Mobile Sinks in Wireless Sensor Networks

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Computer Engineering and Informatics

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Protocols that use multiple mobile BS or mobile relays

1. **Clustering and load balancing in hybrid sensor networks with mobile cluster heads**, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. **mWSN for Large Scale Mobile Sensing**, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008
3. **Increasing lifetime of wireless sensor networks using controllable mobile cluster heads**, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of two types of nodes: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be NP-hard
- They present a heuristic algorithm for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

2. mWSN for Large Scale Mobile Sensing, Ma et al. 2008

An approach that uses the MR as cluster head

- In this paper a three-tier architecture: sensors, mobile sinks and BS tiers
- The sensor nodes in the sensor tier are organised in a cluster with MRs as the cluster heads
- Inside each cluster MRs roam the cluster nodes and bugger the sensing data
- In order to send data to a BS, MRs can comminicate with each other and with the BS through short or long transmissions
- They investigate the following parameters: cluster size, sink velocity, transmission range, and packet length
- They study the effect of relay velocity on message-delivery delay and outage probability when the MRs move randomly

3. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Banerjee et al. 2010

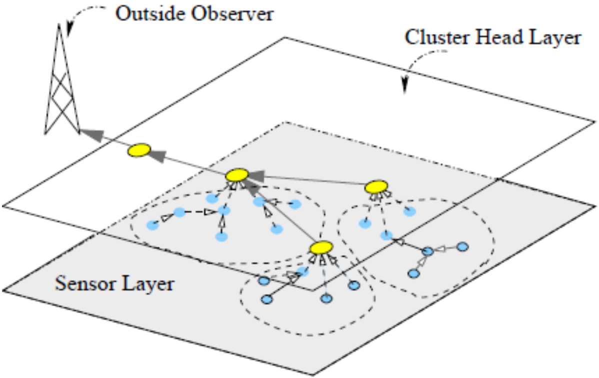
An approach that uses the MR as cluster head

- Author study the problem of energy balance
- They propose to use multiple mobile cluster heads (CHs) that can move in the WSN in a controllable manner
- The CH controllably moves toward the energy-rich sensors or the event area, offering the benefits of maintaining the remaining energy more evenly, or eliminating multihop transmission.
- Sensor nodes form clusters and select MRs as the corresponding cluster heads
- Each cluster head roams among its cluster nodes and collects data and then sends the data to the sink with direct transmission

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

- In a **homogeneous** network, all nodes have identical capability and energy initially and some of them are selected to serve as cluster heads in a deterministic or random way
- However, cluster heads will inevitably consume more energy than other sensor nodes and they may die before finish their round
- On the contrary, a hybrid(**heterogeneous**) sensor network contains a small number of resource-rich specialized cluster heads along with a large number of resource-limited basic sensor nodes.
- Basic sensor nodes have limited communication capability and mainly focus on sensing the environment, while cluster head nodes are equipped with more powerful transceivers and batteries but simpler sensing modules.

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006



Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

The model(1):

- The sensing data is generally collected at a **low rate** and sensing data is not very delay-sensitive
- n_s static sensors and n_c mobile cluster heads are **uniformly deployed** onto a two-dimensional working area
- sensor nodes can only reach nearby nodes within a **limited range**
- The major energy consumption is considered only for communications(ignoring those for sensing and other tasks)
- Cluster heads can move to anywhere within the working area, and are equipped with **more powerful** transceivers and batteries having much longer lifetime than those of sensor nodes

The model(2):

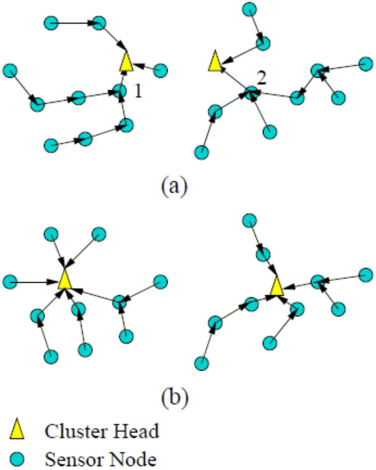
- cluster heads are **connected directly** without the relaying of sensor nodes
- all sensors and cluster heads obtain either their absolute positions from the **GPS** or relative positions from other location services such as detecting the **relative distance and angle**
- The network lifetime is defined as the lifetime of the **first failure** node in the network.

The model(3):

- The **possible location set L** of cluster heads is defined as a set of target positions where cluster heads can move to, stay and be reached by sensor nodes.
- The **neighbor set** of a point is defined as the set of sensor nodes which can communicate with the cluster head placed at this point.
- The possible locations of mobile cluster heads are defined by the **known position scheme** and the **grid scheme**
  - Using the known position scheme, a cluster head can only move in known positions whose neighbor sets have been obtained
  - Using grid scheme cluster heads can only move in grid's crossing points

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An example:



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In figure (a):

- node 1 is a bottleneck node, because it has to relay the packets from its six child nodes to the cluster head
- node 2 suffers heavier load than node 1, which has seven children
- Since node 1 and node 2 are bottlenecks in the corresponding clusters, they will consume energy much faster than other nodes

Figure (b) shows the network layout in which two cluster heads are placed at better positions improving network lifetime

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

For a network with **static** cluster heads, the problem of maximizing network lifetime can be formalized as the following **network flow problem**:

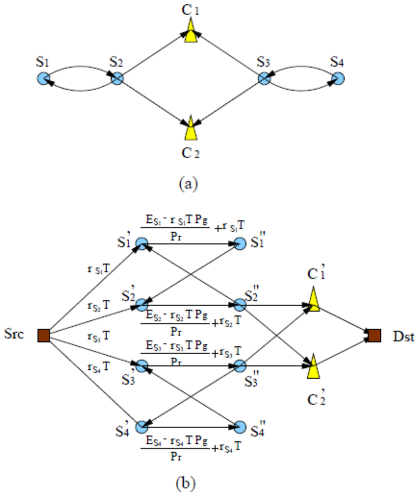
- A static sensor network can be modeled as a directed graph G(S,C,A), where S=$\{s_1,s_2,...,s_n\}$ is the set of all sensor nodes,
- C=$\{c_1,c_2,...,c_n\}$ is the set of all cluster heads and A is the set of all directed links α(i,j) where $i \in S$, $i \in S \bigcup C$

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

Given a directed graph G , its corresponding flow graph $G'(S', C', \text{Src}, \text{Dist}, A')$ can be constructed as follows:

1. For each $s_i \in S$ add two vertices s_i' and s_i'' to S'
2. an arc a(s_i', s_i'') is added to A' with capacity $\frac{Es_i - r_{s_i} TP_g}{P_r} + r_{s_i} T$
3. for each $c_j \in C$ add a vertex c_j' to C'
4. for each arc $\alpha(s_i, s_j) \in A$ where $s_i, s_j \in S$, add an arc $\alpha(s_i'', s_j') \in A'$ with infinity capacity
5. for each arc $\alpha(s_i, c_j) \in A$ where $s_i \in S, c_j \in C$, add an arc $\alpha(s_i'', c_j') \in A'$ with infinity capacity
6. A pair of source and destination nodes Src and Dst are added into G': for each $s_i' \in S'$ connect Src and s_i' by an arc $\alpha(Src, s_i')$ with capacity $r_{s_i} T$
7. for each $c_j' \in C'$ connect c_j' and Dst by an arc $\alpha(c_j', Dst)$ with infinity capacity

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006



Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

- r_{s_i} and E_{s_i} denote the data generating rate and energy limit of node s_i , P_g and P_r represent the power consumption for transmitting and relaying a unit of traffic, respectively and T is the network lifetime.
- For any given T, the problem is a regular maximum flow problem and can be solved by **Ford-Fulkerson** algorithm in polynomial time
- Due to the energy constraint of node s_i , the maximum flow that node s_i can relay within time is $\frac{Es_i - r_{s_i} T P_g}{P_r}$
- Thus, the total flow a node s_i can generate and relay in time T is limited by $\frac{Es_i - r_{s_i} T P_g}{P_r} + r_{s_i} T$

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

- When the maximum flow equals $\sum_{s_i \in S} r_{s_i} T$, it means that until time T, all generated traffic by n_s sensor nodes is received by cluster heads. Thus, all n_s sensors must be alive until T.
- We can keep increasing T and running Ford-Fulkerson algorithm to obtain the maximum flow for every T value, until the maximum flow is less than $\sum_{s_i \in S} r_{s_i} T$, which means that some nodes have failed.
- The value of obtained before the last run of Ford-Fulkerson algorithm is the maximum network lifetime

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

Analyzing the time complexity of this method:

- Let U denote the maximum units of traffic any sensor node generates and relays within time T^* , where T^* is the maximum network lifetime obtained by the algorithm
- Then: U $= max_{s_i \in S} \left\{ \frac{Es_i - r_{s_i} TP_g}{P_r} + r_{s_i} T \right\}$
- The running time of this method is O(UM_s^2), where $M_s^2 = n_c$ $+$ n_s is the total number of cluster heads and sensors in the network.
- The above optimization needs global location information of sensor nodes and cluster heads and connection patterns of the network which is very **energy-consuming** and **impractical** for a large size network

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We now consider the problem of finding the positions of n_c cluster heads from n_l ($n_l \geq n_c$) possible locations, and determining which cluster head serves each of n_s to maximize the network lifetime. The authors call this problem **Cluster Head Location** problem, **CHL**.

Problem definition and **formalization**:

- The sensor network can be modeled as a directed graph G(S,L,A), where S=$\{s_1, s_2, \ldots, s_{n_s}\}$ is a set of all sensor nodes, L=$\{l_1, l_2, \ldots, l_{n_l}\}$ is a set of all possible locations of cluster heads, A is the set of all arcs in G.
- N_{s_j} is the set of sensors that can reach s_j in one hop
- N_{l_i} is the set of sensors that can reach the cluster head at l_i in one hop

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

Problem definition and **formalization**:

- An arc $\alpha(s_j, s_k)$ belongs to A iif sensor s_k can be reached by s_j in one hop
- an arc $\alpha(s_j, l_k)$ exists in G iif the possible location l_k is located within the transmission range of sensor s_j
- Each vertex $s_j(s_j \in S)$ has n_l indicator variables $c_{s_j}^{l_i}, \forall l_i \in L$ denoting whether sensor s_j belongs to the cluster head at possible location l_i
- Each arc $\alpha(s_k, t)$ in A contains n_l flow values $f_{s_k t}^{l_i}$, where $s_k \in S$, $t \in S \bigcup L$ and $l_i \in L$
- Each element l_i in L coresponds to a variable I^{l_i} indicating whether a cluster head stays at l_i

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

Given a graph G(S,L,A), the problem can be formalized as follows:

$$
\begin{aligned}
&Maximize\, T \\
&Subject\ to \\
&I^{l_i} = \{0,1\}, \forall l_i \in L \\
&\sum_{l_i \in L} I^{l_i} = n_c \\
&c_{s_j}^{l_i} = \{0,1\}, \forall l_i \in L, \forall s_j \in S \\
&\sum_{l_i \in L} c_{s_j}^{l_i} = 1, \forall l_i \in L, \forall s_j \in S \\
&\sum_{s_j \in N_{l_i}} f_{s_j l_i}^{l_i} \leq I^{l_i} \times M \\
&\sum_{l_i \in L} \sum_{t \in N_{s_j'}} f_{s_j t}^{l_i} = \sum_{l_i \in L} \sum_{s_k \in N_{s_j}} f_{s_k s_j}^{l_i} + r_{s_j} T, \forall s_j \in S \\
&P_r \sum_{t \in N_{s_j'}} f_{s_j t}^{l_i} + P_g \sum_{s_k \in N_{s_j}} f_{s_k s_j}^{l_i} \leq c_{s_j}^{l_i} E_{s_j}, \forall s_j \in S \\
&All\ variables \geq 0
\end{aligned}
$$

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

- In the forth constraint, since each sensor can only belong to one cluster, only one $c_{s_j}^{l_i}$ for all $i_i \in L$ can be 1, while other equal 0
- in the fifth constraint, M is a large positive constant and represents the maximum traffic a cluster head can handle.
- The sixth constraint accounts for the fact that, for each sensor node, the total outgoing traffic equals the sum of total incoming traffic and the total locally generated traffic
- The seventh constraint says that the total energy consumption of sensor s_j must be limited by its maximum energy limit E_{s_j}

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NP-Hardness of the CHL Problem

- To prove the NP-hardness, the authors give a redunction from the k-center problem.
  - The **k-center problem** is a basic facility location problem, which aims at locating k **facilities** in a graph and to assign **demand** vertices to facilities so as to minimize the maximum distance from a vertex to the facility to which it is assigned
  - The number of cluster heads n_c in the CHL equals the number of facilities, the number of sensor nodes n_s equals to the number of demand vertices n_D and the number of possible locations of cluster heads n_l equals the number of possible facility locations, n_F in the k-center problem.
- Let G denote the graph of the k-center problem, Dem=$\{D_1, D_2, ..., D_{n_D}\}$ denote a set of demand vertices, and Fac=$\{F_1, F_2, ..., F_{n_F}\}$ be the set of possible locations of facilities.

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

A graph of the CHL G'(S,L,A) can be constructed as follows:

1. For each demand vertex D_j in G, add a vertex s_j to S, with infinity energy capacity E_{s_j} and data generating rate r_{s_j}=1
2. For each vertex denoting a possible facility location F_i in G, add a vertex l_i into L.
3. For each pair of D_j and F_i in G add an intermediate vertex m_j^i into S, with the energy capacity $E_{m_j^i} = \frac{1}{d(D_j,F_i)}$ and data generating rate $r_{m_j^i}$=0, where $d(D_j, F_i)$ is the distance between demand vertes D_j and possible location F_i in G.
4. Connect m_j^i and l_i, s_j and m_j^i with two arcs $\alpha(m_j^i, l_i)$ and $\alpha(s_j, m_j^i)$, respectively, where $\alpha(m_j^i, l_i)$, $\alpha(s_j, m_j^i) \in A$

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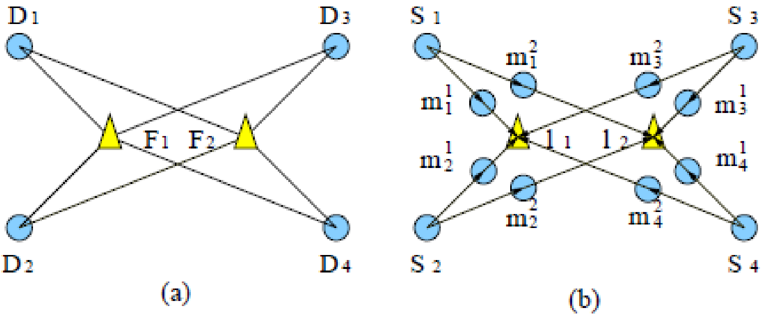
Redunction from the k-center problem to the CHL:



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- Power consumption for generating and relaying a unit of traffic, P_g and P_r both equal 1
- In the optimal solution of the CHL, if there is a non-zero flow goes from s_j to l_i via the path $s_j \rightarrow m_j^i \rightarrow l_i$ a demand node D_j is assigned to the facility F_i
- The max flow generated by s_j whithin time T must be $\leq$ max flow the intermidiate node m_j^i can relay, which equals $\frac{E_{m_j^i}}{P_r}$
- Since $P_{r_i} = r_{s_j} = 1$ the lifetime T is bounded by $min_j max_i E_{m_j^i}$ and since $E_{m_j^i} = \frac{1}{d(D_j, F_i)}$ we have $maxT = maxmin_j max_i \frac{1}{d(D_j, F_i)}$
- The optimal clustering achieves the maximum lifetime T in G', iif demand vertices in G can be organized into k clusters with the maximum-minimum distance from any demand vertex to the facility

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The heuristic clustering algorithm can be devided into 2 faces: Organizing sensor nodes into different clusters and finding the best location for every cluster head.

Organizing sensor nodes into clusters:

1. Each cluster head generates a Hello message, which includes three fields: *Root*, *Parent* and *Level*, where *Root* and *Parent* are marked by cluster's ID and *Level* is set to zero.
2. Every sensor nodes that receives Hello message it checks the *Level* value in the message and compare it with its own level:
    - If the *Level* in the message is less than its own level, it updates its root ID, parent ID and level according to the values in the message Then, it increments the *Level* of the message by one and broadcasts the new message again
    - If the *Level* in the message is not less than its own node level, it simply drops the message

- The complexity of the algorithm is $O(n^2)$

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

Finding the best locations of cluster heads:

- During the clustering forming phase, each cluster head has acquired a "**map**" of the entire cluster which includes the positions and connection patterns of all sensor nodes in the cluster.
- From the map, a cluster head can obtain some possible locations by using the known position scheme or the grid scheme
- Then the cluster head **tests possible locations one by one** assuming that it has moved there and nearby sensors have been organized around it into a cluster
- After all possible locations are tested, it chooses the location that maximizes the lifetime and moves there

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

Finding the best locations of cluster heads:

- Since each cluster only contains one cluster head the problem of maximizing the minimum lifetime of the cluster becomes a simplified version of the CHL problem with $n_c = n_l = 1$. The problem can be formalized as follows:

$$\begin{aligned}
&\textit{Maximize } T \\
&\textit{Subject to} \\
&\sum_{t \in N_{s'_j}} f^{l_1}_{s_j t} = \sum_{s_k \in N_{s_j}} f^{l_1}_{s_k s_j} + r_{s_j} T, \forall s_j \in S \\
&P_r \sum_{t \in N_{s'_j}} f^{l_1}_{s_j t} + P_g \sum_{s_k \in N_{s_j}} f^{l_1}_{s_k s_j} \le E_{s_j}, \forall s_j \in S \\
&\textit{All variables} \ge 0
\end{aligned}$$

- Since the maximum lifetime can be obtained in $O(UM_s^2)$ time with Ford-Fulkerson algorithm, the total running time for finding the best location of the cluster head is $O(UM_L M_s^2)$

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

Simulation Results

- The implementation of simulation was done on the NS-2 simulator
- It is assumed that 800 sensor nodes and 6 cluster heads are uniformly deployed within a $670 \times 670m^2$ two-dimensional square
- maximum transmission power 0.858mw, each node capable of communicating with other nodes as far as 40m away
- radio bandwidth 200kbps and 80 bytes fixed packet size
- Within each cluster, multi-hop polling protocol is used as the inner-cluster protocol to avoid packets collision at the MAC layer
- The algorithm was evaluated from two aspects: **network layout** and **network lifetime**

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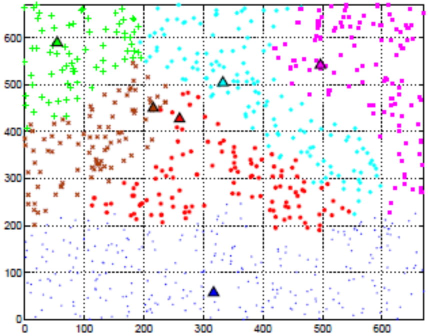
Network layout

- In this scenario the sensing field is divided into $10m \times 10m$ grids by cluster heads



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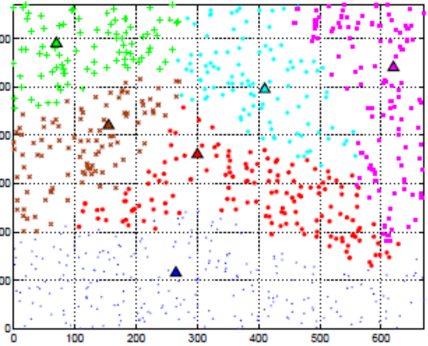
Network layout

- After 3 rounds we can observer that the network layout was readjusted



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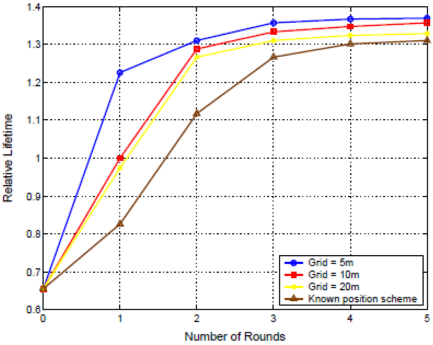
Network lifetime

- After the network is deployed, for the initial layout of a network, the optimal network lifetime can be obtained by running the flow algorithm discussed earlier
- Here it is assumed that the global location information and connection patterns needed by this global algorithm are available, though it may be impractical to obtain such global information in a large network
- The known position scheme and the grid scheme, with grid distances 5m, 10m and 20m, are used to optimize the lifetime of the network in comparison with the optimal lifetime of the network with static cluster heads

Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

Network lifetime

- The simulation shows that both the grid scheme and the known position scheme can achieve at least 30% improvement int the network lifetime



Mobile Sinks in Wireless Sensor Networks

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Protocols that use multiple mobile BS or mobile relays

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1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We investigated the paper and we concluded that:

- It provides solid background of the problem and discusses the problem of positioning mobile clusters heads in a two layer sensor network to maximize lifetime..but:
- The authors propose an **offline algorithm** for computing the positions of the cluster heads
- They don't discuss anything about the existance of a **Base Sink**
- In their model the **cluster heads are connected a priori**
- They don't count the **residual energy** of sensors when computing the cluster heads' new position
- Their solution is **bearly feasible**

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

Deployment model:

- n sensors to be **uniformly** and randomly deployed in a two-dimensional area such as a **disk of radius R**
- they are modeled as a graph $G_s = (V_s, E_s)$ with **Poisson point process** over the area $\pi \times R^2$ and constant node density $\lambda = n/\pi \times R^2$
- the sensor set is denoted by $V_s = \{s_1, \ldots, s_n\}$ with transmission range r_s
- the cluster heads are denoted by $V_c = \{CH_1, \ldots, CH_m\}$, $m < n$ and are also modeled as a graph $G_c = \{V_c, E_c\}$ where e_{jk} denotes a wireless link between CH_j and CH_k
- s_{ik} represents the ith sensor of CH_k
- the transmission range of a mobile CH is r_c with $\mathbf{r_c > r_s}$

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

Energy model

- The lifetime of the network is defined as the time until the first sensor dies
- every **CH** is not subjected to **any power constraints** while each sensor is initially equipped with limited energy denoted by E_0
- In a specific sensor s_i , the energy cost $E_{cost}(i)$ is the energy consumed by data transmission/reception ignoring every other energy cost
- To transmit one bit, the sensor consumes ω energy for running the circuitry
- Additionally, it consumes $\epsilon_{amp} \times r_s^{\alpha}$ energy for radio transmission while $\epsilon_{amp}^{'}$ for radio reception

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

An example:

- When the sensor s_i transmits k_{TX} bits and receives k_{Rx} bits the energy cost $E_{cost}(i)$ is
  $E_{cost}(i) = k_{Tx} \times (\omega + \epsilon_{amp} \times r_s^{\alpha}) + k_{Rx} \times (\omega + \epsilon'_{amp})$
- if the transmission rate and reception rate are k'_{Tx}bps and k'_{Rx}bps, the energy consumption rate is
  $E'_{cost}(i) = k'_{Tx} \times (\omega + \epsilon_{amp} \times r_s^{\alpha}) + k'_{Rx} \times (\omega + \epsilon'_{amp})$
- Therefore the average lifetime of sensor s_i is

$$\tau = \frac{E_0}{E'_{cost}(i) = k'_{Tx} \times (\omega + \epsilon_{amp} \times r_s^{\alpha}) + k'_{Rx} \times (\omega + \epsilon'_{amp})}$$

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Lifetime of a static sensor network:

- We assume the WSN area to be a **disk** and a **single BS** located at the **center**
- The disk can be diveded into q **equal concentric annuli**, $q = \lceil R/r_s \rceil - 1$
- hth annulus is formed by two circles of radii $h \times r_s$ and $(h+1) \times r_s$, $0 \leq h < q$
- The **area** of hth annulus is given by the circles: $a(h) = \pi \times ((h+1)^2 \times r_s^2 - h^2 \times r_s^2)) = \pi \times r_s^2 \times (2h+1)$
- the **number sensors** in the hth annulus is $n(h) = \lambda \times a(h)$
- The data packets for sensors in the hth annulus include:
  - packets that are created by the sensor in the hth annulus
  - packets that are originated from the $(h+1)$th to the qth annulus

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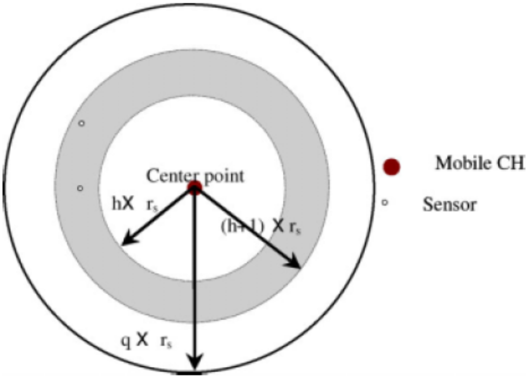
Lifetime of a static sensor network:



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Lifetime of a static sensor network:

- If each sensor has information rate, ρ bits/s and there is **no data loss**, the **total number of bits** generated by the sensors from the $(h+1)$th to the qth annulus is:
  $b(n) = \sum_{i=h+1}^{i=q} [\rho \times n(i)] = \sum_{i=h+1}^{i=q} [\rho \times \lambda \times a(i)]$
- The data bits originated from the *(h + 1)*th to the qth annulus is uniformly distributed among the sensors on the hth annulus and the **reception rate** is given by:
  $k'_{Rx} = b(h)/n(h) = \frac{\rho \times \lambda \times \sum_{i=h+1}^{q} a(i)}{\lambda \times a(h)} = \frac{\rho \times \sum_{i=h+1}^{q} a(i)}{a(h)}$
- So, the **transmission rate** for a sensor(including its own) at the hth annulus is: $k'_{Tx} = \rho + k'_{Rx} = \rho[1 + \frac{\sum_{i=h+1}^{q} a(i)}{a(h)}]$

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

Lifetime of a static sensor network:

- Using the previous equations we can find that the lifetime of a sensor at the hth annulus is given by:

$$\tau(i) = \frac{E_0(i)}{\rho\left\{\left[1+\left(\sum_{i=h+1}^{i=q} a(i)\right)/a(h)\right]\left(\omega+\varepsilon_{\mathrm{amp}}\times r_s^{\alpha}\right)+\left[\left(\sum_{i=h+1}^{i=q} a(i)\right)/a(h)\right]\left(\omega+\varepsilon'_{\mathrm{amp}}\right)\right\}}$$

$$= \frac{E_0(i)}{\rho\left\{\left[1+\left(\sum_{i=h+1}^{i=q} (2i+1)\right)/(2h+1)\right]\left(\omega+\varepsilon_{\mathrm{amp}}\times \mathrm{r}_{\mathrm{s}}^{\alpha}\right)+\left[\left(\sum_{i=h+1}^{i=q} (2i+1)\right)/(2h+1)\right]\left(\omega+\varepsilon'_{\mathrm{amp}}\right)\right\}}$$

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As given by equation above, the lifetime of a sensor in a static WSN is determined by five factors:

1. **Initial energy** (E_0)
2. **Information rate** (ρ bits/s)
3. **Size of the network** ($q = \lceil R/r_s \rceil - 1$)
4. **The sensor transmission range** (r_s)
5. **Energy parameters** for transmission and reception ($\epsilon_{amp}, \epsilon'_{amp}, \omega$)

The sensor density λ does not contribute to the sensor lifetime

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We can see that there are two strategies:

- no constraint on the traffic delay and each sensor has enough storage to store the sensed data before the CH collects it
  - the sensor lifetime can be increased maximally since $k'_{Tx} = k'_{Rx} = 0$ and its lifetime is $\tau_{max}(i) = \frac{E_0(i)}{\rho(\omega + \epsilon \times r_s^{\alpha})}$
  - maximum delay — maximum lifetime
- the data bits of sensors have to be immediately transmitted to the BS
  - minimum delay - minimum lifetime

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Energy Efficient CH Mobility Strategies:

1. Residual Energy-based CH Mobility
2. Event-oriented CH Mobility
3. Hybrid CH Mobility

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

Residual Energy-based CH Mobility

- CH should keep **changing locations** leading to a more **uniform dissipation of energy**
- The residual energy of a sensor can be obtained by adapting the prediction-based **energy-map**
- It is the information regarding the residual energy of each sensor
- The map can be computed in a predicted manner based on **history** and **current state**
- Each sensor send the info to CH which it locally updates the map

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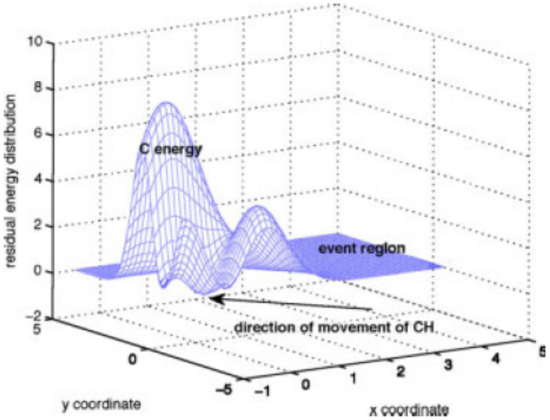
Residual Energy-based CH Mobility(energy map)



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Residual Energy-based CH Mobility

- residual energy center ($\mathbf{C_{energy}}$) is the point where network's residual energy is concentrated
- C_{energy} is the point $(x_{C_{energy}}, y_{C_{energy}})$:

$$x_{C_{energy}} = \frac{\sum_{i \in S_{ik}} (|x_{CH_k} - x_i|) \times E_{resd}(i)}{\sum_{i \in S_{ik}} E_{resd}(i)}$$

$$y_{C_{energy}} = \frac{\sum_{i \in S_{ik}} (|y_{CH_k} - y_i|) \times E_{resd}(i)}{\sum_{i \in S_{ik}} E_{resd}(i)}$$

- $|x_{CH_k} - x_i|$ gives the location of the x-coordinate of sensor s_i w.r.t to the x-coordinate of its CH_k, and similarly for the y-coordinate

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Event-oriented CH Mobility

- CHs always move towards the **event region**, the region with **maximum data flow**
- C_{event} can be represented by the coordinates $(x_{C_{event}}, y_{C_{event}})$:

$$x_{C_{event}} = \frac{\sum_{i \in S_{ik}} (|x_{CH_k} - x_i|) \times g(i)}{\sum_{i \in C} g(i)}$$

$$y_{C_{event}} = \frac{\sum_{i \in S_{ik}} (|y_{CH_k} - y_i|) \times g(i)}{\sum_{i \in C} g(i)}$$

where g(i) is **number of packets transmitted** by node s_i per second

- the CH moves toward the direction of sensors with max flow that are sending data to it, which in turn approximately represents **the direction of the event center**

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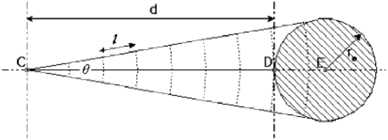
Event-oriented CH Mobility



- Figure shows an example that the CH moves toward the event
- let q be the number of annuli between the CH and the C_{event}
- the distance is $d = q \times l$
- the area of the ith annulus spanned by the cone is: $a(i) = \kappa\pi\big((il)^2 - ((i-1)l)^2\big) = \ldots = k\pi l^2(2i-1),\ \kappa = \frac{\theta}{2\pi}$

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Event-oriented CH Mobility

- The total number of sensors sensing an event is $a(event) \times \lambda = \pi \times r_e^2$
- the number of data bits by all sensor is $a(event) \times \lambda \times \rho$ bits/s
- the number of data bits transmitted by each sensor at ith annulus is $d_i = \frac{event\ data}{no.\ of\ sensors\ in\ ith\ annulus} = \frac{r_e^2}{\kappa l^2(2i-1)}\rho$
- we supposed that for **every sensor not belonging in the event** region dosen't generate any data, $\mathbf{k'_{Tx}} = \mathbf{k'_{Rx}}$
- again it can be seen that **closer the sensor is** to the CH **larger** will be **the number of data bits transmitted**

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Event-oriented CH Mobility

- it is shown that the **residual energy distribution** $f(i, j)$ of a sensor at ith annulus when CH is at jth is:

$$f(i,1) = E_0(i)$$

$$f(i,j) = \begin{cases} E_0(i) - \dfrac{\pi r_e^2 \rho \varepsilon}{v_{\mathrm{CH}}^2 \Delta t(2i-1)} \left(\displaystyle\sum_{u=1}^{i-1} \frac{1}{\theta_u} \right) \\ i \le j \\ f(i, j-1) - \dfrac{\pi r_e^2 \rho \varepsilon}{\theta_j v_{\mathrm{CH}}^2 \Delta t(2i-1)} \\ j < i \le q \end{cases}$$

- Next we will try to analyse the energy dissipation **as the CH moves along the line CD**

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Event-oriented CH Mobility

- Let C be a constant representing the amount of energy required to relay the data generated by event in Δt seconds, then $c = \frac{\pi r_e^2 \rho \epsilon}{\upsilon_{CH}^2 \Delta t}$
- As the CH moves, θ_k **increases gradually**. Therefore, we can find the lower bound of $f(i,j)$ simplifing the function:

$$f(i,j) \geq \begin{cases} E_0(i) - \dfrac{C(i-1)}{\theta_1(2i-1)} & i \leq j \\ E_0(i) - \dfrac{jC}{\theta_1(2i-1)} & j < i \leq q \end{cases}$$

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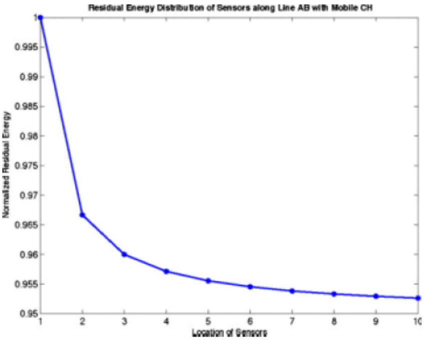
Event-oriented CH Mobility

- As shown in the figure below, sensors near original position(point C) have higher residual energy



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Energy-oriented vs Event-oriented CH Mobility

- The above two CH mobility strategies have some inherent limitations:
  - In the residual energy-based approach if CH needs too much time to move to the energy center some nodes may die before enter to a non router(relay) mode
    Also the **delay in data transmission** is not reduced either
  - In the event-oriented CH mobility strategy, the role of energy-rich nodes is not utilized adequately and may lead to **highly non-uniform distribution of the residual energy**
- To take advantage of both these strategies, a **hybrid mobility** is proposed

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Hybrid CH Mobility

- The hybrid strategy calculates a **center of equilibrium** w.r.t. to both residual energy and event data flow as follows: $C_{comb} = \eta \times C_{energy} + \gamma \times C_{event}$
- the ratio $\frac{\eta}{\gamma}$ determines the **balance** between event area or residual energy
- In most of the scenarios, C_{event} does not change during the period of event occurrence
- On the contrary, the C_{energy} still changes in this period, resulting in a change of C_{comb}

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Ensuring BS Connectivity

- In a **delay-tolerant** application, sensors sensing data can wait until the CH moves in their vicinity
- The BS can also wait for the CH to send the data after collecting it from all the members
- On the contrary, for **real-time** applications, the sensed data needs to be delivered to the BS without significant delay
- To ensure the validity of a new position of CH, several connectivity strategies are proposed:
  1. Ad Hoc Routing-based Connectivity Maintenance
  2. Received Signal Strength Indicator Prediction-based Connectivity Maintenance
  3. Neighbor List-based Connectivity Maintenance

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Ad Hoc Routing-based Connectivity Maintenance

- An ad hoc on-demand distance vector routing (**AODV**) approach
- When a CH wants to find its path to the BS based on its new location, it **broadcasts** a route **request** (RREQ) packet to all its neighbors
- A neighboring CH receiving this packet, may send a route reply (RREP) to this CH if it has a **fresh route** to the BS
- Otherwise, it rebroadcasts the RREQ to all its neighbors.
- **Recursively**, if there is a path, the algorithm finds it
- If the CH does not receive any RREP packet, the CH considers the new location to be invalid and stays at its previous position
- However, this approach has an additional overhead

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Received Signal Strength Indicator Prediction-based Connectivity Maintenance

- The CH_A currently at location $(x_{CH(i)}, y_{CH(i)})$ needs to see if it can still have a connected path to the BS by moving to its new location $(x_{CH(i+1)}, y_{CH(i+1)})$
- Let CH_B be the closest neighboring through which the CH_A has a connected path
- Let $RSSI_{th}$ be the **minimum RSSI** required to have a connection between CH_B and CH_A, corresponding to a maximum distance, d_{th}
- CH_A determines the current distance d_{AB} to this neighbor by evaluating the current RSSI
- CH_A moves to the new location only if its distance from the new location **is less than** $d_{th} - d_{AB}$

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Neighbor List-based Connectivity Maintenance

- Each CH maintains its 2-hop neighbor list, **Neighbor_List** which contains all the CHs (and the BS if there is) within its 2-hop
- In every move CH finds out if any of its 2-hop CHs have BS information in their Neighbor_Lists
- It is shown that when CH mentains a 2-hop neighbor there is a **high probability** to find a neighbor CH with a path to BS
- When moving to a new location CH_i **informs all its neighbours** if it is a gateway for other CHs
- if any neighbour is connected only with CH_i it **follows** CH_i in order not to lose connectivity
- if for some reason CH_i cannot find connectivity with BS it **returns to its previous position**

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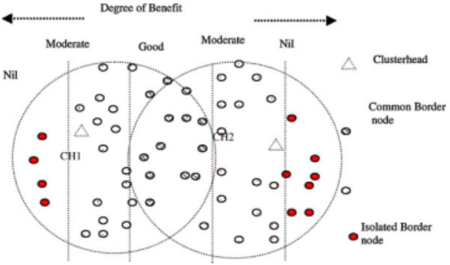
Exploiting the Shortest Path from a CH

- Events occurring at the **boundary of a cluster** can smaller delay and improve lifetime if sensors can send the data to the nearest CH



- In some situations these sensors can get good/moderate benefit increasing their lifetime

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Exploiting the Shortest Path from a CH

- Let $d_{path}(e, k)$ the **shortest path** from event e to CH_k and S_p be the set of sensors over that path
- We define μ as a function of $\mathbf{d_{path}(e, k)}$ and the **minimum residual energy** over all nodes in that path:
  $\mu_{CH_k} = \alpha \times d_{path}(e, k) + \frac{\beta}{min_{\forall i \in S_p} E_{resd}(i)}$
  subject to the constraint $d_{CH_k} - C_e \leq r_c$
- where $min_{\forall i \in S_p} E_{resd}(i)$ is the minimal residual energy of a sensor among S_p
- $d_{CH_k} - C_e \leq r_c$ is the distance between CH_k and the center of event C_e and α, β wheights
- the equation indicates that the longer is d_{path} and the smaller is $E_{resd}(i)$ the larger the value of μ_{CH_k}

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

Simulation Results

- The simulations were performed in a network domain of 300×300m using their own simulator
- sensors were distributed randomly with 5% being mobile CHs
- The sensing and transmission ranges of each sensor is 20 and 15m repsectively
- The transmission range of each mobile CH and the BS are 35 and 50m respectively
- The event range is a disk of 80m
- The speed of the mobile CH is kept fixed 2m/s

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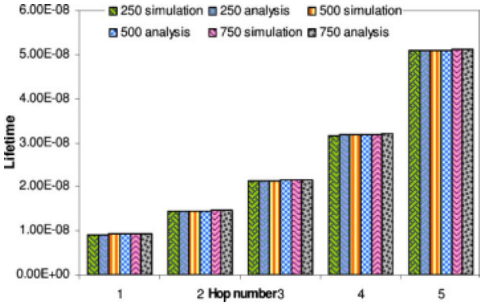
Relation between Density and Lifetime



- Lifetime is independent of the sensor density, which conforms to the analytical result

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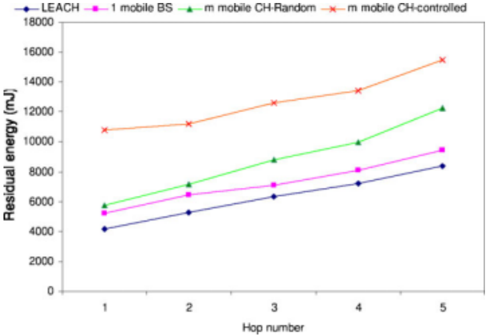
Residual Energy Comparison with Controlled Mobility



- energy saving of 75% over LEACH and 26% improvement over purely random movement
- having one mobile BS is better than having static CHs

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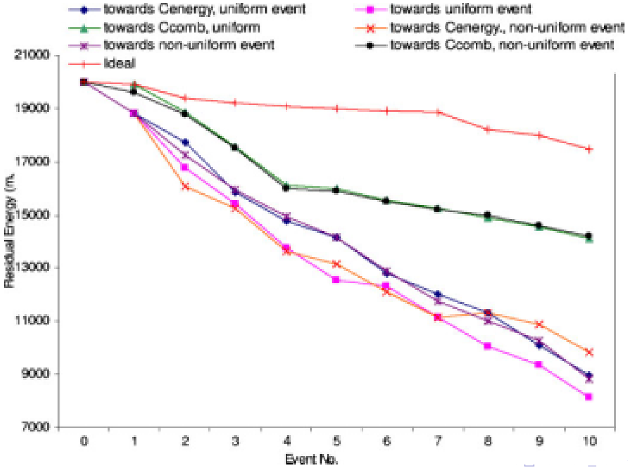
Residual Energy Improvement with Proposed Mobility Strategies



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Residual Energy Improvement with Proposed Mobility Strategies

- The residual energy is measured for the entire network, which is the sum of the residual energy of all the nodes
- Moving towards C_{energy} with **uniform** event generation increases E_{resd} by 5% more than the event-driven case
- However if the events follow a **non-uniform** distribution, then moving towards the event increases the E_{resd} by 8% compared to the C_{energy} strategy
- Moving towards C_{comb} shows the **best performance** by increasing the E_{resd} by 23% more than the former two strategies with $\eta = 0.7$ and $\gamma = 0.3$
- it is only 14% less than the ideal case

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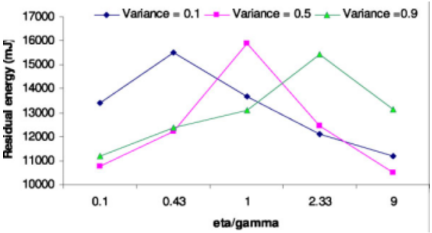
Residual energy savings with varying hybrid mobility parameters



- When event distribution is highly non-uniform (0.1 variance), the value of γ dominates
- for highly uniform random event distribution (variance 0.9), η dominates

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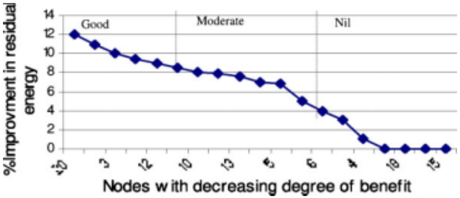
Collaboration Versus Non-collaboration



- Figure shows the percentage improvement in E_{resd} when CH collaboration is allowed, $\beta = 0.5$ for CH selection
- Senors are randomly located in different benefit zones as shown in slide 30
- Sensors situated in the *good benefit zone* have the maximum improvement in E_{resd}

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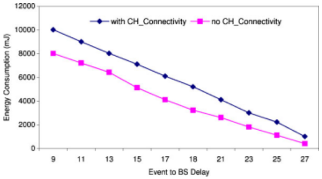
Tradeoff between Energy Consumption and Delay



- To have small delay we have to request connectivity between CH and BS
  - If the CH does not have a connected path to the BS at the new position, it stays in its current position
  - Staying in the same position for multiple rounds leads to a non uniform energy dissipation
- Removing the restrictions CH moves close enough to C_{comb} increasing lifetime(20%) but at the same time delay

Mobile Sinks in Wireless Sensor Networks

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Computer Engineering and Informatics

October 27, 2011

Protocols that use multiple mobile BS or mobile relays

1. **Clustering and load balancing in hybrid sensor networks with mobile cluster heads**, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. **Increasing lifetime of wireless sensor networks using controllable mobile cluster heads**, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010
3. **mWSN for Large Scale Mobile Sensing**, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of **two types of nodes**: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- each sensor has **different** flow generation **rate**
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be **NP-hard**
- They present a **heuristic algorithm** for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We investigated the paper and we concluded that:

- It provides solid background of the problem and discusses the problem of positioning mobile clusters heads in a two layer sensor network to maximize lifetime..but:
- The authors propose an **offline algorithm** for computing the positions of the cluster heads
- They don't discuss anything about the existance of a **Base Sink**
- In their model the **cluster heads are connected a priori**
- They don't count the **residual energy** of sensors when computing the cluster heads' new position
- Their solution is **bearly feasible**

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

An approach that uses the MR as cluster head

- The authors study again the energy balance problem under mobile cluster heads
- They propose to use multiple mobile cluster heads (CHs), each CH can move in its cluster
- They propose 3 protocols
  - CHs move towards the **energy-rich sensors**
  - CHs move towards the **event area**
  - a **hybrid protocol** in which CHs move according to the equation
    $C_{comb} = \eta \times C_{energy} + \gamma \times C_{event}$
- Also they discuss algorithms that mentain **connectivity** between CHs and BS
- In simulation they showed that there is a trade-of between energy consumption and delay

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

We investigated the paper and we concluded that:

- It is a very concrete work that analyses many interesting topics in WSNs but
- In residual energy-based strategy, in case of **multiple energy centres**, it does not find the optimal position for CH
  - Actually if the energy centres are **equal** the new position of CH is the least optimal
- In their model cluster members **does not change** at all. Also every CH moves ONLY **inside** its cluster.
- The algorithms that they proposed for ensuring BS connectivity are very **energy consuming**

mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

Our new paper

mWSN for Large Scale Mobile Sensing
Jian Ma, Canfeng Chen and Jyri P. Salomaa
Nokia Rsearch Center, Beijing, China
Published at Signal Processing Systems 2008

mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

- The paper reviews the state-of-the-art features introduced by sink mobility into WSNs
- it investigates fundamental design parameters in m(obile)WSN, such as cluster size, sink velocity, transmission range, and packet length
  - Optimal Multihop Forwarding Strategy Under Predictable Sink Mobility
    - Characteristic Distance (d_{char})
    - d_{char} based Clustering Scheme with Packet Delivery Delay Guarantee
  - Performance Influence from Sink Mobility in Single-hop mWSN
    - Sensor-sink Meeting Delay
    - Large Message Delivery Delay
    - Outage Probability

Characteristic Distance (d_{char})

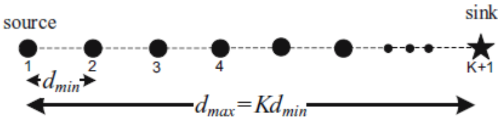
- The link energy consumption rate due to transmissions between node i and node j can be modeled as
  $E_t(i,j) = \alpha \cdot f_{i,j}$
  $E_r(i,j) = \beta \cdot f_{i,j}$
  - where $E_t(i,j)$ denotes the energy consumed at node i for transmission to node j with bit rate $f_{i,j}$
  - similarly for $E_r(i,j)$
- the parameter α for sending cost is typically defined as

$$\alpha = \begin{cases} a + b \cdot d_{i,j}^{\gamma}, & \text{when } d_{min} \leq d_{i,j} \leq d_{max} \\ a + b, & \text{when } 0 \leq d_{i,j} \leq d_{min} \end{cases}$$

  - where $\gamma = 2$ is the decay factor, a=50 nJ/bit and b=100 pJ/bit/n^2
  - the parameter d_{min} is the threshold under which there is no evident signal attenuation

Characteristic Distance (d_{char})

- In a simple one-dimensional linear network illustrated in Figure below, without loss of generality, we assume d_{max} is a K integral multiple of d_{min}, K_{dmin}
- If the distance between the source sensor and sink node is d_{max}, there are basically **two** (extreme) **alternatives**
  - **directly** reach the sink node using the maximal transmission power (single-hop)
  - reach the sink node **hop by hop** along a chain of K relaying sensor nodes with a separation of d_{min} (multihop)



Characteristic Distance (d_{char})

- For direct **single-hop** transmission from source node 1 to sink node K+1, the energy consumption for one bit will be:

  $E_t(1, K+1) + E_r(K+1, 1) = 2a + b \cdot d^2_{1,K+1} = 2a + b(KD_{min})^2$
- in case of **multihop**

  $\sum_{i=1}^{K} E_t(i, i+1) + \sum_{j=2}^{K+1} E_r(j, j-1) = 2Ka + bKd^2_{min}$
- when $\frac{a}{b} \geq \frac{Kd^2_{min}}{2}$ K-hop transmission will not be better than single hop

Characteristic Distance (d_{char})

- Given the distance between the source sensor node and sink node(D), and the number of hops(N), the minimum energy dissipation rate for multihop transmission can be achieved when all the **hop distances** are **identical**, i.e. $d_{i,i+1} = \frac{D}{N}, \forall i$
- There is an optimal number of hops $N_{opt} = \sqrt{\frac{b}{2a}} D$
- the $\sqrt{\frac{b}{2a}}$ is named the **characteristic distance** or d_{char}
- In general the most energy-efficient scheme is to use single-hop transmission if the separation between sensor and sink is no greater than d_{char}, otherwise it is optimal to use multihop forwarding with per-hop distance of d_{char}

d_{char} based Clustering Scheme with Packet Delivery Delay Guarantee

- Apparently, the most economic way is to let the sensor node hold sensed data until the sink approaches
  - However, if the time interval is rather long, ther whould appear an **unacceptable delay**
- The authors create a d_{char}-based multihop cluster formation method as follows:
  - It is assuming that the **sink trajectory can be learned** or estimated (but not controlled) by each sensor node
  - the packet transmission delay is negligible
  - To gurantee delivery, a **deadline** and a **sending timestamp** appear in every packet
  - After a packet reception, each sensor shall decide how to handle it by **comparing** the required deadline T_d with estimated propagation delay T_e

mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

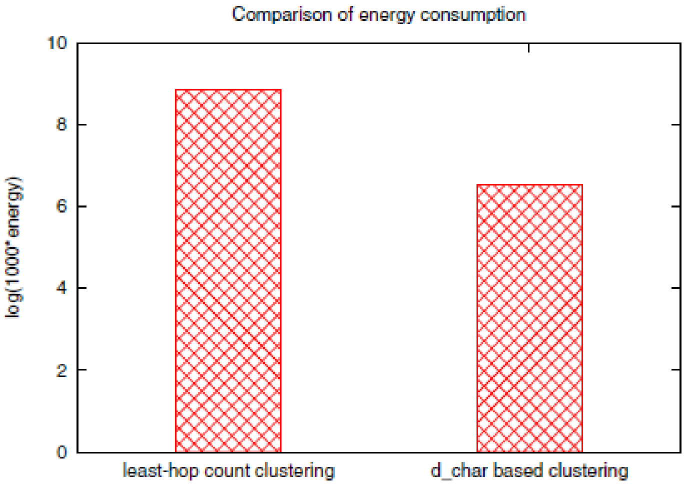
d_{char} based Clustering Scheme with Packet Delivery Delay Guarantee

- The authors create a d_{char}-based multihop cluster formation method as follows:
  - T_e is calculated as the sum of expected sink arrival delay T_{e1} and previously elapsed time before receiving the packet T_{e2}
  - If $T_d < T_e$, then the packet should be **propagated** towards the mobile sink as quickly as **possible**
  - Otherwise, the packet can be **buffered** until the sink arrives within a separation of d_{char}
  - The mobile sinks act as cluster heads(2nd level)
  - The optimal position of cluster head(1st level) should be around the expected position of a mobile sink
  - In order to assure packet delay, the **optimal cluster** radius shall depend on two factors: required packet delivery deadline and sink velocity
    - The higher sink velocity and the looser packet delivery delay, the smaller the cluster radius will be

d_{char} based Clustering Scheme with Packet Delivery Delay Guarantee

- The formation was simulated in a 1-dimensional scenario (!)
- 1,000 sensor nodes and one mobile sink, with **inter-sensor separation** of d_{min} and sink velocity of d_{min} m/s
- The mobile sink shall move along the line and collect all the bits from sensors, 1 bit for each sensor
- Performance evaluation of **least-hop count** clustering scheme ($d_{i,i+1} = d_{max} = 150m$) and **$\mathbf{d_{char}}$-based multihop** clustering with a packet deadline of 2s
- As shown in Figure of next slide, the energy consumption of d_{char}-based multihop clustering is **an order** of magnitude **less** than that of multihop clustering using d_{max}

mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008



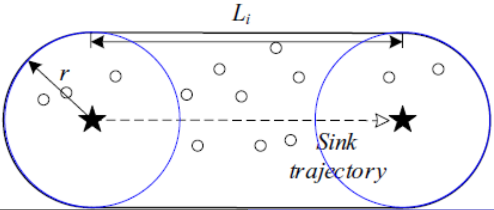
Sensor-sink Meeting Delay

- The network consists of m mobile sinks and n static sensors
- Both sinks and sensors operate with transmission range of r
- The mobility pattern of the mobile sinks M_i(i=1, ..., m) is **random** with a **constant velocity** ν
  - The sink's trajectory is a **sequence of epochs**
  - during each epoch the the moving direction of M_i over the disk is **uniform** and **independent of its position**
- Denote Q_i as the epoch duration of M_i
  - Q_i is an **exponentially distributed** random variable
  - the distributions of different Q_i(i=1, ..., m) are **independent and identically-distributed(i.i.d) random variables** with common average of $\overline{Q}$
- the epoch length of different L_is are also **i.i.d random variables**, sharing the same average of $\overline{L} = \overline{Q}\nu$

Sensor-sink Meeting Delay

- The **meeting** of one static sensor N_j(j=1, ..., n) and one mobile sink M_i is defined as M_i covers N_j during an epoch
- Since M_i will cover an area of size $\pi r^2 + 2rL_{i,k}$ during the k-th epoch, the number of epochs X_i needed till the first sensor-sink meeting is **geometrically distributed** with average of $\frac{1}{p} = \frac{1}{\pi r^2 + 2r\overline{L}_{i,k}}$ with the cumulative density function (cdf)

  $F_{X_i}(x) = \sum_{x_k \leq x} p(1-p)^{k-1}$



Sensor-sink Meeting Delay

- In the case of **multiple** mobile sinks, the sensor-sink meeting delay should be calculated as the delay when the **first** sensor-sink **meeting** occurs
- Thus the number of epochs X needed should be the minimum of all X_i(i=1, ..., m), with the cdf as

  $F_X(x) = 1 - [1 - F_{X_i}(x)]^m \cong \sum_{x_k \leq x} mp(1-p)^{k-1}$
- Denote $\overline{X}$ as the average of X, the expected sensor-sink meeting delay will be $\overline{D}_1 = \overline{X} \cdot \frac{\overline{L}}{\nu}$
- The above result can some hints on choosing the parameters to minimize meeting delay
  - **Increasing** either the radio transmission range **r**, or the number of mobile sinks **m**, or the sink velocity **v** the sensor-sink meeting **delay** can get **reduced**
- However, the above analysis has implicitly neglected the time consumed by packet transmission

mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

Sensor-sink Meeting Delay

- Assume each sensor will alternate between two states, active and sleep, whose durations are be **exponential distributed** with a mean of $1/\lambda$
  - The message arrival is a **Poisson process** with arrival rate λ
- For constant message length of L and channel bandwidth w, the **number of time slots** required to transmit a message is T=L/w
- With a service probability $p = mpr^2$, the service time of the message is a random variable with **Pascal distribution**
- the probability that the message can be transmitted within **no more than x time slots**, is
  $F_X(x) = \sum_{i=0}^{x-T} \binom{T+i-1}{T-i} p^T (1-p)^i$

Sensor-sink Meeting Delay

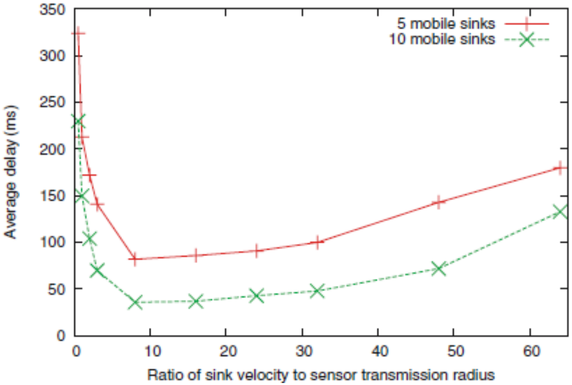
- Under an average Poisson **arrival rate** λ and a Pascal **service time** with $\mu = p/T = pmwr^2/L$, data generation and transmission can be modeled as an **M/G/1 queue**
- Then the **average message delivery delay** can be expressed as follows
  $\overline{D_2} = \frac{1}{\lambda}\left[\rho + \frac{\rho^2+\lambda^2\rho^2}{2(1-\rho)}\right]$ where $\rho = \lambda/\mu$
- If, for simplicity, arrival rate is negleted and set $\lambda = 1$ then
  $\overline{D_2} = \frac{1}{1-\mu} = \frac{1}{\frac{\pi mwr^2}{L}-1}$
- The result shows that, by **decreasing** message length **L**, or **increasing** transmission range **r** and number of mobile sinks **m**, the message delivery delay can be **reduced**

mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

Sensor-sink Meeting Delay (Simulation)

- 1500 sensor nodes have been deployed in a 10,000x10,000-m region
- The data generation of each sensor nodes follows a Poisson process with an average arrival interval of 1s
- Performance evaluation of **average message delivery delay** and **energy consumption**
  - varying the ratio of **sink velocity** against **transmission radius**
  - varying the **number** of **mobile sinks**
- The results are illustrated in the next four slides

Sensor-sink Meeting Delay (Simulation)

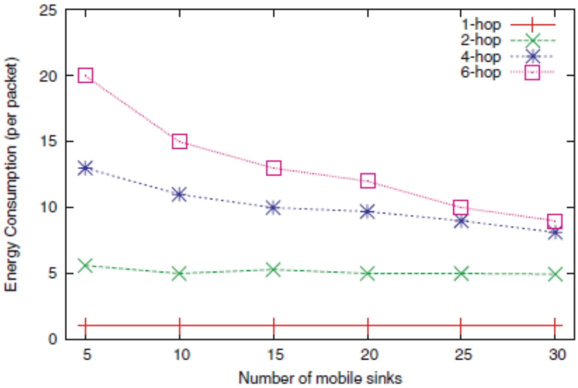


Average message delivery delay under different scenarios by varying the number and velocity of mobile sinks

Sensor-sink Meeting Delay (Simulation)

- As shown in the previous slide, the **more mobile sinks** deployed the **less delay** for message delivery between sensors and sinks
- When the sink **mobility is low**, the sensors have to **wait for a long** time before encountering the sink and delivering the message
- When the sink **moves too fast**, however, although the sensors meet the sink more frequently, they have to have the long messages sent successfully **in several successive transmissions**
- There exists an **optimal velocity** under which the message delivery delay will be minimized

Sensor-sink Meeting Delay (Simulation)



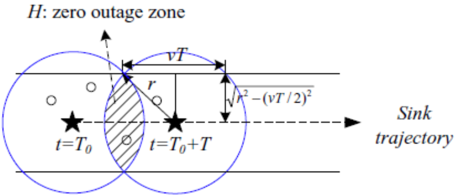
Average energy consumption under different scenarios by varying the cluster size and member of mobile sinks

Sensor-sink Meeting Delay (Simulation)

- When the cluster size is small (1 or 2), the average energy consumption will almost remain constant irrespective of the number of mobile sinks
- When messages can be delivered to a mobile sink multiple hops away then the number of mobile sinks will have influence on the energy consumption
  - the **more mobile sinks**, the **less energy** will be consumed

Outage Probability

- The authors are interested in finding the **relationship** between such parameters as packet length L (number of time slot required is T=L/w), transmission range r, sink velocity v, and outage probability p_{outage}
- To guarantee the packet transmission completed in duration T, a **zero-outage zone** is defined as illustrated below
- Nodes lying in H will be guaranteed with zero outage probability, because the link between sensor and **sink remains stable** for a duration of T with probability 1

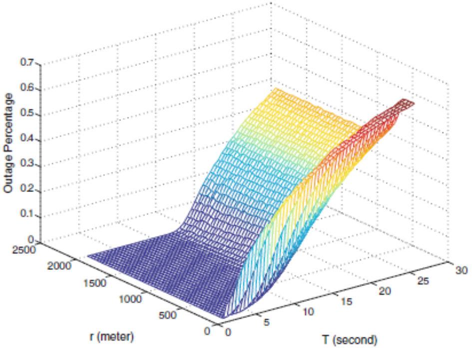


Outage Probability

- Intuitively, if H is viewed as a queuing system, then the **larger the area** of H, the **higher the service rate**, thus the lower the average outage probability
- The border arc of H is the **intersected area** of two circles with radius r, and the width of H is determined by (2r-vT)
- Therefore, the goal of enlarging the area of H can be achieved via **increasing r**, or **decreasing v or T**
- With **constant packet length** (i.e. constant T), we can choose to increase r or to decrease v
  - increasing r will require for larger transmission power, therefore, it is more energy efficient by decreasing sink velocity v

Outage Probability (Simulation)

- With 3,000 sensor nodes and one mobile sink in a 10,000x10,000-m region, when the sink velocity is 15 m/s and transmission range is 80 m, the p_{outage} is shown below



Protocols that use multiple mobile BS or mobile relays

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks [55]
2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010 [3]
3. mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008 [54]
4. Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing [57]
5. Mobile Element Scheduling with Dynamic Deadlines, Arun A. Somasundara, Aditya Ramamoorthy, Mani B. Srivastava, IEEE Transactions on Mobile Computing, 2007 [73]

Protocols that use multiple mobile BS or mobile relays

6. Using Predictable Observer Mobility for Power Efficient Design of Sensor Networks, Arnab Chakrabarti, Ashutosh Sabharwal, Behnaam Aazhang, IPSN'03 [11]
7. Communication power optimization in a sensor network with a path-constrained mobile observer, Arnab Chakrabarti, Ashutosh Sabharwal, Behnaam Aazhang, TOSN 2006 [12]
8. Multiple Controlled Mobile Elements (Data Mules) for Data Collection in Sensor Networks, David Jea, Arun Somasundara, Mani Srivastava DCOSS 2005 [40]
9. Improved sensor network lifetime with multiple mobile sinks, Mirela Marta, Mihaela Cardei, Pervasive and Mobile Computing, 2009 [59]
10. Towards Mobility as a Network Control Primitive, David K. Goldenberg, Jie Lin, A. Stephen Morse, Brad E. Rosen, Y. Richard Yang MobiHoc 04 [30]
11. Energy Optimization under Informed Mobility, Chiping Tang and Philip K. McKinley, IEEE Trans. Parallel Distrib. Syst.

Protocols that use multiple mobile BS or mobile relays

12. Mobile Relay Configuration in Data-intensive Wireless Sensor Networks, Fatmé El-Moukaddem, Eric Torng, Guoliang Xing, and Sandeep Kulkarni, MASS IEEE (2009) [22]
13. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, R C Shah, S Roy, S Jain, W Brunette, Sensor Network Protocols and Applications, 2003 [70]
14. Controlling the Mobility of Multiple Data Transport Ferries in a Delay-Tolerant Network, Wenrui Zhao, Mostafa Ammar, Ellen Zegura, INFOCOM 2005 [102]

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

A different approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of two types of nodes: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be NP-hard
- They present a heuristic algorithm for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Banerjee et al. 2010

A different approach that uses the MR as cluster head

- Author study the problem of energy balance
- They propose to use multiple mobile cluster heads (CHs) that can move in the WSN in a controllable manner
- The CH controllably moves toward the energy-rich sensors or the event area, offering the benefits of maintaining the remaining energy more evenly, or eliminating multihop transmission.
- Sensor nodes form clusters and select MRs as the corresponding cluster heads
- Each cluster head roams among its cluster nodes and collects data and then sends the data to the sink with direct transmission

A different approach that uses the MR as cluster head

- In this paper a three-tier architecture: sensors, mobile sinks and BS tiers
- The sensor nodes in the sensor tier are organised in a cluster with MRs as the cluster heads
- Inside each cluster MRs roam the cluster nodes and bugger the sensing data
- In order to send data to a BS, MRs can comminicate with each other and with the BS through short or long transmissions
- They investigate the following parameters: cluster size, sink velocity, transmission range, and packet length
- They study the effect of relay velocity on message-delivery delay and outage probability when the MRs move randomly

4. Data gathering in wireless sensor networks with mobile collectors, Ma and Yang 2008

- They propose a new data gathering mechanism for large scale wireless sensor networks by introducing mobile collectors, "m-collectors"
    1. An M-collector starts the data gathering tour periodically from the static data sink
    2. polls each sensor while traversing the transmission range of the sensor
    3. then collects data directly from the sensor without relay (i.e., in a single hop)
    4. and finally returns and uploads data to the data sink.
- Since data packets are gathered directly without relay and collision, the lifetime of sensors is expected to be prolonged
- They focus on the problem of minimizing the length of each data gathering tour and show its NP-hardness
- Finally they propose heuristic algorithms, for prolonging network lifetime, that use one or more "m-collectors" using only one-hop communication

5. Mobile Element Scheduling with Dynamic Deadlines, Somasundara et al. 2007

- The authors study again the routing path of multiple MRs traversing the network at a constant speed, but this time each sensor node operates at different sampling rates
- They try to solve the problem of scheduling the mobile element(s) in the network so that there is no data loss due to buffer overflow
- It is shown that the problem is NP-complete
- An algorithm is proposed to find the path that minimizes the buffer overflow at each sensor node based on the constraint of buffer and data generation at each sensor

6. Using Predictable Observer Mobility for Power Efficient Design of Sensor Networks Chakrabarti et al. 2003

- The paper explores the problem of saving power in sensor networks based on predictable mobility of the data sink
- To understand the gains due to predictable mobility, the data collection process is modeled as a queuing system, where random arrivals model randomness in the spatial distribution of sensors
- The success in data collection, and the quantification of the power consumption of the network are analysed
- It is shown that the power savings over a static sensor network are significant
- Finally a simple observer-driven communication protocol is presented

7. Communication power optimization in a sensor network with a path-constrained mobile observer, Chakrabarti et al. 2006

- Again a procedure for power optimization in a network of randomly distributed sensors is presented when a data collector moves on a fixed path
- The process of data collection is modeled by a queue with deadlines, where arrivals correspond to the observer entering the range of a sensor and a missed deadline means data loss.
- The queuing model is then used to identify the combination of system parameters that ensures adequate data collection with minimum power
- For sensor networks that cannot tolerate data loss, a tight bound is derived on minimum sensor separation that ensures that no data will be lost on account of mobility and show power reduncion

8. Multiple Controlled Mobile Elements (Data Mules) for Data Collection in Sensor Networks, Jea et al. 2005

- The authors study the problem of load balancing of multiple mobile elements when the network scalability and traffic make the single mobile element insufficient
- They assume that MRs move on a straight line and propose a load balancing algorithm assuming mobile elements fully cover the entire field of the network
- They show by simulation the benefits of load balancing

9. Improved sensor network lifetime with multiple mobile sinks, Marta and Cardei 2009

- The paper studies the energy holes that appears close to sink
- The solution that is proposed is to use mobile sinks that change their location when the nearby sensors' energy becomes low
- In this way the sensors located near sinks change over time
- In deciding a new location, a sink searches for zones with richer sensor energy
- They propose a distributed and localized algorithm used by the sinks to decide their next movement location such that the virtual backbone formed by the sinks remains interconnected at all times

10 Towards Mobility as a Network Control Primitive, Goldenberg et al. 2004, 11. Energy Optimization under Informed Mobility, Tang and McKindley 2006

A scenario that energy replenishment of MR cannot always be possible due to the constraints of the physical environment

- In both are user to relay data and use the same transmission range as sensor nodes
- Mobility control algorithms are proposed in which each relay node moves to the midpoint of its neighbour coverage
- The communication energy is minimized by reducing the distance between the source and destination

12. Mobile Relay Configuration in Data-intensive Wireless Sensor Networks, El-Moukaddem et al. 2009

- The paper shows that the optimal position of an MR depends on the amount of data to be sent in addition to the initial position of sensor nodes
- The work increases the reliability of the path between the source and destination by improving the connectivity between communicating neighbours which can avoid the cost of control packet overhead
- The optimal relay configuration is shown to depend on both the positions of nodes and the amount of data to be sent
- Algorithms are developed that iteratively refine the configuration of mobile relays and converge to the optimal solution which do not require explicit synchronization

13. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, R C Shah et al. 2003

- Analyzes an architecture to collect sensor data in sparse sensor networks using MRs(called MULES)
- MULEs pick up data from the sensors when in close range, buffer it, and drop off the data to wired access points using short-wireless communications
- Substansial power saving at the sensors since they have only to transmit over a short range
- The model assumes two-dimensional random walk for mobility and incorporates key system variables such as number of MULEs, sensors and access points
- The performance metrics observed are the data success rate (the fraction of generated data that reaches the access points) and the required buffer capacities on the sensors and the MULEs

14. Controlling the Mobility of Multiple Data Transport Ferries in a Delay-Tolerant Network, Zhao and Ammar 2005

- This paper considers the Message Ferrying (MF) scheme which exploits controlled mobility to transport data in delay-tolerant networks, where end-to-end paths may not exist between nodes.
- In the MF scheme, a set of special mobile nodes called message ferries are responsible for carrying data for nodes in the network
- The authors study the use of multiple ferries in such networks, regarding address performance robustness concerns, and they focus on the design of ferry routes.
- Two ways of MRs interaction: either directly or via nodes
- MRs need to sychronize their movements to exchange data directly, while nodes are required to have enough storage and energy for buffering and and relaying data among MRs

Mobile Sinks in Wireless Sensor Networks

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Computer Engineering and Informatics

November 9, 2011

Protocols that use multiple mobile BS or mobile relays

1. **Clustering and load balancing in hybrid sensor networks with mobile cluster heads**, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. **Increasing lifetime of wireless sensor networks using controllable mobile cluster heads**, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010
3. **mWSN for Large Scale Mobile Sensing**, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008
4. **Data gathering in wireless sensor networks with mobile collectors**, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of **two types of nodes**: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- each sensor has **different** flow generation **rate**
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be **NP-hard**
- They present a **heuristic algorithm** for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We investigated the paper and we concluded that:

- It provides solid background of the problem and discusses the problem of positioning mobile clusters heads in a two layer sensor network to maximize lifetime..but:
- The authors propose an **offline algorithm** for computing the positions of the cluster heads
- They don't discuss anything about the existance of a **Base Sink**
- In their model the **cluster heads are connected a priori**
- They don't count the **residual energy** of sensors when computing the cluster heads' new position
- Their solution is **bearly feasible**

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

An approach that uses the MR as cluster head

- The authors study again the energy balance problem under mobile cluster heads
- They propose to use multiple mobile cluster heads (CHs), each CH can move in its cluster
- They propose 3 protocols
  - CHs move towards the **energy-rich sensors**
  - CHs move towards the **event area**
  - a **hybrid protocol** in which CHs move according to the equation
    $C_{comb} = \eta \times C_{energy} + \gamma \times C_{event}$
- Also they discuss algorithms that mentain **connectivity** between CHs and BS
- In simulation they showed that there is a trade-of between energy consumption and delay

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

We investigated the paper and we concluded that:

- It is a very concrete work that analyses many interesting topics in WSNs but
- In residual energy-based strategy, in case of **multiple energy centres**, it does not find the optimal position for CH
  - Actually if the energy centres are **equal** the new position of CH is the least optimal
- In their model cluster members **does not change** at all. Also every CH moves ONLY **inside** its cluster.
- The algorithms that they proposed for ensuring BS connectivity are very **energy consuming**

mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

The paper reviews the reviews the relationship between delay and mobile sink velocity

- The authors show that **increasing** either the radio transmission range **r**, or the number of mobile sinks **m**, or the sink velocity **v** the sensor-sink meeting **delay** can get **reduced**

Next the authors add in their analysis the message length

- Again the result shows that, by **decreasing** message length **L**, or **increasing** transmission range **r** and number of mobile sinks **m**, the message delivery delay can be **reduced**
    - Simulation showed that increasing the ratio of sink velocity to sensor transmission radius, at first decreases the delay, reaches an **optimal condition** but then delay is increasing again !

At last, the Outage Probability is considered

- After an analysis is performed, it is shown that the goal of enlarging the outage area can be achieved via **increasing r**, or **decreasing v or T**

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Our new paper

Data gathering in wireless sensor networks with mobile collectors
Ming Ma, Yuanyuan Yang
Department of Electrical and Computer Engineering, State University of New York, Stony Brook
Published at IEEE International Symposium on Parallel and Distributed Processing 2008

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

The data gathering problem is considered in which the M-collector collects data from sensors in a single hop communication(no relay)

- The m-collector sends a **poll message** to sesnors and then the sensors send the data back to m-collector
- the positions where the M-collector polls sensors are defined as **polling points**
- each data gathering tour of an M-collector consists of a number of polling points
- The problem of finding the optimal tour can be considered as the problem of determining the locations of polling points and the order to visit them
- The **neighbor set** is defined as the set of sensors that can upload data to the M-collector directly
- the union of neighbor sets of all polling points must cover all sensors

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Preliminaries:

- Due to the uncertainties of the wireless environment, it is hard to estimate the boundary of the transmission range without real measurement
- In practice, it is almost impossible to obtain the neighbor set of an unknown point unless the **M-collector** or a **sensor** has been there
- A subset of *polling points* is the **candidate polling points** in which only the known polling points are included
- In order to obtain the candidate polling points without the information on the connection pattern, one or more M-collectors need to **explore** the entire sensing field

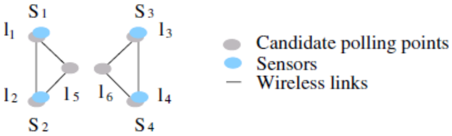
Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Preliminaries:

- While exploring the M-collector sends "Hello" messages and if one or more senrors reply it adds it possition to the candidate polling points
- In addition, each sensor can also **discover** its **one-hop neighbors** by broadcasting the Hello messages during the neighbor discovering phase
  - in that way the position of the sensor can also become a candidate polling point
- Next slide provides an illustration of the definition of *polling points*, *neighbor set*, and *candidate polling points*

Preliminaries:

- During the exploration phase, the M-collector discovers the neighbor sets of l_5 and l_6 by broadcasting Hello messages
- l_5 and l_6 can be added into the candidate polling points set
    - Sensors also report their one-hop neighbors to the M-collector creating more candidate polling points



Sensors : S_1, S_2 , S_3 and S_4

Neighbor set of l_1, l_2 and l_5: { S_1 , S_2 }

Neighbor set of l_3 l_4 and l_6: { S_3 , S_4 }

Candidate polling point set : { l_1, l_2, l_3, l_4, l_5, l_6 }

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Problem formalization:

- $S = s_1, s_2, \ldots, s_{n_s}$, a set of **candidate polling point**
- $L = l_1, l_2, \ldots, l_{n_l}$where l_0 denotes the **starting** and the **ending points** of the tour
- $nb(l_i)$ the **neighbor set** of each candidate polling point l_i

Find a set of polling points and determine the sequence to visit them, such that every sensor in S belongs to the neighbor set of at least one polling point and the total distance of line segments connecting all polling points is minimized.

- A complete graph $G = (L, A)$ is defined
- a non-negative cost c_{ij} is associated in each arc $a_{ij} \in A$
- c_{ij} equals the cost of the **distance** between the candidate polling points l_i and l_j

The SHDGP problem may be formulated as a mixed integer program as follows:

Problem formalization:

$$\text{Minimize} \quad \sum_{i,j \in L, i \neq j} c_{ij} x_{ij} \tag{1}$$

Subject to

$$\sum_{i \in L, i \neq j} x_{ij} = I_j, \forall j \in L \tag{2}$$

$$\sum_{j \in L, j \neq i} x_{ij} = I_i, \forall i \in L \tag{3}$$

$$\sum_{j \in nb(l_i)} I_i \geq 1, \forall j \in S \tag{4}$$

$$y_{ij} \leq |L| x_{ij}, \forall i, j \in L \tag{5}$$

$$\sum_{j \in L \setminus \{l_0\}} y_{jl_0} = \sum_{j \in L \setminus \{l_0\}} I_j \tag{6}$$

$$\sum_i y_{ji} - \sum_k y_{kj} = I_j, \forall j \in L \setminus \{l_0\} \tag{7}$$

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Problem formalization:

$$x_{ij} = \begin{cases} 1, & \text{if the data gathering tour contains arc } a_{ij} \\ 0, & \text{otherwise} \end{cases}$$

x_{ij} is an indicator variable denoting whether arc a_{ij} from candidate polling points l_i to l_j **belongs** to **the optimal tour**

$$l_{ij} = \begin{cases} 1, & \text{if the data gathering tour contains candidate polling point } l_i \\ 0, & \text{otherwise} \end{cases}$$

Binary variable l_i indicates whether **candidate polling point** l_i is on the **optimal tour**

y_{ij}: the **flow value** from l_i to l_j n arc a_{ij}

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Explaining objective function(constraints):

- (1) **minimizes the total cost** (distance) of the data gathering tour
- (2) and (3) ensure the fact that every node in the tour must have **one arc** pointing **towards** it and the **other arc** pointing **away from it**
- (4) enforces that **every sensor must be in the neighbor set of at least one polling point** belonging to the tour, such that every sensor can communicate with the M-collector directly
- (5)-(7) **exclude** the solutions with **sub-tours**
  - (5) restricts that flow can only take place in an arc if it is on the tour
  - (6) specifies that the units of flow entering vertex l_0 equals the number of polling points in the tour
  - (7) enforces that one unit flows out of each of the other points in the tour

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Proving its NP-hardness:

Consider a special case of the problem: the **transmission range** of any sensor is **close to 0**

- the M-collector must visit every sensor one by one to collect data
- Thus, the problem is reduced to finding the shortest tour of visiting every sensor exactly once
- the problem is **reduced to Traveling Salesman Problem (TSP)** problem which is known that is **NP-hard**

Thus, SHDGP is NP-hard

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Heuristic algorithms for the SHDGP problem:

- First, start with an empty set P
- Let U contain the set of remaining uncovered sensors at each stage of the algorithm
- Let F be the family of neighbor sets
- Let $cost\{S\}$ be the **cost** of an uncovered neighbor set S and equal to the **shortest distance** between S and any covered neighbor set
    - The distance between two neighbor sets is defined as the distance between their corresponding candidate polling points
- Let $\alpha = \frac{cost\{S\}}{S \bigcap U}$ and denote the **average cost** to cover each uncovered sensor in S

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Heuristic algorithms for the SHDGP problem:

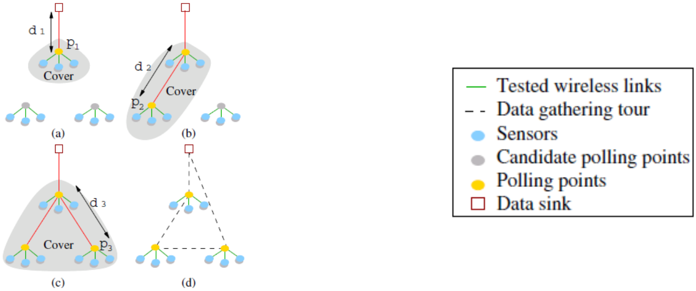
Spanning Tree Covering Algorithm

Create an empty set P
Create a set U containing all sensors
Create the family set F of all neighbor sets
while $U \neq \{\}$
  Find the set $S \in F$ that minimizes $\alpha = \frac{cost\{S\}}{S \bigcap U}$
  Cover sensors in S
  Add the corresponding polling point of S into P
  Remove sensors in S from U
end while
Find an approximate shortest tour on polling points in P

When each neighbor set only contains one sensor the algorithm is exactly same as Prims algorithm for MST problem

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Heuristic algorithms for the SHDGP problem:



- The neighbor set of p_i is covered with the average cost $\frac{d_i}{3}$
- the M-collector chooses p_1 as the first polling point, since compared to other candidate polling points it has the shortest distance

Heuristic algorithms for the SHDGP problem(computational complexity):

Supposing that there are a total of N sensors and M candidate polling points the computational complexity is

- $O(NM)$ times to find a sub-family of neighbor sets which cover all sensors
- $O(M^2)$ for the work of finding an approximate shortest tour on polling points in P

The authors compare their **Spanning Tree Covering Algorithm** with the $[(\sqrt{7^2+3^2}+1)r_{tsp}]$ approximation algorithm designed by Arkin and Hassin for the geometric version of the CSP problem

- CSP: Covering Salesman Problem
- to obtain the **shortest tour** of a **subset of all cities** such that **every city not on the tour** is within some **predetermined distance**, dist, of a city that is on the tour

Heuristic algorithms for the SHDGP problem:

The basic idea of the CSP approximation algorithm is

- Cover all unit circles by a minimum number of vertical covering lines
- choose a representing point from each unit circle region to be the intersection point of the diameter of the region and the covering line
- Finally, find an approximation TSP tour on the representing points

The authors name this algorithm as **covering line algorithm**

- If the transmission range of a sensor can be modeled as a unit circle, the **covering line algorithm** could also approximate the optimal tour for SHDGP
- In practice transmission ranges of sensors are far from unit circles and difficult to be estimated

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Heuristic algorithms for the SHDGP problem(multiple M-collectors):

- A possible solution can be borrowed from the traditional delivery vehicle routing problem in which:
  - a number of trucks are sent out from the facility center
  - each of them moves through a sub-tour, delivering packages home by home
  - and each of them returns to the facility center before the center closes
  - This problem has been defined as Multiple Traveling Salesman Problem (MTSP) and is known to be NP-hard
- Unfortunately this solution is not always feasible
  - in some very large scale networks, some sensors may be deployed too far away from the data sink
  - the round-trip time consumption of the longest data gathering tour may exceed the time constraint for filling the buffer of a sensor
- This can be solved if the **M-collectors can exchange their data**

Heuristic algorithms for the SHDGP problem(multiple M-collectors):

- Basic idea of the algorithm
  1. Build a minimum spanning tree using the polling points found from the **spanning tree covering** algorithm
  2. **Decompose** the spanning covering tree into **a set of subtrees** equal to the number of the M-collectors
  3. Find an **approximate shortest sub-tour** on the points of each subtree
  4. Route data through the M-collectors to the data sink
- Notations
  - Let L_{max} be the upper bound on the length of any sub-tour, which guarantees no buffer overflows
  - Let $t(v)$ denote the subtree of T
    - which is rooted at vertex v and consists of all child vertices of v and edges connecting them in T
  - Let $Parent\{v\}$ be the parent vertex of v in T
  - Let $Weight\{v\}$ represent the total length of the subtree $t(v)$ rooted at v

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Heuristic algorithms for the SHDGP problem(multiple M-collectors):

- The algorithm analysed
  1. Find the polling point set P by running the spanning tree covering algorithm
  2. find the minimum spanning tree $T(V, E)$ on polling points
  3. calculate the weight values of all vertices in T
  4. Repeatedly remove subtrees from T until no vertex is left in T
     - To build a subtree t in each loop

       $\Rightarrow$ start from the deepest leaf vertex of the remaining T, and let it be the root $Root(t)$ of the subtree t

       $\Rightarrow$ if $Weight(Parent(Root(t))) \leq \frac{L_{max}}{2}$ then $Root(t) = Parent(Root(t))$

       $\Rightarrow$ Otherwise, add all child vertices of $Root(t)$ and edges connecting them in T into t, and remove t from T

       $\Rightarrow$ upgrade the weight value of each vertex in the remaining T
     - When T is empty and T has been decomposed into a set of subtrees of length no more than $\frac{L_{max}}{2}$
- Finally, the sub-tour on polling points of each subtree can be determined by running the approximation algorithm for TSP

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Data Gathering Algorithm with Multiple M-collectors

Find the polling point set P
Find the spanning covering tree T on all polling points in P
For each vertex v in T, calculate the weight value $Weight(v)$
while $U \neq \{\}$
  Find the deepest leaf vertex u in T
  Let the root of the subtree t, $Root(t) = u$
  while $Weight(Parent(Root(t))) \leq \frac{L_{max}}{2}$
    $Root(t) = Parent(Root(t))$
  end while
  Add all child vertices of $Root(t)$ and edges connecting them into t and remove t from T
  Update weight value of each remaining vertex in T
end while

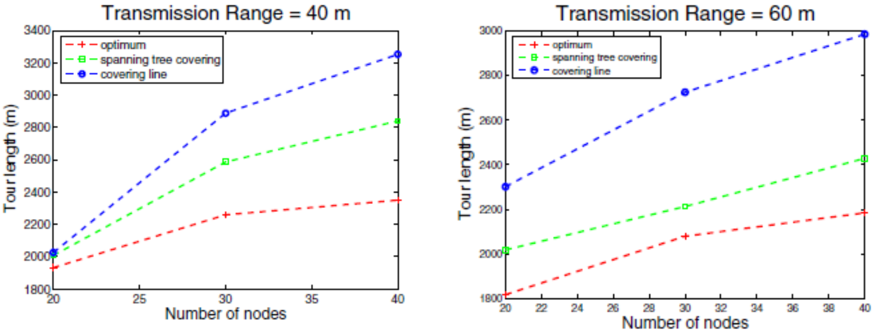
The loop takes $O(M^2)$ time, and the operations before the loops take another $O(NM + M^2)$ time. Total $O(NM + M^2)$.

Simulation - Tour length of a single M-collector:

- The authors find the **optimal path** of the M-collectors using **brutal force** in a few small networks
- The connectivity of a sensor network depends on two major factors: deployment density and the transmission range of sensors
  - They simulated for all combinations of transmission range equal to $40m$, $60m$ and $80m$
  - and the number of nodes equal to 20, 30 and 40 in a $500m$ by $500m$ field
- If the **network tends to be disconnected** (low TR, sparse network) both algorithms are very **close to the optimal** solution
  - In this case, the M-collector may need to visit every sensor, no matter which algorithm is employed

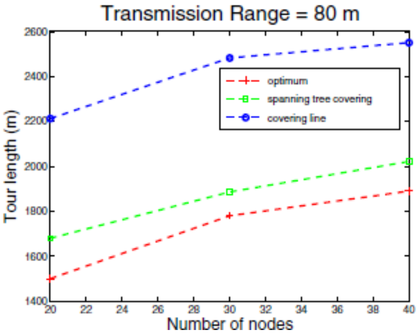
Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

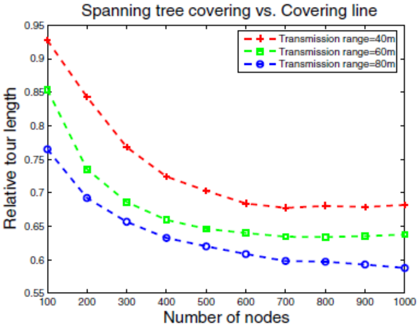
Simulation - Tour length of a single M-collector:



Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Simulation - Tour length of a single M-collector:





Simulation - Tour length of a single M-collector:

In the last figure we can observe two facts:

- for the networks with the same size, the **larger the transmission range** is, the **shorter average moving distance** the M-collector needs to travel
- for any transmission range, the **relative tour length keeps decreasing** as the network size increases

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Simulation - Network Lifetime:

The authors compare three data gathering schemes

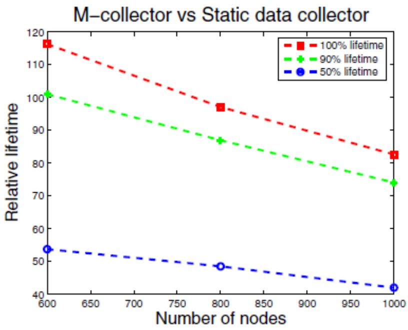
1. A **static** data collector is placed in the **center** of the network
2. A mobile data collector which can only move **back and forth** through the **straight line** between
3. An M-collector which can **move along** a well-planned data **gathering tour** that starts from and ends at point

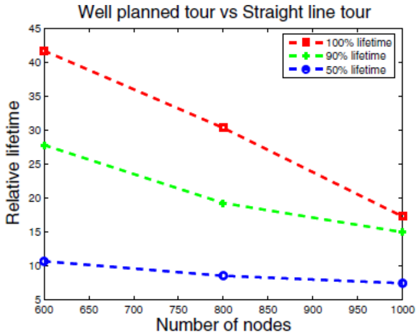
A new metric called *x% network lifetime* is introduced and is defined as **the network lifetime when** $(100x)$**% sensors either run of battery or cannot send data to the data sink due to the failure of relaying nodes**

- Sensors are allowed to relay packets only in Schemes 1 and 2
- the optimal network lifetime by using a load balancing algorithm from another paper

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Simulation - Tour length of a single M-collector:





Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

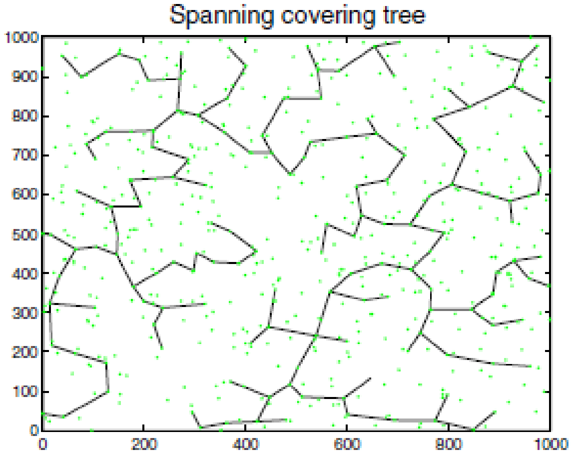
Simulation - Data gathering with multiple M-collectors:

The authors compare three data gathering schemes

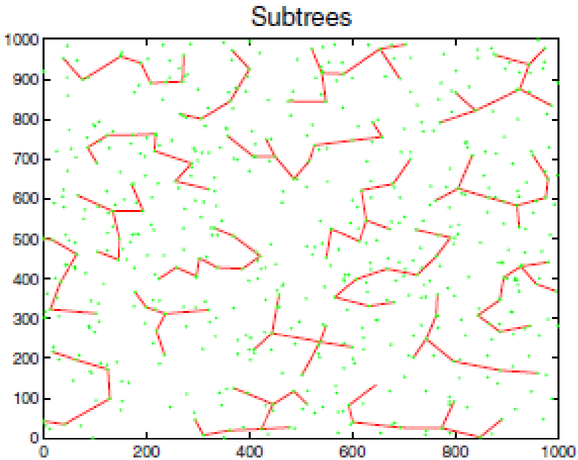
- 600 sensors are deployed into $1000m \times 1000m$ area with a transmission range $40m$
- M-collectors move at the fixed speed of $1m/s$
- The data memory of each sensor can hold at most $512k$ bytes
- each sensor collects data from the environment at the fixed rate of $512Bps$
- Thus, each sub-tour of any M-collector must be no more than $1000m$

Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Simulation - Data gathering with multiple M-collectors:

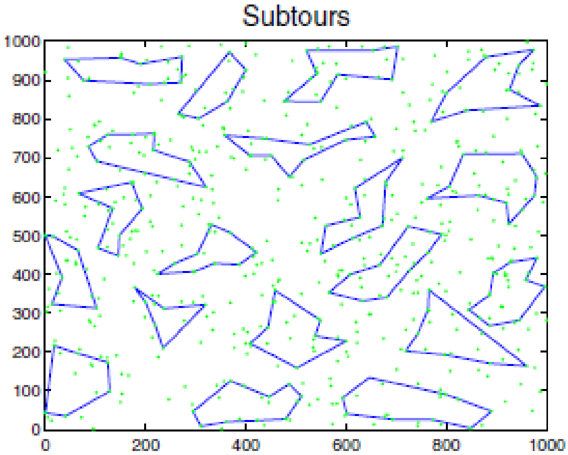


Simulation - Data gathering with multiple M-collectors:



Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

Simulation - Data gathering with multiple M-collectors:



Protocols that use multiple mobile BS or mobile relays

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks [55]
2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010 [3]
3. mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008 [54]
4. Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing [57]
5. Mobile Element Scheduling with Dynamic Deadlines, Arun A. Somasundara, Aditya Ramamoorthy, Mani B. Srivastava, IEEE Transactions on Mobile Computing, 2007 [73]

Protocols that use multiple mobile BS or mobile relays

6. Using Predictable Observer Mobility for Power Efficient Design of Sensor Networks, Arnab Chakrabarti, Ashutosh Sabharwal, Behnaam Aazhang, IPSN'03 [11]
7. Communication power optimization in a sensor network with a path-constrained mobile observer, Arnab Chakrabarti, Ashutosh Sabharwal, Behnaam Aazhang, TOSN 2006 [12]
8. Multiple Controlled Mobile Elements (Data Mules) for Data Collection in Sensor Networks, David Jea, Arun Somasundara, Mani Srivastava DCOSS 2005 [40]
9. Improved sensor network lifetime with multiple mobile sinks, Mirela Marta, Mihaela Cardei, Pervasive and Mobile Computing, 2009 [59]
10. Towards Mobility as a Network Control Primitive, David K. Goldenberg, Jie Lin, A. Stephen Morse, Brad E. Rosen, Y. Richard Yang MobiHoc 04 [30]
11. Energy Optimization under Informed Mobility, Chiping Tang and Philip K. McKinley, IEEE Trans. Parallel Distrib. Syst.

Protocols that use multiple mobile BS or mobile relays

12. Mobile Relay Configuration in Data-intensive Wireless Sensor Networks, Fatmé El-Moukaddem, Eric Torng, Guoliang Xing, and Sandeep Kulkarni, MASS IEEE (2009) [22]
13. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, R C Shah, S Roy, S Jain, W Brunette, Sensor Network Protocols and Applications, 2003 [70]
14. Controlling the Mobility of Multiple Data Transport Ferries in a Delay-Tolerant Network, Wenrui Zhao, Mostafa Ammar, Ellen Zegura, INFOCOM 2005 [102]

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

A different approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of two types of nodes: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be NP-hard
- They present a heuristic algorithm for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Banerjee et al. 2010

A different approach that uses the MR as cluster head

- Author study the problem of energy balance
- They propose to use multiple mobile cluster heads (CHs) that can move in the WSN in a controllable manner
- The CH controllably moves toward the energy-rich sensors or the event area, offering the benefits of maintaining the remaining energy more evenly, or eliminating multihop transmission.
- Sensor nodes form clusters and select MRs as the corresponding cluster heads
- Each cluster head roams among its cluster nodes and collects data and then sends the data to the sink with direct transmission

A different approach that uses the MR as cluster head

- In this paper a three-tier architecture: sensors, mobile sinks and BS tiers
- The sensor nodes in the sensor tier are organised in a cluster with MRs as the cluster heads
- Inside each cluster MRs roam the cluster nodes and bugger the sensing data
- In order to send data to a BS, MRs can comminicate with each other and with the BS through short or long transmissions
- They investigate the following parameters: cluster size, sink velocity, transmission range, and packet length
- They study the effect of relay velocity on message-delivery delay and outage probability when the MRs move randomly

4. Data gathering in wireless sensor networks with mobile collectors, Ma and Yang 2008

- They propose a new data gathering mechanism for large scale wireless sensor networks by introducing mobile collectors, "m-collectors"
  1. An M-collector starts the data gathering tour periodically from the static data sink
  2. polls each sensor while traversing the transmission range of the sensor
  3. then collects data directly from the sensor without relay (i.e., in a single hop)
  4. and finally returns and uploads data to the data sink.
- Since data packets are gathered directly without relay and collision, the lifetime of sensors is expected to be prolonged
- They focus on the problem of minimizing the length of each data gathering tour and show its NP-hardness
- Finally they propose heuristic algorithms, for prolonging network lifetime, that use one or more "m-collectors" using only one-hop communication

5. Mobile Element Scheduling with Dynamic Deadlines, Somasundara et al. 2007

- The authors study again the routing path of multiple MRs traversing the network at a constant speed, but this time each sensor node operates at different sampling rates
- They try to solve the problem of scheduling the mobile element(s) in the network so that there is no data loss due to buffer overflow
- It is shown that the problem is NP-complete
- An algorithm is proposed to find the path that minimizes the buffer overflow at each sensor node based on the constraint of buffer and data generation at each sensor

6. Using Predictable Observer Mobility for Power Efficient Design of Sensor Networks Chakrabarti et al. 2003

- The paper explores the problem of saving power in sensor networks based on predictable mobility of the data sink
- To understand the gains due to predictable mobility, the data collection process is modeled as a queuing system, where random arrivals model randomness in the spatial distribution of sensors
- The success in data collection, and the quantification of the power consumption of the network are analysed
- It is shown that the power savings over a static sensor network are significant
- Finally a simple observer-driven communication protocol is presented

7. Communication power optimization in a sensor network with a path-constrained mobile observer, Chakrabarti et al. 2006

- Again a procedure for power optimization in a network of randomly distributed sensors is presented when a data collector moves on a fixed path
- The process of data collection is modeled by a queue with deadlines, where arrivals correspond to the observer entering the range of a sensor and a missed deadline means data loss.
- The queuing model is then used to identify the combination of system parameters that ensures adequate data collection with minimum power
- For sensor networks that cannot tolerate data loss, a tight bound is derived on minimum sensor separation that ensures that no data will be lost on account of mobility and show power redunction

8. Multiple Controlled Mobile Elements (Data Mules) for Data Collection in Sensor Networks, Jea et al. 2005

- The authors study the problem of load balancing of multiple mobile elements when the network scalability and traffic make the single mobile element insufficient
- They assume that MRs move on a straight line and propose a load balancing algorithm assuming mobile elements fully cover the entire field of the network
- They show by simulation the benefits of load balancing

9. Improved sensor network lifetime with multiple mobile sinks, Marta and Cardei 2009

- The paper studies the energy holes that appears close to sink
- The solution that is proposed is to use mobile sinks that change their location when the nearby sensors' energy becomes low
- In this way the sensors located near sinks change over time
- In deciding a new location, a sink searches for zones with richer sensor energy
- They propose a distributed and localized algorithm used by the sinks to decide their next movement location such that the virtual backbone formed by the sinks remains interconnected at all times

10 Towards Mobility as a Network Control Primitive, Goldenberg et al. 2004, 11. Energy Optimization under Informed Mobility, Tang and McKindley 2006

A scenario that energy replenishment of MR cannot always be possible due to the constraints of the physical environment

- In both are user to relay data and use the same transmission range as sensor nodes
- Mobility control algorithms are proposed in which each relay node moves to the midpoint of its neighbour coverage
- The communication energy is minimized by reducing the distance between the source and destination

12. Mobile Relay Configuration in Data-intensive Wireless Sensor Networks, El-Moukaddem et al. 2009

- The paper shows that the optimal position of an MR depends on the amount of data to be sent in addition to the initial position of sensor nodes
- The work increases the reliability of the path between the source and destination by improving the connectivity between communicating neighbours which can avoid the cost of control packet overhead
- The optimal relay configuration is shown to depend on both the positions of nodes and the amount of data to be sent
- Algorithms are developed that iteratively refine the configuration of mobile relays and converge to the optimal solution which do not require explicit synchronization

13. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, R C Shah et al. 2003

- Analyzes an architecture to collect sensor data in sparse sensor networks using MRs(called MULES)
- MULEs pick up data from the sensors when in close range, buffer it, and drop off the data to wired access points using short-wireless communications
- Substansial power saving at the sensors since they have only to transmit over a short range
- The model assumes two-dimensional random walk for mobility and incorporates key system variables such as number of MULEs, sensors and access points
- The performance metrics observed are the data success rate (the fraction of generated data that reaches the access points) and the required buffer capacities on the sensors and the MULEs

14. Controlling the Mobility of Multiple Data Transport Ferries in a Delay-Tolerant Network, Zhao and Ammar 2005

- This paper considers the Message Ferrying (MF) scheme which exploits controlled mobility to transport data in delay-tolerant networks, where end-to-end paths may not exist between nodes.
- In the MF scheme, a set of special mobile nodes called message ferries are responsible for carrying data for nodes in the network
- The authors study the use of multiple ferries in such networks, regarding address performance robustness concerns, and they focus on the design of ferry routes.
- Two ways of MRs interaction: either directly or via nodes
- MRs need to sychronize their movements to exchange data directly, while nodes are required to have enough storage and energy for buffering and and relaying data among MRs

Mobile Sinks in Wireless Sensor Networks

Filippos Vasilakis – SensorsLab

Computer Engineering and Informatics

November 23, 2011

Protocols that use multiple mobile BS or mobile relays

1. **Clustering and load balancing in hybrid sensor networks with mobile cluster heads**, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. **Increasing lifetime of wireless sensor networks using controllable mobile cluster heads**, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010
3. **mWSN for Large Scale Mobile Sensing**, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008
4. **Data gathering in wireless sensor networks with mobile collectors**, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing
5. **Mobile Element Scheduling with Dynamic Deadlines**, A. Somasundara, A. Ramamoorthy, M. Srivastava, IEEE Transactions on Mobile Computing, 2007

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of **two types of nodes**: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- each sensor has **different** flow generation **rate**
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be **NP-hard**
- They present a **heuristic algorithm** for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We investigated the paper and we concluded that:

- It provides solid background of the problem and discusses the problem of positioning mobile clusters heads in a two layer sensor network to maximize lifetime..but:
- The authors propose an **offline algorithm** for computing the positions of the cluster heads
- They don't discuss anything about the existance of a **Base Sink**
- In their model the **cluster heads are connected a priori**
- They don't count the **residual energy** of sensors when computing the cluster heads' new position
- Their solution is **bearly feasible**

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

An approach that uses the MR as cluster head

- The authors study again the energy balance problem under mobile cluster heads
- They propose to use multiple mobile cluster heads (CHs), each CH can move in its cluster
- They propose 3 protocols
  - CHs move towards the **energy-rich sensors**
  - CHs move towards the **event area**
  - a **hybrid protocol** in which CHs move according to the equation
    $C_{comb} = \eta \times C_{energy} + \gamma \times C_{event}$
- Also they discuss algorithms that mentain **connectivity** between CHs and BS
- In simulation they showed that there is a trade-of between energy consumption and delay

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

We investigated the paper and we concluded that:

- It is a very concrete work that analyses many interesting topics in WSNs but
- In residual energy-based strategy, in case of **multiple energy centres**, it does not find the optimal position for CH
  - Actually if the energy centres are **equal** the new position of CH is the least optimal
- In their model cluster members **does not change** at all. Also every CH moves ONLY **inside** its cluster.
- The algorithms that they proposed for ensuring BS connectivity are very **energy consuming**

3. mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

The paper reviews the reviews the relationship between delay and mobile sink velocity

- The authors show that **increasing** either the radio transmission range **r**, or the number of mobile sinks **m**, or the sink velocity **v** the sensor-sink meeting **delay** can get **reduced**

Next the authors add in their analysis the message length

- Again the result shows that, by **decreasing** message length **L**, or **increasing** transmission range **r** and number of mobile sinks **m**, the message delivery delay can be **reduced**
  - Simulation showed that increasing the ratio of sink velocity to sensor transmission radius, at first decreases the delay, reaches an **optimal condition** but then delay is increasing again !

At last, the Outage Probability is considered

- It is shown that the goal of enlarging the outage area can be achieved via **increasing** r, or **decreasing** **v** or **T**

4. Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

- The authors consider the problem in which M-collectors visit every node in its **transmission range** in order to minimize energy dissipation
- They formulate a **mixed integer program** solution and show that the problem is **NP-hard**
- Also they **compare** it with the **TCP** and **CSP**(Coverin Salesman Problem)
- A new algorithm is constructed to **obtain all polling points** according to their **average cost** from current position of M-collector
- When considering a larger network field, they construct a **MST** of polling points and **decompose** it to **equal subtrees**
- In each subtree an M-collector is scatter using the previous algorithm

Our new paper

Mobile Element Scheduling with Dynamic Deadlines

Arun A. Somasundara, Aditya Ramamoorthy, Mani B. Srivastava

A.A. Somasundara is with Broadcom Corporation, 3151 Zanker Road, San Jose
A. Ramamoorthy is with the Department of Electrical and Computer Engineering, Iowa State University
M.B. Srivastava is with the Electrical Engineering Department, University of California Los Angeles

Published at IEEE Transactions on Mobile Computing, 2007

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Introduction

- The paper analyses the **scheduling** of the mobile elements under **different deadlines**
- The problem that naturally crops up is the scheduling of the visits of the mobile element so that **buffers** on none of the sensor nodes **overflow**
- The problem is rather **different** from Travelling Salesman Problem(TSP)
    - In TSP, the goal is to find a **minimum cost tour** that visits each node exactly **once**
    - In this problem, a node may need to be visited **more than once** depending on the strictness of its deadline, frequency of sampling etc.
- As soon as a node is visited, its deadline (time before which it should be revisited to avoid buffer overflow) is updated

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Problem Formation

The Mobile Element Scheduling (MES) problem with a single mobile can be formulated in the following manner. We are given:

- A fully connected graph of n nodes: $\mathbf{node[1 \ldots n]}$
- A $\mathbf{matrix\_cost[1 \ldots n][1 \ldots n]}$ that denotes the time taken to go from one node to another
  - assumption: the vector consists of **integer** entries
- A vector that contains buffer overflow times, $\mathbf{overflow\_time[1 \ldots n]}$
  - assumption: the matrix consists of **integer** entries
  - The ith element of $overflow\_time[]$ determines the time to fill the buffer of the ith node, buffer size, sensing rate

Making the previous assumptions the $\mathbf{MES}(cost[1 \ldots n][1 \ldots n]$, $overflow\_time[1 \ldots n]$, $node_0)$ problem is the problem of finding a **sequence of visits** to nodes from $node[1 \ldots n]$ starting at $node_0$ so that none of the buffers of the nodes **overflow**.

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Proof of NP-Completeness

First the authors prove the next Lemma1:

Suppose that we are given an instance of **MES**$(cost[1 \dots n][1 \dots n], overflow\_time[1 \dots n], node_0)$ *that* **has a solution S**, *i.e., a schedule such that no nodes buffer overflows. Then, a* **periodic schedule** *can be* **derived** *from S in polynomial time so that, if the periodic schedule is followed, then none of the buffers will ever overflow*

To prove the lemma,

- the authors start observing and recording the sequence S in intervals of length T_O
- The maximum number of such intervals is $(n+1)^{(T_0+1)}$
- It follows that there exist two intervals, I_a and I_b that will be exactly the same if we observe the sequence from t_1 to $t_1 + (n+1)^{(T_0+1)}$
- Hence a valid periodic schedule can be constructed

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Proof of NP-Completeness

The proof of NP-Completeness consists of two parts:

- To see that the problem is in NP, we observe that
  - if we are given a schedule S_1 that is to be verified, by Lemma 1, it is clear that a maximum of $(n+1)^{(T_0+1)}$ successive entries of S_1 need to be examined
  - Thus, **verifying the validity of a schedule can be done in polynomial time**
- To prove that the problem is NP-hard
  - we **reduce** the problem of finding a **Hamiltonian Cycle** in an arbitrary graph $G(V, E)$ to the Mobile-Element-Schedule problem
  - This problem is well-known to be NP-complete

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Proof of NP-Completeness, redunction to Hamiltonian Cycle Problem

Let $G(V, E)$ be an instance of the Hamiltonian Cycle problem. We construct an instance of Mobile-Element-Schedule as follows:

- $\textbf{cost[i][j]} = \begin{cases} \textbf{1} & \text{if}(i,j) \in E \\ \textbf{2} & \text{otherwise} \end{cases}$
- $\textbf{overflow\_time[i]} = \textbf{n}, \forall I$
- $node_0 = 1$

If the constructed instance of Mobile-Element-Schedule returns a valid schedule S, then:

- Let x_t denote the state of the mobile element at time t
- In an interval $[t+1, \ldots, t+n]$, all nodes are visited **at least once**, but since all nodes have $overflow\_time = n$ all nodes are visited **exactly once since**

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Proof of NP-Completeness, reduction to Hamiltonian Cycle Problem

If the constructed instance of Mobile-Element-Schedule returns a valid schedule S, then:

- If we let x_i denote the state of the mobile element when $i \in (t+1), (t+2), \ldots, (t+n)$, then $cost[x_i][x_{i+1}] = 1$
  - if there exists an i such that $cost[x_i][x_{i+1}] = 2$ **then the n nodes cannot be fit in the n time slots**
- $x_{t+n} = x_t$
  - If $x_{t+n} = k \neq x_t$ then k must have appeared somewhere in $(t+1), (t+2), \ldots, (t+n)$ otherwise its buffer would overflow
  - But this is a **contradiction** since we know that each node appears exactly once in $(t+1), (t+2), \ldots, (t+n)$

But then the sequence $x_t, x_{t+1} \ldots, x_{t+n}$ is a **valid Hamiltonian cycle** in G or ... $G(V, E)$ contains a Hamiltonian cycle if and only if the above-constructed instance of Mobile-Element-Schedule has a valid solution

Integer-Linear-Programming (ILP) Formulation

We proved in the last section that the schedule is periodic, giving an upper bound to the period, let it be T.

An ILP formulation consists of variables and constraints on the variables: Variables:

- $x_{ij} : i \in \{1 \dots T\}, j \in \{1 \dots n\}$
  - $x_{ij} = 1$ if **at time** i **the mobile element is at node** j;
  - 0 otherwise
- $y_i : i \in \{1 \dots T\}$
  - $y_i = 1$ if, at **time** i **the mobile element is moving**;
  - 0 otherwise

Constraints:

- At time i, the mobile element is **either** at some sensor node or it is **moving**
  - $\sum_{j=1}^{n} x_{ij} + y_{ij} = 1, \forall i$

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Integer-Linear-Programming (ILP) Formulation

Constraints:

- The **maximum** allowed **time between visits** to a sensor node j is *overflowtime*[j]
  - $$\left.\begin{array}{c} \sum_{i=0}^{overflow\_time[j]} x_{ij} \geq 1 \\ \vdots \\ \sum_{i=T-overflow\_time[j]}^{T} x_{ij} \geq 1 \end{array}\right\} \forall j$$
- The mobile element must be in the **mobile state** between visits to two sensor nodes for at least the time **determined by the cost matrix**
  - $\sum_{t=i}^{k} \geq [s_{ij} + x_{kl} - C] \times \frac{cost[j][l]}{2-C}, \forall i,k \in \{1 \dots T\}, i < k$ and $j,l \in \{1 \dots n\}, j \neq l$, $1 < C < 2$

In general, the exact **period T is not known beforehand** and some amount of experimentation will be required

Heuristic algorithms

Earliest Deadline First (EDF) Algorithm

Main: Repeat the following

1. Choose the $nodei \neq current\_node$ whose deadline is closest
2. If $deadline[i] < current\_time + cost[current\_node][i]$

- Declare failure and stop

3. Else

- $current\_time += cost[current\_node][i]$
- $current\_node = i$
- $deadline[i] = current\_time + overflow\_time[i]$

- If step 1 was ommited, a node could monopolise the algorithm
- The algorithm **does not take into account the cost values** and relies only on deadlines

Heuristic algorithms

EDF with k-lookahead algorithm

Main: Repeat the following:

1. Sort *deadline*[1 . . .] in increasing order.
2. Using the first k entries:
   - Find an ordering of these k entries so that
     1. none of the k nodes miss their deadlines in the next k steps,
     2. the arrival time of the node at the $(k+1)th$ entry is minimal
     3. the first node in the resulting permutation is not the current node.
   - If none exists, declare failure and stop.
3. Let the first node in the ordering found be i.

- $current\_time \mathrel{+}= cost[currentnode][i]$
- $current\_node = i$
- $deadline[i] = current\_time + overflow\_time[i]$

Heuristic algorithms

Minimum Weighted Sum First

Main: Repeat the following:

1. $\forall i$, calculate $weightedsum[i] = \alpha_{mwsf} * (deadline[i] - current\_time) + (1 - \alpha_{mwsf}) * cost[current\_node][i]$
2. Choose the node $i \neq current\_node$ whose $weighted\_sum[i]$ is minimal.

- If $deadline[i] < current\_time + cost[current\_node][i]$
  - Declare failure and stop.
- Else
  - $current\_time \mathrel{+}= cost[current\_node][i]$
  - $current\_node = i$
  - $deadline[i] = curren\_time + overflow\_time[i]$

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Heuristic algorithms- Discussion

Earliest Deadline First Algorithm time complexity:

- At each step nodes are **sorted** based on their deadline, thus $O(nlogn)$

EDF with k-lookahead Algorithm time complexity:

- At each step nodes are **sorted** based on their deadline, thus $O(nlogn)$
- All deadlines for all k nodes for all k **permutation** are checked
- The total complexity of the algorithm is $O(nlogn + k \cdot k!)$

Minimum Weighted Sum First Algorith complexity

- Each step of MWSF takes $O(n)$ for **calculating the weighted sum** for all nodes and $O(n)$ for **choosing the minimum**
- Hence, $O(n)$ time complexity

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Heuristic algorithms- Discussion

It would be easier if there were some necessary and sufficient conditions to check the existence of a schedule.

- **Necessary Condition**
  - a necessary condition for a schedule to exist is the existence of a solution for TSP($max(overflow\_time[i])$) , $i \in [1 \ldots n]$
  - TSP(C) is the decision version of TSP and has a solution if there is a Hamiltonian cycle of length at most C
  - if TSP(C) does not have a solution, we cannot expect to have a solution to our problem as there are overflow time values which are less than this
- **Sufficient Condition**
  - a sufficient condition for a schedule to exist is the existence of a solution for TSP($min(overflow\_time[i])$), $i \in [1 \ldots n]$
  - All nodes having the same minimum overflow time is the strictest case
  - If a solution exists for this, we surely have a solution for MES

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Multiple Mobile Element Scheduling

- **Divide** the **Area** into **Equal Parts** (Schma-1)
  - If the nodes are distributed uniformly at random we can divide the area into parts of equal area
  - each mobile is responsible for the area it is assigned to and can follow the algorithms already presented
- **Combined Scheduling** (Schema-2)
  - we find a node to be visited by the first mobile
  - we find a node to be visited by the second mobile, considering the $n - 1$ remaining nodes
  - continuing this for all m mobiles, $n - m$ nodes are left to be scheduled.
- There seem to be trade-offs in the two approaches:
  - in the first case, each mobile is responsible for only $\frac{n}{m}$ nodes
  - In the second case each mobile has a **global view**

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Vehicle Routing Problem with Time Windows

Our problem can be described precisely by the **Vehicle Routing Problem (VRP)**

- We are given a **set of nodes** and their **service requests**
- There are **vehicles** available for servicing these requests which are **stationed at a special node** (depot)
- Each vehicle has a **certain capacity** (in terms of the quantity of goods it can carry)
- The goal is to find the **number of vehicles** and the **sequence** of nodes each vehicle has to visit such that the **sum of the distances** traveled by the vehicles is **minimal**

Vehicle Routing Problem with Time Windows (VRPTW)

- is an **extension** of VRP in which there is a **time window** $[\alpha, b]$ constraint for each node
    - The node cannot be serviced before α and has to be serviced before b

Both VRP and VRPTW are **NP-hard**

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Vehicle Routing Problem with Time Windows

The authors use a most cited paper for reference in order to solve the VRPTW problem.

Algorithms for the Vehicle Routing and Scheduling Problem with Time Window Constraints
Marius M. Solomon
Operations Research, vol. 35, no. 2, Mar.-Apr. 1987.

Algorithm description

1. It starts with a **single vehicle** and initializes a node to be on its tour
2. Then it finds the **best node to be inserted** into the tour of the current vehicle
3. This continues **till no nodes can be inserted**

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Vehicle Routing Problem with Time Windows

Algorithm description

4. At this point, a **new vehicle is called** to service and the procedure is repeated
    - The number of vehicles is also the result of the algorithm
5. If a vehicle reaches a node before its beginning time window α, it will wait

Two items are to be specified in the above description

- An **algorithm** for **finding the first node** to be inserted when a new vehicle is called for service.
    - the **farthest** unrouted node
    - the unrouted node with the **earliest deadline**
- The **definition of cost**

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Vehicle Routing Problem with Time Windows

Cost definition:

- Let $(i_0, i_1, \dot{;} i_z)$ be the current route with $i_0 = i_z = 0$
- For each unrouted customer u, **first compute its best feasible insertion place in the emerging route**
- Let i, j be adjacent nodes in the current partial route
- For u being inserted between i and j, define 2 cost functions:
  $c_{11}(i, u, j) = cost_{iu} + cost_{uj} - \mu * cost_{ij}, m \geq 0$
  $c_{12}(i, u, j) = time_{j_u} - time_j$
- $cost_{\alpha b}$ is the cost of going from node α to b
- $time_{j_u}$ is the **new time** for service to begin at node j given that u is on the route

Vehicle Routing Problem with Time Windows

Cost definition

- The best feasible insertion place for node u is defined to be **the one that minimizes** the weighted combination of its distance and time insertion
  $c_1(i,u,j) = \alpha 1 cost_{11}(i,u,j) + \alpha 2 cost_{12}(i,u,j)$
  $where\ \alpha 1 + \alpha 2 = 1, \alpha 1 \geq 0, \alpha 2 \geq 0$
- Next, we need to **find the best node u to be inserted**. Define
  $c_2(i,u,j) = \lambda * cost_{0u} - c_1(i,u,j), \lambda \geq 0$
- We need to choose the u that maximizes $c_2(i,u,j)$.
- **To sum up**, the best node and its insertions points can be found by running:
  $c_2(i(u^*), u^*, j(u^*)) = max[min[c_1(i_{p-1}, u, i_p)]]$,
  $p = 1, 2, 3. \ldots, z$

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Modifying VRPTW to solve MES problem

- we are given a set of nodes with *overflow_time* values.
- This implies that the node can be visited any time in the window $[t, t + overflow\_time[i]]$
  - Ideally, it would be better for the node to be revisited **as close to the upper time window**
  - Otherwise more frequent visits will be required

The modified algorithm consists of the following steps:

1. Solve the VRPTW algorithm of the previous section with initial time windows $[(1 - \alpha_{vrptw} * overflow\_time[i]), overflow\_time[i]]$
   - This results in a set of mobiles and a **list of nodes** to be visited by each

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Modifying VRPTW to solve MES problem

The modified algorithm consists of the following steps:

1. Solve the VRPTW algorithm of the previous section with initial time windows
   $[(1 - \alpha_{vrptw} * overflow\_time[i]), overflow\_time[i]]$
   - This results in a set of mobiles and a list of nodes to be visited by each
2. Whenever a node is visited by a mobile at time t
   - Remove the node from the list
   - **Create a new service request** for this node with time window:
     $[t + (1 - \alpha_{vrtw}) * overflow\_time[i], t + overflow\_time[i]]$
3. Find a mobile and the insertion spot to insert this request
   - For each mobile, first find the best insertion spot
   - Insert it in that mobiles list which has the least cost
   - If no feasible insertion spot for all mobiles
     - Call a **new mobile** for service or
     - Use the mobile (and the corresponding insertion spot) which

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Modifying VRPTW to solve MES problem

$\alpha_{vrptw} \rightarrow$	Closer to 0	Closer to 1
Waiting time at the nodes	High	Low
Number of visits to the nodes	Less	More
Distance traveled by the mobiles	Less	More

- As the node is to be visited closer to the upper limit of the time window, time is spent waiting at nodes when the mobiles reach their scheduled nodes early
- Over a certain period of time, the number of visits to a node is less
- This implies that the mobiles travel a shorter distance in a given total time

Time Complexity

- For the EDF with k-lookahead $O(\frac{n}{m} lognm + k \cdot k!)$
- For Combined Scheduling $O((n-m)log(n-m) + k \cdot k!)$
- The complexity of the VRPTW algorithm is $O(n^4)$ (**4 nested loops**)
  - n nodes to be scheduled
  - in each iteration the best unrouted node is chosen
  - in which the best is possible insertion spot is chosen
  - Finally, for any given insertion spot, all nodes following it need to be tested if the current insetion is feasible
- After this initial schedule the algorithm takes $O(m \cdot n^2)$ time
  - There are m mobiles
  - for each mobile, there can be $O(n)$ insertion spots
  - for each insertion spot, all nodes following this spot need to be checked if they miss their deadline due to the insertion of this node

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

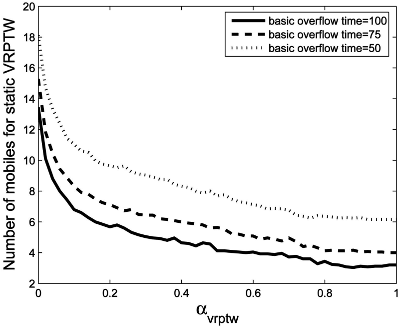
Simulation Methodology

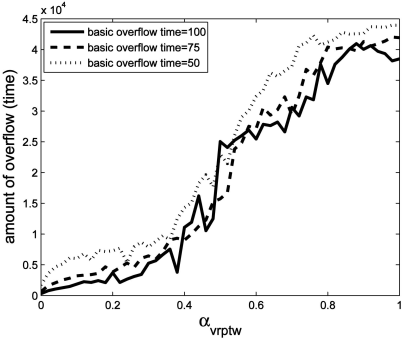
- **Topology**. A circular area of radius of 50 units and speed of 1m/s is considered
- **Simulation Time**. 100,000 time units were simulated
- **Location and number of nodes n**. The nodes were placed uniformly at random in the area
- **overflow_time values**. The point of interest is located in the center of the topology
  - nodes closer to the center have smaller *overflow_time* values
- Most results results were **averaged** over 25 topologies

Evaluation Metrics

- **percentage failure:** the ratio of missed deadlines and total deadlines
  - instead of stopping the algorithm when a node missed its deadline the authors let it continue, noting this fact and updating its deadline
  - in a simulation time of 100,000, each node i would have been visited $num\_visits[i]$ times of which $num\_deadline\_misses[i]$ times the deadline would have missed
  - it is the averaged ratio $100 \times \frac{num\_deadline\_misses[i]}{num\_visits[i]}$
- **amount of overflows:** the amount of time by which the deadline was missed
  - the total amount of time is calculated by which the mobile was late whenever a nodes deadline was missed
  - it is averaged across all the nodes
- **latency:** the time taken between the generation of a sample and the time of collection by the mobile element
  - it is averaged over all the samples, across all the nodes

Static VRPTW & dynamic VRPTW

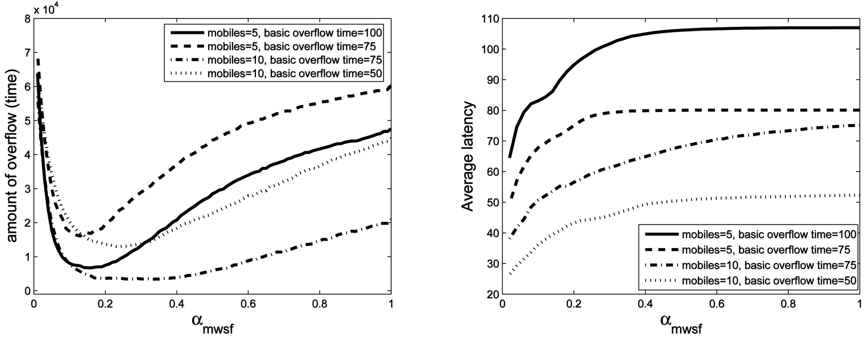




- The first figure shows the **number of mobiles needed** by the algorithm of M. Solomon
- The number of mobiles obtaines by (a) are used in the dynamic MES problem

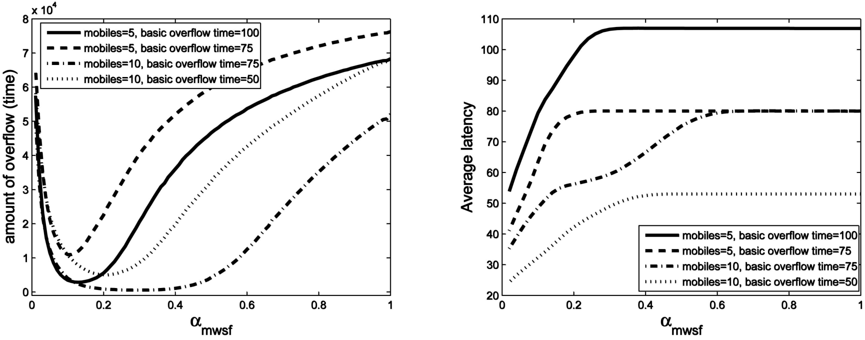
Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

Minimum Weighted Sum First, Schema-1



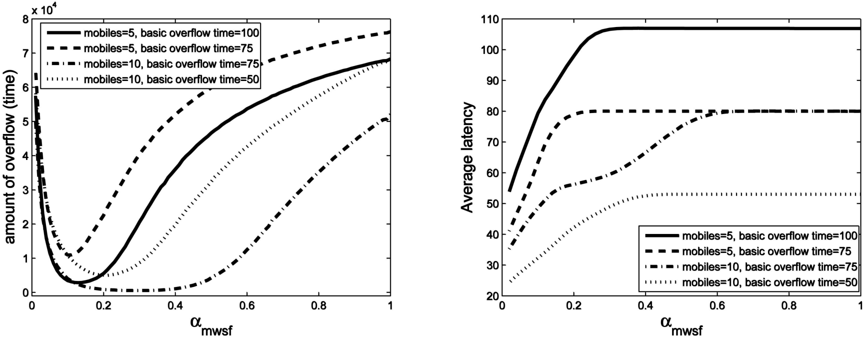
- This figure presents the **Minimum Weighted Sum First** for varying α_{mwsf} values, with the **Scheme-1**

Minimum Weighted Sum First, Schema-2



- The **Minimum Weighted Sum First** for varying α_{mwsf} values, with the **Scheme-2**

Modified VRPTW



- The figure presents the results of using the modified VRPWT algorithm
- The number of mobiles is fixed

Overflow and latency conclusions observations

Overflow

- In all cases, Scheme-2 with Minimum Weighted Sum First **performs better** than Scheme-1
  - in Scheme-2, mobiles have a **global knowledge** of the network
- Minimum Weighted Sum First with Scheme-2 performs better over modified VPRWT only in the case of $nummobiles = 5, overflow\_time = 75$

Latency

- for α_{mwsf} values closer to 0, the latency is less
  - a higher weight is given to cost, the mobile gives higher priority to **closer nodes**
- The average latency is monotonically decreasing as the α_{vrptw} parameter increases
  - as the width of the time window increases, mobiles spend **less time waiting** and data is collected from nodes much before they reach their full capacity

Paper we have analysed

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010
3. mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008
4. Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing
5. Mobile Element Scheduling with Dynamic Deadlines, Arun A. Somasundara, Aditya Ramamoorthy, Mani B. Srivastava, IEEE Transactions on Mobile Computing, 2007

Energy-Conserving Dynamic Routing in Multi-sink Heterogeneous Sensor Networks, Yunyue Lin, Qishi Wu, (CMC), 2010

- Heterogeneous sensor network architecture consisting of a small number of high-end sensors serving as sink nodes
- a path bottleneck-oriented and energy cost-based routing scheme are proposed
- a centralized,semi-distributed and a fully distributed version is proposed
- Extensive simulation results show that the proposed routing scheme outperforms existing routing algorithms in prolonging the lifetime

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vincze, Rolland Vida, Attila Vidacs, IEEE Pervasive Services, 2007

- Every sensor communicates with the closest sink in order to minimize energy consumption
- The authors give a mathematical model that determines the locations of the sinks minimizing the sensors' average distance from the nearest sink
- an iterative algorithm called global is presented that is able to find the sink locations given by the mathematical model
- This is impractical and unfeasible thus another distributed algorithm is presented called 1hop
- 1hop carries out the sink deployment based only on the location information of the neighboring nodes while the location of the distant nodes is being approximated
- The simulation results show that the algorithm extend the network lifetime severely

8. Our roadmap - 21-12-11

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wei Wang, Srinivasan, V., Kee-Chaing Chua, IEEE/ACM Transactions on Networking, 2008

- The authors first study the performance of a large dense network with one mobile relay and show that network lifetime improves up to a factor of four
- Also they show that the mobile relay needs to stay only within a two-hop radius of the sink
- A joint mobility and routing algorithm is constructed which can yield a network lifetime close to the upper bound
    - The advantage of this algorithm is that it only requires a limited number of nodes in the network to be aware of the location of the mobile relay
- The simulation results show that one mobile relay can at least double the network lifetime in a randomly deployed WSN

Architecture of Wireless Sensor Networks With Mobile Sinks: Sparsely Deployed Sensors,Liang Song, Dimitrios Hatzinakos
IEE, Vehicular Technology 2007

- The authors propose to develop wireless Sensor Networks with Mobile Sinks (MSSNs)
- The proposed MSSN is highly energy efficient, because the multihop transmissions of high-volume data over the network are converted into single-hop transmissions
- Their investigation is focused on sparsely deployed networks, where single node-to-sink transmission is considered
- A transmission-scheduling algorithm (TSA-MSSN) is proposed in which a parameter is employed to control the tradeoff between the maximization of the probability of successful information retrieval and the minimization of the energy-consumption cost
- It is shown that the proposed implementation of the TSA-MSSN has a complexity of O(1)

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad Hoc and Sensor Networks,Azzedine Boukerche, Xin Fei WIMOB 2008

- This paper presents an adaptive data gathering protocol (ADG) that employs multiple mobile collectors (instead of sinks) to help an existing wireless sensor network achieve energy efficiency and low message delay
- A virtual elastic-force model is used to help mobile collectors adjust their moving speed and direction while adapting to changes within the network
- Mobile collectors are sent out by sink if the information in the network is beyond the capabilities of existing mobile collectors and are called back when they become redundant
- The ADG protocol is analysed and compared with other existing protocols such as OCOPS and LEACH.

Mobile Sinks in Wireless Sensor Networks

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December 7, 2011

Protocols that we have anaysed so far

1. **Clustering and load balancing in hybrid sensor networks with mobile cluster heads**, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. **Increasing lifetime of wireless sensor networks using controllable mobile cluster heads**, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010
3. **mWSN for Large Scale Mobile Sensing**, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008
4. **Data gathering in wireless sensor networks with mobile collectors**, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing
5. **Mobile Element Scheduling with Dynamic Deadlines**, A. Somasundara, A. Ramamoorthy, M. Srivastava, IEEE Transactions on Mobile Computing, 2007

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of **two types of nodes**: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- each sensor has **different** flow generation **rate**
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be **NP-hard**
- They present a **heuristic algorithm** for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We investigated the paper and we concluded that:

- It provides solid background of the problem and discusses the problem of positioning mobile clusters heads in a two layer sensor network to maximize lifetime..but:
- The authors propose an **offline algorithm** for computing the positions of the cluster heads
- They don't discuss anything about the existance of a **Base Sink**
- In their model the **cluster heads are connected a priori**
- They don't count the **residual energy** of sensors when computing the cluster heads' new position
- Their solution is **bearly feasible**

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

An approach that uses the MR as cluster head

- The authors study again the energy balance problem under mobile cluster heads
- They propose to use multiple mobile cluster heads (CHs), each CH can move in its cluster
- They propose 3 protocols
  - CHs move towards the **energy-rich sensors**
  - CHs move towards the **event area**
  - a **hybrid protocol** in which CHs move according to the equation
    $C_{comb} = \eta \times C_{energy} + \gamma \times C_{event}$
- Also they discuss algorithms that mentain **connectivity** between CHs and BS
- In simulation they showed that there is a trade-of between energy consumption and delay

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

We investigated the paper and we concluded that:

- It is a very concrete work that analyses many interesting topics in WSNs but
- In residual energy-based strategy, in case of **multiple energy centres**, it does not find the optimal position for CH
  - Actually if the energy centres are **equal** the new position of CH is the least optimal
- In their model cluster members **does not change** at all. Also every CH moves ONLY **inside** its cluster.
- The algorithms that they proposed for ensuring BS connectivity are very **energy consuming**

3. mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

The paper reviews the reviews the relationship between delay and mobile sink velocity

- The authors show that **increasing** either the radio transmission range **r**, or the number of mobile sinks **m**, or the sink velocity **v** the sensor-sink meeting **delay** can get **reduced**

Next the authors add in their analysis the message length

- Again the result shows that, by **decreasing** message length **L**, or **increasing** transmission range **r** and number of mobile sinks **m**, the message delivery delay can be **reduced**
    - Simulation showed that increasing the ratio of sink velocity to sensor transmission radius, at first decreases the delay, reaches an **optimal condition** but then delay is increasing again !

At last, the Outage Probability is considered

- It is shown that the goal of enlarging the outage area can be achieved via **increasing** **r**, or **decreasing** **v** **or** **T**

4. Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

- The authors consider the problem in which M-collectors visit every node in its **transmission range** in order to minimize energy dissipation
- They formulate a **mixed integer program** solution and show that the problem is **NP-hard**
- Also they **compare** it with the **TCP** and **CSP**(Coverin Salesman Problem)
- A new algorithm is constructed to **obtain all polling points** according to their **average cost** from current position of M-collector
- When considering a larger network field, they construct a **MST** of polling points and **decompose** it to **equal subtrees**
- In each subtree an M-collector is scatter using the previous algorithm

Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

- The paper analyses the scheduling of the **mobile elements** under **different deadlines**
- The authors firt prrove the **NP-completeness** of the problem and form an **integer programming** formation
- They propose practical algorithms fo single mobile sink and extend them in the case of multiple sinks
  - Earliest Deadline First (EDF)
  - EDF with k lookahead
  - Minimum weighted sum first
- In case of multiple sinks they note the similarity with Vehicle Routing Problem with Time Windows (**VRPTW**)
- Te authors propose and analyse the most cited algorithm for that problem
  - Start with a single vehicle and add new vehicle every time **no new node** can be inserted in **existing tour**
- Simulation shows that VRPTW has the best performance followed by Minimum weighted sum first

Our new paper

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime

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Published at World of Wireless, Mobile and Multimedia Networks(WoWMoM), 2008

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

Introduction

- The paper investigates the problem of **energy holes** that appear near the sinks
- In WSNs, sensors closer to a sink tend to consume more energy than those farther away from the sinks
  - besides transmitting their own packets, they forward packets on behalf of other sensors that are located farther away
  - even if we adopt a multi sink architecture, again the first nodes that will die will be those close to the sink
- In order to avoid the formation of energy holes, **sink mobility** can be used
- When the energy of the sensors near a sink becomes low, the sink can move to a new location in a zone with richer sensor energy

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

Network Model

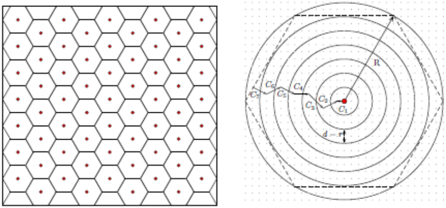
- sinks have **two transceivers**, one to communicate with the sensors, and another to communicate with the other sinks
  - sensor nodes have the same transmission range of r units
  - sinks have the same transmission range of R units
- Sensor nodes are **uniformly** and randomly distributed
- Each link has enough capacity to transfer the data
- Sinks have movement capabilities
- A a **periodic data gathering** application is considered where b data bits are transmitted by each sensor, in each time period T, to the closest sink
- The data is forwarded to the sink using **multihop** communication

Energy Model

- The energy model of a sensor includes the power for sensing, power for receiving, and the power for transmission
- Energy to **sense**: $E_{sense} = \alpha_1 b$
- Energy to **transmit**: $E_{TX} = (\beta_1 + \beta_2 r^n) b$
- Energy to **receive**: $E_{RX} = \gamma_1 b$
- Some typical values:
  $\alpha_1 = 60 \times 10^{-9}$ J/bit
  $\beta_1 = 45 \times 10^{-9}$ J/bit
  $\beta_2 = 10 \times 10^{-12}$ J/bit/m^2, when $n = 2$
  $\beta_2 = 0.001 \times 10^{-12}$ J/bit/m^4, when $n = 4$
  $\gamma_1 = 125 \times 10^{-9}$ J/bit
- Sinks are considered to have unlimited energy resources and thus the energy they spend is not taken into account

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

An example with static sinks



(a) Sensor Network Organization for Static Sinks (b) Coronas Division for a Sink

- when the sinks are static, a **hexagonal tiling** is considered with the sink located in the hexagon centers
- each sensor sends its data to the closest sink
- In order to compute the energy consumed by each sensor, a **corona-based model** is used with width $d = r$

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An example with static sinks

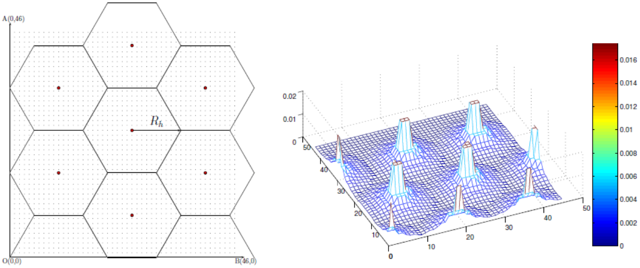
- A data message transmitted from corona C_i is sent to the closest sink using **multihop** communication
  - it is forwarded by sensor nodes in coronas C_{i1}, C_{i2}, and so on until it reaches corona C_1 from where it is transmitted to the sink
- Let k be the number of coronas and ρ the sensor density
  - The traffic load of a sensor in corona C_i, $i = 1 \ldots k$, is computed as follows:

    $$Load_i = \frac{\text{traffic from coronas } C_i, C_{i+1}, \ldots, C_k}{\text{number of sensors in } C_i}$$

    $$Load_i = \frac{\rho(\pi(kr)^2 - \pi((i-1)r)^2)b}{\rho(\pi(ir)^2 - \pi((i-1)r)^2)} = \frac{k^2 - (i-1)^2}{i^2 - (i-1)^2} b$$
- It follows that the energy consumed by a sensor in corona $C_i, i = 1 \ldots k$, is computed as:

  $$E_i = E_{sense} + E_{TX} + E_{RX} = \alpha_1 b + (\beta_1 + \beta_2 r^n) \frac{k^2 - (i-1)^2}{i^2 - (i-1)^2} b + \gamma_1 \frac{k^2 - i^2}{i^2 - (i-1)^2} b$$

An example with static sinks



(a) Multi-Sink Sensor Network Organization

(b) Sensor Energy Consumption after T Time

- Simulation results showed that the energy consumed by the sensors in the seven coronas were: E1 = 0.0175 J, E2 = 0.0056 J, E3 = 0.0031 J, E4 = 0.0019 J, E5 = 0.0012 J, E6 = 0.0006 J, E7 = 0.0002
- A sensor in corona C_1 consumes **more than three times** compared to a sensor in corona C_2

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

The problem of Sink Mobility for Network Lifetime Increase (SM-NLI) is formalized as follows:

Problem Definition

Given a heterogeneous WSN consisting of N sensors randomly deployed for periodic monitoring of an area andM sinks with mobility capabilities, design a sink movement plan such that the network lifetime is maximized and the sinks remain interconnected all the time.

The objective of the SM-NLI problem are:

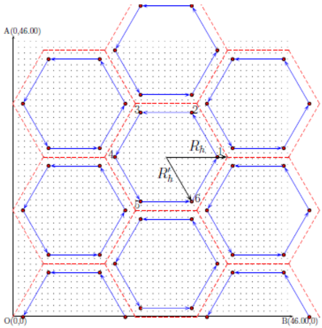
1. design the sinks movements to **balance** the sensors **energy** consumption and to vary the set of sensors located in first coronas
2. maintain the **sinks interconnected**

Sink Mobility with Pre-established Mobility Path

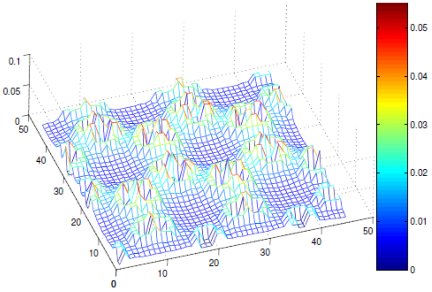
Authors consider the case when sinks move along the hexagon perimeters

- sinks' movements are **synchronized** $\Rightarrow$ their relative positions remain the same $\Rightarrow$ sinks are **connected** all the time
- a sink **moves along the perimeter** of a solid-line hexagon and stops at the corners, as shown in the next figure
- In each stop, the sink collects data over a period T and then moves to the new location
- Each sink moves in the corners of a hexagon (solid-line hexagon) with radius $R_h' = R_h - \frac{2}{\sqrt{3}}(d + \epsilon)$
  - The distance between the two hexagons is $d + \epsilon$
  - This way sensors are prevented from belonging to first corona of **two different sinks**

An example with static sinks



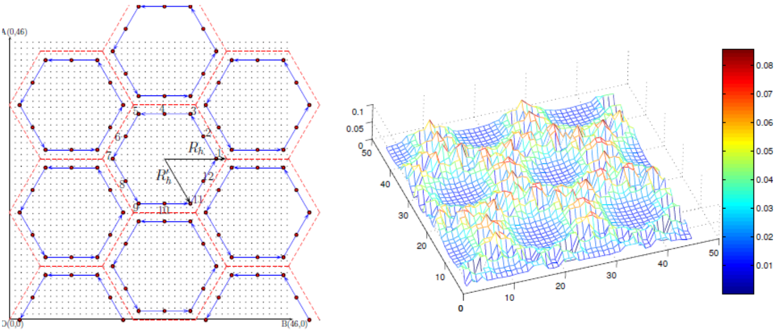
(a) Sinks Movement Trajectories



(b) Sensor Energy Consumption in Joules after $6T$ Time

- Simulation results showed 3.48 times improvement in network lifetime compared to the static sinks case

An example with static sinks using more positions



(a) Sinks Movement Trajectories (b) Sensor Energy Consumption in Joules after $12T$ Time

- This case results in 4.86 and 1.39 times improvement in network lifetime compared with the static sinks case and the 6-positions sink movement case

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

Sink Mobility with Unrestricted Mobility Path

- Data gathering mechanism is organized in rounds of time T
- At the beginning of each round, **data collection trees** are established using a **clustering mechanism**

Clustering Algorithm

```
min hops =; cluster id = NIL;
if CLUSTER INIT(ID, hops) message received then
    if hops+1 ¡ min hops then
        cluster id = ID
        min hops = hops+1
        next hop = sensor from which this message was received
        rebroadcast the message CLUSTER INIT(ID,hops+1)
    end if
end if
```

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Sink Mobility with Unrestricted Mobility Path

- At the end of each round, a sink **decides** whether or not it **moves** to a new location, depending on the **energy levels** of its 1-hop sensor neighbors
- The **1-hop** away sensors send their **current energy** levels to the sink at the end of each reporting interval **piggybacked**
- If at least $p\%$ of the sensors have reached the **low threshold** energy E_{th}, then the sink searches for a new **location**
- The new location must have energy at least E_{th}, where $E_{th} = E_t h + \alpha \cdot E_{th}$ and $0 < \alpha < 1$
- If **no new location** is found, then the **overall energy** level of the nodes has **decreased**
- The energy level E_{th} adjusts dynamically to a **smaller value**, $E_{th} = \beta \cdot E_{th}$, where $0 < \beta < 1$

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

Sink Mobility with Unrestricted Mobility Path

Decide-Sink-Movement(S_i, p, q, E_{th}, E_{th})

```
if p% of the 1-hop sensors have E ≤ E_th then
    sink S_i searches for a new location
    new-location = Find-Best-Location(S_i, E_th)
    if new-location ≠ 0 then
        sink S_i moves to the new-location
    else if E_th ≥ E_min then
        E_th = β · E_th
        go to line 1
    else
        sink does not move
    end if
end if
```

Sink Mobility with Unrestricted Mobility Path

Find-Best-Location(S_i, E_{th}) algorithm:

- S_i **searches incrementally** starting from its n_{hop} neighbours to search for a **new location**
- the sensors' locations in S_i's cluster are used as candidate locations
- For a specific n_{hops} value
  1. Sink S_i broadcasts a *LOCATION-REQ* message in its n_{hops}-neighborhood
  2. When a sensor s_k receives a *LOCATION-REQ* message **exchanges** *HELLO* messages with its **1-hop** sensor neighbors, containing the current **energy levels**
  3. If all s_k neighbors have energy at least E_{th}, then s_k is a candidate location for the sink and thus it sends a *LOCATION-REPLY(sk ,#msg, hops)* message back to the sink
     - #*msg* represents the number of messages transmitted by the node sk in one round

Sink Mobility with Unrestricted Mobility Path

Find-Best-Location(Si , Eth) algorithm:

- For a specific n_{hops} value
  4. After the sink S_i has sent the request, it waits a specific time for sensor replies(proportional to n_{hops})
  5. After the waiting time has expired, the sink **sorts** the received $LOCATION - REPLY$ messages in decreasing order of the $\#msg$ field
     - The sink gives **priority** to the sensor locations that **forward a large number of messages** since these sensors deplete their energy at the fastest rate
  6. At last checks if the candidate location satisfies the sink backbone **connectivity requirement**
- If no candidate location is valid due to the connectivity requirement, then S_i **increments** n_{hops} in order to increase the search neighborhood

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

Sink Mobility with Unrestricted Mobility Path

- Sink S_i then constructs the undirected graph G where one vertex is allocated for every sink in S_i
- One vertex is allocated for S_i's new location s_k
- Edges are added between any two vertices if the corresponding sinks locations are at distance less than or equal to R
- To determine if S_i is still connected to the graph G in the new location, the sink S_i runs the **Breadth-First-Search** (BFS) algorithm for the graph G
- If the resultant BFS tree is connected, then the algorithm returns *TRUE*, otherwise it returns *FALSE*
  - To avoid multiple neighbor sinks to move simultaneously a **locking mechanism** is used
  - If BSF tree is connected, the sink sends a *LOCK* message to its neighbors
  - After the sink Si moves to the new location, it sends an *UNLOCK* message containing its new location

Simulation

- In simulation the authors compare the performance of the static case, 6/12-position algorithm and the distributed algorithm
- Also the values $p = 5\%, 10\%, 15\%$ and 30%, $E_{th} = 0.4, \alpha = 0.05$ and $\beta = 0.75$
- The size of the network is varied between 1000 and 6000
- The number of sinks M is varied between 1 and 9
- The data aggregation factor is varied between 0 and 0.75
- Sensor communication range $r = 2$ units and sink communication range $R = 20$ units

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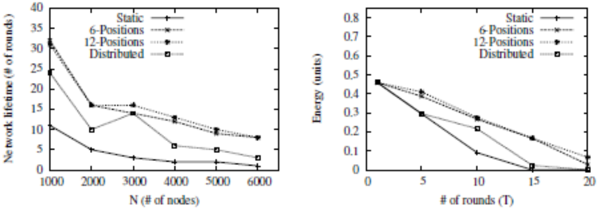
Comparison of static, 6/12 position and distributed algorithm

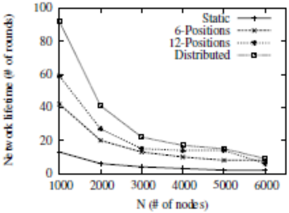


(a) Network Lifetime (b) Power Consumption per Rounds

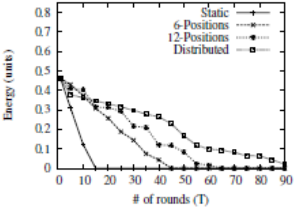
- Sensors are deployed using a random **uniform** distribution
- The distributed algorithm is a localized solution and it obtains a **shorter network lifetime** than the predetermined trajectory cases
- Second figure shows the variation of the minimum sensor energy over time for a network with 1000 sensors

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

Comparison of static, 6/12 position and distributed algorithm



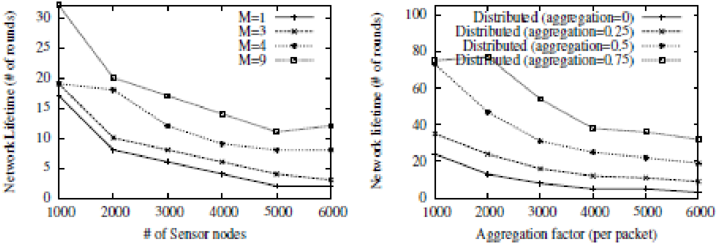
(a) Network Lifetime



(b) Power Consumption per Rounds

- The above figures compares the algorithms performance for the case when sensors are deployed using a **bivariate Gaussian** distribution
- The **distributed algorithm has the best performance**, followed by the predetermined-paths cases
- Right figure shows the minimum sensor energy for a network with 1000 sensors, when the number of rounds vary between 1 and 90.

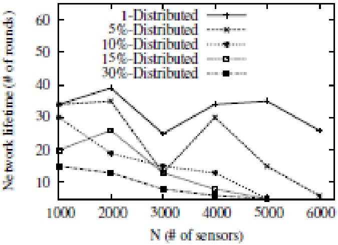
Distributed algorithm simulation

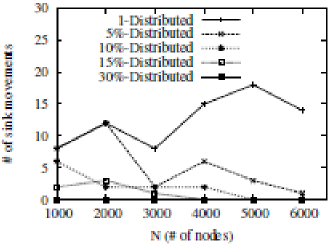


- A larger number of sinks results in more clusters, with smaller data collection trees thus increasing network lifetime
- Right figure shows network lifetime for different aggregation factors $f = 0, 0.25, 0.5$ and 0.75
- An aggregation factor f means that $(1f) \times 100\%$ of the packets are forwarded by a sensor

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

Distributed algorithm simulation

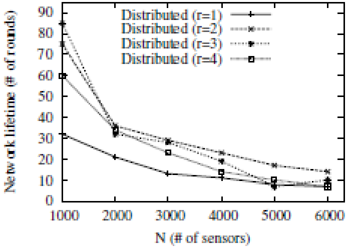




- In the above figures the parameter **p is varied** in the distributed algorithm, when M = 9 sinks
  - if at least $p\%$ of the 1-hop sensors of a sink have reached the low energy theshold E_{th}, then the sink moves to a new location
- the largest network lifetime is obtained for **1-Distributed**(= first sensor from 1-hop neighbor reaches the low energy theshold E_{th})

Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

Distributed algorithm simulation



- The last figure measures network lifetime when we vary the sensor communication range r between 1 and 4
- In general, $r = 2$ and $r = 3$ produce better results

Our new paper

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks

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Published at IEEE, Pervasive Services, 2007

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

- The goal of this paper is to propose a sink deploying algorithm that minimizes the consumed energy in the network
- Since most of the energy is used for the transmission of the packets, a closer look is taken on how the energy is spent in a **multi-hop network**
  - Let $E_{message}$ denote the energy demand of transmitting a packet to the sink of distance d
  - r_c stand for transmission range
  - If the packets are routed using a shortest path algorithm then: $E_{message} \approx \lceil \frac{d}{r_c} \rceil \cdot E_{hop}$
- The energy cost of transmitting a message to the sink is **linearly proportional to the distance** the message has to travel
- Thus to **minimize the energy**, the **sum of the distances** between the sensors and the sink **has to be minimized**

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

Single sink

- Let N denote the number of sensor nodes in the network and $s = (x, y)$ is the location of the sink
- The distance between a given sensor and the sink is given by $d_i = \sqrt{(x - x_i)^2 + (y_i - y)^2}$, $i = 1, \ldots, N$
- The goal is to minimize the average distance from the sink: $\sum\limits_{i=1}^{N} d_i \rightarrow min$
- The optimal sink coordinates are then given by

$$(x_0, y_0) = \arg\min_{x,y} \sum_{i=1}^{N} \sqrt{(x - x_i)^2 + (y_i - y)^2}$$

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

Single sink

- The minimum is obtained by setting the partial derivatives to zero: $\frac{\partial}{\partial x}\sum_{i=1}^{N} d_i \Big|_{x=x_0} = \frac{\partial}{\partial y}\sum_{i=1}^{N} d_i \Big|_{x=y_0} = 0$
- The partial derivatives are: $\frac{\partial}{\partial x}\sum_{i=1}^{N} d_i = \sum_{i=1}^{N} \frac{x-x_i}{d_i}$ $\frac{\partial}{\partial y}\sum_{i=1}^{N} d_i = \sum_{i=1}^{N} \frac{y-y_i}{d_i}$
- By using vector notations, the vector pointing to the location of the ith sensor node and the sink is $d_i = n_i - s = ((x_i - x)), (y_i - y))$
- Let e_i be the unit vector pointing from the ith sensor node towards the nearest sink: $e_i = \frac{d_i}{d_i} = \frac{1}{d_i}((x - x_i), (y - y_i))$

Single sink

- Then the problem is **equivelent of having**

$$r = \sum_{i=1}^{N} e_i \Big|_{s=(x_0,y_0)} = 0$$

  - The average distance is minimized if the resultant vecor r of the oriantation vectors is **zero**

Multiple sinks

- Let K denote the number of sinks
- The coordinates of the jth sink are $s^{(j)} = (x^{(j)}, y^{(j)})$, $j = 1, \ldots, K$
- The distance vector from ith sensor to the lth sink is $d_i^{(l)} = \sqrt{(x^{(l)} - x_i)^2 + (y_i^{(l)} - y)^2}$
- The unit vector pointing from the sensor towards the lth sink is $e_i^{(l)} = \frac{d_i^{(l)}}{d_i}$

Multiple sinks

- The goal is again to minimize the sensors' distance from the nearest sink: $\sum_{i=1}^{N} \min_{l} d_i^{(l)} \to min$
- The minimum is again obtained by setting the partial derivatives to zero: $\frac{\partial}{\partial x^{(k)}} \left(\sum_{i=1}^{N} \min_{l} d_i^{(l)} \right) \Bigg|_{s_0^{(1)},\ldots,s_0^{(K)}} = 0$

$$\frac{\partial}{\partial y^{(k)}} \left(\sum_{i=1}^{N} \min_{l} d_i^{(l)} \right) \Bigg|_{s_0^{(1)},\ldots,s_0^{(K)}} = 0$$

- The partial derivatives are:

$$\frac{\partial}{\partial x^{(k)}} \left(\sum_{i=1}^{N} \min_{l} d_i^{(l)} \right) = \cdots = \sum_{i:d_i^{(k)}=\min_{l} d_i^{(l)}} \left(\frac{x^{(k)}-x_i}{d_i^{(k)}} \right)$$

$$\frac{\partial}{\partial y^{(k)}} \left(\sum_{i=1}^{N} \min_{l} d_i^{(l)} \right) = \cdots = \sum_{i:d_i^{(k)}=\min_{l} d_i^{(l)}} \left(\frac{y^{(k)}-y_i}{d_i^{(k)}} \right)$$

Multiple sinks

- Using vectors requirements then minimizing sensors' distance from the nearest sink is the same as minimizing:
$$\sum_{i:d_i^{(k)}=\min_l d_i^{(l)}} e_i^{(k)}\Big|_{s_0^{(1)},\ldots,s_0^{(k)}} = 0$$
- Let C_j be the set of the sensors that are closest to the sink j: $C_j = \{i : d_i^{(j)} = \min_l d_i^{(l)}\}$
- In that case $C_u \bigcup C_{v|u\neq v} = 0$ and $\bigcup_{u-1,\ldots,K} C_u = 1,\ldots,N$ and the resultant vector of the orientation of the sensors for sink j is: $r_j = \sum_{t\in C_j} e_t^{(j)}$, $j = 1,\ldots,K$
- Thus the average distance between the sensors and the closest sink is minimal if the **resultant vector is zero for every sink**

Similarity with k-mean problem

- Finding the places of multiple sinks minimizing the average communication distance is similar to the **k-mean** clustering problem
  - Given a set of observations $(x_1, x_2, \ldots, x_n)$, where each observation is a d-dimensional real vector, k-means clustering aims to **partition the n observations** into k sets $(k \leq n)$ $S = S_1, S_2, \ldots, S_k$ so as to minimize the within-cluster sum of squares (WCSS):

    $\arg\min_{S} \sum_{i=1}^{k} \sum_{x_j \in S_i} ||x_j - \mu_i||^2$ where μ_i is the mean points in S_i
  - k-mean algorithms minimizes the **square distances**
  - The goal here is to minimize the **sum of the distances**
  - The two algorithms presented here are **similar** to the basic k-mean algorithm
- A moving sink has negative effects as far energy concerned since sensors need always to know its location
  - The authors assume that the sink **broadcasts** periodically its **location** updating **all sensors**

Global algorithm

- It is assumed that every sink knows the **geographical coordinates** of the sensors and the other sinks
- The sink decides which sensors are closest to them and **divide the network** into clusters C_j, $j = 1, \ldots, K$
- Then the centroids of the clusters are determined using *determine_centroid* iterative algorithm
  - Every sink(in its cluster) calculates the **resultant vector**, r_j
  - If $r_j \neq 0$ then the sink S_j **moves** in the **new location** determined by the resultant vector: $s^{(j)} + r_j \cdot max\_step$
  - The clusters are recalculated based on new sink locations
  - The centroids are **recalculated** to determine if the resultant vector is zero

The algorithm terminates when all resultant vectors are zero

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

Global algorithm

Determine_Centroids()

for $j \leftarrow 1$ **to** K

$$\textbf{do} \begin{cases} r_j = \sum_{t \in C_j} e_t^{(j)} \\ \textbf{if} |r_j| == 0 \\ \qquad \textbf{then } s^j = s^j \\ \textbf{else } s^j = s^j + r_j \cdot max\_step \\ \textbf{if } \exists j \in K : |r_j| \neq 0 \\ \qquad \textbf{then } DETERMINE\_CENTROIDS() \end{cases}$$

Recalculating clusters using new sink locations:

$C'_j = \{i : d_i^{(j)} = min_l d_i^{(l)}\} \quad j = 1 \dots K$

if $\forall j \in K : C'_j == C_j$

then exit

else DETERMINE_CENTROIDS()

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

1hop algorithm

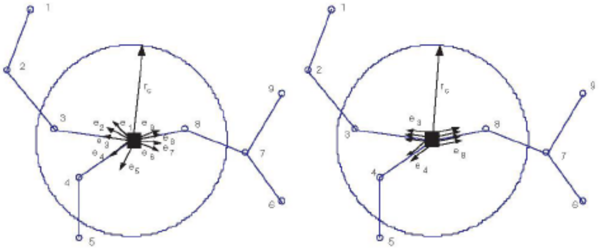
- The global algorithm is **hardly applicable**
- 1hop algorithm uses only **local information**
  - Sinks know only the **location** of their **1-hop neighbours**
  - Sinks knows **how many routes are passing** through these sensors
- Given an initial deployment:
  - The sinks determine which sensors are communicating **directly** with them, let it be $H_J = \{i : d_i^{(j)} < r_c,\ i \in N\}$
  - After that the sinks **wait** for a certain time period such that every sensor $\in\ H_j$ sends **at least one message** to the sink
    - The header of every message contains the ID of the **original sender** node
    - When sink j receives a message from the sensor in H_j it notes the ID of the original sender
  - At the end of the period each sink can determine **how many sensors are hidden** behind sensor t, $t \in H_j$

1hop algorithm

- The previous method used the global knowledge of locations in order to **compute** the **resultant vectors**
- In this local algorithm this is approximated in the following way:
  - let sensor t be the neighbor of sink j and denote nr_t the number of senors that send their messages through sensor t towards sink j
  - let $route_{ij}$ denote the set of sensors on the route from i to j
  - Then $nr_t = \#\{i : t = min_l d_i^{(l)}, t \in route_{it}\}$
  - Sink j assumes that there are nr_t sensors in the direction of sensor t and the resultant vector for sink j is approximated as: $r_j = \frac{\sum_{t \in H_j} e_t^{(j)} \cdot nr_t}{\sum nr_t}, \ j = 1 \dots K$
  - If $|r_j|$ is below a **threshold** then sink j does not move
  - Otherwise it moves to $s^{(j)} + r_j \cdot max\_step$
- If every sink remains at the same position $s^{(j)}$ then the 1*hop* method ends

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

1hop vs global algorithm

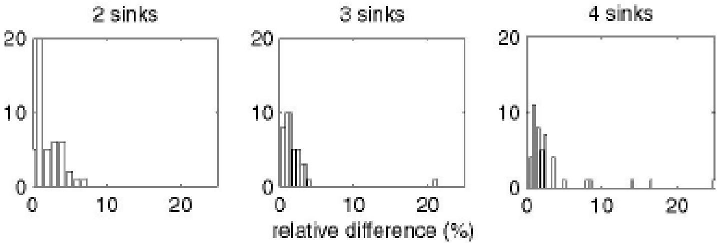


- In global algorithm(left) every sink knows the location of every sensor thus it calculates r as the resultant vector of $e_1, e_2, e_3, \dots, e_9$
- In 1hop algorithm the sink is **only aware** of the location of e_3, e_4, e_8. Thus r is calculatd as the resultant vector of $e_3, e_3, e_3, e_4, e_4, e_8, e_8, e_8, e_8$

Performance of the sink deploying algorithms

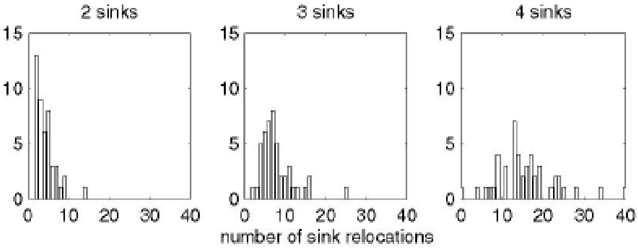
- The performance of the algorithms was evaluated in Matlab
- 1000 sensors were deployed in a random uniform distribution
- The sensong area was $800m \times 800m$
- $r_c = 80m$ and $max\_step = 400m$
- The sinks were initially deployed in the same random places for the two methods
- At the end of a run the**average distance** between the sensors and the closest sinks was calculated for each algorithm avg_dist_{1hop}, avg_dist_{global}
- then the **relative difference** of them was calculated and is presented above $\frac{avg\_dist_{1hop} - avg\_dist_{global}}{avg\_dist_{global}} \cdot 100$

Relative difference between average distances



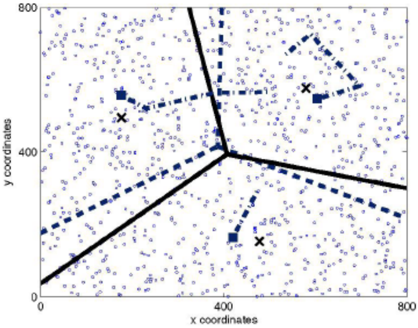
- the **average distance** is no higher than 5% compared to global
- most of the times is around 2-3%
- 1hop algorithm has a good performance taking into account that it uses only local information

Number of relocations



- in case of 2 sinks deployment finishes after less than 8 relocations in the 90%
- in case of 3 sinks 12 relocations are needed in 86% of the runs
- in case of 4 sinks 20 relocations are needed in 80% of the runs

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007



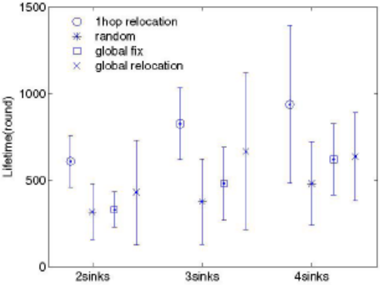
- It can be seen that after 7 relocations the 1*hop* deploys the sink very close to the optimal places given by *global*
- the relative difference of the average distances in that specific run was 1%

Performance of the sink deploying algorithms

- The authors point out that both algorithms have the **"sink hole"** problem
- **1hop relocation** and **global relocation** algorithms are proposed in an effort to make them more dynamically
- the general idea of both extensions is **never stop calculating resultant vectors**
  - actually this has a sense when network lifetime is measured differently from "first node to die"
  - The authors measure it as "the the time until an operating sensor **can not send its message to the closest sink**"
- taking into account simulations specs (1000 sensors, $800m \times 800m$, $r_c = 80m$) relocation algorithms make sense

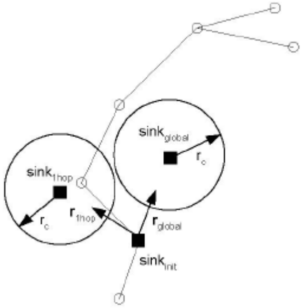
Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

Network Lifetime



- 1*hop relocation* has the best performance
- this can be explained by the following figure

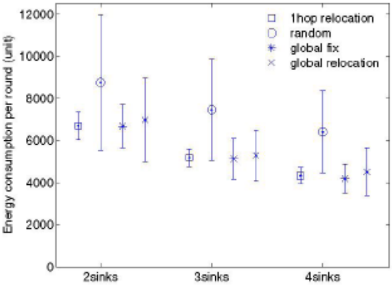
Global algorithm defauts



- *global relocation* calculates the resultant using every unit vector while 1*hop relocation* uses only neighboring sensors' unit vector
- Thus there are cases when *global relocation* algorithm points to an area **without operating sensors** contrary to 1*hop relocation*

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

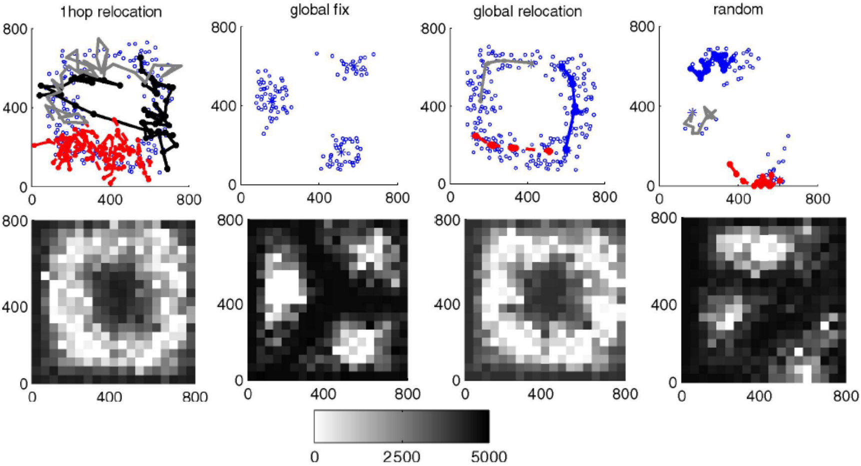
Energy consumption



- As expected the *global* algorithm uses the least energy since the sinks are deployed so as to minimize the average distance between sensors and closest sinks

Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

An example with static sinks



Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

Performance of the sink deploying algorithms

- Previous figure shows how different algorithms relocate the sinks and what is the distribution of the remaining energy at the end of the network operation
  - *1hop relocation*: 408 rounds
  - *global relocation*: 400 rounds
  - *global fix*: 238 rounds
  - *random*: 155 rounds
- *1hop relocation* has better energy dissipation as shown from the heat map
  - in case of *1hop relocation* the sinks are relocated **more often** following a circle movement

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wei Wang, Srinivasan, V., Kee-Chaing Chua, IEEE/ACM Transactions on Networking, 2008

- The authors first study the performance of a large dense network with one mobile relay and show that network lifetime improves up to a factor of four
- Also they show that the mobile relay needs to stay only within a two-hop radius of the sink
- A joint mobility and routing algorithm is constructed which can yield a network lifetime close to the upper bound
  - The advantage of this algorithm is that it only requires a limited number of nodes in the network to be aware of the location of the mobile relay
- The simulation results show that one mobile relay can at least double the network lifetime in a randomly deployed WSN

Our roadmap - 28-12-11

Architecture of Wireless Sensor Networks With Mobile Sinks: Sparsely Deployed Sensors,Liang Song, Dimitrios Hatzinakos IEE, Vehicular Technology 2007

- The authors propose to develop wireless Sensor Networks with Mobile Sinks (MSSNs)
- The proposed MSSN is highly energy efficient, because the multihop transmissions of high-volume data over the network are converted into single-hop transmissions
- Their investigation is focused on sparsely deployed networks, where single node-to-sink transmission is considered
- A transmission-scheduling algorithm (TSA-MSSN) is proposed in which a parameter is employed to control the tradeoff between the maximization of the probability of successful information retrieval and the minimization of the energy-consumption cost
- It is shown that the proposed implementation of the TSA-MSSN has a complexity of O(1)

Our roadmap - 4-1-12

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad Hoc and Sensor Networks,Azzedine Boukerche, Xin Fei WIMOB 2008

- This paper presents an adaptive data gathering protocol (ADG) that employs multiple mobile collectors (instead of sinks) to help an existing wireless sensor network achieve energy efficiency and low message delay
- A virtual elastic-force model is used to help mobile collectors adjust their moving speed and direction while adapting to changes within the network
- Mobile collectors are sent out by sink if the information in the network is beyond the capabilities of existing mobile collectors and are called back when they become redundant
- The ADG protocol is analysed and compared with other existing protocols such as OCOPS and LEACH.

Our roadmap - 11-1-12

Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, R C Shah et al. 2003

- Analyzes an architecture to collect sensor data in sparse sensor networks using MRs(called MULES)
- MULEs pick up data from the sensors when in close range, buffer it, and drop off the data to wired access points using short-wireless communications
- Substansial power saving at the sensors since they have only to transmit over a short range
- The model assumes two-dimensional random walk for mobility and incorporates key system variables such as number of MULEs, sensors and access points
- The performance metrics observed are the data success rate (the fraction of generated data that reaches the access points) and the required buffer capacities on the sensors and the MULEs

Mobile Sinks in Wireless Sensor Networks

Filippos Vasilakis – SensorsLab

Computer Engineering and Informatics

December 7, 2011

Protocols that we have anaysed so far

1. **Clustering and load balancing in hybrid sensor networks with mobile cluster heads**, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. **Increasing lifetime of wireless sensor networks using controllable mobile cluster heads**, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010
3. **mWSN for Large Scale Mobile Sensing**, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008
4. **Data gathering in wireless sensor networks with mobile collectors**, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing
5. **Mobile Element Scheduling with Dynamic Deadlines**, A. Somasundara, A. Ramamoorthy, M. Srivastava, IEEE Transactions on Mobile Computing, 2007

Protocols that we have anaysed so far

6. **Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks**, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007
7. **Using Sink Mobility to Increase Wireless Sensor Networks Lifetime**, Mirela Marta and Mihaela Cardei, 2008
8. **Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays**, Wang, Srinivasan, Chua, 2008

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of **two types of nodes**: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- each sensor has **different** flow generation **rate**
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be **NP-hard**
- They present a **heuristic algorithm** for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We investigated the paper and we concluded that:

- It provides solid background of the problem and discusses the problem of positioning mobile clusters heads in a two layer sensor network to maximize lifetime..but:
- The authors propose an **offline algorithm** for computing the positions of the cluster heads
- They don't discuss anything about the existance of a **Base Sink**
- In their model the **cluster heads are connected a priori**
- They don't count the **residual energy** of sensors when computing the cluster heads' new position
- Their solution is **bearly feasible**

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

An approach that uses the MR as cluster head

- The authors study again the energy balance problem under mobile cluster heads
- They propose to use multiple mobile cluster heads (CHs), each CH can move in its cluster
- They propose 3 protocols
  - CHs move towards the **energy-rich sensors**
  - CHs move towards the **event area**
  - a **hybrid protocol** in which CHs move according to the equation
    $C_{comb} = \eta \times C_{energy} + \gamma \times C_{event}$
- Also they discuss algorithms that mentain **connectivity** between CHs and BS
- In simulation they showed that there is a trade-of between energy consumption and delay

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

We investigated the paper and we concluded that:

- It is a very concrete work that analyses many interesting topics in WSNs but
- In residual energy-based strategy, in case of **multiple energy centres**, it does not find the optimal position for CH
  - Actually if the energy centres are **equal** the new position of CH is the least optimal
- In their model cluster members **does not change** at all. Also every CH moves ONLY **inside** its cluster.
- The algorithms that they proposed for ensuring BS connectivity are very **energy consuming**

3. mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

The paper reviews the reviews the relationship between delay and mobile sink velocity

- The authors show that **increasing** either the radio transmission range **r**, or the number of mobile sinks **m**, or the sink velocity **v** the sensor-sink meeting **delay** can get **reduced**

Next the authors add in their analysis the message length

- Again the result shows that, by **decreasing** message length **L**, or **increasing** transmission range **r** and number of mobile sinks **m**, the message delivery delay can be **reduced**
  - Simulation showed that increasing the ratio of sink velocity to sensor transmission radius, at first decreases the delay, reaches an **optimal condition** but then delay is increasing again !

At last, the Outage Probability is considered

- It is shown that the goal of enlarging the outage area can be achieved via **increasing** **r**, or **decreasing** **v** **or** **T**

4. Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

- The authors consider the problem in which M-collectors visit every node in its **transmission range** in order to minimize energy dissipation
- They formulate a **mixed integer program** solution and show that the problem is **NP-hard**
- Also they **compare** it with the **TCP** and **CSP**(Coverin Salesman Problem)
- A new algorithm is constructed to **obtain all polling points** according to their **average cost** from current position of M-collector
- When considering a larger network field, they construct a **MST** of polling points and **decompose** it to **equal subtrees**
- In each subtree an M-collector is scatter using the previous algorithm

5. Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

- The paper analyses the scheduling of the **mobile elements** under **different deadlines**
- The authors firt prrove the **NP-completeness** of the problem and form an **integer programming** formation
- They propose practical algorithms fo single mobile sink and extend them in the case of multiple sinks
  - Earliest Deadline First (EDF)
  - EDF with k lookahead
  - Minimum weighted sum first
- In case of multiple sinks they note the similarity with Vehicle Routing Problem with Time Windows (**VRPTW**)
- Te authors propose and analyse the most cited algorithm for that problem
  - Start with a single vehicle and add new vehicle every time **no new node** can be inserted in **existing tour**
- Simulation shows that VRPTW has the best performance followed by Minimum weighted sum first

6. Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

- The paper studies the case of minimizing the energy every sensor consumes
- In order to minimize the energy, the sum of the distances between the sensors and the sink has to be minimized
- The authors use the idea of vector that under ideal circumstances should be zero
    - If not zero, it shows the direction the sink should move
- A global algorithm is proposed that makes use of global vectors but is hardly applicable since is uses global information
- A new algorithm is proposed, $1 - hop$ that uses only local information
    - Every mobile sink can determine how many sensors are hidden behind 1-hop sensor retrieving the number of routes traverses its of them

7. Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

- The authors study the energy holes that appear near the sinks
- At first they examine through simulations network lifetime using mobile sinks
    - Mobile sinks move in the peripheries of the coronas stopping only in 12 positions the energy
    - Results show that lifetime is improved 4.86 times in comparison to static case
- A new algorithm is proposed in which every sink asks neighbours energy levels
    - If $p\%$ of sensors have reached the low threshold the sink searches for a new position
    - The new position is determined using energy levels of sensors ¿ $2 - hop$ away
    - If no new position is found the overall network energy has been decreased thus the sinks decrease the low threshold

8. Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Our new paper

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays

Wei Wang, Srinivasan, V., Kee-Chaing Chua

Department of Electrical and Computer Engineering, National University of Singapore

Published in IEEE/ACM Transactions on Networking, 2008

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- The paper studies the performance of a large dense network with one mobile relay
- It shown that the improvement in network lifetime over an all static network is upper bounded by a factor of four
- The proof implies that the mobile relay needs to stay only within a two hop radius of the sink
- A joint mobility and routing algorithm is constructed which comes close to the upper bound

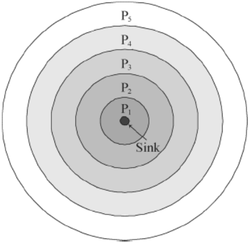
The model

- N sensors are **uniformly** distributed in a **circular** area of radius R
- There is only one sink n_0 at the center of the circular area
- The network density $\lambda = \frac{N}{\pi R^2}$
  - the number of sensors in area A is λA almost surely
- The average number of neighbors for the sink is $\rho = \lambda \pi 1^2 = \lambda \pi$
- All static sensors have same initial energy E
- The total energy consumed by a sensor in transmitting one packet is a constant e
- Each sensor generates **one packet** per time unit
- The set P_i contains all the nodes which can reach the sink with minimal hop count i
  - Sink neighbors belong to P_1

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

The model

- The nodes outside the transmission range of the sink are denoted as $\overline{P_1}$
- The set of all the nodes which can reach the sink within j hops is denoted as $Q_j = \bigcup_{k \leq j} P_k$
- n_k represents a node in P_k and $n \leq j$ represents a node in Q_j



Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Theorem 1

The lifetime of a dense static network is upper bounded by $\frac{E}{R^2 e}$ time units

- Consider a network with $N = p\lambda R^2$ uniformly and independently deployed in the circular area with radius R
- Each sensor will have equal probability of $\frac{\text{Communication area of the sink}}{\text{Total network area}} = \frac{\lambda\pi 1^2}{\lambda\pi R^2} = \frac{1}{R^2}$ to be deployed in the transmission range of the sink
- The number of sensors belonging in P_1 will be a Binomial random variable with parameters N and $\frac{1}{R^2}$
- By the Law of Large Numbers for any $\epsilon > 0$ the probability that $|P_1| \in [(1-\epsilon)\frac{N}{R^2}, (1+\epsilon)\frac{N}{R^2}]$ tends to 1 as $\lambda \to \infty$
- $\Rightarrow$ the number of sensors in P_1 is nearly $\frac{N}{R^2} = \pi\lambda = \rho$ for **high density** networks$\Rightarrow$ energy stired in P_1 is **nearly** ρE

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- **Suppose the lifetime of the network is $\widetilde{\mathbf{T}} > \frac{\mathbf{E}}{\mathbf{R^2 e}}$**
- N packets per time unit are generated/delivered by the sensors
- Since the sink can only receive data from P_1, then packets generated by $P_1, \overline{P_1}$ must pass through P_1 **at least once**
- Thus $\sum_{n1 \in P_1} f_{n1} \geq N$
- Then the total number of packets delivered by nodes in P_1 in time $\widetilde{T}$ will be $D = \widetilde{T} \times \sum_{n1 \in P_1} f_{n1} \geq \widetilde{T} \times N > \frac{E}{R^2 e} \times \lambda \pi R^2 = \frac{\rho E}{e}$
- The total energy used by nodes in P_1 is $D \times e > \rho E$
- But this **contradicts the assumption** that the total initial energy stored in P_1 is ρE
- Thus the lifetime of the static network must be less or equal to $\frac{E}{R^2 e}$

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Theorem 2

With one mobile relay, the lifetime of a dense network is upper nounded by $4\frac{E}{R^2 e}$ time units

- The amount of traffic passing through nodes in Q_i is at least the total traffic generated in $\overline{Q}_i$ which is $N - \rho i^2$
- Due to mobile relay this traffic will have to be relayed for at least $i - 1$ hops by the static nodes in Q_i
- Since the number of nodes in Q_i is ρi^2 the lifetime can be bound by $T^1 \leq \frac{\rho i^2 E}{(N-\rho i^2)\times(i-1)e} = \frac{i^2 E}{(R^2-i^2)(i-1)e}$
- for $i = 2$ we get the **least upper bound**: $T^1 \leq \frac{4E}{(R^2-4)e}$
- Taking into account the traffic generated by Q_2 the upper bound is tightened to $4\frac{E}{R^2 e}$

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

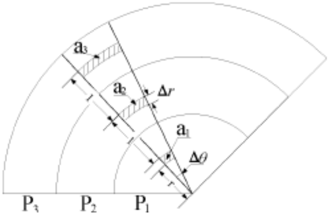
- From Theorem 2, we know that the mobile relay needs to only stay within a two-hop radius in order to maximize the lifetime
- The mobility pattern of the mobile relay can be as follows
  - Starting from the sink, the mobile relay traverses a path which forms a set of **concentric circles**, centered around the sink
  - In each circle the radius is sligtly increased until it reaches the periphery of Q_2
  - It stays at each point on this path for a certain duration and relays traffic to the sink
  - When the mobile is at position M , all traffic in $\overline{Q_2}$ is first aggregated to points **on the line** OM, where O is the position of the sink
  - The traffic is directed hop by hop along the line OM until it reaches the sink
- The authors call this routing algorithm ARA(Aggregation Routing Algorithm)

Theorem 3

There exists a routing sceme which can extend the network lifetime to at least $4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$ with one mobile node when the network radius $R > 16\pi + 4$

Proof:

- Consider 3 arbiratry small areas $\alpha_1, \alpha_2, \alpha_3$ as illustrated in the next figure
- The distance between α_1 and the sink is $0 < r \leq 1$ while the distance between α_1, α_2 and α_2, α_3 is 1



Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- The number of nodes in each area would be
  $\alpha_1: \ x_1 = \lambda r \Delta r \Delta \theta$
  $\alpha_2: \ x_2 = \lambda (r+1) \Delta r \Delta \theta$
  $\alpha_3: \ x_3 = \lambda (r+2) \Delta r \Delta \theta$
- For $0 < r \leq 1$ we have:
  $x_1 + x_2 = \lambda(2r+1)\Delta r \Delta \theta \leq \lambda(r+2)\Delta r \Delta \theta$
- This means that the number of nodes in α_3 **is always bigger** than the sum of that in areas α_1 and α_2
- Therefore we can build an **injective mapping** $f: \ Q_2 \Rightarrow P_3$: for each node $n^r_{\leq 2} \in Q_2$ we can associate a unique node $n^\alpha_3 = f(n^r_{\leq 2}) \in P_3$
- The range of mapping f is defined as the **aggregation set** G

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- If the mobile relay is at distance $0 < r_m \leq 1$ then $r_m \in P_1$, $n^r \in P_2 \in Q_2$, and $r^\alpha \in P_3$
- If the mobile relay is at distance $1 < r_m \leq 2$ then $r_m \in P_2$, $n^r \in P_1 \in Q_2$, and $r^\alpha \in P_3$
- When the mobile relay **cover all the positions** in Q_2 then every node in Q_2 should have been chosen as n^r **once**
- $\rightarrow$Depending on the position of the mobile all traffic in $\overline{Q_2}$ is routed via the associated aggregation node n^α
- $\rightarrow$The number of nodes in Q_2 is almost surely $\lambda\pi 2^2 =$ $= 4 \cdot \pi\lambda = 4\rho$
- Thus we have 4ρ unique paths from P_3 to the sink

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

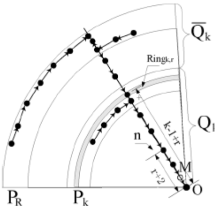
- Suppose that we can aggregate the packets generated by nodes in $\overline{Q_2}$ to the aggregation node n^α
- Then there are at most N packets passing through any of the 4ρ paths in each time unit
- Energy consumption for n^α and n^r will be very high
- **Suppose** we reserve $E^{'} = e \times 4\frac{E}{R^2 e} = 4\frac{E}{R^2}$ in these nodes to send out the data they sense
- Then they will have $E - E^{'}$ **energy left** for relaying traffic
- Therefore the mobile relay **will stand in location** for $\frac{E-E^{'}}{Ne}$ time
- **Draining** all the 4ρ nodes in Q_2 results in a total lifetime of $4\rho \times \left(\frac{E-E^{'}}{Ne}\right) = 4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$
- All we have to do now is to proove that none of the $\overline{Q_2}$ nodes will die before $4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$

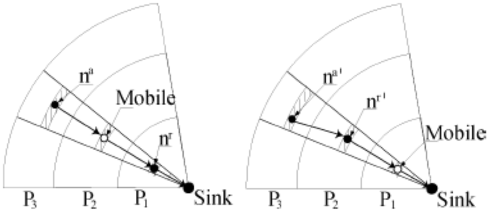
Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

The algorithm proposed is based in the ARA algorithm

- Nodes in Q_3
  - Nodes in P_1 directly send their data to the sink in one hop
  - Nodes in P_2 send their data to nodes in $P_3 \backslash G$
  - Nodes in P_3 also send their data to nodes in $P_3 \backslash G$
    - $P_3 \backslash G$ are spare nodes not used as aggregation points
    - The task for these nodes it to **redirect all the data they receive** to the current aggregation node n^α using $P_3 \backslash G$ as relays
- Nodes in $\overline{Q_3}$
  - A node in annulus P_k which is at distance l from the sink sends its data to line OM **only through the nodes which lie in circle of radius l**
  - Then all nodes in line OM forward data hop by hop to the aggregation point n^α
  - n^α will use the mobile relay and n^r to build a path and send the data to the sink

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008





Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- Due to the nature of the algorithm the traffic load($\rightarrow$lifetime) for the nodes which lie on a circle of a same radius will be the same(**equally distributed**)
- The authors focus on traffic load for nodes within a ring with width of Δr , $Ring_{i,r}$: $[i-1+r, i-1+r+\Delta r]$ for each case

Lifetime for nodes in Q_2:

- A node in P_1 either relays traffic for the rest of the network, either sense its own data to the sink
  - Since we have reserved $E^{'} = \frac{4E}{R^2}$ for its own needs thus its lifetime will be at least $\frac{E-E^{'}}{Ne}$
- A node in P_2 either relays traffic for the rest of the network, either sense its own data to the sink
  - Since we have reserved $E^{'} = \frac{4E}{R^2}$ for its own needs thus its lifetime will be at least $\frac{E-E^{'}}{Ne}$
- The lifetime in $Q_2 = P_1 \bigcup P_2$ will be $4\rho \times \frac{E-E^{'}}{Ne}$

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Lifetime for nodes in P_3:

- Similarly for a node$\in G \subset P_3$ we have also reserved $E' = \frac{4E}{R^2}$ for its own needs thus its lifetime will be at least $\frac{E-E'}{Ne}$
- **The problem is with nodes in** $P_3 \backslash G$ since these nodes carry the task of relaying the data generated by nodes P_2 and P_3
- There are ρ nodes in $P_3 \backslash G$ $(|P_3| - |G| = [(3^2 - 2^2) - (2^2)]\lambda\pi)$
- These nodes must relay $\mathbf{8}\rho$ packets from P_2 and P_3
- Each packet will be forwarded for most $1 + (3\pi + 1)$ hops
- Thus the lifetime for any node in $P_3 \backslash G$ will be at least $\frac{E}{8(3\pi+2)e} > \frac{4E}{R^2 e}$, $R > 20$

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Lifetime for nodes in $P_k,\ k \geq 4$:

- These nodes will have to relay traffic for data generated in P_k and $\overline{Q_k}$
- For **packets generated** in P_k:
  - From previous assumptions the network lifetime will be $4\rho \times \left(\frac{E-E'}{Ne}\right) = \frac{4(E-E')}{R^2 e}$
  - The **total nodes** in a $Ring_{k,r}$ will be $2\rho(k-1+r)\Delta r$ generating each unit time $2\rho(k-1+r)\Delta r$ packets
  - Each packet will be forwarded for most $1+\pi(k-1+r)$ hops
  - Thus the **total energy** used in delivering this part of traffic can be upper bounded by $E_1(k,r) =\leq 2\rho(k-1+r)\Delta r \times \frac{4(E-E')}{R^2 e} \times (1+\pi(k-1+r))e = \frac{8\rho(k-1+r)(\pi(k-1+r)+1)(E-E')\Delta r}{R^2}$

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Lifetime for nodes in $P_k,\ k \geq 4$:

Packets received by $\overline{Q_k}$ $k \geq 4$:

- Nodes in $Ring_{k,r}$ only will be involved in relaying traffic generated by $\overline{Q_k}$
    - Each period($T = \frac{E-E'}{Ne}$) only one node$\in Ring_{k,r}$ will be used
    - The one that has the minimal distance between its location and current aggregation point n^{α}
    - The **total number of aggregation points** is $2\rho(2r+1)\Delta r$
- There will be **at most** N packets from $\overline{Q_k}$ passing through $Ring_{k,r}$ per time unit
- So the total energy consumption during the assumed lifetime will be:
  $E_2(k,r) \leq 2\rho(2r+1)\Delta r \times \frac{E-E'}{Ne} \times Ne = 2\rho(2r+1) \times (E-E')\Delta r$

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

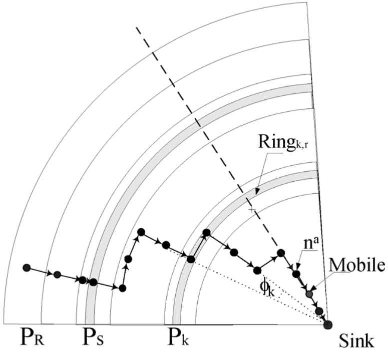
Total lifetime for nodes in $P_k,\ k \geq 4$:

- The total energy in $Ring_{k,r}$ will be $2\rho(k-1+r)\Delta r \times E$
- If we reserve $E^{'}$ energy units in every node for its own need then the **total energy for relaying traffic** will be $2\rho(k-1+r)\Delta r \times (E-E^{'})$
- Thus the total residual energy for nodes in $Ring_{k,r}$ will be $E_{re}(k,r) \geq 2\rho(k-1+r)(E-E^{'})\Delta r - [E_1(k,r)+E_2(k,r)] \geq \ldots \geq \frac{2\rho(R-16\pi-4)(E-E^{'})\Delta r}{R}$
- When R is bigger than $16\pi + 4$ the total energy left will be greater than 0
- Since the total residual energy will be equal distributed among the nodes in the $Ring_{k,r}$ none of them will die before $4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Theorem 4

With Aggregation Routing Algorithm with Limited Nodes, the network lifetime is lower bounded by $4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$, for $s = 22,\ R > 84$



Lifetime for nodes in $\overline{Q_k}$ $k \geq 4$:

- From previous proof the total energy consumption for relaying packets generated in the aggregation ring will be $\frac{8\rho(k-1+r)(\pi(k-1+r)+1)(E-E^{'})\Delta r}{R^2}$ which can be further bounded by $2\rho(E - E^{'})\Delta r$ when $k \leq \frac{R}{4}$
- For data generated in $\overline{Q_k}$ the nodes in $Ring_{k,r}$ will use their residual energy for 2 tasks:
  1. Forward the data by one hop towards the sink
  2. Relay the data in the tangential direction for a certain angle ϕ_k to deliver it to OM
- As shown nodes in a particular ring will only relay data for at most $2\rho(2r+1) \times (E - E^{'})\Delta r$
- Thus lifetime will not exceed $2\rho(2r+1) \times \frac{E-E^{'}}{e}\Delta r$ packets

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Lifetime for nodes in $\overline{Q_k}$ $k \geq 4$:

- In an agregation ring in P_k there will be $2\rho(k-1+r)\Delta r$ nodes thus the total energy in relaying for others would be $2\rho(k-1+r)(E-E^{'})\Delta r$
- Delivering $2\rho(2r+1) \times \frac{E-E^{'}}{e}\Delta r$ packets will consume $2\rho(2r+1) \times (E-E^{'})\Delta r$ energy
- Thus the nodes in the aggregation ring can spend at least $2\rho(k-1+r)(E-E^{'})\Delta r - 2\rho(2r+1) \times (E-E^{'})\Delta r - 2\rho(E-E^{'})\Delta r = 2\rho(k-r-3)(E-E^{'})$
- The angle ϕ_k by qhich every packet generated by $\overline{Q_k}$ can travel in P_k would be:

  $\phi_k = \min\limits_r \frac{2\rho(k-r-3)(E-E^{'})}{(k-1+r)\times 2\rho(2r+1)\frac{E-E^{'}}{e}\Delta r \times e} = \ldots = \frac{k-4}{3k}$

Lifetime for nodes in $\overline{Q_k}$ $k \geq 4$:

- Each packet will at most be relayed for an angle π
- The biggest angle of one hop relay is in P_4, 0.335 thus fue to overshoot property a packet should not be relayed for more than $\pi + 0.335$
- For $s = 22$ we have: $\sum_{k=4}^{21} \phi_k = 3.585 > \pi + 0.335$
- So we need only nodes in $\bigcup_{k=4}^{22} P_k$ to aggregate the traffic
- As assumed $k \leq \frac{R}{4}$ for $e \leq k \leq 22 \Rightarrow R > 84$

Lifetime for nodes in P_k $k = s$:

- The traffic passing through $Ring_{k,r}$, $k \geq s$ will be $\sum_{l=k}^{R} 2\rho(l-1+r)\Delta r = \rho(R-k+1)(R+k=2r-2)\Delta r$
- Also they need to deliver $2\rho(2r+1)\frac{E}{e}\Delta r$ packets to the next ring in total
  - The traffic load for this is $\frac{2\rho(2r+1)\frac{E}{e}\Delta r}{4\frac{E}{R^2 e}}\Delta r$
- Then the average load per time unit for one node in $Ring_{r,k}$ wil be:

$$Load(s,r) = \frac{\rho(R-k+1)(R+k=2r-2)\Delta r + \frac{2\rho(2r+1)\frac{E}{e}\Delta r}{4\frac{E}{R^2 e}}\Delta r}{2\rho(s-1+r)\Delta r} > \frac{7R^2}{4(s-1)}$$

- Since $s > 8$ the lifetime of these nodes will exceed $4\frac{E-E'}{R^2 e}$

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Theorem 5

The lifetime of a uniformly distributed dense network with m mobile relays is upper nounded by $4m\frac{E}{R^2-4m^2e}$

Proof:

- Consider the traffic load in Q_i with $i \geq m$
- The traffic generated in $\overline{Q_i}$ will be $N - \rho i^2$ per time unit
- This traffic will be relayed at least $i - m$ times by static nodes in Q_i
- Constraining the m mobile nodes to remain within Q_i and using similar arguments of proof of Theorem 2 the liferime can be bounded by $T^m \leq \frac{\rho i^2 E}{(N-\rho i^2 \times (i-m)e} = \frac{i^2 E}{(R^2-i^2)(i-m)e}$
- when $i = 2m$ we get the least upper bound

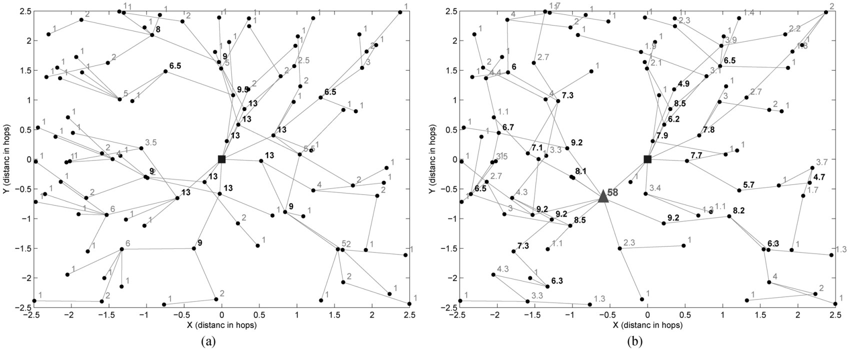
Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Theorem 6

There exists a routing sceme which can extend the network lifetime to at least $4m\frac{E}{R^2 e} - \frac{32\pi m^3 E}{R^4 e}$ with m mobile node when the network radius R is large enough

- The proof follows the proof of theorem 4
- However a different mobility model is used:
  - The m sensors form a path in a straight line OM
  - Each path will use m static sensors and m mobile relays inside the Q_{2m}
  - Q_{2m} has $4m^2$ static sensors
  - Thus there will be $4m$ paths
  - The total lifetime will be $4m\left(\frac{E}{R^2 e} - \frac{32\pi m^3 E}{R^4 e}\right)$

Simulation:

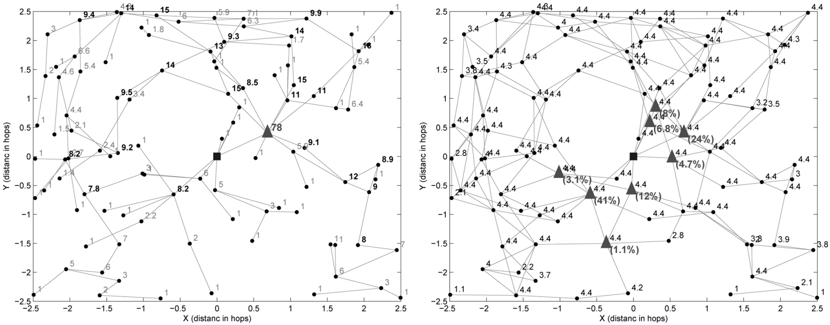


(a) Traffic distribution of static network

(b) Traffic distribution when mobile relay stays at position I (41% network lifetime)

Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Simulation:

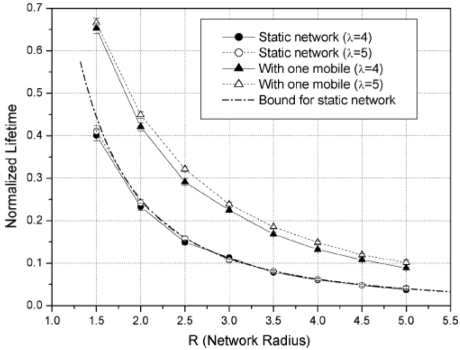


(c) (d)

(c) Traffic distribution when mobile relay stays at position II (24% network lifetime).

(d) The traffic flow averaged over the network lifetime with one mobile relay

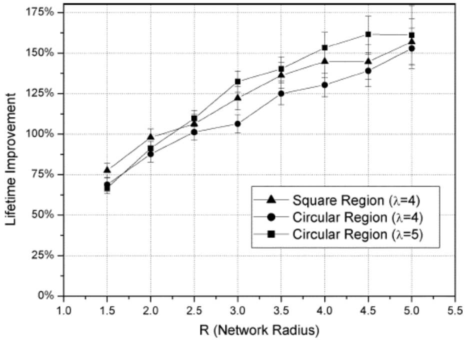
Simulation:



- Network lifetime for nodes randomly deployed on a circular region, for $\lambda = 4, 5$

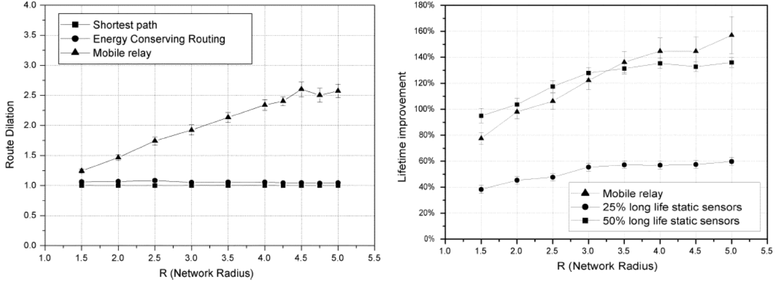
Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

Simulation:



- Average lifetime improvement for networks with one mobile over the static network (confidence interval 95%)

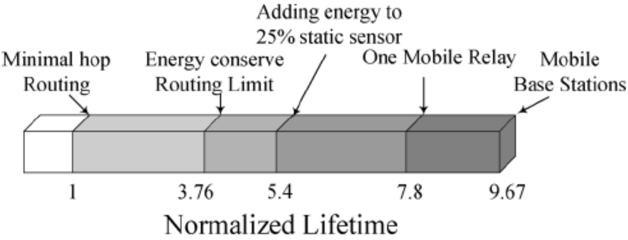
Simulation:



(a) Comparing the route dilation for different approaches (network on square area with $\lambda = 4$, confidence interval 95%).

(b) Comparing the lifetime improvement of adding one mobile relay with solutions that add more(four times more) energy to some static sensors($\lambda = 4$)

Simulation:


Adding energy to
25% static sensor
Minimal hop
Routing
Energy conserve
Routing Limit
One Mobile Relay
Mobile
Base Stations
1
3.76
5.4
7.8
9.67
Normalized Lifetime

Architecture of Wireless Sensor Networks With Mobile Sinks: Sparsely Deployed Sensors, Liang Song, Dimitrios Hatzinakos IEE, Vehicular Technology 2007

- The authors propose to develop wireless Sensor Networks with Mobile Sinks (MSSNs)
- The proposed MSSN is highly energy efficient, because the multihop transmissions of high-volume data over the network are converted into single-hop transmissions
- Their investigation is focused on sparsely deployed networks, where single node-to-sink transmission is considered
- A transmission-scheduling algorithm (TSA-MSSN) is proposed in which a parameter is employed to control the tradeoff between the maximization of the probability of successful information retrieval and the minimization of the energy-consumption cost
- It is shown that the proposed implementation of the TSA-MSSN has a complexity of O(1)

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad Hoc and Sensor Networks,Azzedine Boukerche, Xin Fei WIMOB 2008

- This paper presents an adaptive data gathering protocol (ADG) that employs multiple mobile collectors (instead of sinks) to help an existing wireless sensor network achieve energy efficiency and low message delay
- A virtual elastic-force model is used to help mobile collectors adjust their moving speed and direction while adapting to changes within the network
- Mobile collectors are sent out by sink if the information in the network is beyond the capabilities of existing mobile collectors and are called back when they become redundant
- The ADG protocol is analysed and compared with other existing protocols such as OCOPS and LEACH.

Our roadmap - 11-1-12

Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, R C Shah et al. 2003

- Analyzes an architecture to collect sensor data in sparse sensor networks using MRs(called MULES)
- MULEs pick up data from the sensors when in close range, buffer it, and drop off the data to wired access points using short-wireless communications
- Substansial power saving at the sensors since they have only to transmit over a short range
- The model assumes two-dimensional random walk for mobility and incorporates key system variables such as number of MULEs, sensors and access points
- The performance metrics observed are the data success rate (the fraction of generated data that reaches the access points) and the required buffer capacities on the sensors and the MULEs

Mobile Sinks in Wireless Sensor Networks

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Computer Engineering and Informatics

January 18, 2012

1. **Clustering and load balancing in hybrid sensor networks with mobile cluster heads**, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. **Increasing lifetime of wireless sensor networks using controllable mobile cluster heads**, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010
3. **mWSN for Large Scale Mobile Sensing**, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008
4. **Data gathering in wireless sensor networks with mobile collectors**, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing
5. **Mobile Element Scheduling with Dynamic Deadlines**, A. Somasundara, A. Ramamoorthy, M. Srivastava, IEEE Transactions on Mobile Computing, 2007

Protocols that we have anaysed so far

6. **Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks**, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007
7. **Using Sink Mobility to Increase Wireless Sensor Networks Lifetime**, Mirela Marta and Mihaela Cardei, 2008
8. **Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks**, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007
9. **Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays**, Wang, Srinivasan, Chua, 2008
10. **Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks**, Azzedine Boukerche. Xin Fei, 2008
11. **Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network**, Yu-Chee Tseng et al, 2008

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of **two types of nodes**: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- each sensor has **different** flow generation **rate**
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be **NP-hard**
- They present a **heuristic algorithm** for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We investigated the paper and we concluded that:

- It provides solid background of the problem and discusses the problem of positioning mobile clusters heads in a two layer sensor network to maximize lifetime..but:
- The authors propose an **offline algorithm** for computing the positions of the cluster heads
- They don't discuss anything about the existance of a **Base Sink**
- In their model the **cluster heads are connected a priori**
- They don't count the **residual energy** of sensors when computing the cluster heads' new position
- Their solution is **bearly feasible**

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

An approach that uses the MR as cluster head

- The authors study again the energy balance problem under mobile cluster heads
- They propose to use multiple mobile cluster heads (CHs), each CH can move in its cluster
- They propose 3 protocols
  - CHs move towards the **energy-rich sensors**
  - CHs move towards the **event area**
  - a **hybrid protocol** in which CHs move according to the equation
    $C_{comb} = \eta \times C_{energy} + \gamma \times C_{event}$
- Also they discuss algorithms that mentain **connectivity** between CHs and BS
- In simulation they showed that there is a trade-of between energy consumption and delay

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

We investigated the paper and we concluded that:

- It is a very concrete work that analyses many interesting topics in WSNs but
- In residual energy-based strategy, in case of **multiple energy centres**, it does not find the optimal position for CH
  - Actually if the energy centres are **equal** the new position of CH is the least optimal
- In their model cluster members **does not change** at all. Also every CH moves ONLY **inside** its cluster.
- The algorithms that they proposed for ensuring BS connectivity are very **energy consuming**

3. mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

The paper reviews the reviews the relationship between delay and mobile sink velocity

- The authors show that **increasing** either the radio transmission range **r**, or the number of mobile sinks **m**, or the sink velocity **v** the sensor-sink meeting **delay** can get **reduced**

Next the authors add in their analysis the message length

- Again the result shows that, by **decreasing** message length **L**, or **increasing** transmission range **r** and number of mobile sinks **m**, the message delivery delay can be **reduced**
  - Simulation showed that increasing the ratio of sink velocity to sensor transmission radius, at first decreases the delay, reaches an **optimal condition** but then delay is increasing again !

At last, the Outage Probability is considered

- It is shown that the goal of enlarging the outage area can be achieved via **increasing** **r**, or **decreasing** **v** or **T**

4. Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

- The authors consider the problem in which M-collectors visit every node in its **transmission range** in order to minimize energy dissipation
- They formulate a **mixed integer program** solution and show that the problem is **NP-hard**
- Also they **compare** it with the **TCP** and **CSP**(Coverin Salesman Problem)
- A new algorithm is constructed to **obtain all polling points** according to their **average cost** from current position of M-collector
- When considering a larger network field, they construct a **MST** of polling points and **decompose** it to **equal subtrees**
- In each subtree an M-collector is scatter using the previous algorithm

5. Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

- The paper analyses the scheduling of the **mobile elements** under **different deadlines**
- The authors firt prrove the **NP-completeness** of the problem and form an **integer programming** formation
- They propose practical algorithms fo single mobile sink and extend them in the case of multiple sinks
  - Earliest Deadline First (EDF)
  - EDF with k lookahead
  - Minimum weighted sum first
- In case of multiple sinks they note the similarity with Vehicle Routing Problem with Time Windows (**VRPTW**)
- Te authors propose and analyse the most cited algorithm for that problem
  - Start with a single vehicle and add new vehicle every time **no new node** can be inserted in **existing tour**
- Simulation shows that VRPTW has the best performance followed by Minimum weighted sum first

6. Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

- The paper studies the case of minimizing the energy every sensor consumes
- In order to minimize the energy, the sum of the distances between the sensors and the sink has to be minimized
- The authors use the idea of vector that under ideal circunstances should be zero
  - If not zero, it shows the direction the sink should move
- A global algorithm is proposed that makes use of global vectors but is hardly applicable since is uses global information
- A new algorithm is proposed, $1 - hop$ that uses only local information
  - Every mobile sink can determine how many sensors are hidden behind 1-hop sensor retrieving the number of routes traverses its of them

7. Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

- The authors study the energy holes that appear near the sinks
- At first they examine through simulations network lifetime using mobile sinks
  - Mobile sinks move in the peripheries of the coronas stopping only in 12 positions the energy
  - Results show that lifetime is improved 4.86 times in comparison to static case
- A new algorithm is proposed in which every sink asks neighbours energy levels
  - If $p\%$ of sensors have reached the low threshold the sink searches for a new position
  - The new position is determined using energy levels of sensors ¿ $2 - hop$ away
  - If no new position is found the overall network energy has been decreased thus the sinks decrease the low threshold

8. Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks,Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

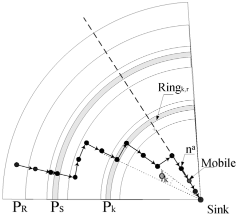
- A mathematical model based in resultant vectors is given that determines the optimal location of the sinks
  - The model tries to minimize the consumed energy through minimizing the sensors' average distance from the sink
  - The authors notice a silarity to the k-mean problem
- The authors then propose two algorithms: *global* and $1 - hop$
- *Global* algorithm finds the sink locations according to the previously analysed mathematical model
- $1 - hop$ algorithm instead uses only local information
  - The algorithm tries to find out how many routes pass from each of the 1-hop neighbours
  - The algorithm then is able to compute how many nodes are hidden behind every node from neighbours list of its 1-hop neighbours
  - It approximates the mathematical model using these informations and computes the new position

9. Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- Sensors are **uniformly** distributed in a **circular** area of radius R while there is 1 sink at the center of the circular area
- Using this model the authors proove upper bounds in the network lifetime
  - The lifetime of a dense static network is upper bounded by $\frac{E}{R^2 e}$ time units while
  - With one mobile relay, the lifetime of a dense network is upper nounded by $4\frac{E}{R^2 e}$ time units
- The authors present an algorithm that can extend the network lifetime to at least $4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$ with one mobile node when the network radius $R > 16\pi + 4$
  - The algorithm tries to create $4\pi\lambda$ paths P_3 to sink using sensors of Q_2 and the mobile as bridge connectors
  - Each time, mobile stands either in P_2 or P_1 and drains one sensor $\in Q_2$

9. Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- Afterwards authors propose a slightly different algorithm with limited aware nodes, in which the lifetime is lower bounded by $4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$, for $s = 22$, $R > 84$



- In case of m mobile relays the authors prove that the lifetime is upper nounded by $4m\frac{E}{R^2 - 4m^2 e}$
- The same algorithm is proposed for multiple mobile relays and proove that the network lifetime to at least $4m\frac{E}{R^2 e} - \frac{32\pi m^3 E}{R^4 e}$
- Simulation shows that latency is increased linear in respect to network radius

10. Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, Azzedine Boukerche. Xin Fei, 2008

Our new paper

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks

Azzedine Boukerche, Xin Fei

University of Ottawa

This paper appears in: **Networking and Communications, WIMOB 2008, IEEE International Conference on Wireless and Mobile Computing**

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

The paper studies the vehicular netowkrs

The network model:

- **Sink:** the final destination of all data aggregations in a wireless sensor network
- **Mobile collector:** a special data collection node with sufficient energy supplies and mobility, which collects data directly from sensors in **one-hop** and relays data to the sink
- the **distribution** of events in the monitoring area is **unbalanced**
- Mobile collectors only collect data from sensors when the lowest latency requirement can be satisfied
- The rest of the data is forwarded to the sink through an **existing** routing protocol
  - It serves as a **secondary** data collection method
- each mobile collector has two channels
  - one for communication with sensors
  - one to relay data to the sink

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

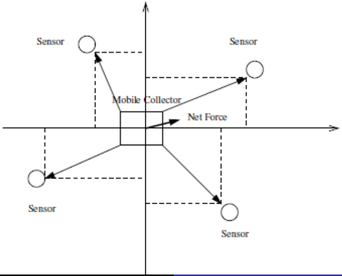
The net force model

- The authors adopted the radio model of Network Simulator (NS2) for transmissions in their approach
- When the distance between two sensors is lower than $d_{crossover}$ the Friss free space model is used
- otherwise two-ray ground propagation model is adopted
- The $d_{crossover}$ is defined as: $d_{crossover} = \frac{4\pi\sqrt{L}h_r h_t}{\lambda}$
- L is the system loss factor, h_t and h_r are the height of the receiving and transmitting antennas above ground and λ is the wavelength of the carrier signal
- The energy dissipation for an m bit message is defined as:
  $E_T = mE_{elec} + mE_{ampl}d^2$ when $d \leq d_{crossover}$
  $E_T = mE_{elec} + mE_{ampl}d^4$ when $d \geq d_{crossover}$
- It can be seen that **closer** the mobile collector is, **lesser** the energy dissipation

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

The net force model

- The authors simulate the energy usage for transmitting data to a mobile sink as a **force** $F = mE_{ampl}d^2$
- The problem of finding a moving route is equal to the problem of finding a path to an **equilibration point** while the net force shows the **direction** of movement
- the **acceleration** of mobile collectors is $a = \frac{F}{m}$, where F is net force and m is the sum of sensors' data volume in cache



Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

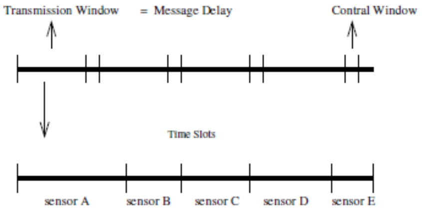
Single mobile collector

- Mobile collector is **released** from the sink, **guided** by the net force and moves toward a networks energy optimal position
- the data gathering process is divided into time windows which last for δ minutes
  - δ is the lowest message delay requirement
- Each sensor broadcasts a request message (REQ) to one-hop neighbors, asking them **report**
  - the **amount of data** in cache
  - the **data generation** rate in the last ten minutes
- The mobile collector arranges a time slot for each one-hop neighboring sensor that has data, and broadcasts a CWIN (communication windows) message with the time arrangement to the one-hop sensors

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

Single mobile collector

- The sensors with **high** data generation **rates** have high **priority** for being fitted into a time window
- The length of a time slot depends on the volume of the data stored in caches of sensors
- Sensors that receive a CWIN message transmit data in their own time slots



Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

Single mobile collector

- In order to maintain the lowest message delay requirement, those sensors have not been assigned a time slot **send** their data through the **routing protocol**
- The **sink** sends the volume of received data and the **senders location** to the collector to **help collector** change its path
- Generally collectors move to where sensors have **more data minimizing the distance** of each sensor
- Collector keeps moving until there is not force existing in a time window
- when the speed exceeds the limitation, the movement maintains a fixed speed
- When net force becomes zero, a collector switches to the **CallBack model** by moving back to the sink

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

Multi collector management

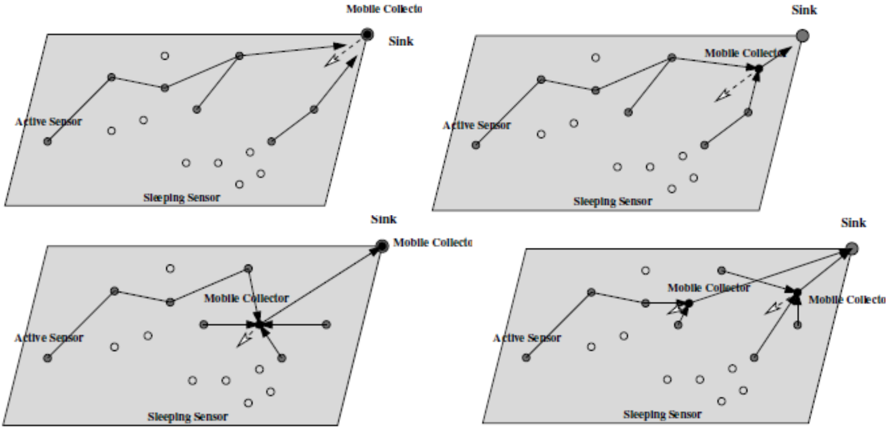
- In order to maintain a low boundary of message delay the remaining data must still be routed to the sink through other sensors
  - The above situation is refered as **saturation**
  - In a saturation, although the energy dissipation for sensors around the sink is reduced, the hot-spot still exist
  - To improve network lifetime **more mobile collectors** are released
- As all existing mobile collectors are saturated and the sink receives over X percent data from other sensors, a new mobile collector is sent out
  - The newly issued mobile collector broadcasts a REQ message with the length of its free time window
  - The sensors that have data pick up those collectors with more free time windows
- Under uniform distribution collectors first serve sensors with more data

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

Multi collector management

- The net force model **prevents** collectors **crowding**
  - collectors being crowed in very active areas while none of them are saturated
- Sensors between collectors sent data to different collectors the net force directed to the active spot becomes weak for each collector
- The forces from the sensors on the opposite direction keep collectors away from each other and avoid collectors crowed in the same place

Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

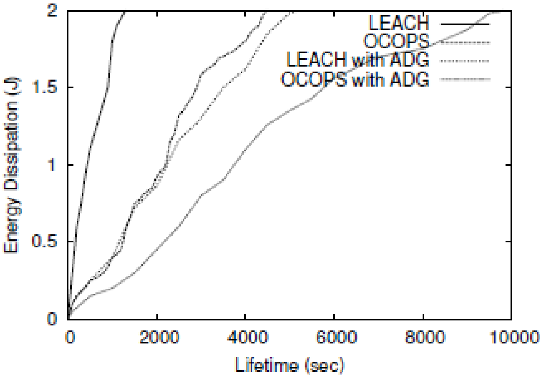


Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

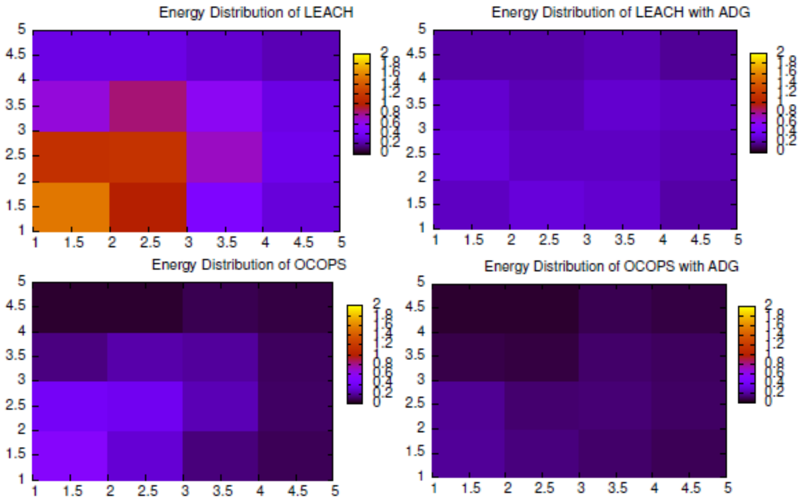
Simulation

- Sensors were randomly deployed in the $50m \times 50m$ to $400m \times 400m$ area
- the number of sensors varies from 10 to 400
- If there was over 5% data received from the routing protocol in a time window, the sink sent out mobile collectors
- It switches to the CallBack model if and only if its utilization ratio in the last 5 time windows is lower than 20%
- **It should be mentioned that the algorithm is independent of the underlying routing protocol**
- The authors used the already known OCoPS and LEACH protocols with ADG

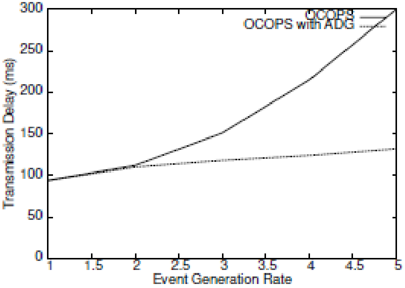
Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008

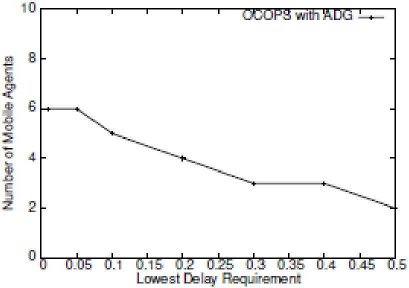


Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008



Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, 2008





11. Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Our new paper

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network

You-Chiun Wang, Member, Wen-Chih Peng, Yu-Chee Tseng

Departement of Computer Science, National Chiao-Tung University

This paper appears in: **IEEE Transactions on Parallel and Distributed Networks**

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Problem Statement

- a hybrid WSN with both static and mobile sensors is considered
- Sensors are aware of their own locations
- Mobile sensors are more **resource-rich** and can be dispatched to event locations to conduct more in-depth analysis
- The **time** is divided into **rounds**
- Static sensors report those events and mobile sensors then visit these event locations
- The paper focuses on the dispatch problem **in one round**
  - given a set of m event locations $L = \{l_1, l_2, \ldots, l_m\}$
  - a set of n mobile sensors $S = \{s_1, s_2, \ldots, s_m\}$
  - The objective is to assign each s_i a dispatch schedule DS_i $i = 1 \ldots n$ which contains a sequence of event locations
  - remaining unvisited locations are forwarded in the next round

Problem Statement

- The energy required to complete s_is dispatch schedule is formulated as $F(DS_i =$
$$e_{move} \times \left(d(s_i, DS_i[1]) + \sum_{j=1}^{|DS_i - 1} d(DS_i[j], DS_i[j+1]) \right)$$
- where $|DS_i|$ is the number of locations and $d(\cdot,\cdot)$ is the distance between two locations

NP-Completeness

- The authors prove that the sensor dispatch decision problem is NP-complete
- They reduce it to the **partition problem**
  - Given a finite set X in which each element $x_i \in X$ is associated with a number
  - determine whether X can be partitioned into two subsets such that the sums of their associated nubers are equal

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Centralized Algorithm (case of $|S| \geq |L|$)

- The authors first construct a weighted complete **bipartite graph** $G = (S \bigcup L, S \times L)$
- Each mobile senor and event location is converted into a vertex
- Edges only connect vertices between S and L
- For each $s_i \in S$ and each $l_i \in L$ its weight is defined as $w(s_i, l_i = e_{move} \times d(s_i, l_j)$
- Then the sensor dispatch problem is formulated as the problem of finding a **matching** M in G such that
  1. The number of matches is maxumum
  2. The sum of weights associated with all matches is as small as possible
  3. The standard deviation of the weights associated with all matches is as small as possible

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Centralized Algorithm (case of $|S| \geq |L|$)

The authors propose a heuristic to find M:

1. For each location $l_j \in L$, a **preference list** P_j is accosiated
   - It contains all mobile sensors ranked by their weights in correspondence with l_i in an ascending order
2. Construct a queue Q containing all locations in L
3. Create a bound B_j for each location $l_j \in L$ to restrict the mobile sensors that l_i can match with
   - Initially set $B_j = w(s_i, l_j)$ such that s_i is the βth element in the list
   - That way a low standard deviation is achieved
4. Dequeue an event location, say, l_j from Q
5. Select the first candidate mobile sensor s_i from P_j and try to match it with l_j
   - If s_i is also unmatched, match M and remove s_i from P_j
   - Otherwise if s_i is matched to another location l_0:

Centralized Algorithm (case of $|S| \geq |L|$)

5. Select the first candidate mobile sensor s_i from P_j and try to match it with l_j
   - If s_i is also unmatched, match M and remove s_i from P_j
   - Otherwise if s_i is matched to another location l_0, l_j and l_o will compete by their bounds B_j and B_o
   - Location l_j wins if:
     - $B_j > B_o$
     - $B_j = B_o$ and $w(s_i, l_j) < w(s_i, l_0)$
     - $B_j = B_o$ s_i is the only candidate of l_j and l_o has more than one candidate
   - If l_j wins the competition we replace the pair (s_i, l_0) in M by (s_i, l_j), remove s_i from P_j, enqueue l_o intp Q and go to step 7
   - Otherwise remove s_i from P_j and go to step 6

Centralized Algorithm (case of $|S| \geq |L|$)

6. If l_j still has candidates in P_j go to step 5 directly. Otherwise increase l_j's bound to $B_j = w(s_k, l_j)(s_k$ is the βth element in the current P_j
7. If Q is empty the algorithm terminates. Otherwise go to step 4

- Since $|S| \geq |L|$ each event location will find a mobile sensor to match with
- The bound location indicates that if the current candidate mobile sensor cannot match with the event location, **the event location may possibly match with another mobile sensor** of a distance equal to that bound

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Centralized Algorithm (case of $|S| \leq |L|$)
When mobile sensors are fewer than event locations L is deveded into $n(= |S|)$ **clusters** $\hat{L}_1, \hat{L}_2, \ldots, \hat{L}_n$ and each sensor is dispatched to visit one cluster of event locations

- A weighted complete **bipartite graph** $G = (S \bigcup \tilde{L}, S \times \tilde{L})$
- The vertex set contains all mobile sensors and clusters
- Edge set contains all $(s_i, \hat{L})$ such that $s_i \in S$ and $\hat{L}_j \in \tilde{L}$
- The weight of $(s_i, \hat{L})$ is defined as $w(s_i, \hat{L}_j) = e_{move} \times (d(s_i, \hat{L}_j) + \phi(\tilde{L}_j))$
- $d(s_i, \hat{L}_j)$ is the distance from s_i to the nearest event in $\hat{L}_j$
- $\phi(\hat{L}_j)$ is the moving distance for S_i to visit all events in $\hat{L}_j$
- Then the **previous algorithm is adopted** to find a maximum **matching** M on G
- For the clusters a TSP **heuristic solution** is applied

Centralized Algorithm (case of $|S| \leq |L|$)

- There are two remaining issues in the above algorithm:
  1. How to estimate cluster cost
  2. How to cluster event locations
- For the cluster cost the sum of all edges of cluster's minimum spanning tree is proposed
  - Many TSP heuristics are base on constructing minimum spanning trees
- For clustering event locations 3 solutions:
  1. K-means clustering scheme
  2. MaxMin clustering scheme
  3. Balanced clustering scheme

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Centralized Algorithm (case of $|S| \leq |L|$)
K-means custering scheme

- Initially L is randomnly partitioned into $|S|$ nonempty clusters
- Then an interative process is conducted"
  - The central point of each cluster is computed
    - Given a cluster of locations $\{(x_1, y_1), (x_2, y_2), \ldots, (x_p, y_p)\}$
    - its central point is calculated as $(\frac{1}{p}\sum_{i=i}^{p} x_i, \frac{1}{p}\sum_{i=1}^{p} y_i)$
  - Then L is repartitioned such that locations **closest to the same central point** are put into the **same cluster**
  - The process is repeated until no cluster is changed
- It is proven that the time complexity is $O(mn\rho)$ in which ρ is the number of iterations

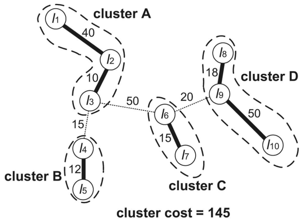
The K-means clustering scheme could be **inefficient** when the **distribution** of event locations is **irregular** or sparse

Centralized Algorithm (case of $|S| \leq |L|$)

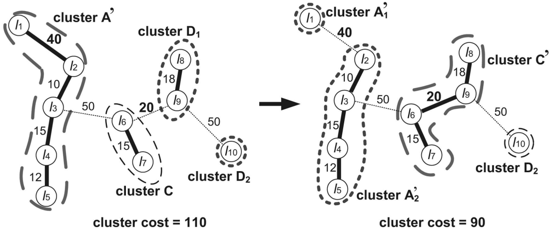
MaxMin clustering scheme

- It is based on the result of K-means and then iteratively split and merge some clusters to obtain better clustering
  - In each iteration a minimum spanning tree of each cluster is constructed
  - Let w_{max}^{intra} be the **maximum of the maximum** edge weight in each cluster among all clusters
  - w_{max}^{inter} the **minimum of the distances between all cluster pairs**
    - the distance between two clusters is the distance between the two closest locations in the two clusters
  - split the cluster which contains the edge with weight w_{max}^{intra} by removing that edge
  - Among all $|S|+1$ merge two clusters with distance w_{max}^{inter}
  - The above operation is repeated until $w_{max}^{intra} \leq w_{max}^{inter}$
- It is proven that the time complexity is $O(mn\rho + m^2 logm)$

Centralized Algorithm (case of $|S| \leq |L|$)



(a)



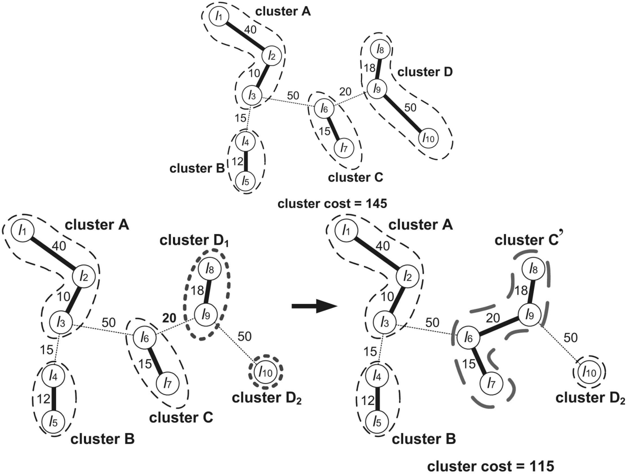
(b)

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Centralized Algorithm (case of $|S| \leq |L|$)
Balanced clustering scheme

- The MaxMin clustering scheme can minimize the total cost of clusters, but it may lead to **unbalanced clusters**
- A reduce in both the total cost of clusters and the standard deviation of clusters costs is the optimal goal
  - we first cluster event locations by K-means
  - Then, we iteratively split and merge some clusters. In each iteration:
    - we split the cluster with the maximum cost into two new clusters $\hat{c}_i$ and $\hat{c}_j$ such that $|\phi(\hat{c}_i) - \phi(\hat{c}_i)|$ is minimized
    - Then among all $|S| + 1$ clusters we merge two clusters into one new cluster $\hat{c}_k$ such that $\phi(\hat{c}_k)$ ini minimized
  - This operation is repeated until the total cluster cost is no longer reduced

Centralized Algorithm (case of $|S| \leq |L|$)



(c)

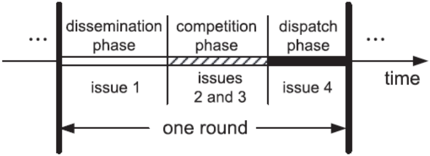
Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Distributed Algorithm

- The sensing field is partitioned into grids and **elect** one static sensor as the **grid head**
- The time is divided into multiple rounds and each round is further divided into three phases
  - dissemination phase
    - each grid head **collects the locations** of events by static sensors
    - each grid head collects the reports(location,energy) of mobile sensors
    - Then, the existence of mobile sensors is **advertised** by grids with mobile sensors
  - competition phase
    - event grids **bid** for mobile sensors by sending invitation messages
    - mobile sensors determine their target grids and **compute** their **dispatch schedules**
  - dispatch phase
    - mobile sensors travel **according to** their schedules

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Distributed Algorithm



- To balance the energy consumption among mobile sensors each event grid maintains a preference list according to their energy costs
- For competition purpose, it also maintains a bound
- event grids send *invitation* (INV) messages containing their bounds to bid for mobile sensors

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Distributed Algorithm

- each mobile sensor s_i maintains a **dispatch schedule** DS_i to record its target grids
- Each s_i limits the size of its DS_i to $\lceil \frac{m}{n} \rceil$
  - m is the number of event grids
  - n is the number of mobile sensors
- Each s_i determines the winners based on event grids bounds
- inserts them into its DS_i, and replies a *confirmation* (CFM) message to each of them
- For each nonwinning grid, s_i replies a *reject* (RJT) message containing the remaining number of free entries in its DS_i
- An event grid removes those mobile sensors with no remaining capacity from its preference list
  - It tries to invite other mobile sensors until a CFM is received or all mobile sensors run out of their capacities in this round

Distributed Algorithm

There are four remaining issues in the above discussion

1. How event grids collect locations of mobile sensors in a message-efficient way?
2. How event grids bid for mobile sensors?
3. How mobile sensors accept bids and determine their dispatch schedules?
4. How mobile sensors visit event locations in an energy-efficient way?

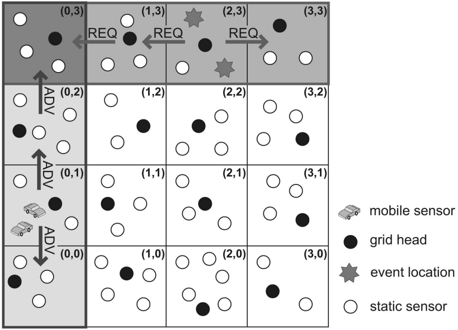
Issue 1

- a grid-quorum scheme is adopted
- Each grid with mobile sensors periodically sends an *advertisement* (ADV) message (location,energy) to grids in the same column

Distributed Algorithm
Issue 1

- On the other hand, each event grid sends a *request* (REQ) message to grids in the same row
- each ADV and each REQ will intersect
- When an REQ meets an ADV, a *reply* (RPY) message containing the mobile sensors in the ADV is sent back to the REQ-initiating grid
- and an RPY containing the event locations in the REQ is sent back to the ADV initiating grid
- In this way, both ADV-initiating and REQ initiating grids can obtain each others information

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008



Issue 2

- Each event grid g_j calculates the energy cost for each mobile sensor s_i to visit its grid
  - Energy cost: $w(s_i, g_j) = e_{move} \times (d(s_i, \gamma_j) + \phi(L_j))$
  - γ_j is the center of all events in g_j and L_j is the set of event locations in g_j
- g_j sorts all available mobile sensors into a preference list P_j according to their costs in an ascending order
- Each event grid g_j maintains an iteration counter α_j and a bound B_j
  - Initially, $\alpha_j = 1$ and $B_j = w(s_i, g_j)$, where s_i is the βth mobile sensor in P_j
- each mobile sensor in P_j is marked as *unsolicited*
  - It is changed to *solicited* if g_j has ever sent an INV to the mobile sensor in the current iteration
- A mobile sensor s_i in P_j is called a *candidate* for g_j if it is unsolicited and $w(s_i, g_j) \leq B_j$

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Issue 2

- Each event grid g_j selects the first candidate s_i from P_j sends s_i an INV message
- If receives a CFM from s_i , this algorithm terminates. Otherwise, g_j should receive an RJT containing s_i s remaining capacity
  - If s_i s remaining capacity is zero it algorithm terminates removing it from the list
  - Otherwise g_j marks s_i as solicited and:
    - If g_j still has candidates under bound B_j , it repeats step 3 again
    - If g_j has no candidate under bound B_j and there still exist unsolicited mobile sensors in P_j , g_j increases its bound
    - Otherwise, g_j has reached the end of its P_j

      $\Rightarrow$ If P_j is empty, the algorithm terminates

      $\Rightarrow$ Otherwise g_j resets P_j, increases counter α_j and repeats step 3

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008

Issue 3

- Each mobile sensor s_i maintains a dispatch schedule DS_i to record event girds that it has to visit
- For all INVs with the same iteration counter, only one event grid is accepted and the others are rejected
  - (All requesting event grids with the same iteration counter will compete for one position)
- INV$(g_j, \alpha_j, w(s_i, g_j), B_j, c_j, n)$ VS INV$(g_j, \alpha_k, w(s_i, g_k), B_k, c_k, n)$ g_j wins if:
  - $B_j > B_k$
  - $B_j = B_k$ and $w(s_i, g_j) < w(s_i, g_k)$
  - $B_j = B_k$, $c_j = 1$ and $c_k > 1$
- Then, s_i sends out CFMs and RJTs, updates its DS_i and deducts its remaining capability accordingly

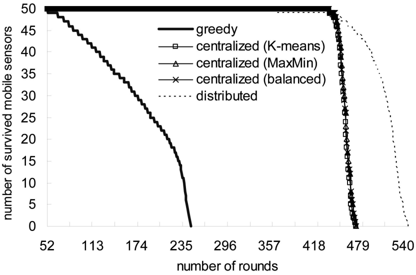
Issue 4

- To deal with issue 4, a two-level TSP scheme is proposed
- Given the dispatch schedule DS_i , s_i first applies any TSP solution on DS_i by regarding each event grid in DS_i as one node
- This TSP solution forms the first-level solution
- For the second level, for each event grid in DS_i , s_i can apply any TSP solution again to visit all event locations inside that grid

Algorithm's message complexity: $O(m\hat{M} + n\hat{N} + m^2h)$

- where the sensing field is partitioned into $\hat{M} \times \hat{N}$
- h is the network diameter

Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008



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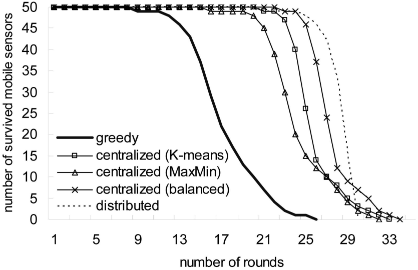
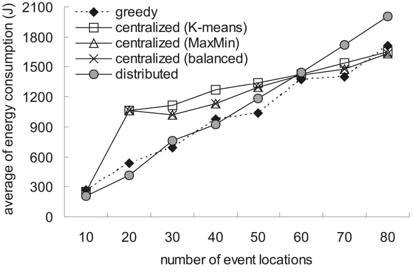


Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008



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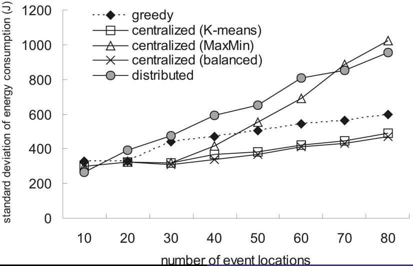
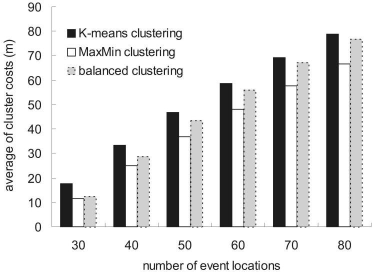


Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008



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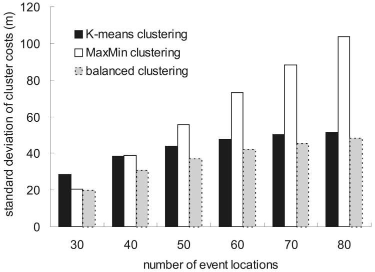
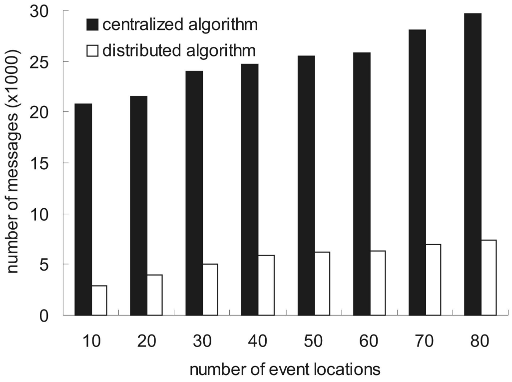
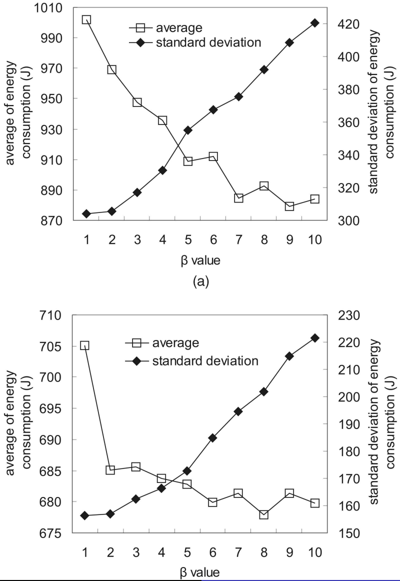


Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008



Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Yu-Chee Tseng et al, 2008



Our roadmap - 11-1-12

Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, R C Shah et al. 2003

- Analyzes an architecture to collect sensor data in sparse sensor networks using MRs(called MULES)
- MULEs pick up data from the sensors when in close range, buffer it, and drop off the data to wired access points using short-wireless communications
- Substansial power saving at the sensors since they have only to transmit over a short range
- The model assumes two-dimensional random walk for mobility and incorporates key system variables such as number of MULEs, sensors and access points
- The performance metrics observed are the data success rate (the fraction of generated data that reaches the access points) and the required buffer capacities on the sensors and the MULEs

Mobile Sinks in Wireless Sensor Networks

Filippos Vasilakis – SensorsLab

Computer Engineering and Informatics

February 1, 2012

Protocols that we have anaysed so far

1. **Clustering and load balancing in hybrid sensor networks with mobile cluster heads**, Ming Ma, Yuanyuan Yang, '06 International conference on Quality of service in heterogeneous wireless networks
2. **Increasing lifetime of wireless sensor networks using controllable mobile cluster heads**, Torsha Banerjee, Bin Xie, Jung Hyun Jun, Dharma P. Agrawal, Wireless Communications and Mobile Computing 2010
3. **mWSN for Large Scale Mobile Sensing**, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008
4. **Data gathering in wireless sensor networks with mobile collectors**, Ming Ma, Yuanyuan Yang, 2008 IEEE International Symposium on Parallel and Distributed Processing
5. **Mobile Element Scheduling with Dynamic Deadlines**, A. Somasundara, A. Ramamoorthy, M. Srivastava, IEEE Transactions on Mobile Computing, 2007

Protocols that we have anaysed so far

6. **Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks**, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007
7. **Using Sink Mobility to Increase Wireless Sensor Networks Lifetime**, Mirela Marta and Mihaela Cardei, 2008
8. **Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks**, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007
9. **Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays**, Wang, Srinivasan, Chua, 2008
10. **Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks**, Azzedine Boukerche. Xin Fei, 2008
11. **Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network**, Yu-Chee Tseng et al, 2008

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

An approach that uses the MR as cluster head

- They consider the problem of positioning mobile cluster heads and balancing traffic load in a hybrid sensor network
- it consists of **two types of nodes**: mobile cluster heads(high level) and basic static sensor nodes which form the clusters(low level)
- each sensor has **different** flow generation **rate**
- The problem of maximizing network lifetime through dynamically positioning cluster heads in the network turns out to be **NP-hard**
- They present a **heuristic algorithm** for positioning cluster heads and balancing traffic load in the network that prolong network lifetime

1. Clustering and load balancing in hybrid sensor networks with mobile cluster heads, Ma and Yang 2006

We investigated the paper and we concluded that:

- It provides solid background of the problem and discusses the problem of positioning mobile clusters heads in a two layer sensor network to maximize lifetime..but:
- The authors propose an **offline algorithm** for computing the positions of the cluster heads
- They don't discuss anything about the existance of a **Base Sink**
- In their model the **cluster heads are connected a priori**
- They don't count the **residual energy** of sensors when computing the cluster heads' new position
- Their solution is **bearly feasible**

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

An approach that uses the MR as cluster head

- The authors study again the energy balance problem under mobile cluster heads
- They propose to use multiple mobile cluster heads (CHs), each CH can move in its cluster
- They propose 3 protocols
  - CHs move towards the **energy-rich sensors**
  - CHs move towards the **event area**
  - a **hybrid protocol** in which CHs move according to the equation
    $C_{comb} = \eta \times C_{energy} + \gamma \times C_{event}$
- Also they discuss algorithms that mentain **connectivity** between CHs and BS
- In simulation they showed that there is a trade-of between energy consumption and delay

2. Increasing lifetime of wireless sensor networks using controllable mobile cluster heads, Dharma P. Agrawal et al. 2010

We investigated the paper and we concluded that:

- It is a very concrete work that analyses many interesting topics in WSNs but
- In residual energy-based strategy, in case of **multiple energy centres**, it does not find the optimal position for CH
    - Actually if the energy centres are **equal** the new position of CH is the least optimal
- In their model cluster members **does not change** at all. Also every CH moves ONLY **inside** its cluster.
- The algorithms that they proposed for ensuring BS connectivity are very **energy consuming**

3. mWSN for Large Scale Mobile Sensing, Jian Ma, Canfeng Chen and Jyri P. Salomaa, Signal Processing Systems 2008

The paper reviews the reviews the relationship between delay and mobile sink velocity

- The authors show that **increasing** either the radio transmission range **r**, or the number of mobile sinks **m**, or the sink velocity **v** the sensor-sink meeting **delay** can get **reduced**

Next the authors add in their analysis the message length

- Again the result shows that, by **decreasing** message length **L**, or **increasing** transmission range **r** and number of mobile sinks **m**, the message delivery delay can be **reduced**
  - Simulation showed that increasing the ratio of sink velocity to sensor transmission radius, at first decreases the delay, reaches an **optimal condition** but then delay is increasing again !

At last, the Outage Probability is considered

- It is shown that the goal of enlarging the outage area can be achieved via **increasing** **r**, or **decreasing** **v** **or** **T**

4. Data gathering in wireless sensor networks with mobile collectors, Ming Ma, Yuanyuan Yang, 2008

- The authors consider the problem in which M-collectors visit every node in its **transmission range** in order to minimize energy dissipation
- They formulate a **mixed integer program** solution and show that the problem is **NP-hard**
- Also they **compare** it with the **TCP** and **CSP**(Coverin Salesman Problem)
- A new algorithm is constructed to **obtain all polling points** according to their **average cost** from current position of M-collector
- When considering a larger network field, they construct a **MST** of polling points and **decompose** it to **equal subtrees**
- In each subtree an M-collector is scatter using the previous algorithm

5. Mobile Element Scheduling with Dynamic Deadlines, A. Somasundara, A. Ramamoorthy, M. Srivastava, 2007

- The paper analyses the scheduling of the **mobile elements** under **different deadlines**
- The authors firt prrove the **NP-completeness** of the problem and form an **integer programming** formation
- They propose practical algorithms fo single mobile sink and extend them in the case of multiple sinks
  - Earliest Deadline First (EDF)
  - EDF with k lookahead
  - Minimum weighted sum first
- In case of multiple sinks they note the similarity with Vehicle Routing Problem with Time Windows (**VRPTW**)
- Te authors propose and analyse the most cited algorithm for that problem
  - Start with a single vehicle and add new vehicle every time **no new node** can be inserted in **existing tour**
- Simulation shows that VRPTW has the best performance followed by Minimum weighted sum first

6. Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks, Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

- The paper studies the case of minimizing the energy every sensor consumes
- In order to minimize the energy, the sum of the distances between the sensors and the sink has to be minimized
- The authors use the idea of vector that under ideal circunstances should be zero
  - If not zero, it shows the direction the sink should move
- A global algorithm is proposed that makes use of global vectors but is hardly applicable since is uses global information
- A new algorithm is proposed, $1 - hop$ that uses only local information
  - Every mobile sink can determine how many sensors are hidden behind 1-hop sensor retrieving the number of routes traverses its of them

7. Using Sink Mobility to Increase Wireless Sensor Networks Lifetime, Mirela Marta and Mihaela Cardei, 2008

- The authors study the energy holes that appear near the sinks
- At first they examine through simulations network lifetime using mobile sinks
  - Mobile sinks move in the peripheries of the coronas stopping only in 12 positions the energy
  - Results show that lifetime is improved 4.86 times in comparison to static case
- A new algorithm is proposed in which every sink asks neighbours energy levels
  - If p% of sensors have reached the low threshold the sink searches for a new position
  - The new position is determined using energy levels of sensors ¿ $2 - hop$ away
  - If no new position is found the overall network energy has been decreased thus the sinks decrease the low threshold

8. Deploying Multiple Sinks in Multi-hop Wireless Sensor Networks,Zoltan Vineze, Rolland Vida, Attila Vidacs, 2007

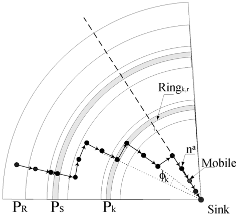
- A mathematical model based in resultant vectors is given that determines the optimal location of the sinks
  - The model tries to minimize the consumed energy through minimizing the sensors' average distance from the sink
  - The authors notice a silarity to the k-mean problem
- The authors then propose two algorithms: *global* and $1 - hop$
- *Global* algorithm finds the sink locations according to the previously analysed mathematical model
- $1 - hop$ algorithm instead uses only local information
  - The algorithm tries to find out how many routes pass from each of the 1-hop neighbours
  - The algorithm then is able to compute how many nodes are hidden behind every node from neighbours list of its 1-hop neighbours
  - It approximates the mathematical model using these informations and computes the new position

9. Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- Sensors are **uniformly** distributed in a **circular** area of radius R while there is 1 sink at the center of the circular area
- Using this model the authors proove upper bounds in the network lifetime
  - The lifetime of a dense static network is upper bounded by $\frac{E}{R^2 e}$ time units while
  - With one mobile relay, the lifetime of a dense network is upper nounded by $4\frac{E}{R^2 e}$ time units
- The authors present an algorithm that can extend the network lifetime to at least $4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$ with one mobile node when the network radius $R > 16\pi + 4$
  - The algorithm tries to create $4\pi\lambda$ paths P_3 to sink using sensors of Q_2 and the mobile as bridge connectors
  - Each time, mobile stands either in P_2 or P_1 and drains one sensor $\in Q_2$

9. Extending the Lifetime of Wireless Sensor Networks Through Mobile Relays, Wang, Srinivasan, Chua, 2008

- Afterwards authors propose a slightly different algorithm with limited aware nodes, in which the lifetime is lower bounded by $4\frac{E}{R^2 e} - \frac{16E}{R^4 e}$, for $s = 22,\ R > 84$



- In case of m mobile relays the authors prove that the lifetime is upper nounded by $4m\frac{E}{R^2-4m^2 e}$
- The same algorithm is proposed for multiple mobile relays and proove that the network lifetime to at least $4m\frac{E}{R^2 e} - \frac{32\pi m^3 E}{R^4 e}$
- Simulation shows that latency is increased linear in respect to network radius

10. Adaptive Data-Gathering Protocols with Mobile Collectors for Vehicular Ad-hoc and Sensor Networks, Azzedine Boukerche. Xin Fei, 2008

- The paper presents an adaptive data gathering protocol (ADG) that employs multiple mobile collectors to facilitate an existing routing protocol
- The ADG aims to improve energy efficiency and low message
- the acceleration of mobile collectors is $a = \frac{F}{m}$, where F is net force and m is the sum of sensors data volume in cache
- Mobile collector is released from the sink, guided by the net force and moves toward a networks energy optimal position
- An aloha-like protocol is used to communicate with the sensors
- To achieve delay requirements urgent packets are send through the routing protocol

11. Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Tseng et al, 2008

- In this paper the energy of mobile collectors is not endless
- Authors try to minimize both sensors' and mobile collectors' energy
- It is shown that the problem is NP-complete and contruct a centralized algorithm that uses bipartite graph(collectors-events)
- In case $N_{collectors} > N_{events}$ the sensor dispatch problem is the problem of finding a **matching** M in G such that
  1. The number of matches is maxumum
  2. The sum of weights associated with all matches is as small as possible
  3. The standard deviation of the weights associated with all matches is as small as possible
- In case $N_{collectors} < N_{events}$ $|S| = N_{collectors}$ clusters are constructed and again the problem is to find a **matching** M in G

11. Energy-Balanced Dispatch of Mobile Sensors in a Hybrid Wireless Sensor Network, Tseng et al, 2008

The authors then propose a distributed algorithm

- The sensing field is partitioned into grids and **elect** one static sensor as the **grid head**
- The time is divided into multiple rounds and each round is further divided into three phases
  - dissemination phase
    - each grid head **collects the locations** of events by static sensors
    - each grid head collects the reports(location,energy) of mobile sensors
    - Then, the existence of mobile sensors is **advertised** by grids with mobile sensors
  - competition phase
    - event grids **bid** for mobile sensors by sending invitation messages
    - mobile sensors determine their target grids and **compute** their **dispatch schedules**
  - dispatch phase
    - mobile sensors travel **according to** their shcedules

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Our new paper

Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks

Rahul C. Shah, Sumit Roy, Sushant Jain and Waylon Brunette

Departement of Computer Science and Engineering, University of Washington

Intel Research

This paper appears in: **IEEE Sensor Network Protocols and Applications Workshop**

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

- The MULE architecture provides wide-area connectivity for a **sparse** sensor network by exploiting mobile agents
  - people, animals, or vehicles moving in the environment
- The system architecture comprises of a **three-tier layered abstraction**:
  - A top tier of WAN connected devices
  - A middle tier of mobile transport agents
  - A bottom tier made of fixed wireless sensor nodes
- The top tier is composed of **access points**, which can be set up at convenient locations where network connectivity and power are present
- The intermediate layer of mobile **MULE nodes** provides the system with scalability and flexibility for a relatively low cost
- The bottom tier of the network consists of randomly distributed wireless **sensors**

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

System modeling

- The underlying topology on which sensors, MULEs and access points are placed is assumed to be a discrete and finite **two-dimensional grid**
  - the planar topology is assumed to be the **surface of a torus**
- The access points are modeled to be **uniformly spaced** on the grid while the sensors are randomly distributed
- The network evolves **synchronously** with a global clock. At every clock:
  - Sensors generate one unit of data
  - Every MULE moves on the grid
- The MULE motion is modeled as a simple **symmetric random walk** on the grid
- The MULEs communicate with the sensors or access-points **only when** they are co-located at the grid points

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Case: $N_{AP} = 1$ and $N_{mules} = 1$

- The simplest scenario consists of one access point ($N_{AP} = 1$) and one MULE ($N_{mules} = 1$) in the system
- The AP is at some position (the exact position is not critical) in the grid of size $\sqrt{N}$ on a side
- The state space S consists of the points on the grid and forms a **vector** of length N
- The transition probabilities for the Markov chain with state space S are $p_{ij} = \begin{cases} \frac{1}{4} & \text{if } (i,j) \text{ has an edge} \\ 0 & \text{otherwise} \end{cases}$
- Since $\sum_{i \in S} \pi_i = 1$ and all states are **equiprobable**, we get $\pi_i = \frac{1}{N}$

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Case: $N_{AP} = 1$ and $N_{mules} = 1$

- The **average time** it takes for the MULE to return to the same sensor node i: $E[R_i] = \frac{1}{\pi_i} = N$
- since a unit data is generated every clock tick, this is also the **average value of the buffer** occupancy at the sensor $E[Z_i]$ when the MULE visits it
- Similarly, the **average** number of **steps** the MULE takes **before returning** to the access point is $E[R_{AP}] = \frac{1}{\pi_{AP}} = N$
- The number of data samples the MULE picks up during one traversal depends on:
  - the length of the traversal R_{AP}
  - the number of sensors encountered which depends on $\rho_{sensors}$
  - the buffer occupancy at the sensors Z_i
- Since the three quantities are **independent**, the average is simply given by $E[M] = E[R_{AP}] \cdot \rho_{sensors} \cdot E[Z_i] = \rho_{sensors} N^2$

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Case: $N_{AP} = 1$ and $N_{mules} = 1$

- The above results show that
  - the time between MULE visits to a sensor or AP grows **linearly** with the grid
  - the required buffer at the sensor **needs to scale** with the grid size to prevent loss of data
  - the **latency** for data samples also **increases** with the **grid size**

Scaling with the number of Access Points

- We assume that the access points are $\sqrt{K}$ spaced at a distance of K points on the grid in both the x and y directions
  - $K = \frac{N}{N_{AP}} = \frac{1}{\rho_{AP}}$

Result 1

The expected length of excursion for the MULE starting from the set of access points till it reaches the set again is $E[R_{AP}] = K = \frac{1}{\rho_{AP}}$

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Scaling with the number of Access Points

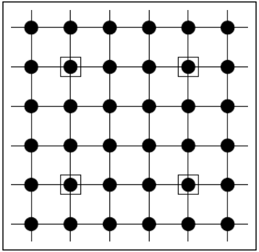
Proof:

- We **reduce** the state space to a smaller grid of size $\sqrt{K} \times \sqrt{K}$ as shown in the figure(next slide)
- This can be seen to be the result of folding the entire grid onto the smaller box containing **only one** access point A (which represents all the access points)
  - This is possible because from the perspective of a MULE, all access points are **equivalent**
  - The resultant grid also remains a **torus**
- Similarly, the **stationary distribution** for a node i in this reduced grid can be shown to be $\pi_i = \frac{1}{K}$
- Using this stationary distribution, the return time to the point "A" is: $E[R_{AP}] = \frac{1}{\pi_{AP}} = K = \frac{1}{\rho_{AP}}$

Scaling with the number of MULEs

- The fraction of MULEs in the system is kept **constant** as the size of the grid is increased, $\frac{N_{mules}}{N} = \rho_{mules}$
- Consider a sensor and a particular MULE M_0. Then the probability that M_0 intersects the sensor is given by

$$Y_k = \begin{cases} 1 & \text{if one or more MULEs intersects} \\ & \text{the sensor at time } k \\ 0 & \text{If no MULE intersects the sensor at time } k \end{cases}$$



Scaling with the number of MULEs

- The probability that **no MULE intersects** with the sensor is given by:
$P\{Y_k = 0\} = \left(1 - \frac{1}{N}\right)^{N_{mules}} \Rightarrow P\{Y_k = 1\} = 1 - \left(1 - \frac{1}{N}\right)^{N_{mules}}$
- The **expected number** of MULE visits to a sensor per unit time is $\lim_{n\to\infty} \frac{1}{n} E\left[\sum_{k=0}^{n-1} P\{Y_k = 1\}\right] = 1 - \left(1 - \frac{1}{N}\right)^{N_{mules}} \overset{\text{large } N}{\approx} 1 - e^{\rho_{mules}} \overset{\text{small } \rho_{mules}}{\approx} \rho_{mules}$

Result 2

The average inter-arrival time between MULE visits to a sensor i is given by: $E[R_i^{N_{mules}}] = \frac{1}{1-(1-\frac{1}{N})^{N_{mules}}} \overset{\text{large } N}{\approx} 1 - e^{\rho_{mules}} \overset{\text{small} \rho_{mules}}{\approx} \rho_{mules}$

Proof:

- Consider the Markov chain composed of the **product** of the Markov chains of each of the MULEs

Proof:

- Thus the new state space is given by: $\underbrace{S' = S \times S \times S \ldots \times S}_{N_{mules} \text{ times}}$
- In the modified state space S , we are interested in the **set of states A** which represent one or more MULEs intersecting i
- Since all the states are **equally likely**, the stationary distribution for the set A can be calculated as $\pi(A) = \frac{|A|}{|S'|} = \frac{|S'|-|S'-A|}{|S'|} = \frac{N^{N_{mules}}-(N-1)^{N_{mules}}}{N^{N_{mules}}} = 1-(1-\frac{1}{N})^{N_{mules}}$
- Using Kac's formula, the **average inter-arrival** time between MULE visits to a sensor i is $E[R_i^{N_{mules}}] = \frac{1}{\pi(A)} = \frac{1}{1-(1-\frac{1}{N})^{N_{mules}}} \overset{\text{large } N}{\approx} 1-e^{\rho_{mules}} \overset{\text{small} \rho_{mules}}{\approx} \rho_{mules}$

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Corollary 2.1

Average buffer occupancy on a sensor can now be calculated as $E[Sensor\ Buffer] = E[R_i^{N_{mules}}] \approx \frac{1}{\rho_{mules}}$

- Although this is just the average buffer occupancy seen at the times of MULE arrivals at the sensor and not at all times, we can see that **sensors' buffer depends on MULEs' density**
- As long as ρ_{mules} remains constant, the buffer requirements remain the same

Corollary 2.2

Average buffer occupancy on a MULE can also be calculated as $E[Mule\ Buffer] = \rho_{sensors} E[R_{AP} | E[R_i^{N_{mules}}]] \approx \frac{\rho_{sensors}}{\rho_{AP}\rho_{mules}}$

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Hitting time distribution at a sensor

- The hitting time for a sensor i is defined as the **first time a MULE hits** i when all the MULEs start from the stationary distribution
- It is shown that the **mean of the hitting time** for a **single MULE** is $\boxed{\theta(NlogN)}$ for simple **symmetric random walk** on the surface of a **torus**
- Furthermore, the distribution of hitting times for an **ergodic Markov chain** can be approximated by an **exponential distribution** of the same mean
- Therefore $P\{H_i > t\} \approx exp(\frac{-t}{cNlogN})$, $c \approx 0.34$ as $N \to \infty$

Result 3

The hitting time for a sensor i when there are N_{mules} in the system, all of which start in the stationary distribution is given by $P\{H_i^{N_{mules}} > t\} \approx exp(\frac{-t}{0.34\frac{N}{N_{mules}}log(N)})$

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Proof:

- Let $H_i^{(k)}$ denote the hitting time to a sensor i for a single MULE k. Then $H_i^{N_{mules}} = \min_{k \in MULEs} H_i^{(k)}$
- Thus we obtain: $P\{H_i^{N_{mules}} > t\} = [P\{H_i > t\}]^{N_{mules}} \approx$
$$\left[exp\left(\frac{-t}{0.34\frac{N}{N_{mules}}log(N)}\right)\right]^{N_{mules}} = \mathbf{exp}\left(\frac{\mathbf{-t}}{\mathbf{0.34\frac{N}{N_{mules}}log(N)}}\right)$$

Inter-arrival time distribution at a sensor

- To obtain the distribution we derive a recursive equation to compute $P\{R_i = t\}$
  - Let the **initial position** of the MULE be at the grid position 0
  - Define $L_{i,j}(t)$ to be the **number of paths** starting from i and ending at j of length t, avoiding the point 0
  - Then, without loss of generality, for any sensor node i $P\{R_i = t\} = \frac{L_{0,0}(t)}{4^t}$

12. Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks, Rahul C. Shah et al, 2003

Inter-arrival time distribution at a sensor

- For any sensor node i $P\{R_i = t\} = \frac{L_{0,0}(t)}{4^t}$
  - $L_{0,0}(t)$ denotes the total number of **valid paths** that return to 0 in t steps
  - 4^t denotes the total number of **possible paths** of t steps
- The following **recursive equation** can now be used to compute $L_{0,0}(t)$:
  - $L_{i,j}(t) = \sum_{substack k \in N(t) \wedge k \neq 0} L_{k,j}(t-1), \; t > 1$
  - $L_{i,j} = \begin{cases} 1 & \text{if } j \in N(i), \\ 0 & \text{otherwise} \end{cases}$

Result 4

If the number of MULEs in a system is N_{mules} , the inter-arrival time at a sensor i can be written as:
$P\{R_i^{N_{mules}} > t\} \approx P\{H_i^{N_{mules}-1} > t\} \cdot P\{R_i > t\}$

Result 4

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$P\{R_i^{N_{mules}} > t\} \approx P\{H_i^{N_{mules}-1} > t\} \cdot P\{R_i > t\}$

Proof:

- We **ignore multiple MULEs** at the sensor which is a very unlikely event
  - we consider only the moments at which one MULE intersects the sensor
- At this instant in time, the rest of the MULEs are in the stationary distribution thus: $R_i^{N_{mules}} = min(R_i, H_i^{N_{mules}-1})$

Data success rate

- The ratio of the average amount of **data delivered** to the access points by time t to the total **data generated** by time $t \to \infty$

Data success rate

Result

The data success rate of the system is given by:

$$S = \sum_{k \in MULEs} \frac{E[min(\rho_{sensors} \sum_{i=1}^{R_{AP}} min(R_i^{N_{mules}}, SB), MB)]}{E[R_{AP}]N_{sensors}}$$

Proof:

- One **excursion** of the **MULE** from the access point set back to the set is considered a **cycle** (R_{AP} is a cycle)
- The average data generated in the system per unit time is $N_{sensors}$
- Thus the success rate S is $S = \frac{E[\sum_{k \in MULEs} M^{(k)}]}{E[R_{AP}]N_{sensors}}$
  - $M^{(k)} =$ Data **picked up** by the MULE k in time R_{AP}
    $M^{(k)} = min\left(\rho_{sensors} \sum^{R_{AP}} Y_i^{(k)}, MB\right)$
  - The min-function is included because the **buffer capacity** of the MULE **bounds** the total amount of data a MULE can carry

Data success rate

Proof:

- $Y_i^{(k)}$ is the **amount of data** at a sensor visited by MULE k at **time i**
- $Y_i^{(k)} = min(Z_i, SB)$
  - Similarly, the sensor **buffer capacity bounds** the amount of data that can be present at a sensor
  - Z_i is the amount of data generated and not yet picked up at the sensor
  - it has the same distribution as the inter-arrival time at a sensor
- Putting this all together we get:

$$S = \sum_{k \in MULEs} \frac{E[min(\rho_{sensors} \sum_{i=1}^{R_{AP}} min(R_i^{N_{mules}}, SB), MB)]}{E[R_{AP}] N_{sensors}}$$

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Latency (at sensor D_s)

Droptail queuing discipline

- The sensor node stops generating any more data once the sensor buffer gets filled up

Result

For the droptail protocol, the distribution of the latency at a sensor is given by $P\{D_s = t\} = P\{H_i^{N_{mules}} = t\}$

Corollary

The average latency at the sensor for the droptail protocol is given by $E[D_s] = E[H_i^{N_{mules}}] = \frac{0.34 N log N}{N_{mules}}$

Drophead queueing discipline

- In this protocol, new data pushes out old data if the sensor buffer gets full

Latency (at sensor D_s)

Drophead queueing discipline

- Thus the oldest data is the first to get dropped when new data is generated

Result

For the drophead protocol, the distribution of the latency at a sensor is given by $P\{D_s = t\} = \begin{cases} \frac{P\{H_i^{N_{mules}}=t\}}{P\{H_i^{N_{mules}}\leq SB\}}, & t \leq SB, \\ 0, & t < SB \end{cases}$

Corollary

The average latency at the sensor for the drophead protocol is given by $E[D_s] = \sum_{t=1}^{SB} \frac{t \cdot P\{H_i^{N_{mules}}=t\}}{P\{H_i^{N_{mules}}\leq SB\}} = \frac{1}{1-e^{-1/\bar{H}}} - \frac{SB \cdot e^{-SB/\bar{H}}}{1-e^{-SB/\bar{H}}}$

where $\overline{H} = E[H_i^{N_{mules}}] = \frac{0.34 N log(N)}{N_{mules}}$

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Latency (on MULE D_m)

Result

The distribution of latency on a MULE for data picked up at a random sensor is given by $P\{D_m > t\} \approx exp\left(\frac{-t}{0.34\frac{N}{N_{AP}}log(N)}\right)$

- It is as finding the time taken to hit the access point (AP hitting time)

Corollary

The average latency on a MULE is given by $E[D_m] = \frac{0.34NlogN}{N_{AP}}$

- The result comes directly from the mean of the exponential distribution

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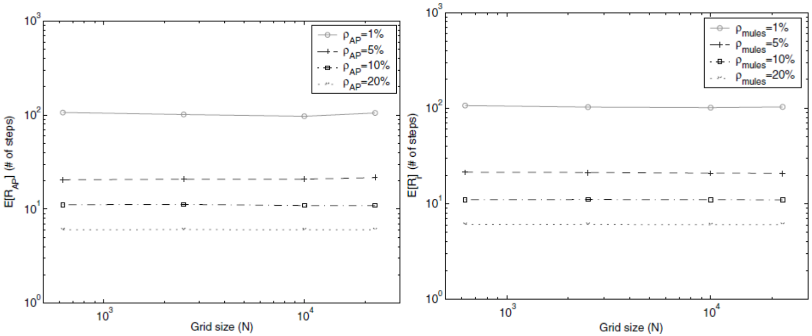

Figure: $E[R_{AP}]$ and $E[R_i]$ whicle scaling the grid size

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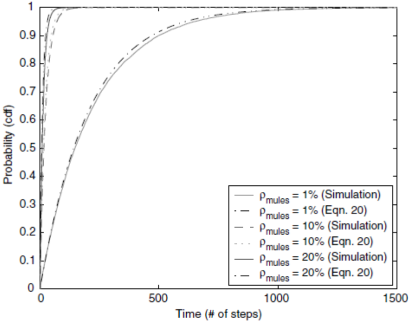

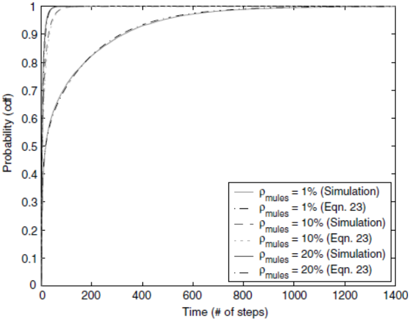

Figure: CDF of the hitting times ($H_i^{N_{mules}}$) and and inter-arrival times ($R_i^{N_{mules}}$)

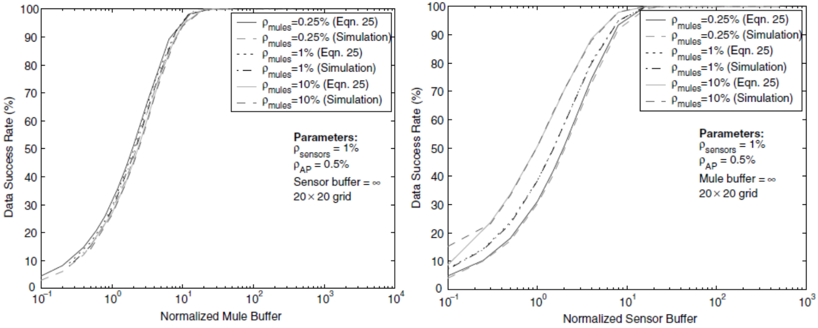

Figure: Data success rate vs normalized MULE and sensor buffer size

- Normalized MULE Buffer $= \dfrac{\text{Actual value of the MULE Buffer}}{E[MULE\ \ Buffer]}$
- Normalized sensor Buffer $= \dfrac{\text{Actual value of the Sensor Buffer}}{E[Sensor\ \ Buffer]}$

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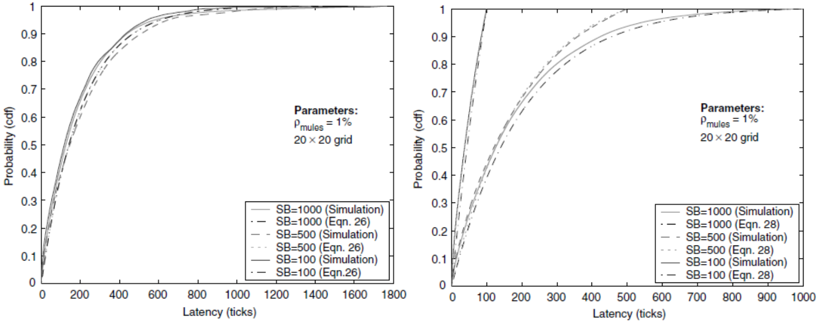

Figure: CDF of the latency at a sensor with droptail and drophead protocol

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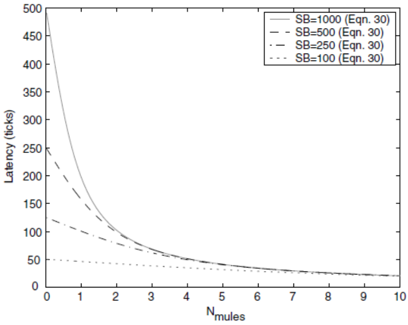

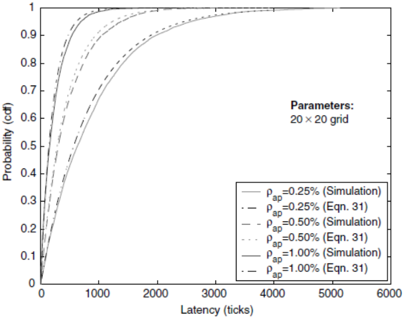

- Left: Average latency on a sensor with drophead protocol
- Right: Cdf of the latency on a MULE