Trajectory Computation of Mobile Data Collectors in Wireless Sensor Networks

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Abstract:
Sensors are used to monitor the physical environment. Sensors have limited energy supply. However a sensor network is expected to be functional for a long time. Thus optimizing the energy consumption to prolong network lifetime is an important issue. In static sensor networks, sensors closer to the base station die first because they send their own data, and also forward data from other sensors located farther away from the base station. The residual energy of sensors can be balanced by using Mobile Data Collectors (MDCs) or mobile nodes to prolong the lifetime of Wireless Sensor Networks (WSNs). In this survey, we review the research on trajectories followed by MDCs in order to extend the network lifetime. We divide trajectories into three groups: dynamic or multiple trajectories, fixed or predictable trajectories and numerical trajectories (math curves).

Categories and Subject Descriptors: A.1 [Introductory and Survey]:; H.4.3 [Communication Application]: wireless sensor networks

General Terms: wireless sensor networks, mobile data collectors, trajectory

Additional Key Words and Phrases: network lifetime, latency, TSP, ILP, energy dissipation, cluster.

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1. INTRODUCTION

Wireless Sensor Networks (WSNs) have been largely deployed for different applications since inexpensive wireless sensors are equipped with radio communication, processing, storage, and battery power [Pazzi et al. 2008]. Among numerous challenges faced while designing WSNs, maximizing the network lifetime stands out as a critical consideration [Ekici et al. 2006]. Some sensors drain their energy faster than other nodes in a static WSN, which is demonstrated by Heinzelman et al. [2000] through experiments. Using Mobile Elements (MEs) to collect and carry data mechanically has many advantages over static multi-hop routing [Jea et al. 2005].

In this survey, we study trajectories which are followed by Mobile Data Collectors (MDCs) to improve network lifetime. The trajectories are classified into three categories: dynamic trajectories (or multiple trajectories), predictable trajectories (or fixed trajectory), and numerical trajectories. Trajectories can be followed by a single or multiple MEs.

1.1 Dynamic Trajectories

Dynamic trajectories are computed while MDCs are collecting data from sensor nodes and delivering data to the base station, processing the data from mobile collection, at the beginning of each round.

Moving base stations to balance the energy dissipation of sensor nodes is the earliest mobile approach proposed by Gandham et al. [2003]. It is to prolong the network lifetime. Azad et al. [2006] proposed heuristic algorithms: Top- K_{max}, Max-Min-RE and MinDiff-RE to determine the base station locations. Alsalih et al. [2008] proposed two algorithms to make uniform energy consumption with or without delay constraints in Underwater Acoustic Sensor Networks (UASNs). Xing et al. [2008] proposed a rendezvous-base to reduce the latency when MEs collect data from large sensing fields due to their slow speed.

For a single MDC, Ekici et al. [2006] introduced a Partitioning Based Scheduling (PBS) algorithm to compute periodic trajectories of an MDC to avoid sensor data loss at low MDC speeds. Gu et al. [2006] proposed a PBS algorithm to form the entire MDC trajectory for preventing from buffer overflow. Bi et al. [2007] proposed a one-step moving scheme and a multi-step moving scheme to construct trajectories. Hanoun et al. [2008] proposed the approx-TSP algorithm (where TSP stands for Travelling Salesman Problem) to construct collector route dynamically during the network operational time regardless of sensor data generation rates. Pazzi and Boukerche [2008] improved their own idea, CPEQ/PEQ, in Boukerche et al. [2006] for delay-sensitive systems, which include cluster configuration, route maintenance and data transmission. Basagni et al. [2008] combined their previous works and then presented a new Mixed Integer Linear Programming (MILP) and Greedy Maximum Residual Energy (GMRE) algorithm including the cost and the mobility rate of sink movement from both data latency and energy consumption. Zhu et al. [2009] presented two Multi-Path Planning (MPP) heuristic schemes where they invoke TS heuristics for an initial partial travel path and update path, called fixed-K and adaptive-K.

1.2 Fixed Trajectories

Mendis et al. [2006] applied Particle Swarm Optimization (PSO) for the placement of sink and then obtained the optimum movement path followed by sink node within a sensor field to achieve efficient energy management and longer lifetime of WSN with maximum field. Basing on queuing theory, Jain et al. [2006] theoretically analyzed the MULE architecture introduced by Shah et al. [2003], which saves the energy of up to two-order magnitude by MULEs as compared to the traditional ad-ho network approach. However the MULE architecture is limited to non real time applications since it causes more latency for data delivery. Aioffi et al. [2007] proposed Single-hop Strategy (SHS) and Multi-hop Strategy (MHS) to reduce the sink tour length by considering density control and sink mobility. Srinivasan and Wu [2008] introduced a novel idea, which is based on the Connected Dominating Set (CDS), to build TRACK for maximizing network lifetime, minimizing buffer-overflow and optimizing the length of the sink trajectory.

For multiple MDCs, Jea et al. [2005] exploited multiple data MULEs in large scale WSNs by dividing an area into equal parts and distributing one data MULE in each part. They also proposed a load balancing algorithm to balance each MULE’s load of data collection on straight trajectories. Ma and Yang [2008] introduced a new data gathering mechanism with mobile collectors for large scale sensor networks, called Single-Hop Data Gathering Problem (SHDGP). They also proposed their heuristic algorithm for the SHDGP by referring Covering Salesman Problem (CSP) in Current et al. [1989] and Arkin et al. [1994], and Minimum Set Cover Problems (MSCP) in Johnson [1974]. Ma et al. [2008] introduced the characteristic distance (d_{char}) for analyzing the optimization of sink velocity by compromising between sink-sensor meeting delay and message delivery delay, which optimizes the delay of message delivery and the energy consumption by increasing the number of mobile sinks with an optimal velocity. Almi'ani et al [2010] proposed two heuristic algorithms: (1) obtaining a solution of TSP and partitioning the resulting tour into smaller ones, (2) constructing the ME path in a greedy fashion based on a certain "cost" function for each node, which is for transit constrained ME Scheduling (MES) problem and outperforms previously proposed solutions.

1.3 Numerical Trajectories

Numerical trajectories are computed by solving radial and angular cost functions with an optimal policy. Vidács et al. [2007] adopted the pursuit problem to a WSN scenario: the pursuer in this case is the mobile sink while the tracked object (sensor node) takes the role of the pursuee. They used the Bellman-Ford algorithm in Bellman [1957] to factorize the cost function into radial and angular function to describe the transmission cost with an optimal policy. Then they reduced the partial differential equation governing the cost function to an ordinary differential equation for angular functions. Finally, they solved the equation as well as the related optimal trajectories numerically.

Note that in this survey, some terms have the same meaning, such as MDC could be ME, mobile sink, mobile base station or data MULE, trajectory could be path, tour, route or cycle, respectively. Meanwhile, dynamic trajectory and multiple trajectories are the same; fixed trajectory and predictable trajectory are the same, too.

2. OVERVIEW OF THE RESEARCH

This chapter surveys the research on the trajectory of MDC for prolonging the lifetime of WSNs. These trajectories can be divided into three groups: dynamic trajectory, predictable trajectory, and numerical trajectory.

2.1 Dynamic trajectories

2.1.1 Multiple MDCs

Using multiple mobile base stations to prolong the lifetime of WSNs was proposed by Gandham et al. [2003]. It balances the energy dissipation of the sensors' neighbour of the base station. That sensors drain their energy faster than other nodes in the network is demonstrated by Heinzelman et al. [2000] through experimental results for a static WSN.

The method proposed by Gandham et al. [2003] uses Integer Linear Program (ILP) to determine new locations for base stations and ensures energy-efficient routing during each round, in which the lifetime is spitted into equal periods of time. Since that sensor nodes which are one-hop away from a base station have been changed by moving base stations to locations where energy dissipation of sensors is balanced.

Azad et al. [2006] considered that the complexity of the optimal ILP solution for multiple mobile base stations by Gandham et al. [2003] is high. Therefore Azad et al. [2006] proposed energy efficient low-complexity algorithms to determine the base station locations. These algorithms includes: 1) Top-K_{max} algorithm, 2) algorithm of maximizing the minimum residual energy (Max-Min-RE), and 3) algorithm of Minimizing the Residual Energy Difference (MinDiff-RE). Since almost every available network's energy is utilized by their approach before network ends and the significant amount of energy is left before the network dies by other algorithms, network lifetimes can be increased in further.

Alsalih et al. [2008] proposed two schemes for routing and placement of MDCs to make sure uniform energy consumption across the network prolongs its lifetime with and without delay constraints in UASNs, the Delay Tolerant Placement and Routing (DTPR) and the Delay Constrained Placement and Routing (DCPR). The lifetime of UASNs is divided into fixed length rounds. At the beginning of each round, data collectors move to new locations which are found by ILP solver.

To reduce the latency when MEs collect data from large sensing fields due to their slow speed, Xing et al. [2008] proposed a rendezvous-base approach in which a subset of nodes serves as the Rendezvous Points (RPs) that buffer data originated from sources and then transfer to MEs when they arrive.

Xing et al. [2008] proposed two algorithms: RP-CP and RP-UG to find a set of RPs that can be visited by MEs within a required delay while the network energy consumed in transmitting data from sources to RPs is minimized. RP-CP finds the optimal RPs when MEs move along the data routing tree while RP-UG finds RPs with good ratios of network energy saving to ME travel distance. They also designed the Rendezvous-based Data Collection (RDC) protocol which facilitates reliable data transfers at RPs.

Year	Author	Title	Contribution
2003	Gandham et al.	Energy efficient schemes for wireless sensor networks with multiple mobile base stations	First introduced the mobile sinks to balance the energy dissipation of all sensors.
2006	Azad et al.	Mobile base stations placement and energy aware routing	Their algorithm can achieve a goal which almost all energy to

		in wireless sensor networks	be utilized.
2008	Alsalih et al.	Placement of multiple mobile data collectors in underwater acoustic sensor network	Their algorithm assures uniform energy consumption across a UASN.
2008	Xing et al.	Rendezvous planning in wireless sensor networks with mobile elements	They introduced RP to reduce the latency for mobility networks.

2.1.2 Single MDC

Gu et al. [2006] considered that the controlling of ME motion leads to the Mobile Element Scheduling (MES) problem, which is defined as the problem of scheduling the visits of a ME to sensor nodes so that there is no data loss even if sensor node buffer overflow. To solve "back-and-forth" movement between far away nodes occurs frequently although the Minimum Weight Sum First algorithm considers both deadlines as well as distances in Somasundara et al. [2004], Gu et al. [2006] proposed a PBS algorithm which tackles the related MES problem by dividing it into two sub-problems: partitioning and scheduling. There are three steps in their PBS: partitioning all nodes into several groups with respect to their data generation rates and locations; then generating node visiting schedules for the ME by minimizing the overhead of moving back and forth across far-away nodes; at last, concatenating scheduling solutions of groups to form the entire ME path so that all nodes can be visited at adequate frequencies for preventing from any buffer overflow.

Considering data loss rates when the speed of ME is below the minimum required level, Ekici et al. [2006] introduced a PBS algorithm that computes periodic trajectories of an ME to avoid sensor data loss at low ME speeds, and the Multi-hop Route to Mobile Element algorithm that extends PBS to deliver urgent messages to MEs within specific delay bounds.

Akkaya et al. [2005] and Vincze et al. [2006] proposed that all sensors report data periodically because the sink will move near the center of the network. Bi et al. [2007] proposed two autonomous moving schemes: one-step moving scheme and multi-step moving scheme. One-step moving scheme is which the mobile sink arrives at the node with highest residual energy in one step and forces it uploads data as much as possible to consume its energy, and multi-step moving scheme is which the mobile sink approaches the node with the highest energy gradually and makes moving decisions according to the information of the neighbour nodes within two hops. A path of ME is constructed by TSP heuristics with seed nodes. There are two schemes to select seed to build the path: fixed-K scheme and adaptive-K scheme.

Hanoun et al. [2008] considered that the route of the mobile collector is crucial to impact the data collection time and the lifetime of WSNs when constructing the mobile collector route dynamically during the network operational time regardless of sensors data generation rates. They reduce the mobile collector route construction to the TSP tour for the set of sensors sleeping and waiting the collection of their buffers by the mobile collector by improving the works of Somasundara et al. [2004] and Ngai et al. [2007]. Their approx-TSP algorithm computes the Minimum Spanning Tree (MST) by the mobile collector and obtains a Hamiltonian cycle as the tour by using Depth First Search (DFS) on the tree.

Considering the WSNs for emergency preparedness application or other delay-sensitive systems, Pazzi and Boukerche [2008] improved the scheme for their work by extending their own idea CPEQ/PEQ in Boukerche et al. [2006]. The PEQ routing protocol uses a sink-based and restricted flooding to configure the initial route and to propagate the first interest subscriptions. Each node has a routing table entry that specifies the destination of data packets in order to reach the sink specified by a field SINK ID. Their algorithm is divided by three steps: cluster configuration, route maintenance and data transmission.

Basing on Basagni et al. [2006] schemes to determine optimal sink routes and sojourn times, which is from the knowledge of global network parameters proposed, Basagni et al. [2008] showed the performance of distributed solutions for controlled sink movements on network lifetime, which is a new MILP including the cost and the mobility rate of sink movement from both data latency and energy consumption. Meanwhile they also introduced the GMRE algorithm that takes crucial parameters, such as the cost of data route release and establishment when the sink moves, sink mobility rates and adapts to different data routing protocols.

To improve the rendezvous multi-hop approach proposed by Xing et al. [2007] and Ma et al. [2008], Zhu et al. [2008] proposed an idea of exploiting multiple paths for ME in WSNs to extend this WSN’s lifetime. Zhu et al. [2009] presented the details of two MPP heuristic schemes where they invoke TS heuristics for an initial partial travel path and update parts, called fixed-K and adaptive-K. The central idea of these schemes is to plan multiple paths and make ME follow them in turn to balance the energy consumption on individual sensor nodes, thus extending the lifetime of WSNs.

Year	Author	Title	Contribution
2006	Gu et al.	Data harvesting with mobile elements in wireless sensor networks	They solved “back-and-forth” movement between far away nodes which occurs frequently
2006	Ekici et al.	Mobility-based communication in wireless sensor networks	Their PBS algorithm can avoid sensor data loss at low ME speeds

2007	Bi et al.	Moving schemes for mobile sinks in wireless sensor networks	They built trajectory through the seed node depending on residual energy of sensors.
2008	Hanoun et al.	Dynamic Route Construction for Mobile Collectors in Wireless Sensor Networks	They applied the MST and DFS to obtain a Hamiltonian cycle as the trajectory of ME.
2008	Pazzi and Boukerche	Mobile data collector strategy for delay-sensitive applications over wireless sensor networks	Their algorithm can be applied in delay-sensitive WSNs
2008	Basagni et al.	Controlled sink mobility for prolonging wireless sensor networks lifetime	Their MILP can handle both data latency and energy consumption
2009	Zhu et al.	Multi-path planning for mobile element to prolong the lifetime of wireless sensor networks	They improved the rendezvous multi-hop approach by multi-paths.

2.2 Fixed trajectories

2.2.1 Multiple MDCs

Kansal, Somasundara and Srivastava [2004] used a robot as a data MULE, which moves in a straight line up and down. Its speed is controlled to help improve data collection from these sensor nodes. One year later, to improve the performance of large scale WSNs, Jea, Somasundara and Srivastava [2005] exploited multiple data MULEs in large scale WSNs by dividing the area into equal parts and distributing one data MULE in each part. Meanwhile for various sensor nodes distribution WSNs (sensor nodes are distributed uniformly and randomly), they proposed a load balancing algorithm to balance each MULE's load of data collection.

Considering the approach, proposed by Jea et al. [2005] that is not flexible for multiple mobile collectors, called data MULEs, traversing the sensing field along parallel straight lines and gathering data from sensors in a large scale, uniformly distributed or randomly distributed WSNs, Ma and Yang [2008] introduced a new data gathering mechanism with mobile collectors for large scale sensor networks, in which MDCs collect data from all sensors through one-hop communications: SHDGP. They formalized the SHDGP into a mixed integer program, proved its NP-hardness, and proposed their heuristic algorithm for the SHDGP referred as CSP by Current et al. [1989] and Arkin et al. [1994], and MSCP in Johnson [1974]. The authors also presented a data gathering method with multiple mobile collectors by extending above algorithm.

Considering that the energy of the rendezvous nodes is still depleted quickly due to their high data transmission activities in the approach proposed by Xing et al. [2008] and Somasundara et al. [2005], Almi'ani et al [2010] defined MEs, scheduling problem, and solve the problem by ILP which can handle larger input instances than previously proposed ILP formulation. They also proposed two heuristic algorithms: (1) obtaining a solution of TSP and partitioning the resulting tour into smaller ones, (2) constructing the ME path in a greedy fashion based on a certain "cost" function for each node, which transits constrained MES problem and outperforms the previously solutions.

Year	Author	Title	Contribution
2005	Jea et al.	Multiple controlled mobile elements (data MULEs) for data collection in sensor networks	Their algorithm balances each MULE’s load of data collection for various distribution WSNs.
2008	Ma and Yang.	Data gathering in wireless sensor networks with mobile collectors	Their trajectories are more flexible to be followed by ME for one-hop data collection.
2010	Almi'ani et al.	Mobile Element Path Planning for Time-Constrained Data Gathering in Wireless Sensor Networks	Their ILP can handle large input instance

2.2.2 Single MDC

Mendis et al. [2006] first applied PSO, introduced by Kennedy and Eberhart [1995] and developed to the numerous versions by Ratnaweera et al. [2004], for the placement of sink and deriving the optimum movement path within a sensor field. Mendis et al. [2006] combined PSO system and SIMSENS into their algorithm, called PSO-SIMSENS algorithm, to achieve efficient energy management and longer lifetime of WSN with maximum field coverage while sink node moves.

Jain et al. [2006] theoretically analyzed the MULE architecture introduced by Shah et al. [2003], which extends the lifetime of the network by minimizing the communication responsibility of the resource-constrained sensors. In their analytical model based on queuing theory, the primary component is a queue of generated data at each sensor and the queue is served for transferring the data whenever a MULE is in a sensor’s range. Jain et al. [2006] proved that the system is stable and the model can express the Data Success Ratio (DSR) and average queuing delay correctly. The energy savings of up to two-order magnitude can be achieved by MULEs when compared to the traditional ad-ho network approach. But the MULE architecture is limited to non real-time applications since it causes more latency for data delivery.

Aioffi et al.[2007] proposed two new method for the organization of WSNs, which integrate density control and sink mobility: 1) SHS, the network is divided into a set of clusters with radius up to *R* (senor node communication range), and mobile sink located at a cluster centroid could communicate with all sensor nodes in the cluster, 2) MHS, the network is divided into several trees with the property that each sensor node in the network is up to *h* hops of the tree root for minimizing the number of trees to reduce the sink tour length. The sink tour is determined by the classical TSP.

Srinivasan and Wu [2008] introduced a novel idea, TRACK—a sink mobility model exploiting the CDS property of a network graph to solve the problem of WSN lifetime longevity and secure data aggregation, based on CDS in their previous work by Dai and Wu [2004]. Their new algorithms build TRACK to maximize network lifetime and M-TRACK to minimize buffer-overflow by optimizing the length of the sink trajectory and trading a slightly large fraction of sensor energy.

To optimize the delay of message delivery and the energy consumption, Ma et al. [2008] combined the rationales in previous approaches, such as Data MULE of Ye et al. [2002] and Two Tier Data Dissemination (TTDD) model of Shah et al. [2003], into their mobile-enabled WSN (mWSN) in Chen et al. [2006] and Ren et al. [2006]. They introduced the characteristic distance (d_{char}) for analyzing the optimization of sink velocity by compromising between sink-sensor meeting delay and message delivery delay. The energy consumption of characteristic d_{char}-based multi-hop clustering is less than the consumption of multi-hop clustering d_{max}.

Year	Author	Title	Contribution
2006	Mendis et al.	Optimized sink node path using particle swarm optimization	They applied PSO to achieve efficient energy management and longer lifetime
2006	Jain et al.	Exploiting mobility for energy efficient data collection in wireless sensor networks	Their analytical model based on queuing theory is a good tool for analyzing MULE architecture in WSNs.
2007	Aioffi et al.	Optimization issues and algorithms for wireless sensor networks with mobile sink	Their algorithms extend the lifetime by considering density control and sink mobility.
2008	Srinivasan and Wu	A Novel Connected Dominating Set Based Sink Mobility Model for WSNs	They adopted CDS to solve the problem of WSN lifetime longevity and secure data aggregation

2008	Ma et al.	mWSN for large scale mobile sensing	They introduced the characteristic distance (d_{char}) for analyzing the optimization of sink velocity

2.3 Numerical trajectories

Vidács et al. [2007] translated the pursuit problem into a WSN problem: the pursuer in this case is the mobile sink while the tracked object (sensor node) takes the role of the pursuee. They used the Bellman-Ford algorithm in Bellman [1957] to factorize the cost function into radial and angular function to describe the transmission cost with an optimal policy. Then they reduced the partial differential equation governing the cost function to an ordinary differential equation for the angular functions. Finally, they solved the equation as well as the related optimal trajectories numerically. The energy of radio transmission obeys the well-known power-law $\rho^{-\alpha}$ as a function of the distance ρ between the mobile sink and sensor nodes.

Year	Author	Title	Contribution
2007	Vidács et al.	Minimum Transmission Energy Trajectories for a Linear Pursuit Problem	They translated the pursuit problem into a WSN problem.

3. DETAILED DISCUSSION OF THE RESEARCH

3.1 Dynamic trajectories

3.1.1 Multiple MDCs

Gandham[2003]: Energy efficient schemes for wireless sensor networks with multiple mobile base stations.

The authors state that conservation of the energy available at each sensor node is one of the main design issues for a sensor network, i.e. prolonging the lifetime of sensor network is crucial.

The authors state that Heinzelman et al. [2000] demonstrated through experimental results that the sensor nodes which are one-hop away from a base station drain their energy faster than other nodes in the network, since they not only send their own data but also forward data for other nodes which cannot reach the base station immediately.

The authors state that the shortcoming of previous work only focus on static WSN.

The authors propose to use multiple mobile base stations to prolong the lifetime of WSNs. Their method use ILP to determine new locations for the base stations and a flow-based routing protocol to ensure energy efficient routing during each round, which the lifetime is spitted into an equal periods of time.

The authors claim that there are two sets of simulations to compare their solutions: 1) they assess the impact of the number of base stations on the lifetime of the sensor network by increasing number of base stations; 2) they study the impact of the transmission range on network lifetime by increasing the transmission range of the sensor nodes.

The authors state that the lifetime increases with the number of base stations until every sensor node one hop away from a feasible site and further increasing the number of base stations does not increase the lifetime. They also state that increasing transmission rang from some value extends the lifetime up to a maximum, after the maximum value the lifetime decreases with transmission range further increasing.

The authors claim that their approach to optimize energy utilization leads to a significant increase in the lifetime of WSN. And they also claim that the time for computing near-optimal solutions is a reasonable time for the network sizes around hundred.

Azad[2006]: Mobile base stations placement and energy aware routing in wireless sensor networks.

The authors state that increasing network lifetime is important in wireless sensor/ad-hoc networks. They deploy multiple mobile base stations and develop algorithms by dynamically choosing the locations of these base stations for increasing network lifetime and amount of data delivery in the sensor network field.

The authors state that Gandham et al. [2003] formulated the base station placement problem and optimized the base station locations by ILP solution for multiple mobile base stations.

The authors state that the shortcoming of their previous work is that the complexity of the ILP solution is high.

The authors propose energy efficient low-complexity algorithms to determine the base station locations including: 1) Top-K_{max} algorithm, 2) maximizing the minimum residual energy (Max-Min-RE) algorithm, and 3) MinDiff-RE algorithm.

The authors present a formal analysis of their algorithm: the complexity of Top-K_{max} is linear in n (O(n)), the complexity of Max-Min-RE is $O(n^2)$, and MinDiff-RE is $O(n^2)$.

The authors claim that they conduct the six different simulations and evaluated their relative performance in terms of network lifetime and amount of data delivered during the network lifetime.

The authors claim that 1) all the three proposed algorithms utilize almost all the available network energy before network ends while the significant amount of energy is left before the network dies for other algorithms, 2) Top-K_{max} algorithm delivers much less number of packets than Max-Min-RE and MinDiff-RE, 3) Max-Min-RE and MinDiff-RE perform well in terms of network lifetime and amount of data delivered, but have higher complexity than Top-K_{max} and less than ILP solution.

The authors claim that their algorithms provide increased network lifetimes and amount of data delivered during the network lifetime compared to single base station scenario as well as multiple static base stations scenario. They also claim that the use of energy aware routing along with multiple base stations resulted in further enhancement in network lifetime.

Alsalih[2008]: Placement of multiple mobile data collectors in underwater acoustic sensor networks.

The authors state that prolonging the lifetime of UASNs is crucial for UASNs to deliver their full potential and to enable variety of fundamental applications because the energy supply of sensor nodes is limited by battery-operating. They also state that data collector mobility makes uniform energy consumption across the network to prolong its lifetime with and without delay constraints.

The authors state that Gandham et al.[2003], Azad et al. [2006] and Jain et al. proposed promising mobility planning schemes to routing the MDCs for prolonging the lifetime of terrestrial sensor networks.

The authors state that the shortcoming of previous schemes is that they only locate the data collectors at predefined spots in the sensing field or ate the boundary of the network. Those constraints do not apply to UASNs where data collectors are free to go virtually anywhere on the surface of the ocean.

The authors propose two schemes for routing and placement of MDCs in UASNs: the DTPR and the DCPR. They divide the lifetime of UASNs into fixed length rounds and move the data collectors to new locations at the beginning of each round. Both schemes are formulated as ILPs and an ILP solver is used to find the optimal placement of data collectors with the multi-hop routing paths to deliver data from underwater sensors to data collectors.

In their two schemes, authors use their heuristics to find Maximal Overlapping Regions for obtaining P, set of points, from each MOR, then to formulate ILP for the DTPR and DCPR to find the optimal locations of MDCs and the routing paths from sensor nodes to data collectors. Their heuristics to find MORs runs in $O(n^2 log\ n)$.

The authors claim that there are two sets of experiments to study quality of their schemes: 1) they compared the DTPR scheme with a static scheme in which data collectors are stationary, and with a mobile scheme that ignores the residual energy of different sensor nodes, 2) they compared the DCPR scheme with the DTPR scheme to show the performance with a delay constraint.

The authors state that the DTPR has a much longer lifetime than fixed scheme and Minimize the Maximum (MM). And they also state that the DTPR has longer lifetime and longer delay.

The authors claim that their work is a pioneering effort in the placement of MDCs in three-dimensional UASNs. Furthermore, they claim that their DCPR has a slightly shorter lifetime then their DTPR scheme, and it can be used to solve the problem of prolonging the lifetime with a delay-based Quality of Service guarantees.

Xing[2008]: Planning in wireless sensor networks with mobile elements.

The authors state that the low movement speed of MDC hinders the use under stringent delay constraints for saving energy in WSNs to prolong the lifetime of WSNs. In this paper, the authors propose a rendezvous-base approach in which a subset of nodes serves as RPs that buffer data originated from sources ad transfer to MEs when they arrive.

The authors state that several heuristics schedule the movement of MEs to visit the source sensor nodes before their buffer overflow. Gu et al. [2006] and Somasundara et al. [2007] proposed the approach to minimize the network energy consumption by avoiding multi-hop wireless transmissions.

The shortcoming of such approach is that incurs high latency when MEs collect data from large sensing fields due to their slow speed.

The authors propose two algorithms: RP-CP and RP-UG to find a set of RPs that can be visited by MEs within a required delay while the network energy consumed in transmitting data from sources to RPs is minimized. RP-CP finds the optimal RPs when MEs move along the data routing tree while RP-UG finds RPs with good ratios of network energy saving to ME travel distance. They also design the RDC protocol which facilitates reliable data transfers at RPs.

Since RP-CP is optimal when the ME is only to move along the routing tree, the path of ME is twice of the total length of edges on the tree. The time complexity of RP-CP is O(|E| log |E|). By using TSP(I) to compute the minimum length of a tour that visits all points in set I, the time complexity of RP-UG is $O((L_T/L_0)^2\ C(TSP))$,where *C(TSP)* is the complexity of the TSP(I) procedure.

In this paper, the authors constructed three sets of simulations: (1) for a single ME in the network and all sources have the same data delivery deadline, (2) for multi ME in the network and all sources have the same data delivery deadline, (3) for multi ME in the network and different sources have difference delivery deadlines.

The authors state that the average deadline miss ratio of all data packets is below 3%. Since deadline misses are caused by the packets that are dropped due to lost links, deadline misses are higher when the speed of MEs experiences significant variance.

The authors claim that their approaches significantly reduces network energy consumption and scale well with network density, ME speed, and the number of different deadlines. Moreover, RDC is robust to significant variance of ME speed.

3.1.2 Single MDC

Gu[2006]: Data harvesting with mobile elements in wireless sensor networks.

The authors state that using mobile collectors is an effective way of prolonging sensor network lifetime and relaying information in partitioned networks, but as the data generation rates of sensors vary some sensors need to be visited more frequently than others. The authors also state that controlling the ME motion leads to the MES problem, which is defined as the problem of scheduling the visits of a ME to sensor nodes so that there is no data loss due to sensor node buffer overflow.

The authors state that the MES problem in WSNs has been proved to be NP-complete and three heuristic algorithms, Earliest Deadline First (EDF), EDF with k-look-ahead and MWSF algorithm are presented in Somasundara et al. [2004].

The authors state that the shortcoming of their previous work is that “back-and-forth” movement between far away nodes occurs frequently although the MWSF solution considers both deadlines as well as distances.

The authors propose a PBS algorithm which tackles the related MES problem by dividing it into two sub-problems: partitioning and scheduling. There are three steps in their PBS algorithm: Step 1 partitions all nodes into several groups with respect to their data generation rates and locations, Step 2 generates node visiting schedules for the ME by minimizing the overhead of moving back and forth across far-away nodes, Step 3 concatenates the scheduling solutions of the groups to form the entire ME path so that all nodes can be visited at adequate frequencies for preventing any buffer overflow.

The authors present a formal time complexity analysis of their PBS algorithm. And they state that their algorithm has an overall time complexity of $O(N^2 + 4^M)$, where N is the number of sensor nodes and M is the number of sub-bin by partitioning.

The authors claim to have constructed six sets of simulations for PBS performance evaluation compared to the MWSF algorithm: 1) to observe the data loss rate as a function of the ME speed, 2) to observe the effect of the node density on the minimum required ME speed to prevent data loss, 3) to evaluate the effect of number of bins for different network sizes and properties, 4) to observe the impact of sensor buffer size in sensor nodes, 5) to analyze the effect of wireless transmission rate between sensor nodes and ME on the data loss rates, 6) to study sensor visit predictability as a function of overflow time and node density through inspection of the standard deviation of inter-visit times.

The authors state that their results can be summarized as follows: their PBS algorithm provides higher performance in terms of decreasing loss rate, reducing the minimum required speed, and providing high predictability by comparing to MWSF algorithm.

The authors claim that their PBS performs well in terms of both metrics as well as providing high predictability in nodes inter-visit schedule. They also claim that the resulting schedules and paths are usually shorter, which reduces the minimum required speed of the ME to prevent buffer overflow.

Ekici[2006]: Mobility-based communication in wireless sensor networks.

The authors state that maintaining connectivity and maximizing the network lifetime stand out as critical considerations during the design of WSNs and protocols, and mobile platforms equipped with communication devices can be leveraged to overcome these two problems. They summarize existing proposals using mobility in WSNs and introduce two new approaches to compute mobile platform trajectories.

The authors state that Somasundara et al [2004] proposed the MES, in which an MDC is scheduled in real time to visit sensors such that no sensor buffer overflow occurs.

The authors state that the shortcoming of previous approaches is that the minimizing the ME speed was not considered in MES, neither minimizing data loss rates when the ME speed is below the minimum required level.

The authors introduce a PBS algorithm that computes periodic trajectories of an ME to avoid sensor data loss at low ME speeds, and the Multihop Route to Mobile Element (MRME) algorithm that extends PBS to deliver urgent messages to MEs within specific delay bounds.

The authors do not analysis the complexity of their PBS and MRME algorithms in this work.

The authors claim that there are two sets of simulations to study the performance of their new approaches: 1) they compared the data loss rates of the PBS algorithm with the MWSF solution; 2) they compared the performance of the MRME algorithm with the PBS and MWSF.

The authors state that the minimum required ME speed is consistently lower for PBS solutions than for the MWSF solution and that the data loss rates are significantly smaller for PBS when the ME is constrained to move at slower speeds. Furthermore, they state that MRME guarantees lossless delivery of urgent messages for much smaller speeds than PBS and MWSF while providing guaranteed collection of regularly generated data at the same time.

The authors claim that mobility-based communication can prolong the lifetime of WSNs and increase the connectivity of sensor nodes and clusters. They also claim that their new approach is well suited to compute the mobile device trajectories in sparse WSNs where data generation rates of sensors are known.

Bi[2007]: Moving schemes for mobile sinks in wireless sensor networks.

The authors state that a sinks mobility can reduce hotspots in static WSNs and balance energy consumption among sensor nodes to extend the lifetime of WSNs. By investigating the moving schemes of the single mobile sink in a WSN, they propose two autonomous moving schemes: a one-step moving scheme and a multi-step moving scheme, to alleviate the hotspot problem and prolong network lifetime.

The authors state that several researchers have studied autonomous moving strategies for mobile collectors. Akkaya et al. [2005] proposed a heuristic algorithm to determine the moving directions, such as moving toward the nodes which generate the most number of data packets. Vincze et al. [2006] proposed two strategies to move a sink adaptively to react to dynamics events that follow a correlated random walk mobility model.

The authors state that a shortcoming of the previous approaches is that they are not applicable to where all sensors report data periodically because the sink will move near the center of the network.

The authors introduce, what they claim to be, a novel idea, of their proactive algorithms aimed at data-collecting applications. In their schemes, a mobile sink moves once in each data-collecting period to balance energy consumption among sensor nodes. They propose two moving schemes: a one-step moving scheme in which the mobile sink arrives at the node with highest residual energy in one step and forces it to upload data as much as possible to consume its energy, and a multi-step moving scheme in which the mobile sink approaches the node with the highest energy gradually and makes moving decisions according to the information of the neighbour nodes within two hops.

The authors construct a path of ME using TSP heuristics with seed nodes. There are two schemes to select seed to build the path: fixed-K scheme and adaptive-K scheme. The complicity of their algorithm is corresponding TSP heuristics since the selection of seed nodes is in O(n) for both schemes.

In this paper, the authors describe four sets of experiments: first, one to check network lifetime performance with different initial energy for each sensor node, second to test network lifetimes with different node deployments, third to investigate the lifetime when node density changed, last one to study the lifetime performance with different transmission power settings, for four schemes: one-step scheme, multi-step scheme, random scheme where a mobile sink moves randomly within the network area, and convention scheme where a stationary sink locates at the network center.

The authors claim that their schemes prolong network lifetime and achieve stable performance under different topologies. They also claim that the advantage of sink mobility may be overwhelmed by the cost of maintaining valid data-forwarding paths to the mobile sink.

The authors claim that their moving schemes can extend the lifetime of WSNs significantly.

Hanoun[2008]: Dynamic Route Construction for Mobile Collectors in Wireless Sensor Networks.

The authors state that MDCs have been adapted to extend the sensor networks lifetime. The route of the mobile collector is crucial to impact data collection time and the lifetime of WSNs. In this paper, the authors refer to the works of Somasundara et al. [2004] and Ngai et al. [2007], and indicate that their paper is an improvement compared to these previous works. All these papers (include the authors' paper) present a practically efficient algorithm for constructing the mobile collector route dynamically during the network operational time regardless of the sensors data generation rates.

The authors state that many studies propose MEs for collecting data in WSNs. Kansal et al. [2004] proposed a predesigned route for the ME. But it lacks flexibility and scalability required for redesigning the route when network conditions change. Somasundara et al. [2004] and Ngai et al. [2007] proposed an approach of building the mobile collector path according to the network operational parameters.

The authors state that a shortcoming of the previous approaches is that computing the sensor next overflow deadline depends on knowing in advance its buffer size and sensing rate, and it works offline.

The authors state that reducing the mobile collector route construction to the TSP tour for the set of sensors sleeping and waiting the collection of their buffers by the mobile collector. Their approx-TSP algorithm computes the MST by the mobile collector and obtains a Hamiltonian cycle as the tour by using DFS on the tree.

The complexity of their algorithm is upper bounded by the complexity of finding the MST in $O(n^2)$ since obtaining Hamiltonian cycle is in $O(n)$ and the DFS is in $O(n)$ too.

In this paper, the authors described two sets of experiments: the first set was to test the impact of the node density on their algorithm; the second set was to test the effect t of the mobile collector speed and number on the network performance.

The authors claim that their algorithm is more effective in reducing the sensors sleeping time and the data collection time. And the speed required for minimizing the number of sleeping sensors is less for their algorithm since the length of the route constructed is optimized to produce lower travelling time. They also claim that the number of mobile collectors is less than the number required for the nearest neighbour heuristic.

The authors claim that their algorithm provides higher performance in terms of decreasing the sensors sleeping time and the distance travelled by the mobile collector. They also claim that they demonstrated a positive effect of the speed and number of mobile collectors on reducing the average number of sleeping sensors.

Pazzi[2008]: Mobile data collector strategy for delay-sensitive applications over wireless sensor networks.

The authors state that most routing solutions for WSN utilize static sinks to collect data from the entire network, and that the solutions result in high traffic load in the adjacent sink nodes, which will consume more energy and face high congestion in a large scale network. They propose an approach to alleviate the high traffic load resulting bottleneck in a sink's vicinity by using MDCs.

The authors state that their scheme is similar to the second protocol in Kinalis et al. [2007] and indicate that they improve the scheme for their work by extending their own idea CPEQ/PEQ in Boukerche et al. [2006]. The PEQ routing protocol uses a sink-based restricted flooding to configure the initial route and to propagate the first interest subscriptions, and each node has a routing table entry that specifies the destination of the data packets in order to reach the sink specified by the field SINK ID.

The authors do not mention the shortcomings of previous work on the PEQ protocol. But it is only used for a static sink.

In their approach, the authors propose the MDC/PEQ protocol solution by justifying the use of a group-based random mobility model, Bounded Random Mobility Model (BRMM). Their algorithm is divided by three steps: Step 1 is cluster configuration, Step 2 is route maintenance and handoff, Step 3 is data transmission.

The authors describe two parts of the implementation of their MDC/PEQ protocol and an extensive set of NS-2 simulations: 1) the performance of their scheme over the simulation time, 2) the scalability of MDC/PEQ by varying the number of MDSs and their speed, 3) the number of route changes per round(BEACON) for MDC/PEQ protocol.

The authors state that the performance of the packet delivery ratio is improved from 86% to above 90%, and the performance in energy savings is slightly better. They also have the results: increasing the number of MDCs shows a positive impact on the delivery ratio, but increasing the speed of MDCs is a negative impact for the energy consumption because higher speed induces more route changes per BEACON and the route changes cause more messages in order to reconfigure the routes.

The authors claim that the introduction of MDCs in WSNs reduces the bottleneck at the nodes closer to the sink and almost halves packet delivery delay, and their MDC/PEQ scheme will work well for emergency preparedness application or other delay-sensitive systems.

Basagni[2008]: Controlled sink mobility for prolonging wireless sensor networks lifetime.

The authors state that using controlled mobility in WSNs are increases their lifetime. They combined their two previous works, Basagni et al. [2006], to show the performance of distributed solutions for controlled sink movements on network lifetime.

The authors state that in recent years, several protocols have been proposed that show the improvements for extending lifetime of WSNs by controlled sink mobility. The authors state that Gandham et al. [2003] proposed an ILP model to identify the location s of multiple sinks and the routes from in which time is divided into rounds and information of sensor's residual energy is centrally obtain at the beginning of each round. They refer to Luo et al. [2005] who formulated max-lifetime as a min-max problem by considering together sink mobility and data routing to obtain a load balancing solution. The authors also refer to Papadimitriou et al. [2005] and Wang et al. [2005] presented centralized LP solution to determine the sink sojourn times at the given sites route the packets to the current position of the sink which moves in grid.

The authors state that the shortcoming of previous approaches is that they centralized, that is, the proposed schemes determine optimal sink routes and sojourn times based on the knowledge of global network parameters. They consider that centralized solutions are unbearably time and energy consuming for most WSNs applications. The authors also state that the shortcoming of previous approaches is that they did not include the cost and the mobility rates of sink movement.

The authors present a new MILP including the cost and the mobility rate of sink movement from both points of view data latency and energy consumption. They also introduce the GMRE algorithm that takes crucial parameters, such as the cost of data route release and establishment when the sink moves, sink mobility rates and adapts to different data routing protocols.

The authors claim to have constructed three sets of experiments thorough NS2-based simulation: 1) they demonstrated the bare effectiveness of the proposed MILP and heuristic solutions for prolonging network lifetime with respect to the static case, 2) they quantified the impact of key protocol parameters on OPT (Optimum route derived by MILP), GMRE and RM (Random Movement heuristic) performance, 3) they assessed nodes deployment, data routing, and the freedom of movement of sink.

The authors state that moving the sink always increases network lifetime, controlling the mobility of the sink leads to remarkable improvements, which are as high as six fold compared to having the sink statically placed, and as high as twofold compared to uncontrolled mobility.

The authors claim that they demonstrated mobility is the key for improving network lifetime, whether controlled or not. What is more, they state that controlled mobility is effective to improve lifetime up to 6 times than when the sink is static. Furthermore, they claim that their GMRE algorithm is the first completely distributed and localized solution for sink mobility in WSNs.

Zhu[2009]: Multi-path planning for mobile element to prolong the lifetime of wireless sensor networks.

The authors state that developing energy efficient data collection schemes is ultimately important to reduce the energy consumption on individual sensor nodes, and thus extending the lifetime of WSNs since sensor nodes are generally battery powered and it is hard to replace their batteries. They also state that introducing MEs in WSNs is a good way for energy efficient data collection.

The authors state that Xing et al. [2007] and Ma et al. [2008] proposed that the rendezvous multi-hop schemes aggregate data locally and then the ME visits the RPs to pick up the data.

The authors state that the shortcoming of previous works is that since the researchers focused on only single tour for each mobile, the solution may still lead to uneven energy depletion rates for the sensor nodes in WSNs, especially for the cases where the ME needs to collect data directly from every sensor node but it cannot visit the location of all sensor nodes.

The authors state that they have proposed the idea of exploiting multiple paths for the ME in WSNs to extend the WSN's lifetime in their previous work, Zhu et al. [2008]. They also state that they present the details of the two MPP heuristic schemes, called fixed-K and adaptive-K. The central idea of these schemes is to plan multiple paths and have the ME follow them in turn to balance the energy consumption on individual sensor nodes, thus extending the lifetime of WSNs.

In their MPP heuristics algorithms, they invoke TS heuristics for an initial partial travel path and update parts have, therefore the complexity of the algorithms depend on the TSP heuristics.

The authors claim that they produce two set of simulations to examine the performance of their MPP heuristic schemes: 1) the performance of MPP versus the number of paths K to be planned, 2) the performance of MPP versus the path length limit.

The authors claim that their multi-path approaches can extend the life-time of WSNs by up to four times. They also claim that their adaptive–K scheme treats the sensor nodes more fairly with less variation on their energy consumptions.

3.2 Fixed trajectories

3.2.1 Multiple MDCs

Jea[2005]: Multiple controlled mobile elements (data MULEs) for data collection in sensor networks.

The authors state that the problem of energy-efficiency is very important for large scale WSNs since the sensors are battery-constrained in most cases. And they also state that using MEs to collect and carry data mechanically has many advantages over static multi-hop routing.

The authors claim that they already have implemented employing a single ME for WSNs data collection in Kansal et al. [2004], where a robot as the data MULE moves in a straight line up and down and its speed is controlled to help improve data collection from these sensor nodes.

The authors state that the shortcoming of previous work is that the single data MULE approach does not scale well, that is, the network scalability and traffic leads a single ME insufficient.

The authors refer to their previous work and indicate that their paper is an improvement on the single ME approach. They exploit multiple data MULEs for large scale WSNs (sensor nodes are distributed uniformly and randomly) by dividing the area into equal parts and having one data MULE in each. For various distribution WSNs, they propose a load balancing algorithm to balance each MULE's load of data collection.

The authors present a complexity analysis of their load balancing algorithm. And they state that their algorithm has complexity $O(n^2)$.

The authors claim that they consider three schemes to simulate mobility for sharing the shareable load between data MULEs:1) First Come First Serve (FCFS), 2) Equal Sharing, 3) Load Balancing.

The authors state that the results of their simulations show that Load Balancing approach leads to more uniformity, that is, a minor variation compared to FCFS and Equal Sharing

The authors claim that multiple MEs should be used to improve the performance of large scale and various sensor nodes distribution WSNs, the load balancing algorithm is beneficial of each MEs services and whole networks.

Ma[2008]: Data gathering in wireless sensor networks with mobile collectors.

The authors state that the data gathering scheme is the most important factor that determines the lifetime of WSNs and MDC can gather data packets directly from sensor nodes without relay and collision to prolong the lifetime of sensors.

The authors state that recently several researchers exploit MDCs for data gathering strategies to extend the lifetime of WSNs. They state that Jea et al. [2005] employed multiple mobile collectors, called data MULEs, traversing the sensing field along parallel straight lines and gathering data from sensors in a large scale, uniformly distributed or randomly distributed WSNs.

The authors state that the shortcoming of previous work is that the straight tour of MDCs might be not always allowed for some applications, and the performance and cost of the mobility scheme depends on the number of data MULEs and the distribution of sensors.

The authors claim that they introduce a new data gathering mechanism with mobile collectors for large scale sensor networks, in which the MDCs will collect data from all sensors through one-hop communications: SHDGP. They formalize the SHDGP into a mixed integer program and prove its NP-hardness, and propose their heuristic algorithm for the SHDGP by referring CSP in Current et al. [1989] and Arkin et al. [1994], and MSCP in Johnson [1974]. The authors also present the data gathering with multiple mobile collectors by extending above algorithm.

The authors present a complexity analysis of their SHDGP algorithm. And they state that their algorithm has complexity $O(m^2 + nm)$, where m is the number of candidate polling points and n is the number of sensor nodes. They also state that the extending algorithm has the same complexity $O(m^2 + nm)$ obviously since the number of mobile collectors is less than sensor nodes.

The authors claim that they produced three sets of simulations to validate their algorithms: 1) to study the tour length by varying transmission range and number of sensors, 2) to study the network lifetime by comparing to static sink and straight line tour, 3) to study data gathering with multiple mobile collectors.

The authors state that the results of their simulations show that for a fixed sensing field, the higher deployment density and the longer transmission range lead to shorter moving distance of mobile collector and their solution is very close to the optimal solution. They also state that the mobile collector moving along the tour obtained by their algorithm prolong the lifetime significantly.

The authors claim that their single-hop data gathering scheme improves the scalability and solves intrinsic problems of large scale homogeneous networks. They also claim that their greedy algorithm greatly reduces the tour length of mobile collectors and the results are very close to the optimal algorithm in small networks. Furthermore, they claim that their data gathering mechanism prolong the network lifetime significantly.

Almi'ani[2010]: Mobile Element Path Planning for Time-Constrained Data Gathering in Wireless Sensor Networks.

The authors state that path planning is a basic problem. Planning the path of the MEs, as described by the authors, can improve the energy consumption and prolong its lifetime. In this paper, the authors tackle the problem that planning process will be complicated because of the variant transit time between different sensors.

The authors state that in recent years, many approaches have been proposed to solve this problem: how to handle the path planning problem when sensors have different transit time. Xing et al.[2008] and Somasundara et al. [2005] proposed a method of using multiple MEs and partitioning the network among them. What's more, Almi'ani et al. [2008] and Xing et al. [2008] proposed an alternative way of combining data gathering by MEs with wireless multi-hop forwarding. The shortcoming of such approach is that the energy for the rendezvous nodes will still be quickly depleted due to their high data transmission activities, thus limiting the lifetime of WSNs.

The authors define the MEs, visiting all nodes and passing the base station, scheduling problem and present an ILP formulation. Further, they also discuss two heuristic algorithms: (1) their algorithm is base on obtaining a solution of (TSP) and partitioning the resulting tour into smaller ones, (2) constructs the ME path in a greedy fashion based on a certain "cost" function for each node.

In their ILP formulation, the authors defined $O(n^2)$ variables and $O(n^2)$ constraints which can solve instances of up to 150 vertices by using the CPLEX/AMPL solver. They announced that the optimal solution is not computationally practical for larger network instances. On the other hand, their first heuristic approach, “tour cutting”, cuts segments from large tours to form smaller ones for all

In this paper, the authors constructed two sets of experiments: they compared their heuristic algorithms and ILP approach in small-scale size of networks, and they compared their heuristic algorithms with previous well-known heuristics algorithms for VRPTW problem in large size of the network.

The authors state that they their results can be summarized as follows: their heuristic results are close to the optimal results of their ILP approach in small nodes networks and better than all other heuristic algorithms in large nodes networks.

The authors claim that their heuristic solution for transit constrained MES problem outperforms the previously proposed solutions. They also claim that their ILP can hand larger input instances than previously proposed ILP formulation.

3.2.2 Single MDC

Mendis[2006]: Optimized sink node path using particle swarm optimization.

The authors state that the performance of WSN depends on the behaviour of the sink node and its location. And they also state that an optimized sink node path will be efficient and economical for operation of the network.

The authors state that Kennedy and Eberhart [1995] first introduced PSO and Ratnaweera et al. [2004] developed the numerous versions of PSO as time varying acceleration coefficients.

The authors state that the shortcoming of previous work about PSO is that it is only used for static networks, that is, the sink is non mobile and fixed in the centre.

The authors claim that they apply PSO for the placement of sink and derive the optimum movement path within the sensor field. Their algorithm, called PSO-SIMSENS algorithm, is combined from PSO system and SIMSENS.

In their algorithm, the authors compute the sink-node-path points by using PSO with fitness function in O(1) since the angular is selected finitely and independently. Therefore, their algorithm complexity depends on PSO.

The authors claim that there are three sets of simulations to study the performance of their algorithm: 1) original benchmark simulations, 2) PSO-SIMSENS benchmark simulation, 3) sink movement simulation.

The authors state that their approach achieves efficient performance of WSN with maximum field coverage while sink node is mobile.

The authors claim that their new sink placement technique has a great value to deal with proper placement of sensor nodes to get the best data from an event, and fast and efficient placement strategy is required for efficient energy management and longer lifetime for the networks.

Jain[2006]: Exploiting mobility for energy efficient data collection in wireless sensor networks.

The authors state that main constraint is the energy budget of the sensors which is limited due to their size and cost for data collection in sparse sensor networks. They also state that their analytical model in the MULE architecture concerns the key performance metrics such as data transfer, latency to the destination, and power.

The authors state that Chatzigiannakis et al. [2001] and Grossglauser et al. [2002] focused on no immediate end-to-end path between two nodes that wish to communicate because of limited radio range. The authors also state that Shah et al. [2003] introduced the MULE architecture along with simple analytical model.

The authors state that the shortcoming of their previous work is that they did not address sensor duty cycle, ratio range, capacity and only on mobility model (random-walk).

The authors present and theoretically analyzed the MULE architecture which extends the lifetime of the network by minimizing the communication responsibility of the resource-constrained sensors. In their analytical model based on queuing theory, they consider different MULE mobility models and radio characteristic.

In their analytical model, the primary component is a queue of generated data at each sensor and the queue is served for transferring the data whenever a MULE is in a sensor’s range. The authors prove that the system is stable and their model can express the DSR and average queuing delay correctly.

The authors claim that they consider four mobility models: random waypoint, random walk, deterministic arrivals (fixed route and velocity), and Poisson arrivals. And they also compare energy consumption between the MULE architecture and ad-hoc networks.

The authors claim that 1) the performance results determined using analysis were close to results of detailed simulation in 5%, 2) the Poisson arrivals and random waypoint were almost same and similar to deterministic arrivals, 3) the MULE architecture is much longer than the ad-hoc network, 4) latency in MULE network is much more than in ad-hoc network.

The authors claim that through their theoretical analysis, energy savings of up to two-orders magnitude can be achieved with MULEs as compared to eh traditional ad-ho network approach, but the MULE architecture is limited to non real time applications since it cause more latency for data delivery.

Aioffi[2007]: Optimization issues and algorithms for wireless sensor networks with mobile sink.

The authors state that the main aim in the different research area of WSNs is to prolong the network lifetime since to charge or to exchange the sensor nodes' batteries is an impossible and unfeasible activity in the operational environment. They present algorithms to extend the lifetime by considering density control and sink mobility.

The authors state that Jea et al. [2005] employed a controlled sink to collecting data for improving the WSNs lifetime, and Siqueira et al. [2006] proposed a cross-layer design to integrate the OGDC density control with a tree routing protocol for managing the WSN redundancy keeping active only a minimum set of sensor nodes at a certain time.

The authors state that the shortcoming of the previous work is that the motion control is reduced to define the sink speed, that is, only the speed of motion control is considered, since the sink trajectory is a fixed straight line.

The authors propose two new methods for the organization of WSNs, which integrate density control and sink mobility: 1) SHS, the network is divided into a set of clusters with radius up to *R* (senor node communication range), and mobile sink located at a cluster centroid could communicate with all sensor nodes in the cluster, 2) MHS, the network is divided into several trees with the property that each sensor node in the network is up to *h* hops of the tree root for minimizing the number of trees to reduces the sink tour length. The sink tour is determined by the classical TSP in Dantzig et al. [1954] for both methods.

In their SHS, the greedy algorithm is based in the MST method to construct clusters, the complexity of SHS is $O(n^2)$ since there are two loops to divide the network in a set of clusters.

And in their MHS, the trees are built by solving the optimization problem (set cover problem), the complexity of MHS is $O(n^2)$ since MHS have to initial a $n \times n$ matrix to represent connection of sensor nodes. The final complexity is depending on above complexity and the TSP complexity.

The authors claim that they conduct three sets of simulation to compare their algorithm SHS and MHS with RT (implement that tree routing algorithm in Siqueira et al. [2006]) on the performances of 1) the network delay, 2) the network reliability, and 3) the network coverage.

The authors state that RT has the greater advantage than SHS and MHS in delay metric, but SHS and MHS are the better scalability than RT. About the network lifetime, they state that SHS method decreases the performance as the network size grows, and the MHS is 60% better than RT algorithm in average. About the network coverage, they claim that their methods improve significantly the network coverage, over 80%.

The authors claim that their methods improve on extending WSN lifetime and its message delay is acceptable for a large number of WSN applications. Furthermore, they claim that their methods improve on the network coverage for a period larger than methods using data forwarding and increase the WSN operation time up to 2 times for 80% of coverage.

Srinivasan[2008]: TRACK: A Novel Connected Dominating Set Based Sink Mobility Model for WSNs.

The authors state that the core functionality of a WSN is to detect deviations in expected normal behaviour and report it to the sink and prolonging WSN lifetime is important for WSN.

The authors refer to the CDS in Dai and Wu [2004]'s work and indicate that they use the CDS as basis for their work.

The authors don't mention the shortcoming of their previous work.

The authors introduce, what they claim to be the novel idea, TRACK—a sink mobility model exploiting the CDS property of a network graph to solve the problem of WSN lifetime longevity and secure data aggregation. They also present algorithms for the construction of TRACK to maximize network lifetime and M-TRACK to minimize buffer-overflow by optimizing the path-length of the sink trajectory by trading a slightly large fraction of sensor energy.

In their TRACK, Step 1 is to initialize the edge pool in $O(V^2)$, where V is number of sensor nodes, Step 2 is to compute the CDS on the given network graph by applying Rule-k in O(E), where E is number of edges in the edge pool, Step 3 is to compute MST from CDS edges in O(E), Step 4 is to build Hamiltonian Circuit (HC) of the CDS-MSK, which is the trajectory of the sink along. Therefore, the complexity of their algorithm to build the TRACK is $O(V^2)$.

The authors claim to have constructed two sets of simulation: 1) they studied the impact of different parameters on size of the CDS; 2) they studied the impact of density on CDS size by fixing the transmission range.

The authors state that their TRACK and M-TRACK outperform a WSN with static sink(s). Furthermore, they claim that their models can improve the network lifetime up to seven times that which is achieved in a network with a static sink.

The authors claim that their TRACK is a novel sink mobility model based on the Connected Dominating Set (CDS) property of a network graph. They also claim that their two models are valid.

Ma[2008]: mWSN for large scale mobile sensing.

The authors state that an unbalanced energy dissipation pattern is inevitable since non-uniform traffic pattern leads to increased traffic for those sensor nodes close to the sink node, and multiple sinks can only partly tackle this problem by sacrificing the information accuracy and increasing the infrastructure cost. The authors also claim that they addressed the problem by leveraging mobility and multi-radio heterogeneity to create a cellular-sensor hybrid system with clustered and tiered network architecture.

The authors state that they combined the rationales in precious approaches such as Data MULE of Ye et al. [2002] and TTDD model of Shah et al. [2003] into their mWSN in Chen et al. [2006] and Ren et al. [2006].

The authors state that the shortcoming of their previous work is that the TTDD works only for local sensing, and the Data MULE works not scalability since the communication between data MULE and sensors is by single-hop.

The authors use their mathematic model with Poison process and Pascal distribution for their theoretical analysis. They also introduce the characteristic distance (d_{char}) for analyzing the optimization of sink velocity by compromising between sink-sensor meeting delay and message delivery delay.

The authors design four sets of simulations to verify their analysis: 1) comparison between least-hop count clustering and characteristic distance based multi-hop clustering, 2) to show the message delivery delay by changing number and velocity of mobile sinks, 3) and the energy consumption by changing the number of mobile sinks and cluster size, 4) to show the outage probability by changing transmission range and packet length.

The authors state that the energy consumption of characteristic d_{char}-based multi-hop clustering is less than the multi-hop clustering d_{max}. They also state that the delay of message delivery and the energy consumption reduces as increasing the number of mobile sinks and there is the optimal velocity under which that message delivery delay will be minimized. Furthermore, they state that the outage percentage is decreasing as increasing the transmission range, or decreasing the packet length.

The authors claim that the characteristic distance based multi-hop clustering can forward the packets to the estimated sink position in a timely and most energy-efficient way. They also claim that sink mobility can reduce the energy consumption level to extend the network lifetime, but its side effects are the increased message delivery delay and outage probability.

3.3 Numerical trajectories

Vidács[2007]: Minimum Transmission Energy Trajectories for a Linear Pursuit Problem.
The authors state that pursuit problem is common in many areas. And they adopt the pursuit problem to a WSN scenario: the pursuer in this case is the mobile sink while the tracked object (sensor node) takes the role of the pursuee.

The authors refer to the dynamic programming in the work of Bellman [1957] and in Bertsekas [1976] and indicate that they use the Bellman-Ford algorithm for their work.

The authors do not mention the shortcomings of the Bellman-Ford algorithm.

In their method of dynamic programming, the authors factorize the cost function into radial and angular function to describe the transmission cost with an optimal policy. Then they reduce the partial differential equation governing the cost function to an ordinary differential equation for the angular functions. Finally, they solve the equation as well as the related optimal trajectories numerically.

In their approach, the energy of radio transmission obeys the well-known power-law $\rho^{-\alpha}$ as a function of the distance ρ between the mobile sink and the sensor nodes. But they do not show any heuristic for their computation.

The authors show three sets of computation: $\alpha=0$, $\alpha=2$, $\alpha=5$ to obtain trajectories in moving and fixed coordinates.

The authors state that when $\alpha=0$, the optimal trajectories are straight lines leading directly towards the rendezvous-point, when $\alpha\geq2$, the optimal trajectories are the minimum overall energy consumption in the network.

The authors claim that the optimal pursuit (mobile sink) curves are self-similar in the sense, which any magnification of the curve results in an optimal trajectory as well, but for different initial conditions.

4. CONLUDING COMMENTS

In static WSNs, sensors close to the sink run out of energy much faster than sensors in other parts of the sensing area. This leads to a limited network lifetime. Here we provided a survey of research on trajectories followed by mobile nodes to prolong the network lifetime. Since predictable trajectories are computed previously, the complexity of trajectory computation is less important than with dynamic trajectories. Dynamic approaches obtain better performance for WSNs, especially network lifetime. However, introducing the MDC into WSNs leads to some new problems, such as delay of data delivery, buffer size and movement speed, for some special required application.

Future work could focus on following directions: “the heuristics can be modified by allowing the elements to wait at the nodes as long as the time constraints can be met” [Almi’ani et al. 2010], “consider cases where a WSN can operate until X% of the sensor nodes die” [Zhu et al. 2009], “the property of triangle-inequality for optimizing the sink trajectory path-length along the minimum spanning tree” [Srinivasan and Wu 2008], “some strategies to reduce the message delay by using more than one mobile sink” [Aioffi et al. 2007], “WSN with dynamic requirements” [Ekici et al. 2006], and “mobile elements can be added or removed once the system is in operation” [Jea et al. 2005]

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