A Survey On Mobile Sensor Networks

Technical Report on August 19, 2010, Osaka University

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***Abstract*—Wireless sensor networks (WSNs) which is proposed in the late of 1990s have received unprecedented attention because of their exciting potential applications in military, industrial and civilian areas (e.g, environmental and habitat monitoring). Although WSNs have become more and more prospective in human life with the development of hardware and communications technologies, there are some natural limitations of WSNs (e.g., network connectivity, network lifetime) due to the static network style in WSNs. Moreover, more and more application scenarios require the sensors in WSNs to be mobile rather than static so as to make traditional applications in WSNs become smarter and enable some new applications. All this induce the mobile wireless sensor networks (MWSNs) which can greatly promote the development and application of WSNs. However, to the best of our knowledge, there is not a comprehensive survey about research issues in MWSNs. In this paper, we research the communication issues and data management issues in MWSNs, discuss different research methods in MWSNs and propose some further research areas in MWSNs. We hope that our work provide some guidance about research in MWSNs.**

***Index Terms*—Wireless sensor networks (WSNs), Mobile wireless sensor networks (MWSNs), survey, communication, data management.**

I. Introduction

The concept of wireless sensor networks (WSNs) is proposed in [1]. WSNs which are consisted of spatially distributed autonomous sensors to cooperatively monitor physical or environmental conditions have great exciting potential applications in areas of military, industry and civilian, including battlefield surveillance, battle damage assessment, industrial process monitoring and control, machine health monitoring, home automation, traffic monitoring, etc. [2]. With the advancement in micro-electro-mechanical systems, digital electronics and wireless communications, the availability of small sensor nodes which are low-cost, low-power and multifunctional further leverages the implementation of WSNs [2]. However, because nodes are generally static in WSNs and they communicate in a default many-to-one hop-by-hop communication pattern, sensor nodes near the gateway of sink always accumulate the most data which makes them die very soon. This strongly worsens the network connectivity and network lifetime of WSNs, apart from the natural battery depletion which results in disconnections in WSNs. Among all challenges in the design of WSNs, network connectivity and lifetime stand out as critical considerations in WSNs [3]. Contrarily, if the sensors can be mobile, not only the mobile sensors can carry information between isolated parts, but also they will disperse the energy consumption of sensors to deliver data. What's more, applications with the help of mobility will definitely make them become smarter and create some new applications [4]. For example, traditional traffic applications of WSNs monitor, analyze the traffic information at a given time and then send the information back to a central gateway or sink. The customers can not get the traffic information in real time. Using the mobility of devices (e.g, mobile phone users, mobile cars), if we make a link between the gateway and the mobile phone users, we can immediately provide the latest traffic information to the customers. Smarter applications can also be found in security monitoring, health monitoring and etc. Mobility also can enable some new applications (e.g., social interaction, miscellaneous applications).

Mobile wireless sensor networks (MWSNs) are a new class of sensor networks where small sensors move in space over time to collaboratively monitor or control physical or environmental conditions (e.g, temperature, sound, vibration, pressure, motion). If has three reference architectures [4] [5] which is presented in Figure 1. The first reference architecture is a **flat architecture**. A set of heterogeneous sensors communicate over the same network and sensors which can be either mobile or static communicate in an ad hoc manner. **Two-tier architecture** is the second reference architecture. There are a set of static sensors and a set of mobile sensors in the architecture. If the density is high, then mobile nodes form an overlay network to collect data. Otherwise, mobile nodes perform the role of data relays or data agents to gather data. They don't forward the data to the access points or other peers instantly when they gather data and they have a large size of memory. The last architecture is the **three-tier architecture**. A set of static sensors which pass data to the mobile agents constitute the lowest tier. Mobile agents that collect data are the second tier. Access points where data are forwarded to comprise the highest tier.

The characteristics of MWSNs are as follows [4] [5]. **More dynamic topology**. Because nodes generally are mobile

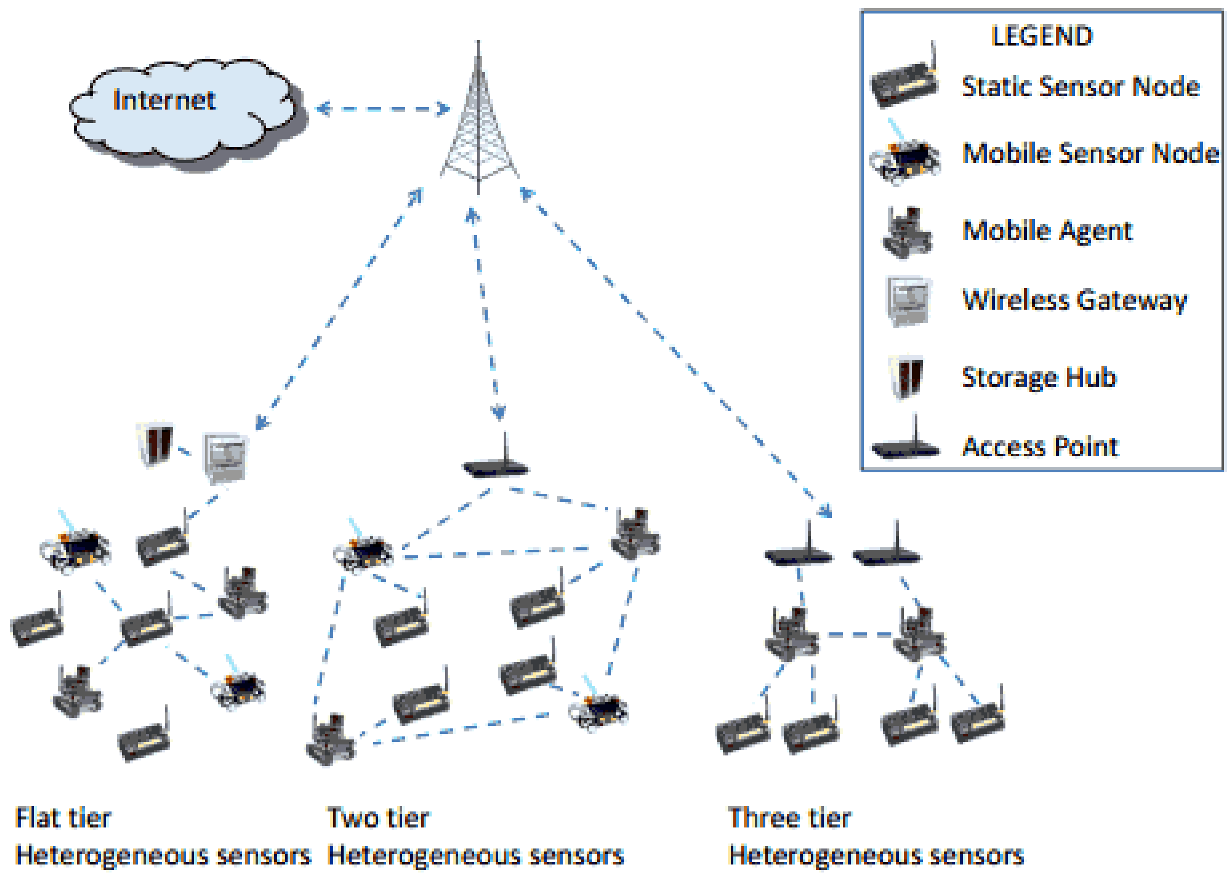

Fig. 1. Reference architectures of MWSNs

in MWSNs, the topology is dynamic. New routing and MAC protocols are needed in MWSNs. **High power requirement**. The additional power for sensors to be mobile will increase the power requirement, sensors generally have a larger energy reserve or can be recharged or changed with fresh ones. **Unreliable communication links**. Dynamic topology, transmission failures, battery depletions, etc will result in unreliable communication links, especially in hostile and remote areas. **More accurate localization**. The mobilities of nodes require a more accurate location estimation of the base station or other sensors.

And the advantages of MWSNs are shown as follows [4] [5]. **Long network lifetime**. Because sensors can move, they will make the transmission more disperse and energy dissipation more efficient so as to get ride of the flaw that sensors near the gateway or sink lose their energy first. **More channel capacity**. Experiments have demonstrated that the capacity gains can be 3-5 times more than static WSNs if the number of mobile sinks increases linearly with the number of sensors. **Better targeting**. Since sensors are mostly deployed randomly instead of precisely, they are generally required to move for better sight or for close proximity which is favorable for targeting. **Better data fidelity**. The reduced number of hops due to mobility will increase the probability of successful transmissions.

There are four possible mobile entities in MWSNs. Namely, **mobile base stations**, **mobile sensor nodes**, **mobile relay nodes** and **mobile cluster heads**. And there are three mobile paradigms in MWSNs, **controllable movement**, **predictable movement** and **unpredictable movement**. Controllable movement is the movement which is planned and controlled (e.g., mobile base stations move to the nearest sensor to collect data). If the movement of mobile entity has a clear direction or track (e.g., sensors transmit data on moving cars), then the movement is the predictable. Unpredictable movement is the movement which is random (e.g., sensors bound to birds or animals to monitor and gather data about their habits, behaviors and environments).

To the best of our knowledge, there is not a comprehensive survey about MWSNs for the state of art. The main contribution of this paper is that we try to present a synthetical survey about the research issues in MWSNs. Specifically, we explore the communication and data management issues in MWSNs which is shown in Figure 2. We also compare and analyze different research methods in MWSNs. Further research areas in MWSNs are also provided. We hope that this paper can provide some guidance to researchers who are interested in MWSNs.

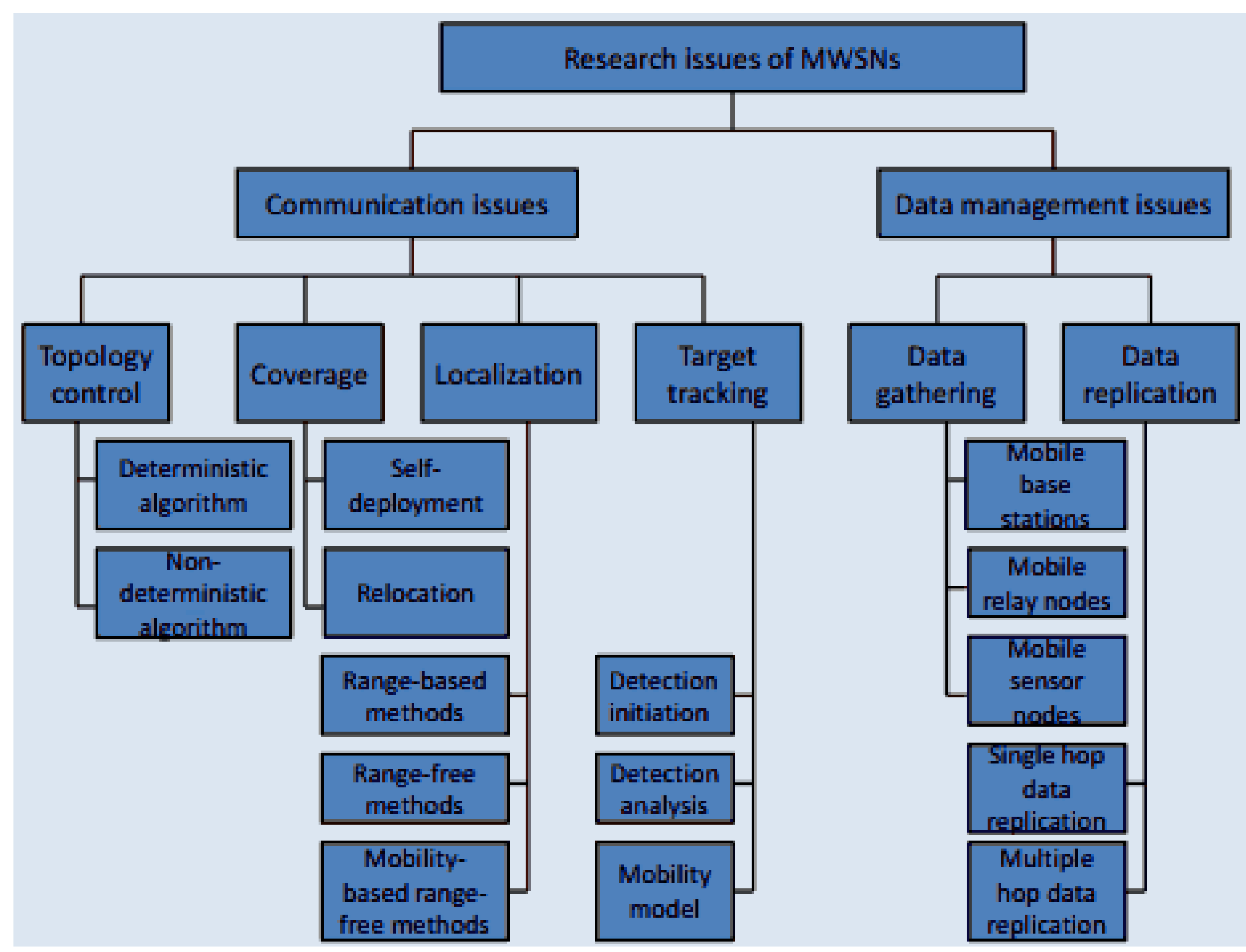

Fig. 2. Communication and data management issues of MWSNs

The remaining part of this paper is organized as follows. Section II and section III present the research issues about communication and data management in MWSNs, respectively. Section IV summarizes different research methods and provides some further valuable areas in MWSNs. We conclude this paper in section V.

II. Communication Issues

A. Topology control issue

Topology control is the problem of assigning transmission power to keep the network connected while minimizing the energy consumption of nodes. Further, there are two functions the assignment of transmission power to nodes aims to achieve [6]. One is MINMAX whose goal is to minimize the maximum power used by any node in the network. The other one is MINTOTAL which tries to minimize the total power used by all nodes in the network. The latter one is equivalent to minimize the average power utilized by the nodes. In static WSNs, there are a lot of researches which focus on topology control. As for topology control in MWSNs, there are few related researches and they can be categorized into: 1) deterministic algorithms and 2) non-deterministic algorithms.

1) Deterministic algorithms: [7] [8] propose the first theoretical results for topology control incorporating mobility. The network model in [7] is a simple network model (SMN), where there is one moving node and n static nodes while the network model in [8] is a constant rate mobile network (CRMN) in which n sensors may move and each moving node is associated with constant moving speed, direction. Assuming slicing the network lifetime into unit time intervals and studying the topology control problem during each time interval, both [7] [8] make extensive of the algorithm for static WSNs in [9] [10]. The insight of that algorithm named as MINMAXGRAPH by [7] [8] is that the minimum maximum power p should come from the threshold values associated with node pairs in the network which enables a binary search over the threshold values to find the minimum maximum power which can keep network connectivity. As for topology control in MWSNs, [7] and [8] further suppose the movement of each node can be represented by a line segment and try to keep network connectivity in every segment so that the network can be connected during the entire movement. Specifically, they partition the whole moving route into smaller line segments based on adjacent bisector points. For every partitioned line segment, they construct a threshold graph and independently compute the minimum power for each threshold graph to keep network connectivity using the MINXMAX-GRAPH method. Further improving algorithm running time methods are also developed in [7] and [8], mainly by avoiding the explicit construction of threshold graphs and computing the MINMAX edge incrementally rather than independently. As [8] focuses on constant rate mobile network, [8] further slices the unit time interval into constant-connectivity time slots and constant order time slots thus connectivity can be further checked for individual time slot. Different from the methods which find the minimum maximum shown in [7] and [8], aiming to solve more practical topology control problem resulting from variant rate mobile sensor network (VRMN) instead of CRMN, [11] presents two polynomial algorithms, centralized and distributed, respectively. Based on the similar assumption that the whole network lifetime can be divided into unit time intervals and centering on unit time interval topology control method, for each unit time interval, the centralized algorithm first computes the initial one hop neighbor list for each node and sorts that list in decreasing order by the maximum distances between every node and its neighbors in that list. Then for each node, it further eliminates its furthest neighbors in the neighbor list reachable by the one-hop relay of its closer neighbors to reduce the power to keep connectivity. With that, a breadth first search to determine whether the resultant is disconnected and full power will be assigned to each node if it is true. As for the distributed algorithm, it is transformed from the centralized algorithm by using the local asynchronous "Hello" message exchanges to let each node make its own decision about the resultant topology. The main limitation of the algorithms in [7] [8] [11] is their assumption about dividing whole network lifetime into unit time interval and the suitability to unique network model.

2) Non-deterministic algorithms: As for the the disk mobile network (DMN) in which there are n moving nodes without specific moving direction, [6] presents us another type of topology control algorithms. Those algorithms also try to divide the whole time into unit time interval and minimize the maximum power assigned to each node throughout each time interval. Their main mechanism is recomputing the transmission power levels of the nodes at the start of each interval, based on the current location of the nodes and any additional information about the movement of the nodes. Trying to extend many existing mobility-insensitive protocols into random waypoint [12] networks (RWN), [13] introduces two mechanisms to deal with the inconsistent information and outdated information resulting from mobility. Specifically, consistent local views using either synchronous or asynchronous "Hello" messages are enforced to keep the topology logical. And each node increases its actual transmission range which creates a buffer zone so as to cover its logical neighbors to make the topology effective. For both [6] and [13], it is difficult to choose the frequency of rerunning the algorithm or the appropriate value of redundant transmission range.

B. Coverage issue

Coverage is one fundamental design and application factor in MWSNs. Measured by the overall area a WSN is monitoring, not only is sensor coverage closely related to the quality of service that the network can provide, but it will also strongly affect the application (e.g, localization, target tracking) performance of MWSNs. Sensor coverage is mainly weakened by unfavorable initial deployment and sensor failures. Specifically, tough application scenarios (e.g., disaster areas, toxic regions) and external harsh environments (e.g, wind, fire) both make the initial deployment far from desirable and decrease the sensor lifetime. Internal limitations of sensors (e.g., battery depletions, hardware defects) further shorten their lifetime.

In case of such undesirable condition and sensor failures, sensors should have the ability to keep coverage. There are two ways to achieve this goal. The first one is 1) self-deployment which means sensors autonomously adjust their positions to improve coverage after their initial deployment. The other one is 2) relocation referring to strategically relocate some redundant sensors to fill the position of failed nodes to enhance coverage.

1) Self-deployment issue: The self-deployment issue in MWSNs can be discussed according to the following categories: movement-assisted methods, potential field methods and virtual force methods.

Movement-assisted methods: [14] shows us a classic movement-assisted method to achieve self-deployment. Its main idea is to discover the existence of coverage holes (the area not covered by any sensor) first, and then calculate the target positions where the sensors should move to improve coverage. Specifically, it uses the Voronoi diagrams [15] [16] to discover the coverage holes and proposes three movement-assisted sensor deployment protocols, VEC (VECtor-based), VOR (VORonoi-based) and Minimax to move sensors from densely deployed areas to sparsely deployed areas in an iterative way. As for the Voronoi diagrams, each sensor needs to know the existence of its Voronoi neighbors to construct the Voronoi polygon and each sensor is responsible for the sensing task to examine the coverage hole in its Voronoi polygon. With respect to the three sensor deployment protocols, VEC pushes sensor away from a densely covered area if the sensors are too close, VOR pulls sensors to their local maximum coverage holes and Minimax fixes holes by moving closer to the farthest Voronoi vertex. Those protocols can achieve good performance in terms of coverage, deployment time and moving distance. However, the methods in [14] equip every sensor with a motor which will increase the sensor cost and may not be necessary under certain initial distribution (e.g, random initial deployment). In order to balance the sensor cost and coverage, [17] deploys a mixture of mobile sensors and static sensors and then introduces a bidding protocol. In the protocol, static sensors detect coverage holes using the Voronoi diagrams and bid for mobile sensors based on the size of the detected hole. Mobile sensors choose the highest bids and move to heal the largest holes. The process stops until no static sensor give a bid higher than the base price of any mobile sensor. Although the bidding protocol can be used to achieve good coverage at low sensor cost, but sensors may move in a zig-zig way which wastes a lot of energy as the sensors don't move to the final location directly. Then in [18], a proxy-based sensor deployment protocol is designed to distributively identify the final target positions and let sensors move there directly. To determine the final location, it proposes the idea of logical movement which means sensors logically move from small holes to large holes by exchanging messages and assigning proxies. [18] can reduce the energy consumption and also keep good coverage. But for all the three methods, they don't consider the real-time response requirements to new events (e.g., sensor failures) during self-deployment.

Potential field methods: Although potential field methods are commonly used in mobile robotics to achieve local navigation and obstacle avoidance [19], the potential field approach can also be employed to achieve self-deployment [20]. Based on only one assumption that each node is equipped with a sensor allowing it to determine the range and bearing of both nearby nodes and obstacles, a potential field can be constructed for each node as nodes can be repelled if their nearby nodes or obstacles are not appropriate, thus the whole network can be forced to spread itself throughout the environment. The potential field based method in [20] is quite robust, scalable and the network can be converged to a state of equilibrium using the method. Based on the potential fields, [21] [22] investigate the strategy to maximize the coverage with certain constraints, such as the K neighbors each node should at least have in [22].

Virtual force methods: Virtual force algorithm (VFA) is inspired by disk packing theory [23] and the virtual force potential field concept from robotics [20]. VFA algorithms generally models the interactions among sensors as a combination of attractive (positive) and repulsive (negative) forces and attempts to maximize the coverage using these forces. Sensors do not physically move until effective positions are identified. Specifically, pre-determined thresholds about the distance between nodes are needed to exert repulsive forces to the sensors if they are too close or exert attractive forces to the sensors if they are too far apart from each other [24]. What's more, sensors in [24] are also subjected to forces exerted by obstacles and preferential coverage. Improved VFA algorithms are introduced in [25] considering the convergence, the boundary in Region Of Interest (ROI) and the virtual force effective distance. For both [24] and [25], they suffer from the oscillatory sensor behaviors, for example, sensors may collide when they are not stable at the desirable threshold. Moreover, networks in [24] and [25] are cluster-based and the cluster head is responsible for executing the algorithm which suffers from the sing point failure.

2) Relocation issue: In order to solve the relocation problem, [26] proposes a two-phase solution including finding the redundant sensors and relocating them. Specifically, redundant sensors are first identified using a Grid-Quorum method and then relocated to the target location with cascaded movement. About the Grid-Quorum method, based on the grid model and the concept of Quorum [27], the whole gird is divided into the demand quorum organized by the grid heads in one row and the supply quorum referring to the grid heads in one column. When a grid head finds redundant sensors, it propagates the information to all the grid heads in the supply quorum. And when a grid head wants more sensors, it searches its demand quorum. Because the every demand quorum has interaction with all supply quorums, all grid heads can always find the redundant sensors. As for the cascaded movement, the idea comes from moving intermediate nodes to the target location can reduce the delay and balance the energy consumption compared with moving one sensor node for a long distance. In order to demonstrate the feasibility of the Grid-Quorum method in [26] which has good relocation time and energy consumption, [28] presents us the real mobile sensor design and relocation process, based on the popular sensor node platform Mica2 [29] and mobile robot built with commercial off-the-shelf (CTOS) components. However, the relocation methods in [26] and [28] both need strong pre-knowledge about sensing field which affects the practicality and they may fail if there are void areas in the sensing field. A variant of the grid-quorum method in [26] [28] named a zone based sensor relocation protocol (ZONER) is shown in [30], but ZONER requires no preknowledge of the sensor field and it uses a Zone Flooding (ZFlooding) method to penetrate the void area first. Aiming at achieving good coverage as well as getting localized message transmissions and optimal per node storage load rather than global message transmissions and non-constant storage load in [26] [28] [30], [31] proposes a mesh-based sensor relocation protocol (MSRP) to discover the redundant sensors and fulfills the node relocation in a shifted way which has a better relocation path compared with the cascaded way in [26] [28] [30], MSRP can also gain guaranteed nearby replacement node discovery and node replacing.

C. Localization issue

Localization is significant for WSNs as many application of WSNs (e.g., target tracking, environment monitoring) rely on knowing the locations of sensors and perform further tasks. Location awareness can also enhance the performance of routing protocols and security [32]. Because mobility generally increases the uncertainty of nodes, localization in MWSNs are assumed more difficult. But some algorithms try to exploit mobility to improve location accuracy [32] [33] [34]. Localization algorithms in MWSNs can be classified into: 1) range-based methods, 2) range-free methods and 3) mobility-assisted range-free methods.

1) Range-based methods: Range-based methods refer to the methods which use distance estimates or angle estimates to achieve localization. Specifically, they exploit time of arrival (TOA) [35], received signal strength [36] [37], time difference of arrival of two different signals (TDOA) [38] or angle of arrival (AOA) [39]. As most of the range-based techniques require specifical hardware (e.g., ultrasound device required by TDOA, antenna arrays required by AOA), the localization cost are generally expensive and they all need some seed or anchor nodes which know their own positions by GPS. However, [40] presents us the range-based GPS-free work on mobile nodes. Under the assumption that every node has a compass and can measure the distance between their neighbors using range-based methods (e.g., TOA) as well as can move to a specific direction, its core algorithm is based on well defined rounds to achieve localization. Whenever the nodes need localization, it initiates a round which begins with distance measurement between neighbors, continues with nodes individual movement and ends with an exchange between neighbors about the direction and values during the round. The algorithm is quite accurate and requires constant storage per one-hop neighbor during localization.

2) Range-free methods: Range-free methods depend only on the contents of received messages and are a alternative to the more expensive range-based methods [41]. There are two main types of range-free localization methods [32]: local techniques and hop counting techniques. Local techniques rely on a high density of seeds (e.g., APIT [41]) and hop counting techniques rely on flooding the network (e.g, DV-HOP [42]). Recently there are some derivated hop counting techniques considering mobile nodes (e.g., ELA [43]). Rather than paying particular attention to group movement in [40], taking advantage of accelerometers in standard motes, [44] proposes a gps-free range-free localization algorithm named MGDL for MWSNs. First, a local map is constructed by using the hop-coordinates [45] (similar to hop-counting) as well as the Dijkstra's algorithm to get the distance and shortest path between each pair of nodes, combined with MDS (multidimensional scaling). The local map is then merged into a global map. After that, whenever there is movement detected by the accelerometer which is a standard component in many current motes, the local map and the merging process which transforms the local map into global map will be redo again based on the acceleration. MGDL achieves good performance at localization accuracy, coverage and communication overhead.

3) Mobility-assisted range-free methods: Although mobility generally makes localization less accurate and almost all range-based methods and range-free methods for static WSNs can be adapted for MWSNs by refreshing location estimates frequently, the localization technique in [32] first takes advantage of mobility to improve localization accuracy for range-free methods. Based on the key idea of Monte Carlo localization (MCL) [46] [47] and Sequential Monte Carlo (SMC) [48] that representing the posterior distribution using a set of weighted samples and updating the distribution using filtering and resampling methods, [32] extends the MCL methods in robotics to support localization in MWSNs. Specifically, in the prediction step, nodes use the transmission distribution to predict the possible locations based on previous samples and movement. In the filtering step, nodes use new information they observe to filter impossible locations. Resampling step are also used mainly for maintaining the number of location samples. MCL methods can provide quite accurate localization even when there are severe memory limits, low seed densities and highly irregular network transmissions. Similar methods based on MCL are shown in [33] [34] to further reduce the computation cost and improve the location accuracy in [32], mainly by using a box to reduce the scope of searching candidate samples.

D. Target tracking issue

Target tracking is one of the most important application of MWSNs. Generally, sensors detect targets by measuring the energy of signals emitted by the targets. The probability of false alarm (PF) and probability of detection (PD) are main performance metrics of detection. Low detection delay, low detection time, low moving distance, etc are also desirable characteristics of target tracking. And we classify current target tracking issues into the following three categories: 1) detection initiation issue, 2) detection analysis issue, 3) mobility model issue.

1) Detection initiation issue: To efficiently utilize network resources for target tracking, [49] proposes a dynamic group management method for detection initiation and maintenance. Motivated by the natural advantage of geographic proximity in sensing and detecting, sensors are organized into geographically local collaborative groups. Each group is responsible for tracking one target and sensor nodes within the group use geographically-limited message passing to coordinate their behaviors. This dynamic group method can have a good tradeoff between performance and scalability compared with traditional centralized schemes which move all sensor data to one central site. Moveover, [50] envies a hierarchial network architecture for tracking initiation. The network is composed of a static backbone and moderate densely populated low-end sensors. The static backbone is constituted by sparsely placed high-capacity sensors and only the moderate densely sensors can be mobile. Triggered by certain signal events, the sparsely placed high-capacity sensors assume the role of cluster heads (CHs). And the densely populated low-end sensors provide sensor information to CHs in order to achieve target tracking. The dynamic clustering architecture can effectively eliminate the contention among sensors.

2) Detection analysis issue: In order to analyze the detection exposure which refers to the region covered by the sensor network for detection, [51] proposes algorithms utilizing the time expansion graph to find the upper and lower bounds on exposure for any sensor route plan and sensing schedule with and without the presence of obstacles. Similarly, [52] investigates the detection delay about the presence or absence of a target using MWSNs. Using nodes with uncoordinated mobility and a collaborative sensing approach, it presents an analytic method based on Markov chain to evaluate the detection latency.

3) Mobility model issue: [53] shows us the benefits of a flocking-based mobility model about improving tracking quality, by trying to achieve target tracking basing on the distributed Kalman filtering (DKF) algorithm introduced in [54]. It gets that the flocking mobility model has a natural choice of a moving rendezvous point that is the target. During the detection process, small flocks merge into larger flocks and eventually a single flock with connected topology will be formed. This allows the sensors to perform cooperative filtering which can improve the tracking performance. Also, [55] exploits the reactive mobility to improve detection performance. In the approach, mobile sensors collaborate with static sensors and reactively move to a possible target position when detection consensus is reached by a group of sensors. Detailed sensor movement scheduling algorithm is also developed. Likewise, a data fusion model which also enables the effective collaboration between static and mobile sensors is proposed in [56] and it proposes an optimal sensor movement scheduling algorithm to minimize the total moving distance of sensors in [55].

III. Data management issues

A. Data gathering issue

Data gathering is the most basic and essential task of MWSNs. Different mobile entities require different data gathering methods. And we analyze the data gathering issue from the following three terms: 1) mobile base stations, 2) mobile relay nodes and 3) mobile sensor nodes.

1) Mobile base stations: Predictable mobility is a good model for public transportation vehicles (e.g., buses, shuttles and trains) since they can act as mobile observers in MWSNs. [57] shows the significant power saving using predictable mobile base station data gathering overs static WSNs, with a queuing system which models the data collection process. Sensors can transmit data to the mobile base stations if the base stations are not busy. Once the mobile station starts communication with the sensor, it will not listen to any other node that may come within range. And there is a range limitation for the sensors and the base stations to begin transmission. Aiming to gather all the information packets with minimum energy consumption using predictable mobile base stations, [58] proposes a transmission scheduling algorithm trying to find the best time slots for packets transmission and use minimum transmission power for these slots. And it finds that a parameter λ can be used to control the tradeoff between the maximization of successful transmission probability and the minimization of energy cost. Similar to [57], focusing on analyzing the data collection process using mobile base stations, [59] and [60] own the same data gathering method that uses the Query and Response packet which is shown as follows. The Query packet is injected by the mobile base stations and routed to specific area. Then the corresponding Response packet is returned to the base station through multi-hop communication. The difference about these two methods is that the efficient query-based data collection scheme (QB-DCS) in [60] optimizes the method in [59] by choosing the right moment to inject the Query packet and finding a predicted base station position to forward the Response packet. Because the sensors in [57] [58] transmit data to the base station in single hop, sensors should wait for the base station to come into their transmission range, the transmission delay is higher compared with methods in [59] [60] using multi-hop transmission.

Considering the mobile base stations being controllable, the movement pattern of base station is quite critical to efficient gather data to maximize the network lifetime. [61] proposes a novel linear programming algorithm and finds that the network lifetime can be maximized if mobile base stations move and sojourn ceratin times at certain positions calculated by the linear programming algorithm. [62] also studies the movement strategy and concludes that the best movement follows the periphery of the network if the sensors are deployed within a circle. Moreover, it considers jointing mobility and routing to gather data and finds it very useful to improve network lifetime.

2) Mobile relay nodes: [63] [64] research the work using mobile relay nodes to collect data. Relay nodes pick up data from the sensors in close range, buffer the data and drop the data to wireless access points or base stations. Specifically, [63] utilizes a simple model to analyze the key system parameters (e.g., number of relay nodes, sensors and access points) in terms of the data success rate and requires buffer capacities on sensors and relay nodes. More detailed research about system parameters (e.g., relay node mobility pattern, data generation rate, radio characteristics) about the relay nodes and Mule structure in [63] are shown in [64], using a model based on queuing theory. Because sensors must wait for a relay node to approach before transmitting data and relay node then transfer data to access points or base stations, relay nodes method has a natural disadvantage of high latency.

3) Mobile sensor nodes: Mobile sensor nodes is also a quite efficient way to gather data in sparse network. The movement of mobile sensor nodes are carefully researched in [65] [66] [67]. [65] proposes two novel movement methods aiming at reducing the moving distance and improve the data gathering throughput. The first one is the moving-distance-based static topology (MST) method that each node moves from its sensing position to a predetermined position to join a gathering network which can communicate to the base station by multi-hop communication. The second one is the shortest route with negotiation (SR-N) method. Based on a broadcast telling the information about the positions of nodes that have already connected to the base station, other nodes can move to the nearest positions where they can communicate with the base station by multi-hop communication, i.e., joining the gathering network for data transmission. Both MST and SR-N can reduce the moving cost and gather more data, but MST relies on a static environment and achieves less data than SR-N. Targeted to further reduce the moving distance and tolerate node failures for SR-N, a SR-N2 method is shown in [66]. It extends the initial distance between nodes when constructing the gathering network to decrease the moving distance and predicts the nodes' arrival time based on past elapsed time to deal with node failures. In both [65] [66], there are no specific fixed nodes for transmitting data to the base station, [67] originally proposes a DAFTM scheme which uses the combination of mobile nodes and static nodes to efficiently gather data. The data gathered by the mobile nodes are accumulated by these static fixed nodes and the static fixed nodes construct a communication route to transfer the data to the base station. The scheme is very effective to reduce the moving distance and improve throughput. But some further issues (e.g., the initial deployment of static fixed nodes and the handle for node failures in harsh environments) are not solved.

B. Data replication issue

In MWSNs, resulting from the free moving of sensors, harsh environments, sensor depletions, etc, disconnections occur frequently and it will result in network partitions. In such cases, sensors in one of the partitioned network cannot access data in other partitioned networks. One possible solution to deal with the network partition problem to keep high data accessability is to replicate data from other sensors or clients. Improved data accessability by replicating is also an effective way to reduce the bandwidth requirement or energy consumption for query processing in MWSNs. We introduce the data replication issues from two aspects: 1) single hop data replication issues and 2) multiple hop data replication issues.

1) Single hop data replication issues: [68] [69] consider the situation that the mobile computers or mobile clients have access to large number of databases. It is similar with the relationship between mobile base stations and static sensors. Specifically, [68] proposes a dynamic data replication scheme based on the read/write ratio. Read means the behavior that the mobile node access database, write refers to the behavior when database has updates. For every latest k requests, If reads are more frequent, then the mobile node and the database both should have the copy of data, otherwise, only the database should have the copy. Based on caching the frequently accessed data, [69] focuses more on invalidating the caches by periodical broadcasting the reports which contain the database changing information, when mobile nodes are disconnected (e.g, the mobile nodes are out of communication range). Similar work paying more attention to cache invalidation also exist in [70] [71]. [70] also uses a broadcast invalidation report, but the invalidation report should include all recent update information contained in a special group in the database. Using the group method, mobile node in [70] can be disconnected to save energy regardless of the database update. [71] tries to use bit-sequence to dynamically adjust the size of the invalidation report.

2) Multiple hop data replication issues: Assuming multi-hop communication, [72] proposes three replica allocation methods taking the access frequency and the network topology into account. In the static access frequency (SAF) method, mobile hosts replicate data with high access frequencies. The dynamic access frequency and neighborhood (DAFN) method eliminates the replica duplication owned by mobile hosts with less access frequency if there are replica duplication among neighboring mobile hosts in SAF. In the dynamic connectivity based grouping (DCG) method, stable groups are created and replicas are shared in the group. DCG has the highest accessibility and SAF occupies the lowest traffic. Checking the data update in database and stability of radio links among mobile hosts, respectively, extension of the above three methods are presented in [73] and [74]. Accounting for the data correlation between data items, another extension [75] replicates data at mobile hosts with data priority. Considering the access frequency, network topology, data update and user profile, the latest extension is in [76].

IV. Research methods comparisons and further research areas

The comparisons and analysis about different methods we mention above are summarized in Table I II III IV V VI. By conducting this survey, we also find some new interesting researching areas in MWSNs.

Holes avoiding base station repositioning. Random aerial deployment or tough terrains will make it easy to form the coverage holes. During such cases, mobile base stations usually play the role to reposition to certain locations inside the WSNs fixing the hole so as to improve the network lifetime or capacity. However, when the desired repositioning position is inside the hole, mobile base stations actually can not move into the hole for it will result in disconnections between base stations and other sensor nodes or physical level damage to the base stations. How to find one or a set of locations outside the hole which can also improve network lifetime or capacity is very interesting.

Mobility supported localization technologies. Localization methods in MWSNs generally take mobile base stations or mobile sensors nodes as anchor nodes to perform localization. Using mobile cluster heads as seed nodes is worth a try.

Mobile base station based continuous object tracking. Existent target tracking methods in MWSNs mainly focus on gathering the target energy signal using mobile sensor nodes while base stations are generally static. Tracking objects using mobile base stations is also very promising. During the movement of mobile base stations, the energy signal of objects can be continuously measured. It seems to be more direct and accurate.

Data gathering using multiple mobile base stations. When multiple controllable mobile base stations exist in the network, they can collaboratively gather sensor data. Efficient collaborative method to gather data by multiple base stations will be an interesting and challenging research topic.

Mobility-aware in-network query processing. Various kinds of advanced in-network query processing (e.g, k-nearest neighbor, top-k, skyline queries) have been studied to efficiently acquire data in static WSNs. In MWSNs, several new research issues about querying should be addressed, such as the mobility-aware query routing and specialized queries based data replication.

Mobile multimedia sensor networks (MMSNs). The availability of low cost hardware (e.g, CMOS cameras and microphones) will enable a new mobile multimedia sensor network (MMSN) [77]. It has great potential for utilizing a number of mobile multimedia sensor nodes to enhance the network capacity to retrieve multimedia event (e.g., video, audio streams, images), such as the Mobile Sensor Platform from AICIP laboratory at the Electrical Engineering and Computer Science Department of the University of Tennesses which is shown in Figure 3. For MMSNs, the large size of the multimedia streams need multiple and stable paths for transmission. This is also a rather tough but interesting issue.

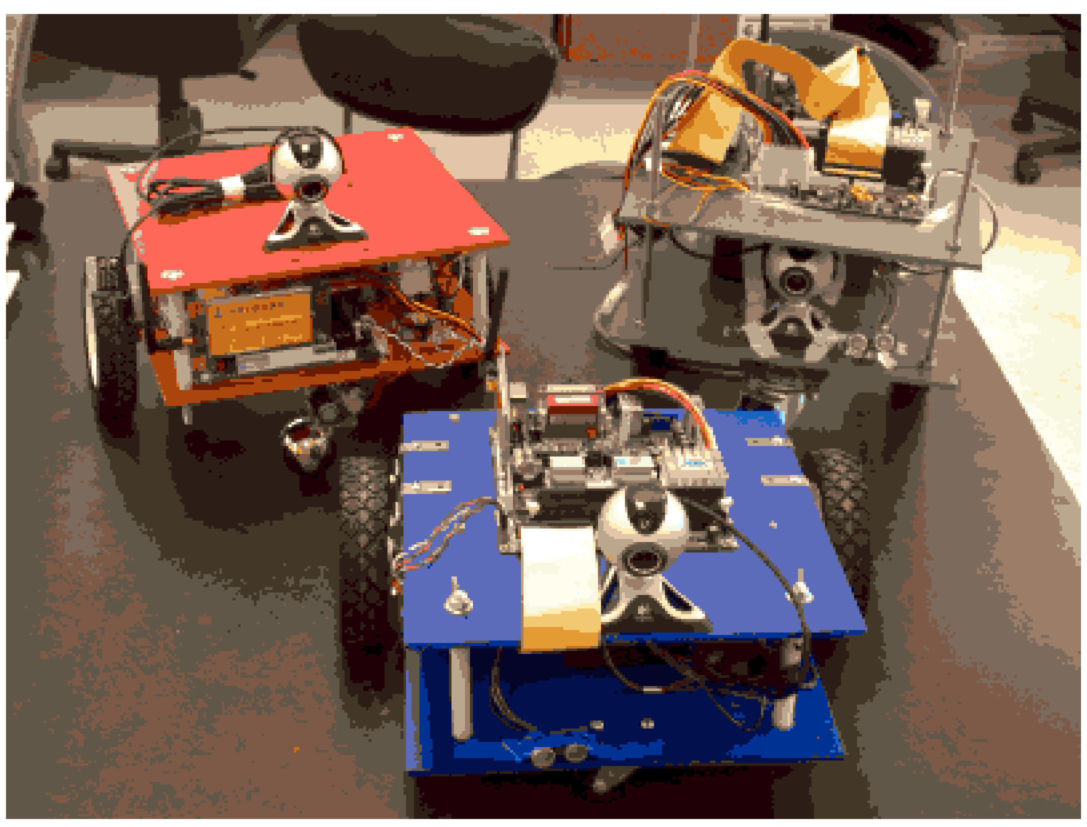

Fig. 3. Both mobility function and multimedia function are available in these Mobile Sensor Platforms (MSP), which can be considered as mobile multimedia sensor nodes.

V. Conclusions

The inspiring potential applications of WSNs make WSNs get boundless attention. Although WSNs are developing quite fast with the development of hardware and communication technologies, the static network property of WSNs results in some inherent limitations (e.g, network connectivity, network lifetime). What's more, a lot of new and more intelligent applications appeal the networks to be mobile. However, about the research on mobile wireless sensor networks (MWSNs), no comprehensive survey is provided. In this paper, we survey the communication and data management issues with respect to MWSNs. Specifically, we research the topology control, coverage, localization, target tracking for communication as well as data gathering and data replication about data management. Further quite interesting and valuable areas about MWSNs are also proposed. We believe that our work can offer a useful overview about the research and development of MWSNs.

VI. Acknowledgement

Lei Shu's research in this paper was supported by Grant-in-Aid for Scientific Research (S) (21220002) of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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Method name	Mobile-entity	Mobility-paradigm	Deterministic	Centralized/Districuted	Characteristics	Function	Network model
Zhao'06t []	All	Controllable	Yes	Centralized	Polynomial	MINMAX	SMN
Zhao'06t []	All	Controllable	Yes	Centralized	Polynomial	MINMAX	CRMN
Li'08 []	All	Controllable	Yes	Both	Polynomial	MINMAX	VRMN
Zhao'06d []	All	Unpredictable	No	Both	Rerunning the aglorithm	MINMAX	DMN
Wu'06 []	All	Unpredictable	No	Distributed	Buffer zone	MINMAX	RWN

TABLE I
TOPOLOGY CONTROL METHODS COMPARISON

Method name	Mobile-entity	Mobility-paradigm	Purpose	Characteristics	Real-time	Real-sensor-implementation	Centralized/Districuted
Wang'04m []	All	Controllable	Self-deployment	Movement-assisted	No	No	Distributed
Wang'03 []	All	Controllable	Self-deployment	Movement-assisted	No	No	Distributed
Wang'04p []	All	Controllable	Self-deployment	Movement-assisted	No	No	Distributed
Howard'02 []	All	Controllable	Self-deployment	Potential-fields	Yes	No	Distributed
Popa'04 []	All	Controllable	Self-deployment	Potential-fields	Yes	No	Distributed
Poduri'04 []	All	Controllable	Self-deployment	Potential-fields	Yes	No	Distributed
Zou'03 []	All	Controllable	Self-deployment	Virtual-force	No	No	Centralized
Chen'07 []	All	Controllable	Self-deployment	Virtual-force	No	No	Centralized
Wang'05 []	All	Controllable	Relocation	Grid-Quorum	Yes	No	Distributed
Teng'07 []	All	Controllable	Relocation	Grid-Quorum	Yes	Yes	Distributed
Li'06 []	All	Controllable	Relocation	Flooding and ZONE	Yes	No	Distributed
Li'07 []	All	Controllable	Relocation	Mesh	Yes	No	Distributed

TABLE II
COVERAGE METHODS COMPARISON

Method name	Mobile-entity	Mobility-paradigm	Range-based/free	Characteristics	GPS	Anchor	Centralized/Distributed
Ackan'06 []	All	Unpredictable	Range-based	Compass	No	No	Distributed
Xu'07 []	All	Unpredictable	Range-free	Accelerometer	No	No	Distributed
Hu'04 []	All	Unpredictable	Range-free	Mobility-assisted	Yes	Yes	Distributed
Baggio'06 []	All	Unpredictable	Range-free	Mobility-assisted	Yes	Yes	Distributed
Shigeng'08 []	All	Unpredictable	Range-free	Mobility-assisted	Yes	Yes	Distributed

TABLE III
LOCALIZATION METHODS COMPARISON

Method name	Mobile-entity	Mobility-paradigm	Main purpose	Characteristics
Liu'03 []	All	Controllable	Detection initiation	Group
Chen'04 []	All	Controllable	Detection initiation	Cluster
Chin'05 []	All	Controllable	Detection analysis	Exposure
Chin'06 []	All	Unpredictable	Detection analysis	Latency
Olfati-Saber'07 []	All	Controllable	Mobility model	Flocking-based
Tan'08 []	All	Controllable	Mobility model	Reactive
Xing'08 []	All	Controllable	Mobility model	Data-fusion

TABLE IV
TARGET TRACKING METHODS COMPARISON

Method name	Mobile-entity	Mobility-paradigm	Communication hop	Characteristics
Chakrabarti'03 []	Mobile base stations	Predictable	Single	Queuing system
Song'06 []	Mobile base stations	Predictable	Single	Scheduling
Tacconi'07 []	Mobile base stations	Predictable	Multiple	Query-based Routing
Cheng'09 []	Mobile base stations	Predictable	Multiple	Query-based Routing
Wang'05 []	Mobile base stations	Controllable	Multiple	Linear programming
Luo'05 []	Mobile base stations	Controllable	Multiple	Joint mobility and routing
Shah'03 []	Mobile relay nodes	Unpredictable	Multiple	Mule structure
Jain'06 []	Mobile relay nodes	All	Multiple	Mule structure
Shinjo'08 []	Mobile sensor nodes	Controllable	Multiple	Moving distance and throughput
Shinjo'09 []	Mobile sensor nodes	Controllable	Multiple	Moving distance and throughput
Treeprapin'09 []	Mobile sensor nodes	Controllable	Multiple	Moving distance and throughput

TABLE V
DATA GATHERING METHODS COMPARISON

Method name	Mobile-entity	Mobility-paradigm	Communication hop	Characteristics	Cache invalidation
Huang'94 []	Mobile base stations	All	Single	Read and write frequency	Yes
Barbará'94 []	Mobile base stations	All	Single	Access frequency	Yes
Wu'96 []	Mobile base stations	All	Single	Access frequency	Yes
Jing'97 []	Mobile base stations	All	Single	Access frequency	Yes
Hara'01 []	Mobile base stations	Unpredictable	Multiple	Access frequency (AF), network topology (NT)	No
Hara'03r []	Mobile base stations	Unpredictable	Multiple	AF, NT, data update	Yes
Hara'03d []	Mobile base stations	Unpredictable	Multiple	AF, NT, radio link	No
Hara'04 []	Mobile base stations	Unpredictable	Multiple	AF, NT, data correlation	No
Hara'06 []	Mobile base stations	Unpredictable	Multiple	AF, NT, data update, user profile	Yes

TABLE VI
DATA REPLICATION METHODS COMPARISON

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