STATIC

Small t_{min}

Residual energies at lifetime



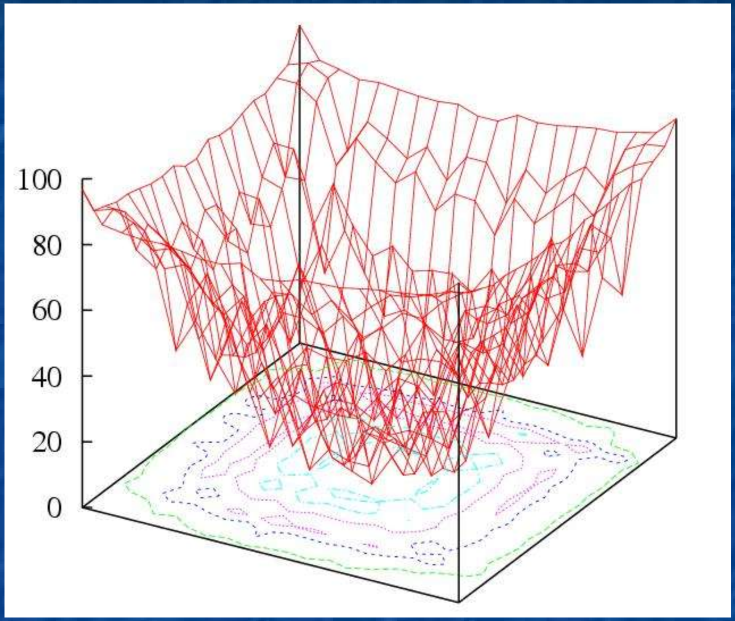
STATIC



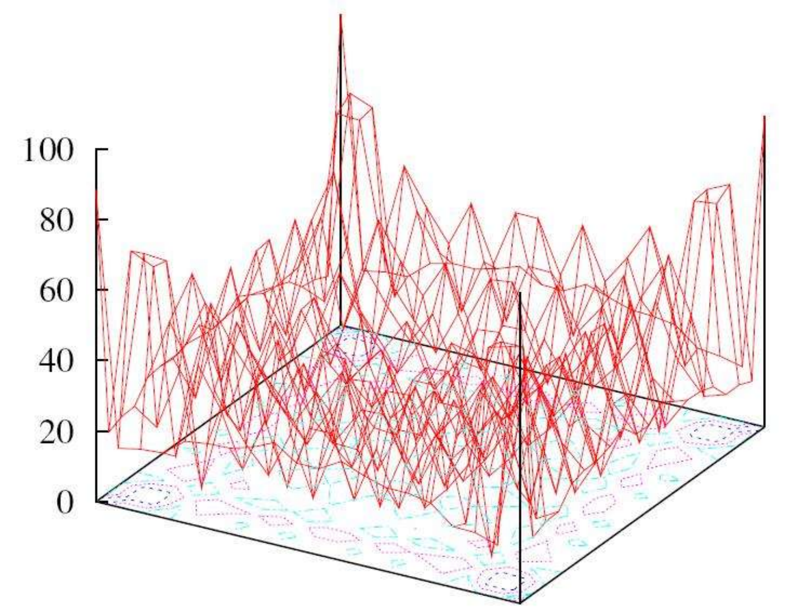
GMRE 8x8 sites

- STATIC: almost half of the nodes have >95% of the initial energy left at lifetime!!
- The other schemes are better able to load balance energy consumption among network nodes: the better the higher the network lifetime

Residual energies at lifetime



RM



GMRE 8x8 sites

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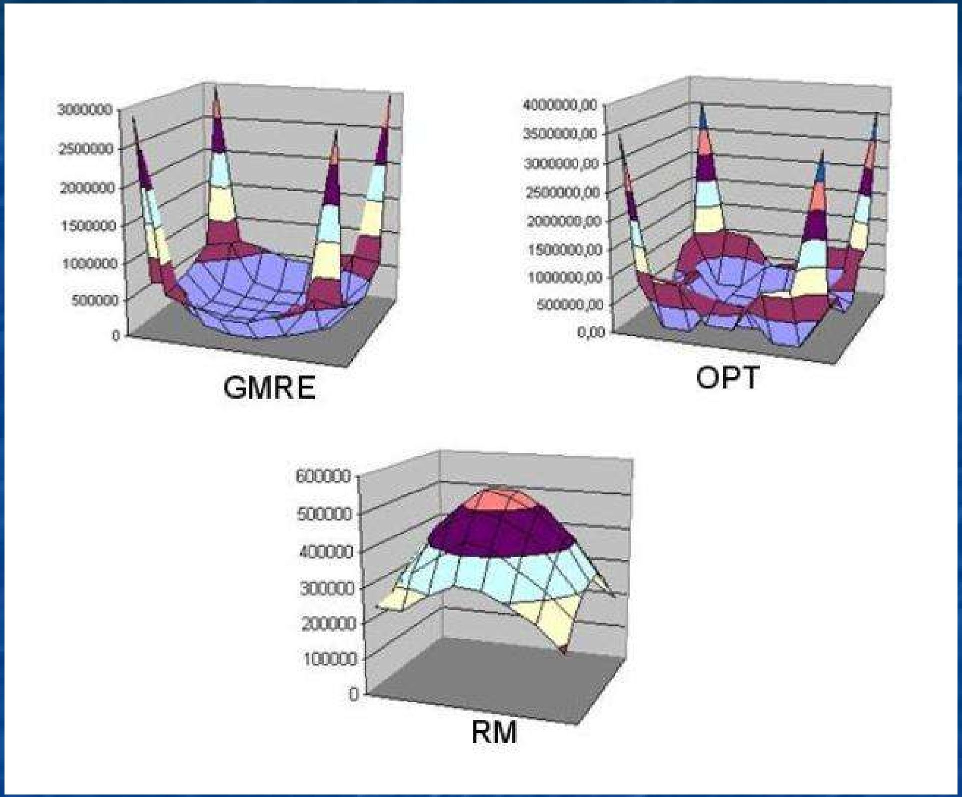
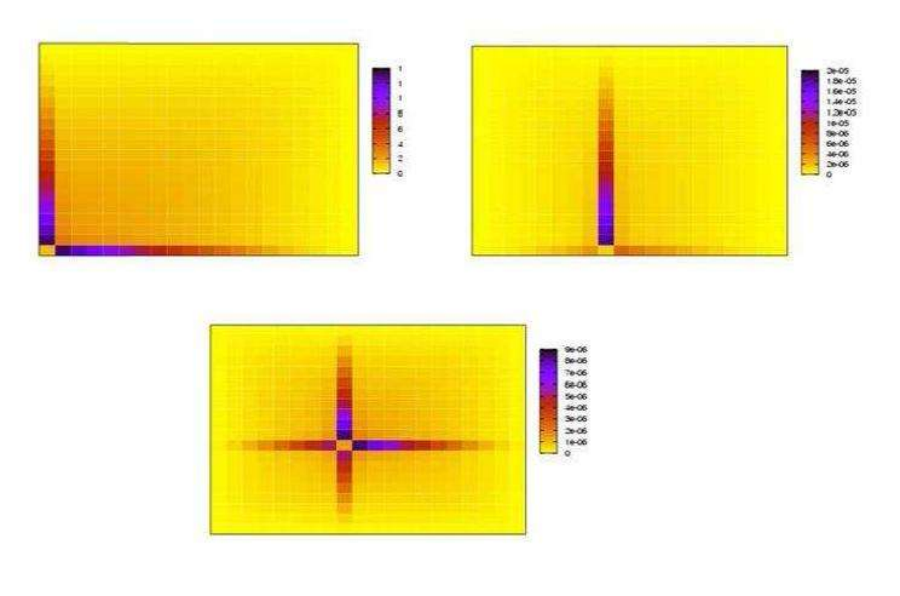
Sojourn times



Sojourn times

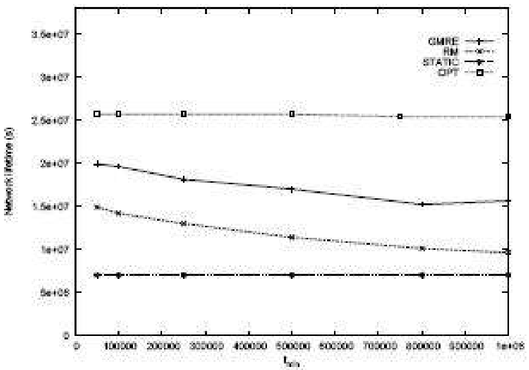


Energy consumption at the different Nodes when the sink stays at various Sink sites

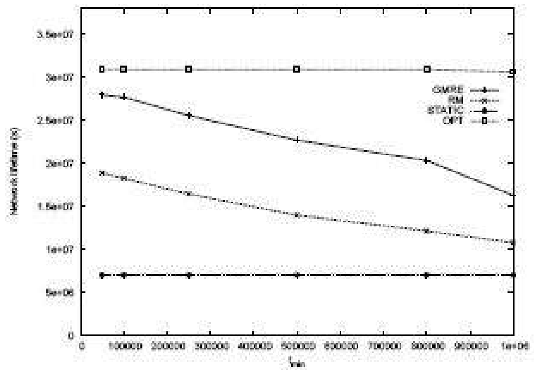
- RM does not account for residual energy
- OPT and GMRE spends most time at sites which impose
High energy consumption on nodes otherwise not stressed
- OPT able to better fine tune sojourn times

Basic Scenario: Results

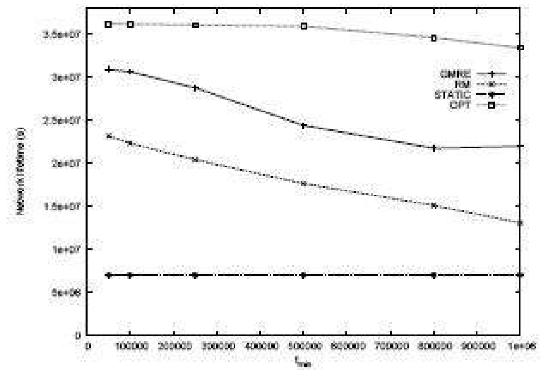
Network Lifetime



(a) 4×4 sink sites



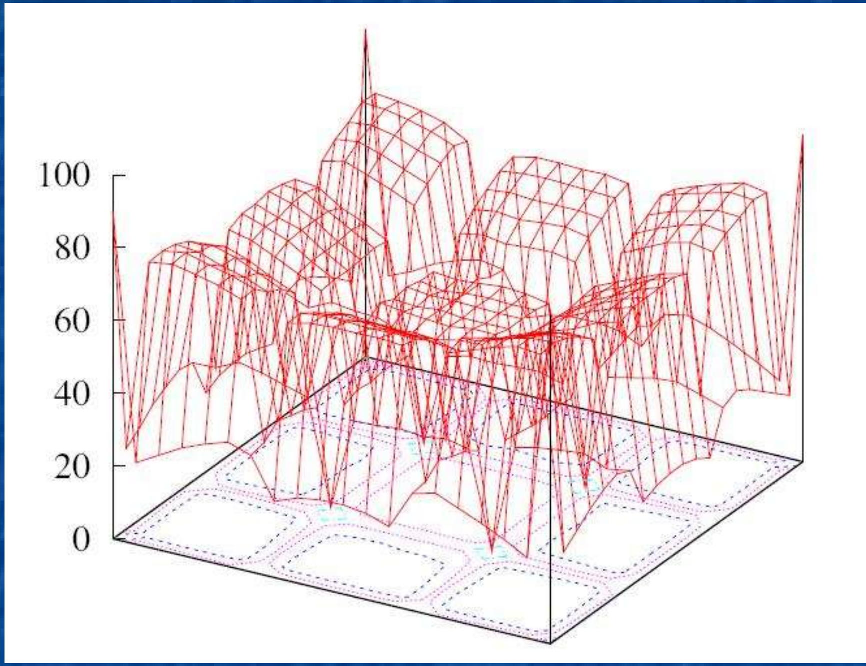
(b) 6×6 sink sites

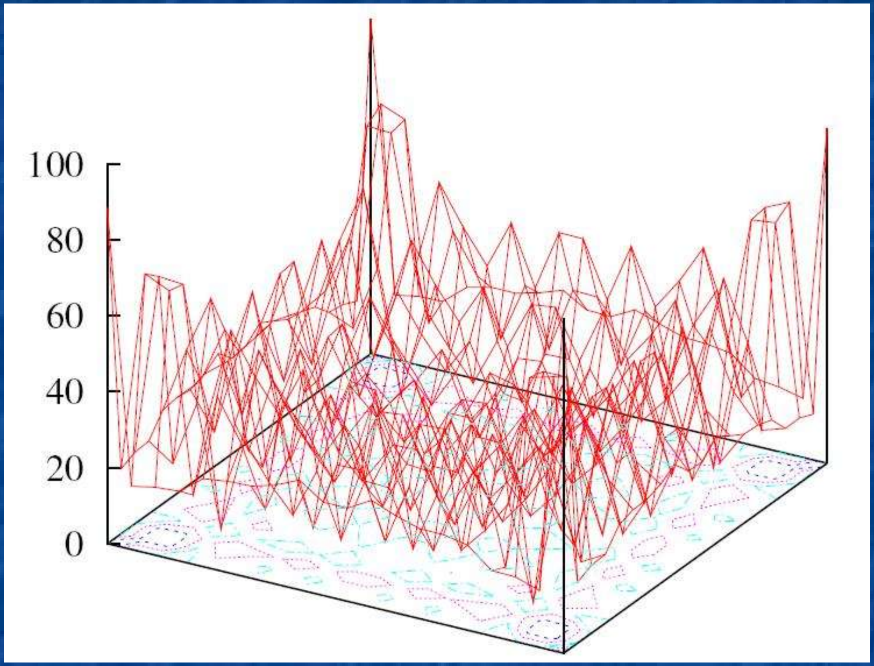


(c) 8×8 sink sites

- Decreases with t_{min} (low tmin better tuning of the sojourn times, less price to pay in case of a bad move)
- Increases with number of sites (better ability to drain energy from all the different parts of the network)

Impact of changing the number of sink sites

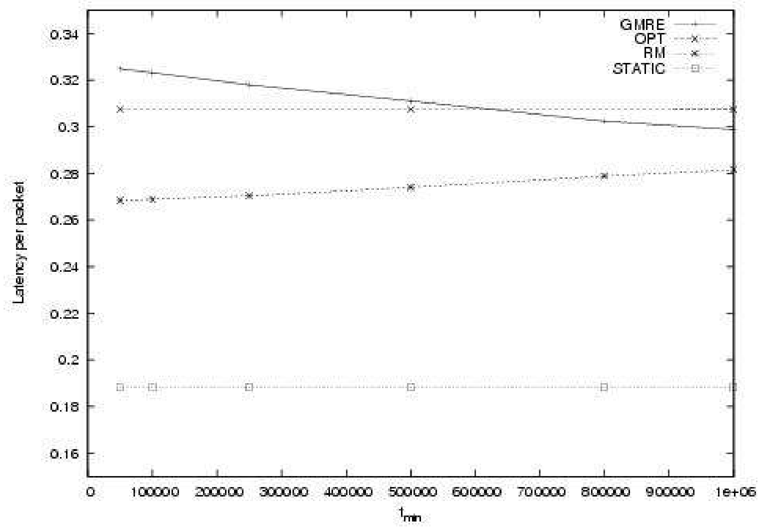


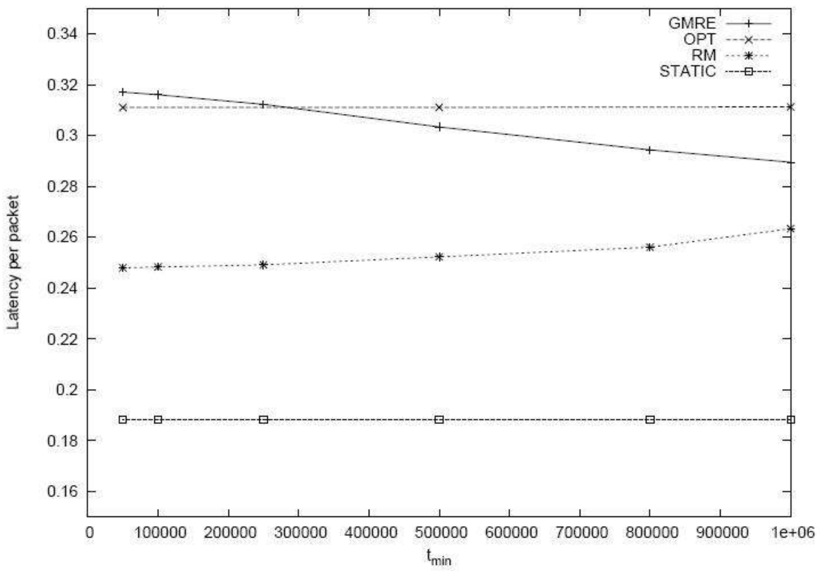


- GMRE, 16 and 64 sink sites
- Increasing the number of sink sites improves the ability to drain energy from all the different parts of the network

Packet Latency

Packet Latency

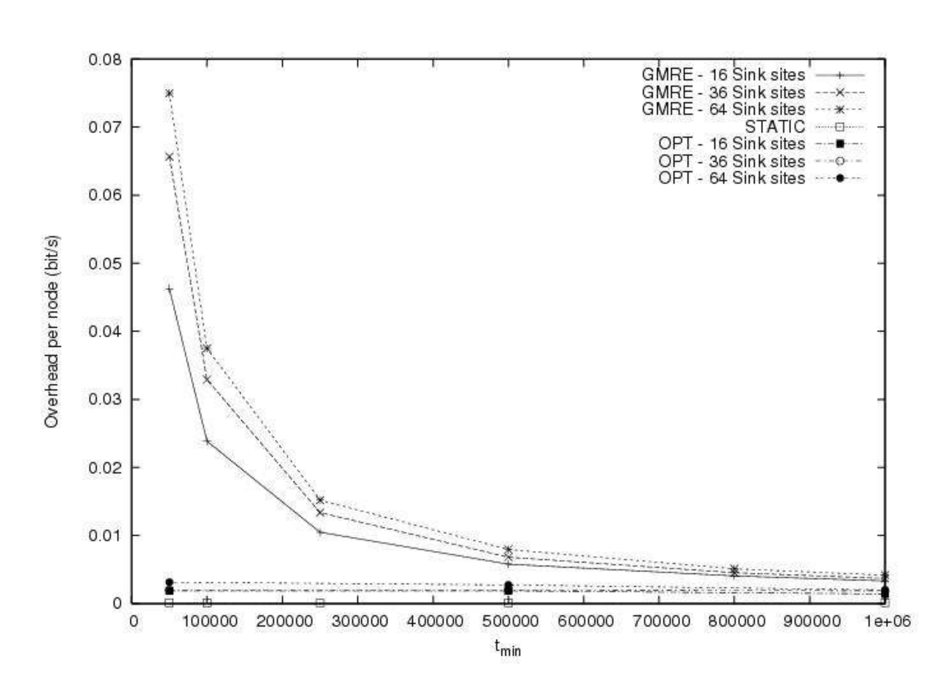


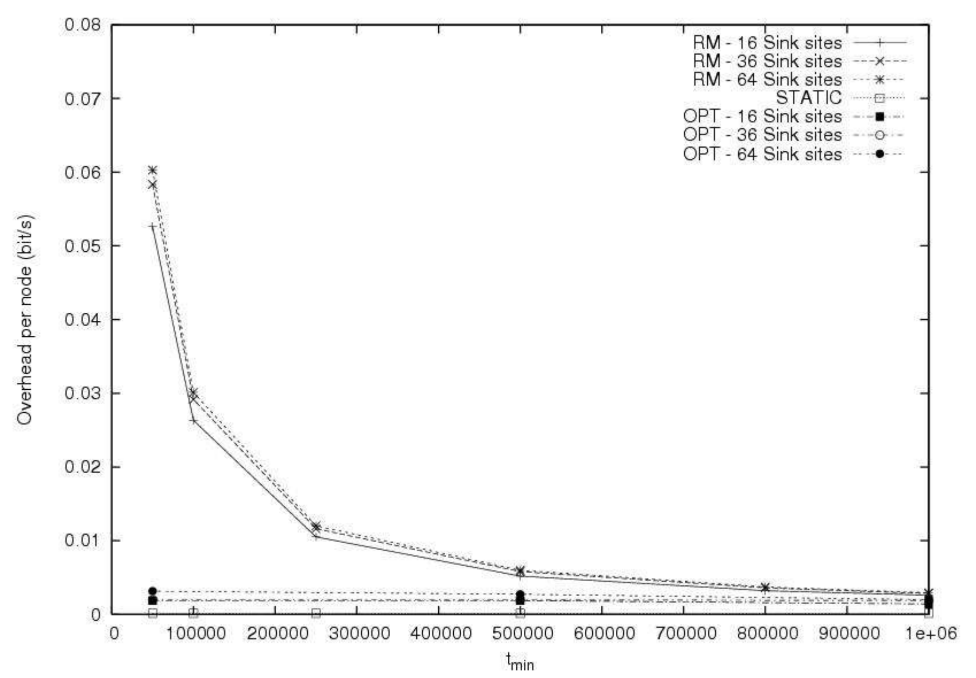


- Schemes which tend to stay also in external areas (for sake of energy conservation) results in higher latencies

Overhead

Overhead (bps)

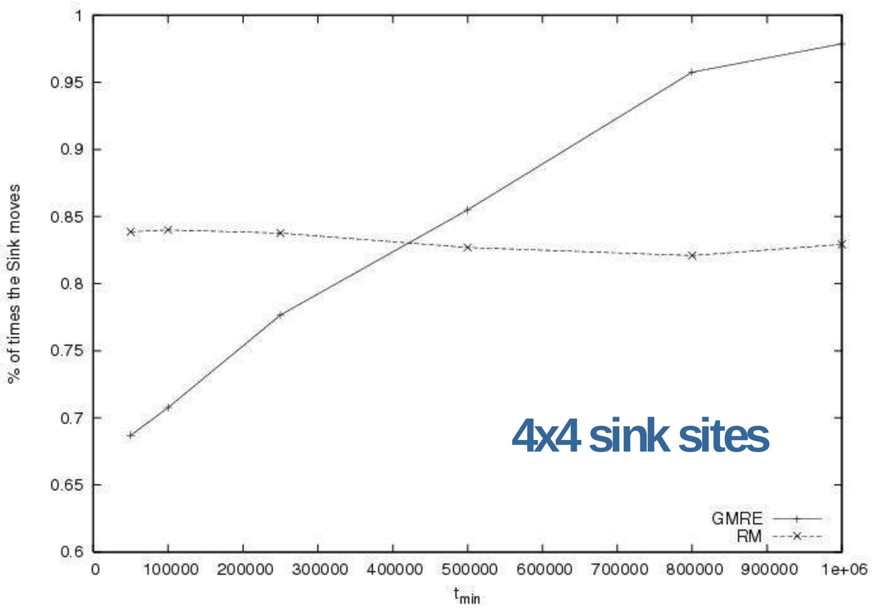


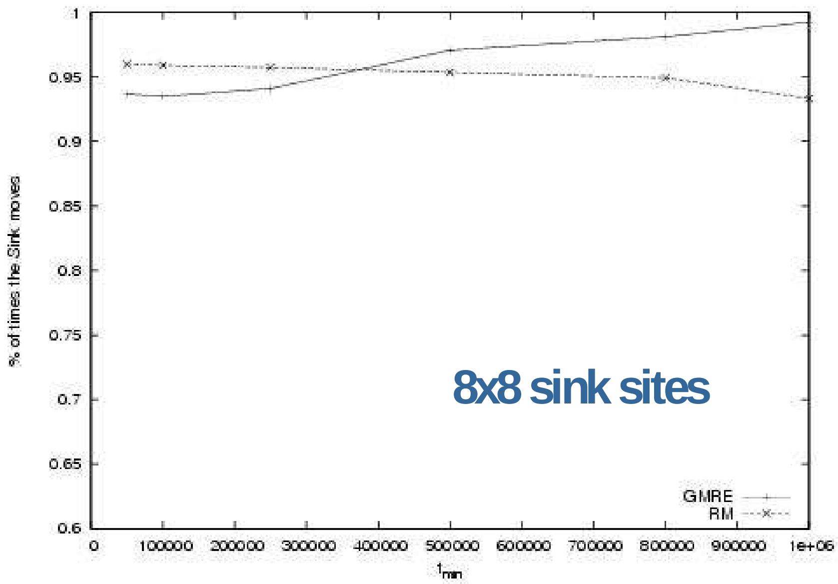


- OPT and STATIC result in basically no overhead
- GMRE and RM overhead decreases when the sink mobility rate decreases
- GMRE has higher costs (to inquiry sentinels and compute residual energies)→ especially at high num. sites

Percentage of times the sink moves

Percentage of times the sink moves



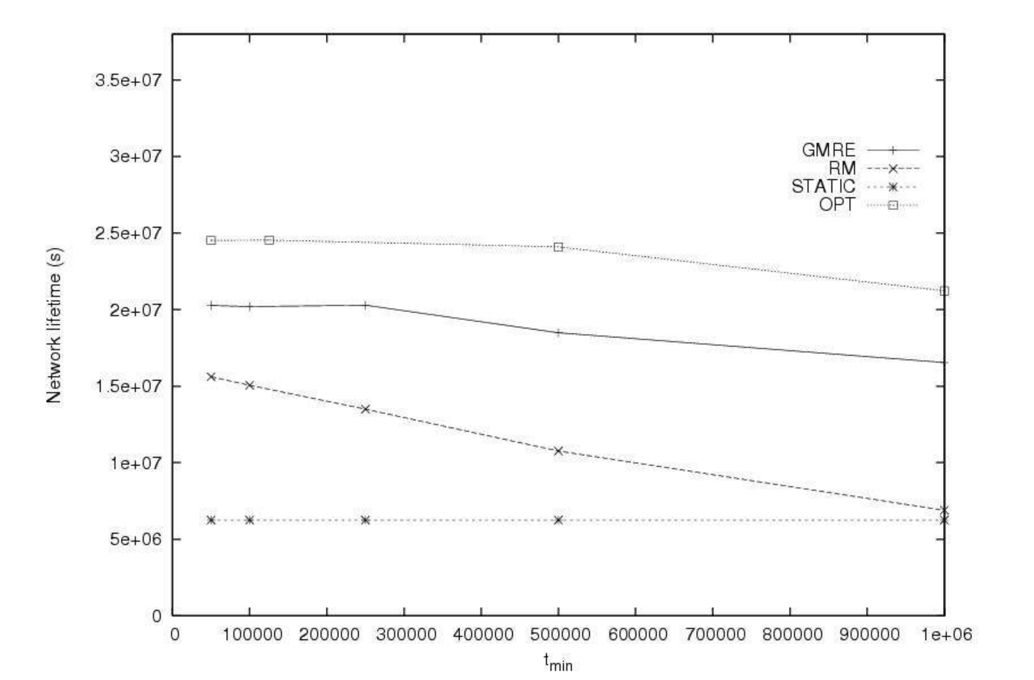


- Sink always almost moves
- The higher t_{min} the more RM stays at the external part of the area → the less it moves
- The higher t_{min} the more in GMRE is likely that one of the adjacent sites has more residual energy → the more the sink moves

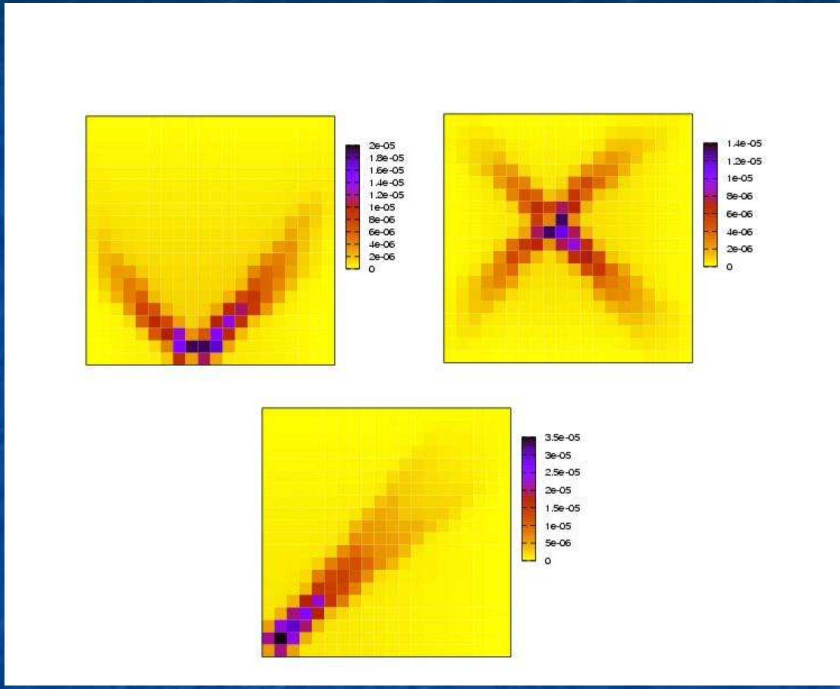
Other Results

- We have tested the proposed schemes when
  - Changing the transmission range or routing (→ changes the sojourn times and sink route but does not change the relative behavior of the different schemes)
  - Varying dmax (little effect in terms of lifetime)
  - Imposing limits on the area where the sink can stay
- Results show that the mobility pattern DEPENDS on the specific scenario but that the proposed heuristic well adapts to the different scenarios achiving performance close to the optimum.

GeRaF Results



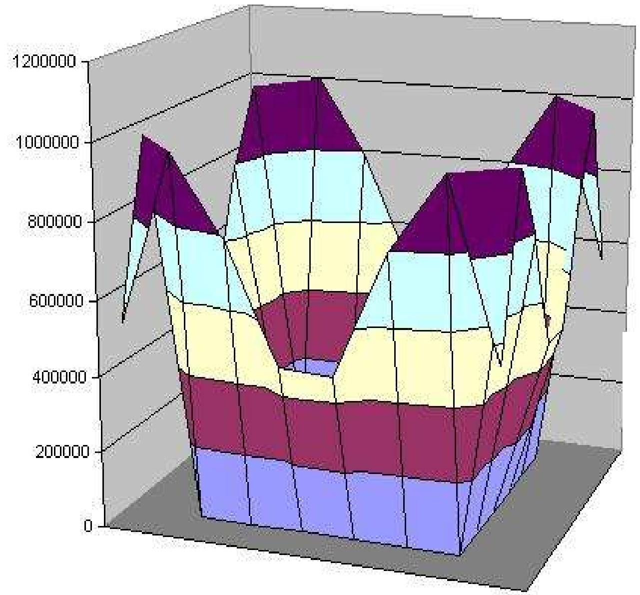
Network Lifetime



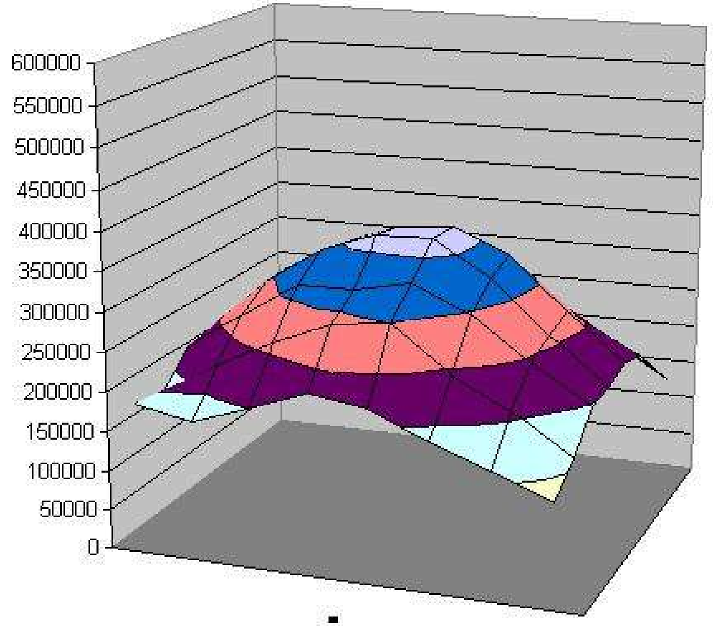
Energy costs

- OPT better than GMRE better than RM better than STATIC
- Changing routing changes energy cost at node i to forward data, changes sojourn times and sink route

GeRaF Results – Sojourn Times

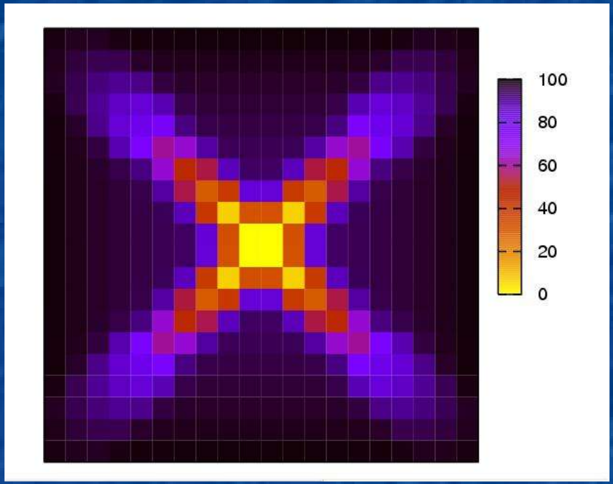


GMRE

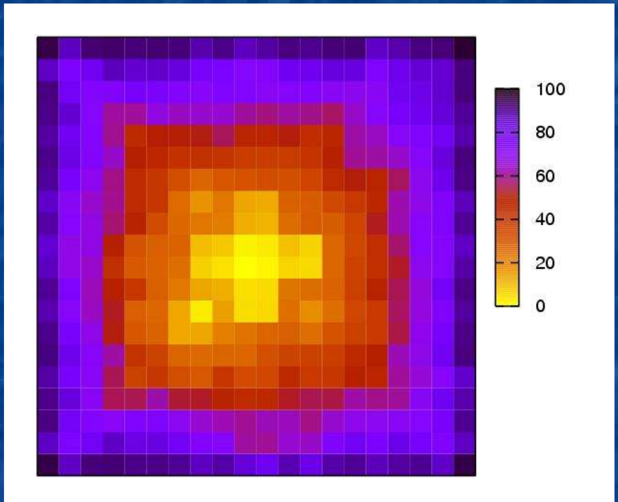


RM

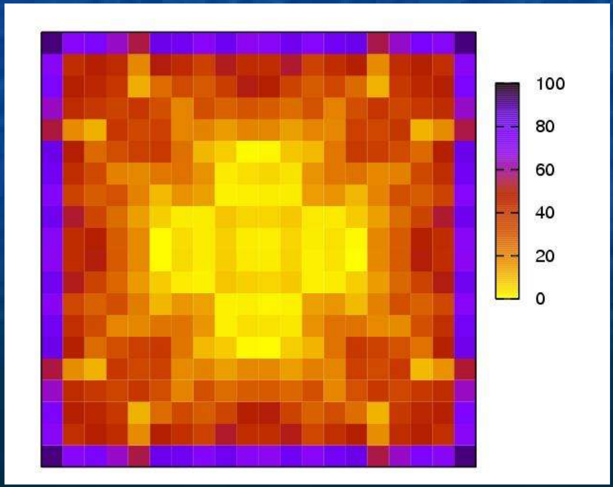
GeRaF Results – Residual energy at network lifetime



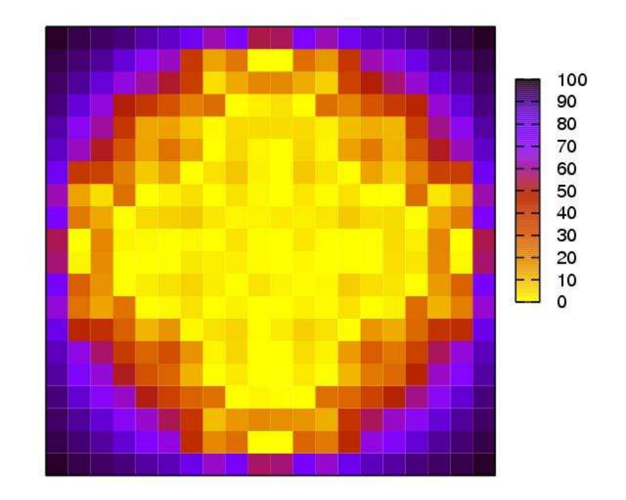
STATIC



RM

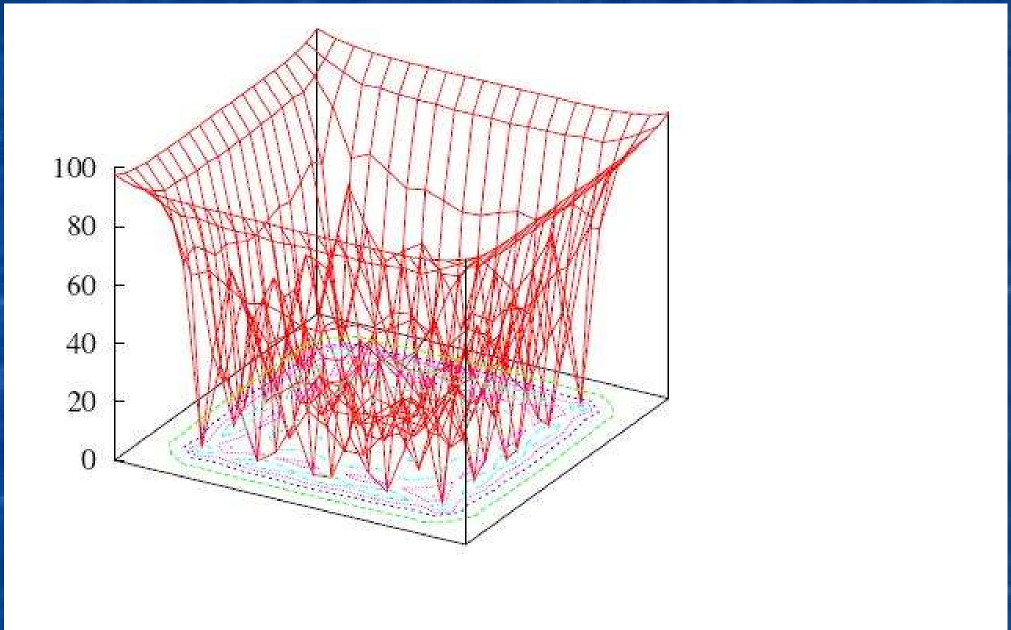


GMRE



OPT

Limiting the sink sites

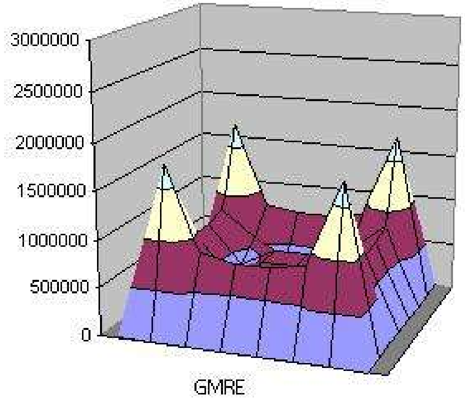


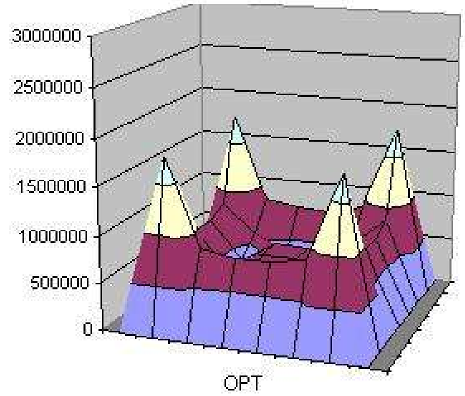
GMRE residual energy at lifetime: 50Ks

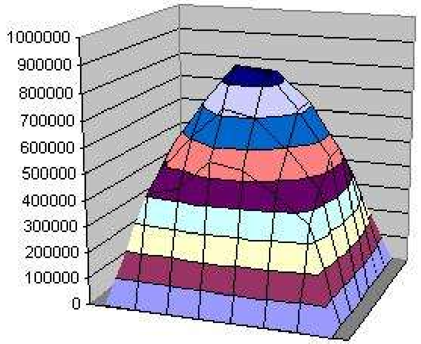
- OPT and GMRE very close for low t_{min}
- Both are able to very effectively drain energy from all the internal areas in the network (external areas only consume little enrgy as the sink cannot visit them)

Limiting the sink sites

Sojourn times: tmin= 50,000s







RM