Research Issues on Mobile Sensor Networks

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***Abstract*—More and more researches focus on the development of mobile wireless sensor networks (MWSNs) due to the favorable advantages and applications of MWSNs. However, there is not a comprehensive survey about the research issues on MWSNS for the state of art. In this paper, we survey the communication and data management issues on MWSNs and provide extensible research directions of MWSNs.**

***Keywords*—Mobile wireless sensor networks, Survey, Overview, Research Issues, Communication, Data management**

I. Introduction

A. Background

Wireless sensor networks (WSNs) have become more and more prospective in human life during the past decade [1]. However, there are still some critical issues proved to be difficult to be achieved in static WSNs, e.g., long network lifetime and reliable network connectivity [2]. With the help of mobility, mobile wireless sensor networks (MWSNs) have some natural advantages for overcoming these critical issues [2] [3]. In addition, more and more exciting and complex applications require WSNs to be mobile rather than static, e.g., the smart transport system, security system, social interaction, miscellaneous scenarios [3].

B. Mobile wireless sensor networks

Mobile wireless sensor networks (MWSNs) are a class of networks where small sensing devices move in space over time to collaboratively monitor physical and environment conditions (e.g., temperature, sound, vibration, pressure, motion). The architecture of MWSNs can be divided into three catalogs, flat-tier, two-tier and three-tier [3] [4].

- Flat-tier architecture. In a flat-tier architecture, a set of heterogeneous devices, which can be mobile or static, communicate in a multi-hop ad hoc fashion. All sensor nodes route data to a remote sink, which can be mobile or static.
- Two-tier architecture. It consists of a set of mobile devices and a set of static devices. If the network density is high, in which nodes are always connected, then the mobile devices can form an overlay network to transmit data. Otherwise, the network can become disjoint, mobile devices must perform as mobile agents. Those kind of mobile devices normally need large memories to gather data from their neighborhood sensors, since they do not forward data to the access points instantly but cache them in their memories.
- Three-tier architecture. A set of static devices constitute the bottom tier, mobile agents which gather sensory data form the middle-tier and forward data to the access points which are the top tier.

The characteristics of MWSNs, which distinguish from the static WSNs, are as follows [3] [4]:

- High power requirement. As devices in MWSNs require additional power to perform mobility, they have a larger energy reserve or can be recharged or changed with fresh ones.
- Dynamic topology. Because base stations or sensor nodes can move, the topology of the whole network is generally dynamic. Data becomes outdated quickly, and new routing and MAC protocols are needed.
- Unreliable communication. Dynamic topology, transmission failures, etc will result in unstable communications, especially in some hostile environments.
- Accurate localization. The involvement of mobility makes the location estimation of mobile devices more significant and critical.

And, the major advantages of MWSNs over static WSNs are [3] [4]:

- More efficient energy usage. In static WSNs, the nodes near the gateway will die sooner due to the many-to-one hop-by-hop communication pattern. In MWSNs, this tough problem can be greatly alleviated, as base stations or sensor nodes can move and the energy dissipation is more efficient.
- More channel capacity. [5] has demonstrated that the capacity gains using mobile sinks can be 3-5 times more than that of static WSNs if the number of mobile sinks increases linearly with the growth of number of sensor nodes.
- Better targeting. In MWSNs, as sensors are generally deployed randomly instead of precisely, nodes are required to move for better sight or closer proximity.
- Better data fidelity. The mobility of nodes in MWSNs can reduce the number of hops, and then decrease the probability of errors during transmission.

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There are four possible mobile entities in MWSNs, namely, mobile base stations, mobile sensor nodes, mobile relay nodes and mobile cluster heads. And three mobile paradigms exist in MWSNs.

- Controllable movement. When the movement of a mobile entity is planned and controlled, the entity is doing controllable movement. For example, a base station continuously moves to its interested nodes to collect data.
- Unpredictable movement. It refers to the scenarios when the movement of mobile entities are random. For instance, small mobile devices bound to birds or animals to monitor and collect data about their habits, behaviors and environments.
- Predictable movement. If the movement of a mobile entity has clear direction or track, then the movement is predictable, such as the sensors on moving cars which have a clear route.

C. Structure of research issues of MWSNs

We analyze the research issues on MWSNs according to two aspects: communication issues and data management issues. Communication issues include topology control, coverage, target tracking as well as localization. Data management issues are data gathering and data replication.

D. Contribution and organization

MWSNs have the great potential to further promote the development of WSNs. However, to the best of our knowledge, there is no existing survey on the research issues of MWSNs. In this paper, we analyze the research issues, compare different research methods and identify new research areas on MWSNs. Our main purpose is to present a comprehensive study about MWSNs so as to facilitate further researches on MWSNs.

The remaining parts of this paper are organized as: Section II and section III show the communication and data management issues on MWSNs, respectively. Some further research issues of MWSNs are presented in section IV. We conclude this paper in section V.

II. Communication Issues

A. Topology control issue

Topology control is the problem of assigning transmission powers to every node in order to maintain connectivity while minimizing the energy consumption of the whole network. There are considerable theoretical attention about topology control in static WSNs [6]. In MWSNs where sensors are generally mobile, the setting of transmission powers, which are strongly related to connectivity and energy efficiency, is more significant.

To the best of our knowledge, there are few topology control algorithms in MWSNs and they can be classified into: 1) non-deterministic algorithms and 2) deterministic algorithms.

1) Deterministic algorithms: [6] provides the first theoretical results for topology control considering mobility. It proposes three polynomial algorithms to solve the topology control problem. However, it only considers one moving node. The total power consumption is high and the topology control algorithms are centralized, which is less practical. Considering a constant rate mobile networks (CRMN), where sensor nodes move at constant speed and direction, another two polynomial algorithms are also proposed in [7]. But minimizing the total power consumption is not solved and a distributed version of the centralized algorithms is not proposed. Aiming to solve the topology control problem under a variant rate mobile networks (VRMN) in a distributed fashion, [8] presents two polynomial algorithms to further reduce power consumption. However, the division of whole network time into time intervals and the generality of the algorithms are not considered.

2) Non-deterministic algorithms: [9] shows a distributed algorithm to solve the topology control problem in a practical network composed of both static and mobile nodes, which mainly uses a redundant transmission range (RTR) factor to consider all possible movements of nodes to ensure network connectivity. Moreover, a mobility-sensitive topology control algorithm is proposed in [10], which uses a buffer zone similar to RTR to increase the actual transmission range. Both mechanisms are non-deterministic because it is difficult to choose the appropriate value of RTR or buffer zone.

B. Coverage issues

One of the basic and significant factor in the design and application of MWSNs (e.g., target tracking) is sensor coverage measured by the overall area that a WSN is currently monitoring. Sensor coverage is closely related to the quality of service that the network can provide, and it will decrease due to undesirable sensor deployment and sensor failures. Critical application scenarios (e.g., disaster areas, toxic regions or battlefields) will make the initial deployment obviously far from having the desirable features of full coverage. Moreover, natural limitations (e.g., battery depletions, hardware defects) and external harsh environments (e.g., wind, fire) will also strongly affect the lifetime of sensors.

During such conditions, sensors should have the ability to preserve the coverage. And there are two ways to maintain sensor coverage in these cases: 1) self-deployment and 2) relocation. Self-deployment means that mobile sensors should have the ability to autonomously adjust their positions to improve the coverage after their initial deployment. Sensor relocation refers to deploy a moderate number of redundant sensors and strategically relocate them as needed to fill the position of failed nodes.

1) Self-deployment issues: Current researches on achieving the self-deployment in MWSNs are mainly based on three methods: movement-assisted, potential fields and virtual force.

Movement-assisted: [11] focuses on the principle of even distribution and proposes three movement-assisted protocols for network where sensors are all mobile. After discovering the coverage hole (the area not covered by any sensor) using the

Voronoi diagrams, the protocols calculate the target positions of the sensors, where they should move. Mobile sensors from densely deployed areas are moved to sparsely deployed areas in an iterative way. However, to obtain coverage by equipping all mobile sensors with a motor in a network will increase the sensor and hardware cost. [12] optimizes their previous work to balance cost and coverage by designing a bidding protocol for deploying a mix of mobile and static sensors. Static sensors detect coverage holes locally by Voronoi diagrams and mobile sensors can move from dense areas to sparse areas to improve the overall coverage. But sensors may move in a undirect zig-zag way which wastes lots of energy. In [13], a proxy-based sensor deployment protocol is proposed to distributively identify the target locations of mobile sensors, move there logically and exchange new logical target locations with their new neighbors. Mobile sensors move directly after they determine their final locations. All the above three methods do not consider the real time response requirements to new events (e.g., sensor failures) during self-deployment.

Potential fields: A distributed and scalable potential-field-based approach to solve the area coverage problem is proposed in [14]. Potential fields are constructed so that each node is repelled by other nodes and obstacles which force the network to spread itself throughout the whole network. In order to maximize the coverage while maintaining the full line-of-sight connectivity, similar algorithms based on potential fields are presented in [15] [16], and they do not require a global map of the environment. These three methods also do not satisfy the real time response requirements.

Virtual force: A virtual force algorithm (VFA) is shown in [17] to maximize the sensor field coverage by combining attractive and repulsive forces to determine virtual motion paths and the movement rate for randomly deployed sensors. Improved VFA algorithms are presented in [18] to improve coverage rate, and reduce moving energy consumption by setting communication parameters. They all suffer from oscillatory sensor behaviors, for example, sensor collisions may happen because the sensors are not stable at the desirable threshold.

An original snap and spread algorithm for autonomous deployment is proposed in [19]. Locally available information are used to make decisions regarding the behavior of each node without the prior knowledge of the operating conditions and manual key parameters tunings. It could gain a stable sensor sensing behavior and meet the real time response requirements but it does not consider uniformity guarantees, obstacle detection and avoidance.

2) Relocation issues: A two-phase sensor relocation solution is proposed in [20], in which redundant sensors are first identified using Grid-Quorum and then are relocated in a cascaded movement in a timely, efficient and balanced way. [21] addresses the real implementation issues in [20] and testifies the feasibility of their mobile sensor node platform. Both of the two methods consider the response time requirements. But the message complexity is high, the storage load is non-constant and they depend on the preknowledge of the sensor field. Without the knowledge of the sensor field, a zone-based sensor relocation protocol for MWSNs is proposed in [22] on the basis of flooding to discover the redundant nodes and relocate them in a shifting way. It also suffers from the high message complexity and non-constant storage load. To replace failed sensors with the redundant ones scattered through autonomous and strategic nodal movement, a localized mesh-based sensor relocation protocol (MSRP) based on distance sensitive node discovery algorithm (DSND) found on a novel structure named information mesh is proposed in [23]. It can guarantee lower message complexity and constant storage load but has not been experimented.

C. Target tracking issues

Target tracking is the one of the most classic applications of MWSNs. Coverage, data gathering, localization algorithms, etc are all foundations to achieve successful target tracking. As environmental factors (e.g., wind) are easy to affect the performance of tracking, target tracking is a tough practical issue. And we classify the current target tracking issues into three categories: 1) target mobility issues, 2) detection parameter issues and 3) detection performance issues.

1) Target mobility issues: [24] presents a dynamic group management method for tracking initiation and maintenance in related applications. Sensors in a group use geographically-limited message passing to achieve coordination. [25] evaluates a decentralized, light-weight, dynamic clustering algorithm for a hierarchical sensor network. The network composes of a backbone of cluster heads and densely populated low-end sensors. The cluster heads can be active and the low-end sensors provide information to cluster heads. It researches the collaboration among cluster heads.

2) Detection parameter issues: [26] evaluates the upper and lower bounds on exposure for any sensor route plan and sensing schedule with and without the presence of obstacles in MWSNs. [27] presents an analytic method to evaluate the tradeoff between the number of nodes and detection latency based on a collaborative sensing approach using nodes with uncoordinated mobility. Moreover, [28] explores the problem to find the minimum velocity for covering sensors as well as the minimum number of sensors to be deployed in case of fixed velocity.

3) Detection performance issues: [29] proposes two novel distributed particle filters with Gaussian Mixer approximation to localize and track multiple moving targets by running on a set of uncorrelated sensor cliques, which update partial results and are dynamically organized based on moving target trajectories. The method can conserve bandwidth and power by a low dimensional Gaussian mixer model (GMM) and reduce communication overhead by an application layer communication protocol. Considering the dynamic network topology in MWSNs, a distributed Kalman filtering (DKF) algorithm is introduced in [30] to establish the direct connections between distributed target tracking and flocking-based information-driven mobility, which demonstrates that the model can improve the tracking performance. [31] introduces a two phase detection model based on data fusion in which mobile sensors initially remain static and directly move towards a possible target when a detection consensus is reached by a group of sensors. Under given detection delay bounds, the movement scheduling algorithm can achieve near-optimal detection performance. [32] improves their previous work in [31] by optimizing the movement scheduling algorithm to minimize the total moving distance of sensor while achieving a set of spatiotemporal performance requirements.

D. Localization issue

The applications of WSNs (e.g., target tracking) need sensors to be aware of the position of nodes in order to make sense of data and perform further navigation tasks. Because of mobility which increases the uncertainty of nodes, localization in MWSNs is more difficult. The localization algorithms in MWSNs can be categorized into: 1) range-based method, 2) range-free methods, and 3) mobility-based methods.

1) Range-based methods: Range-based methods are more expensive than range-free methods in localization because they require expensive hardware to measure signal arrival time, angle of signal arrival, etc [33]. However, recently two range-based methods [34] [35] are distinctive without the dependence of GPS. [34] first proposes localization algorithms in MWSNs without GPS and uses the distance between nodes to build a coordinative system computing node positions in two dimensions. Another GPS-free localization algorithm is proposed in [35] and uses wireless communication properties and a compass to find positions of neighboring nodes. It only needs a single round of node movement to perform localization. Both of these two algorithms require non-limited storage in sensor nodes during localization.

2) Range-free methods: Range-free methods are an cost effective alternative to range-based approaches [33] as they mainly use local techniques and hop-counting techniques. Most of them can be adapted for MWSNs by refreshing location estimates frequently. [36] proposes an elastic localization algorithm (ELA) to perform localization using hop counting techniques. An anchor-free mobile geographic distributed localization (MGDL) algorithm for MWSNs is proposed in [37] using accelerometers. They also assume non-limited storages in sensor nodes.

3) Mobility-based methods: [33] first exploites the mobility of sensors to assist localization in MWSNs. It introduces the sequential monte carlo (SML) localization method to improve accuracy and precision of localization without additional hardware expect for GPS. Similar techniques using SML are proposed in [38] [39] without decreasing the non-limited computation ability. [40] tries to optimize the computation cost for SML methods. [41] proposes algorithms for MWSNs utilizing doppler shifts of the radio signal transmitted by a tracked node. [42] proposes similar algorithms by using the principles of doppler shift and radio interferometry to achieve accurate localization.

III. Data Management Issues

A. Data gathering issue

Data gathering is the fundamental task of WSNs. In MWSNs, as sensor can move, different mobile entities need different data gathering methods. We analyze the data gathering issues with specific mobile entity scenarios: 1) mobile base stations, 2) mobile relay nodes, and 3) mobile sensor nodes.

1) Mobile base stations: [43] [44] [45] [46] analyze the data collection scheme when the movement of base stations are predictable. [43] [45] [46] model the data collection process as a queueing system and [44] uses a similar scheduling algorithm to collect data. As sensor nodes in [43] and [44] transmit data to the moving base stations only in one hop, some sensor nodes must wait for base stations to move into their transmission ranges to forward data. It will aggravate the transmission delay. [46] improves the routing of response packet in [45] and consideres a complete query-based data collection cycle.

Considering that the behaviors of base stations are controllable, [47] describes a message ferrying approach to collect data in one hop fashion, [48] [49] explore the movement of base stations to efficiently collect data to prolong the network lifetime. But both of them require the sensor nodes to be aware of the location of base stations.

2) Mobile relay nodes: Considering sparse networks, [50] evaluates the performance of uncontrollable data mules or relay nodes to collect data in a three-tier architecture. Long transmission delay is also a major drawback of data mules, which collect data in one hop fashion. Based on the data mule architecture and the queuing theory, [51] presents an analytical model to further understand the performance of data mule architectures. [52] [53] analyze the performance of relay nodes when they are uncontrollable and controllable which can improve capacity and network lifetime, respectively.

3) Mobile sensor nodes: [54] proposes sensor control methods to deliver data to the sink energy-efficiently, considering node failures using broadcasting information. By constructing a communication route of multiple mobile nodes between fixed nodes without broadcasting, a data acquisition and transmission with fixed and mobile node (DATFM) is proposed in [55]. However, they do not consider node failures. Based on some applications which can tolerant delay and fault, [56] [57] analyze and implement an efficient data delivery scheme in such network using queuing theories and statistics.

B. Data replication issue

In MWSNs, due to the free moving of sensors and harsh environments, disconnection occurs frequently which results in network divisions. In such situations, sensors in one of the divided network cannot access data in other divided networks. One possible solution to solve the network division problem for improving data accessibility is to replicate data items from other sensors. We analyze the data replication issues in MWSNs from two aspects: 1) single-hop data replication issues and 2) multi-hop data replication issues.

1) Single-hop data replication issues: [58] presents and analyzes different data allocation methods, mainly about one-copy and two-copy schemes, the connection model and the message model, the expected cost and the average expected cost as well as the worst case cost. [59] divides the mobile units into sleepers and workaholics based on the amount of time they spent in the sleep mode and then proposes three invalidation methods, in which servers periodically broadcast reports that reflect the changing database state. [60] also presents an energy-efficient cache invalidation method which allows mobile computers to operate in a disconnected mode to save energy while retaining most caching benefits after reconnections. [61] proposes a cache invalidation algorithm for mobile environments using adaptable mechanisms to adjust the size of the invalidation report so as to optimize the communication bandwidth while retaining the invalidation effectiveness. All of these four mechanisms use the one hop communication pattern, and sensors all have non-limited memory spaces.

2) Multi-hop data replication issues: [62] considers the environments, where sensors have limited memory spaces and transmit in a multi-hop fashion. Then it proposes three replica allocation methods taking the access frequencies and network topology into account to improve data accessibility. [63] and [64] extend their previous work in [62] considering data updates and environments, in which nodes issue access requests to correlated data items. By considering aperiodic updates and integrating user profiles consisting of user behaviors, another extension of this research work is shown in [65].

IV. Further research issues of MWSNs

MWSNs have the potential to make many applications in WSNs more powerful [3]. By conducting the survey work on MWSNs, we find that many areas in MWSNs are still worthy of further researches.

- Mobile multimedia sensor networks (MMSNs). MMSNs are composed of mobile multimedia sensor nodes, which can provide more flexibility to enhance the capability for event description than that of traditional static wireless multimedia sensor networks [66]. Due to the large size of multimedia streaming data, multiple and stable paths to gather and transmit data are needed in MMSNs when multimedia source nodes can move.
- Mobility supported localization technologies. Localization algorithms in WSNs and MWSNs generally use the base stations or sensor nodes as the anchor nodes to locate the unknown nodes. Using mobile cluster heads as anchor nodes is worthy trying.

V. Conclusions

The favorable advantages and interesting applications of MWSNs make MWSNs get more and more attention. We investigate the topology control, coverage, target tracking, and localization about communication issues as well as the data gathering and data replication for the data management issues on MWSNs. Moreover, there are a lot of valuable areas for further exploring of MWSNs. Mobile multimedia sensor networks (MMSNs) have the great potential to further promote the development of MWSNs. Interesting areas also exist in localization algorithms. We believe that this survey work can provide a valuable overview about the development of MWSNs.

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