ABSTRACT

Wireless sensor networks (WSNs) which is proposed in the late 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 communication 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 the communication and data management issues in MWSNs. In this paper, focusing on researching the communication issues and data management issues in MWSNs, we discuss different research methods regarding communication and data management in MWSNs and propose some further open research areas in MWSNs. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
wireless sensor networks (WSNs); mobile wireless sensor networks (MWSNs); survey; communication; data management

1. 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 (e.g., temperature, sound, vibration, pressure, motion), 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, and so on [2]. With the advancement in micro-electromechanical 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 or 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 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 is more, applications with the help of mobility will definitely make them become smarter and create some new applications [4–6]. 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 cannot 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 so on. Mobility also can enable some new applications (e.g., social interaction, miscellaneous applications).

Mobile wireless sensor networks (MWSNs) are a new class of wireless networks where small sensors move in space over time. There are four possible mobile entities in MWSNs, namely, mobile base stations, mobile sensor nodes, mobile relay nodes, and mobile cluster heads [7].

There are three mobile paradigms in MWSNs [7].

- **Controllable movement.** The movement which is planned and controlled (e.g., mobile base stations move to the nearest sensor to collect data) is controllable movement.
- **Predictable movement.** If the movement of a mobile entity has a clear direction or track (e.g., sensors transmit data on moving cars), then the movement is predictable movement.
- **Unpredictable movement.** 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).

The characteristics of MWSNs are as follows [4–6]:

- **More dynamic topology.** Because nodes generally are mobile in MWSNs, the topology is dynamic. New routing and Medium access control (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, and so on 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.

The advantages of MWSNs are shown as follows [4–6]:

- **Long network lifetime.** Because sensors can move, they will make the transmission more disperse and energy dissipation more efficient so as to get rid 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 increase linearly with the number of sensors.
- **Better targeting.** Because 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.

To the best of our knowledge, there is not a comprehensive survey about the communication and data management issues of MWSNs for the state of art. The main contribution of this paper is that we present a synthetic survey about the communication and data management issues in MWSNs. Specifically, as shown in Figure 1, the topology control, coverage, localization, and target tracking issues regarding communication are discussed. The data gathering and replication methods with respect to data management are analyzed. Furthermore, we also provide some open interesting research areas in MWSNs.

For the rest of this paper, Sections 2 and 3 present the research issues and methods about communication and data management in MWSNs, respectively. Section 4 offers some further open research problems in MWSNs; and we conclude this paper in Section 5.

## 2. COMMUNICATION ISSUES

### 2.1. 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 that the assignment of transmission power to nodes aims to achieve [8]. 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. According to the certainty of the resultant network topology, they can be categorized into the following: (i) deterministic algorithm method; and (ii) nondeterministic algorithm method.

#### 2.1.1. Deterministic algorithm method.

About the deterministic algorithm method, [9,10] propose the first theoretical results for topology control incorporating mobility. Specifically, the network model in [9] is a simple network model, where there is one moving node and n static nodes, whereas the network model in [10] is a constant rate mobile network 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
[9,10] make extension of the topology control algorithm for static WSNs in [11,12]. The insight of that algorithm named as MINMAXGRAPH by [9,10] 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 that can keep network connectivity. Based on that, [9] and [10] further suppose that 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 MINXMAXGRAPH method. Further improving algorithm running time methods are also developed in [9] and [10], mainly by avoiding the explicit construction of threshold graphs and computing the MINMAX edge incrementally rather than independently. Moreover, as [10] focuses on constant rate mobile network, [10] further slices the unit time interval into constant-connectivity and constant-order time slots, thus connectivity can be further checked for individual time slot. Different from the methods which find the minimum maximum power shown in [9] and [10], aiming to solve more practical topology control problem resulting from variant rate mobile sensor network instead of constant rate mobile network, [13] 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 one-hop relay of its closer neighbors to reduce the power to keep connectivity. With that, there is a breadth first search to determine whether the resultant topology 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 limitations of the algorithms in [9,10,13] are their assumption about dividing whole network lifetime into unit time intervals and the suitability to unique network model.

2.1.2. Nondeterministic algorithm method.

Targeted to analyze the topology control for the disk mobile network in which there are $n$ moving nodes without specific moving direction; [8] presents us another type of topology control algorithms which are nondeterministic. Those algorithms also try to divide the whole time into unit time intervals and minimize the maximum power assigned to each node throughout each time interval; but their main mechanisms are 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. What is more, focusing on extending many existing mobility-insensitive protocols into random waypoint [14] networks, [15] introduces two mechanisms to deal with the inconsistent and outdated information resulting from mobility which are also nondeterministic. Specifically, consistent local views using either synchronous or asynchronous ‘Hello’ messages are enforced to keep the topology logical. 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 [8] and [15], the main drawbacks are the difficulties to choose the appropriate frequency of rerunning the algorithm or the appropriate value of redundant transmission range. To deal with these two difficulties, [16] considers utilizing explicit coordinations between neighboring nodes to replace the periodically rerunning phase or dynamically adjusting transmission power method to produce similar topology control results in [8,15].

**Summarization:** As shown in Table I, although deterministic algorithm methods tend to result in more deterministic topologies compared with nondeterministic algorithm methods, deterministic algorithm methods are based on a strong assumption that the whole network lifetime can be divided into intervals. New topology control methods which are both practical and deterministic are needed.

### 2.2. Coverage issue

Coverage is one fundamental design and application factor in MWSNs as shown in Figure 2. Measured by the overall area, a WSN is monitoring, not only sensor coverage closely related to the quality of service that the network can provide, but also strongly affect the application (e.g., localization, target tracking) performance of MWSNs. Sensor coverage is mainly weakened by unfavorable initial deployments 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 conditions and sensor failures, sensors should have the ability to keep coverage. There are two methods to achieve this goal. The first one is (i) self-deployment which means sensors autonomously adjust their positions to improve coverage after their initial deployment. The other one is (ii) relocation referring to strategically relocate some redundant sensors to fill the position of failed nodes to enhance coverage.

#### 2.2.1. Self-deployment method.

Based on the self-deployment source (e.g., movement, potential field), the self-deployment method in MWSNs can be discussed according to the following more
detailed categories: movement-assisted methods, potential-field methods, and virtual-force methods.

Movement-assisted methods: [17] shows us a classical 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 for improving coverage. Specifically, it uses the Voronoi diagrams [18,19] to discover the coverage holes and proposes three movement-assisted sensor deployment protocols, VECtor based (VEC), VORonoi based (VOR), 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 the sensor away from a densely covered area if the sensors are too close, VOR pulls the 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 [17] equip every sensor with a motor which increases 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, [20] deploys a mixture of mobile and static sensors and then introduces a bidding protocol. In the protocol, static sensors detect coverage holes using the Voronoi diagrams and bid them for mobile sensors based on the size of the detected hole. Mobile sensors choose the highest bid and move to heal the largest hole. The process stops until no static sensor gives 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, sensors may move in a zigzag way which wastes a lot of energy as the sensors do not move to the final location directly. Then, in [21], 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. [21] can reduce the energy consumption and also keep good coverage. But for all the three methods, they do not 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 [22], the potential field approach can also be employed to achieve self-deployment [23]. 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 converged to a state of equilibrium using the method. Based on the potential fields, [24,25] investigate the strategy to maximize the coverage with certain constraints, such as the $K$ neighbors each node should at least have in [25].

Virtual force methods: Virtual force algorithm (VFA) is inspired by disk packing theory [26] and the virtual force
potential field concept from robotics [23]. VFA algorithms generally model the interactions among sensors as a combination of attractive (positive) and repulsive (negative) forces and attempt to maximize the coverage using these forces. Sensors do not physically move until effective positions are identified. Specifically, predetermined 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 [27]. What is more, sensors in [27] are also subjected to forces exerted by obstacles and preferential coverage. Improved VFA algorithms are introduced in [28] considering the convergence, the boundary in the region of interest, and the virtual force effective distance. For both [27] and [28], they suffer from the oscillatory sensor behaviors, for example, sensors may collide when they are not stable at the desirable threshold. Moreover, networks in [27] and [28] are cluster based, and the cluster head is responsible for executing the algorithm which suffers from the sing point failure.

### 2.2.2. Relocation method.

In order to achieve relocation, [29] proposes a two-phase solution including finding the redundant sensors first 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 [30], the whole grid 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 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 that 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 [29] which has good relocation time and energy consumption, [31] presents us the real mobile sensor design and relocation process based on the popular sensor node platform Mica2 [32] and mobile robot built with commercial off-the-shelf components. However, the relocation methods in [29] and [31] both need strong preknowledge about sensing field which affects the practicability, and they may fail if there are void areas in the sensing field. A variant of the Grid-quorum method in [29] [31] named a zone-based sensor relocation protocol (ZONER) is shown in [33], 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 nonconstant storage load in [29,31,33], [34] proposes a mesh-based sensor relocation protocol (MSRP) to discover the redundant sensors and fulfill the node relocation in a shifted way which has a better relocation path compared with the cascaded way in [29,31,33]; MSRP can also gain guaranteed nearby replacement node discovery and node replacement. Furthermore, [35] tries to minimize the relocation task completion time in [34], by relocating the close node to the task location and utilizing some redundant intermediate nodes to help the close node connect the sink.

### Summarization:

Self-deployment and relocation are both very effective to keep coverage. A comparison of the aforementioned coverage methods is presented in Table II. As for self-deployment method, potential field methods own better real-time performance than movement-assisted methods and virtual force methods. However, the sensor failure issue should be well deal with for all self-deployment methods. Regarding relocation method, the energy consumption should be minimized during the process to find the redundant sensors as well as relocate them.

### 2.3. Localization issue

Localization issue is significant for WSNs, as many application of WSNs (e.g., target tracking, environment monitoring) rely on the locations of sensors to perform further tasks. Location awareness can also enhance the performance of routing protocols and security [36]. Because mobility generally increases the uncertainty of nodes, localization in MWSNs as shown in Figure 3 is assumed more difficult; but some algorithms try to exploit mobility to improve location accuracy [36–38]. According to whether the localization method is range based and mobility-assisted, localization algorithms in MWSNs can be classified into the following: (i) range-based method; (ii) range-free method; and (iii) mobility-assisted range-free method.

#### 2.3.1. Range-based method.

Range-based method refers to the method which uses distance estimates or angle estimates to achieve localization. Specifically, it exploits time of arrival (TOA) [39], received signal strength [40,41], time difference of arrival of two different signals (TDOA) [42] or angle of arrival (AOA) [43]. As most range-based techniques require specific hardware (e.g., ultrasound device required by TDOA, antenna arrays required by AOA), the localization cost are generally expensive and they all need some seeds or anchor nodes which know their own positions by global positioning system (GPS). However, [44] 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 moving direction and distance during the round. The algorithm is quite accurate and requires constant storage per one-hop neighbor during localization.

### 2.3.2. Range-free method.

Range-free method depends only on the content of received messages and is the alternative to the more expensive range-based method [45]. There are two main types of range-free localization methods [36]: local and hop counting techniques. Local techniques rely on a high density of seeds (e.g., Approximate Point-In-Triangulation Test (APIT) [45]), and hop-counting techniques rely on flooding the network (e.g., DV-HOP [46]). Recently, there are some derivates of hop-counting techniques considering mobile nodes (e.g., Elastic Localization Algorithm (ELA) [47]). Rather than paying particular attention to group movement in [44], taking advantage of accelerometers in standard motes, [48] proposes a GPS-free, range-free localization algorithm named Mobile Geographic Distributed Localization (MGDL) for MWSNs. First, a local map is constructed by using the hop coordinates [49] (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 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 merging process transforming the local map into a global map will be redone again based on the acceleration. MGDL achieves good performance regarding localization accuracy, coverage, and communication overhead.

### 2.3.3. Mobility-assisted range-free method.

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 [36] first takes advantage of the mobility to improve localization accuracy for range-free method. Based on the key idea of Monte Carlo localization [50,51] and Sequential Monte Carlo [52] that is representing the posterior distribution using a set of weighted samples and updating the distribution using filtering and resampling methods, [36] 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 movements. In the filtering step, nodes use new information they observe to filter impossible locations. Resampling step is 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 [37,38] to further reduce the computation cost and improve the location accuracy in [36], mainly by using a box to reduce the scope of searching candidate samples. Furthermore, based on the previous MCL methods, the fuzzy logic is applied into the localization phase in [53] in order to formulate the fuzzy-grid prediction so as to achieve localization in challenging environments.

Summary: Both range-based methods and range-free methods generally require GPS and anchor nodes. Range-based methods are generally with expensive cost as they require special hardware. As described in Table III, some new methods (e.g., [44]) which can reduce the special hardware cost for range-based methods should be proposed. As for range-free methods, they are less expensive compared with the range-based method; and the mobility of sensor nodes can be utilized by range-free methods to further improve the localization accuracy. However, the requirement of GPS and anchor nodes is still a bottleneck for all range-free methods. Other GPS-free, range-free localization methods (e.g., [48]) should be put forward. Moreover, currently, there is no GPS-free, mobility-assisted range-free localization method.

2.4. Target tracking issue

Target tracking is one of the most important applications of MWSNs as shown in Figure 4. Generally, sensors detect targets by measuring the energy of signals emitted by the targets. The probabilities of false alarm and detection are the main performance metrics of detection. Low detection delay, low detection time, and so on are also desirable characteristics of target tracking. Based on the specific problem target tracking methods research, we classify current target tracking issue into the following three more detailed categories: (i) detection initiation issue; (ii) detection analysis issue; and (iii) mobility model issue.

Table III. Localization methods comparison.

<table>
<thead>
<tr>
<th>Method name</th>
<th>Mobile entity</th>
<th>Mobility paradigm</th>
<th>Range based/free</th>
<th>Characteristics</th>
<th>GPS</th>
<th>Anchor</th>
<th>Centralized / distributed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ackan’06 [44]</td>
<td>All</td>
<td>Unpredictable</td>
<td>Range based</td>
<td>Compass</td>
<td>No</td>
<td>No</td>
<td>Distributed</td>
</tr>
<tr>
<td>Xu’07 [48]</td>
<td>All</td>
<td>Unpredictable</td>
<td>Range free</td>
<td>Accelerometer</td>
<td>No</td>
<td>No</td>
<td>Distributed</td>
</tr>
<tr>
<td>Hu’04 [36]</td>
<td>All</td>
<td>Unpredictable</td>
<td>Range free</td>
<td>Mobility assisted</td>
<td>Yes</td>
<td>Yes</td>
<td>Distributed</td>
</tr>
<tr>
<td>Baggio’06 [37]</td>
<td>All</td>
<td>Unpredictable</td>
<td>Range free</td>
<td>Mobility assisted</td>
<td>Yes</td>
<td>Yes</td>
<td>Distributed</td>
</tr>
<tr>
<td>Shigeng’08 [38]</td>
<td>All</td>
<td>Unpredictable</td>
<td>Range free</td>
<td>Mobility assisted</td>
<td>Yes</td>
<td>Yes</td>
<td>Distributed</td>
</tr>
<tr>
<td>Chenji’10 [53]</td>
<td>All</td>
<td>Unpredictable</td>
<td>Range free</td>
<td>Mobility assisted</td>
<td>Yes</td>
<td>Yes</td>
<td>Distributed</td>
</tr>
</tbody>
</table>

GPS, global positioning system.
2.4.1. Detection initiation issue.

To efficiently utilize network resources for target tracking, [54] 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 trade-off between performance and scalability compared with traditional centralized schemes which move all sensor data to one central site. Moreover, [55] devises a hierarchical network architecture for tracking the 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). 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.

2.4.2. Detection analysis issue.

In order to analyze the detection exposure which refers to the region covered by the sensor network for detection, [56] proposes algorithms utilizing the time expansion graph to find the upper and lower bound on exposure for any sensor route plan and sensing schedule with and without the presence of obstacles. Similarly, [57] 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.

2.4.3. Mobility model issue.

Olfati-Saber [58] shows us the benefits of a flocking-based mobility model about improving tracking performance, by trying to achieve target tracking based on the distributed Kalman filtering algorithm introduced in [59]. 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, [60] 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 [61], and it proposes an optimal sensor movement scheduling algorithm to minimize the total moving distance of sensors in [60].
Summarization: Target tracking is a very complex task with great potential for MWSNs. From Table IV, we can obtain that different detection initiation, detection analysis methods, and mobility models can strongly affect the performance of target tracking. More researches should be conducted to explore more aspects of this issue.

3. DATA MANAGEMENT ISSUES

3.1. Data gathering issue

Data gathering is the most basic and essential task of MWSNs as shown in Figure 5. Different mobile entities require different data gathering methods. As there are few researches about data gathering using mobile cluster heads, we analyze the data gathering issue with the following three methods: (i) mobile base stations method; (ii) mobile relay nodes method; and (iii) mobile sensor nodes method.

3.1.1. Mobile base stations method.

As predictable mobility is a good model for public transportation vehicles (e.g., busses, shuttles and trains) because they can act as mobile observers in MWSNs, [62] shows the significant power saving using predictable mobile base station WSNs over static WSNs, with a queuing system which models the data collection process. Sensors can transmit data to the mobile base station if the base station is not busy. Once the mobile station starts communication with the sensor, it will not listen to any other node that may come within the communication range. Aiming to gather all the information packets with minimum energy consumption using predictable mobile base stations, [63] proposes a transmission scheduling algorithm trying to find the best time slots for packet transmissions and use minimum transmission power for these slots. It concludes that a parameter \( \lambda \) can be used to control the trade-off between the maximization of successful transmission probability and the minimization of energy cost. Similar to [62], focusing on analyzing the data collection process using mobile base stations, [64] and [65] own the same data gathering method that uses the Query and Response packet which is illustrated as follows. The Query packet is injected by the mobile base station and routed to a specific area. Then, the corresponding Response packet is returned to the base station through multihop communication. The difference about these two methods is that the efficient query-based data collection scheme in [65] optimizes the method in [64] 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 [62,63] 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 the methods in [64,65] using multihop transmission.

Considering the mobile base stations being controllable, the movement pattern of base station is quite critical to efficiently gather data to maximize the network lifetime. Wang et al. [66] propose a novel linear programming algorithm and finds that the network lifetime can be maximized, if mobile base stations move and sojourn certain times at certain positions calculated by the linear programming algorithm. Luo and Hubaux [67] 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 that it is very useful to improve network lifetime. Recently, [68] proposes a mobile-based station data gathering method with constrained path. It finds that it can first utilize a discover phase to find the maximum shortest paths with subsinks and then perform the data gathering task according to the found shortest paths to increase the total data gathering throughput.

3.1.2. Mobile relay nodes method.

Shah et al. [69] and Jain et al. [70] research the method 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, [69] 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 (the fraction of generated data that reaches the access points) and the required buffer capacities on sensors and relay nodes. Using a model based on queuing theory, [70] shows more detailed research about the system parameters (e.g., relay node mobility pattern, data generation rate, radio characteristics) of the relay nodes and Mule structure in [69]. Because sensors must wait for a relay node to approach before transmitting data and relay nodes then transfer data to access points or base stations, relay nodes method has a natural disadvantage of high latency.

3.1.3. Mobile sensor nodes method.

Mobile sensor nodes method is also a quite efficient way to gather data in sparse network. The movement of mobile sensor nodes are carefully researched in [71–73]. Shinjo et al. [71] propose two novel movement methods aiming at reducing the moving distance and improving the data gathering throughput. The first one is the moving distance-based static topology (MST) method, in which each node moves from its sensing position to a pre-determined position to join a gathering network which can communicate with the base station by multihop 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 multihop communication; that is, 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, an SR-N2 method
Table IV. Target tracking methods comparison.

<table>
<thead>
<tr>
<th>Method name</th>
<th>Mobile entity</th>
<th>Mobility paradigm</th>
<th>Main purpose</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liu’03 [54]</td>
<td>All</td>
<td>Controllable</td>
<td>Detection initiation</td>
<td>Group</td>
</tr>
<tr>
<td>Chen’04 [55]</td>
<td>All</td>
<td>Controllable</td>
<td>Detection initiation</td>
<td>Cluster</td>
</tr>
<tr>
<td>Chin’05 [56]</td>
<td>All</td>
<td>Controllable</td>
<td>Detection analysis</td>
<td>Exposure</td>
</tr>
<tr>
<td>Chin’06 [57]</td>
<td>All</td>
<td>Unpredictable</td>
<td>Detection analysis</td>
<td>Latency</td>
</tr>
<tr>
<td>Olfati-Saber’07 [58]</td>
<td>All</td>
<td>Controllable</td>
<td>Mobility model</td>
<td>Flocking based</td>
</tr>
<tr>
<td>Tan’08 [60]</td>
<td>All</td>
<td>Controllable</td>
<td>Mobility model</td>
<td>Reactive</td>
</tr>
<tr>
<td>Xing’10 [61]</td>
<td>All</td>
<td>Controllable</td>
<td>Mobility model</td>
<td>Data-fusion</td>
</tr>
</tbody>
</table>

Figure 5. Data gathering issues of mobile wireless sensor networks.

is shown in [72]. It extends the initial distance between nodes, by constructing the gathering network to decrease the moving distance as well as predicts the nodes’ arrival time based on past elapsed time to deal with node failures. In both [71,72], there are no specific fixed nodes for transmitting data to the base station. However, in [73], a scheme named Data Acquisition and Transmission with Fixed and Mobile node (DATFM), which uses both the mobile and static fixed nodes, is originally proposed 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 handling for node failures in harsh environments) are not solved.

**Summarization:** As presented in Table V, mobile base stations, mobile relay nodes, and mobile sensor nodes are three major and very effective methods to gather data in MWSNs. The mobility patterns of the mobility entities in these three methods are critical for the performance of these methods. Data gathering throughput, data gathering cost, and data gathering time are the most important performance metrics for data gathering. Data gathering methods (e.g., mobile base station and mobile sensor node-based data gathering method) which combine different mobile entities are very prospective. Moreover, using the mobile cluster heads to gather data also has potential and is unexplored.

3.2. Data replication issue

In MWSNs, resulting from the free moving of sensors, harsh environments, sensor depletions, and so on, disconnections occur frequently, and they 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 accessibility is to replicate data from other sensors or clients. Improved data accessibility by replication is also an effective way to reduce the...
bandwidth requirement or energy consumption for query processing in MWSNs. In view of the hops during data replication, we introduce the data replication issue from two aspects: (i) single hop data replication issue; and (ii) multiple hop data replication issue.

### 3.2.1. Single hop data replication issue.

About data replication with single hop, [74,75] consider the situation that the mobile computers or mobile clients have access to large number of databases. Specifically, [74] proposes a dynamic data replication scheme based on the read/write ratio. Read means the behavior that the mobile node accesses 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, [75] focuses more on invalidating the caches by periodically 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 [76,77]. Both [76] and [77] also use the broadcast invalidation report. But [76] optimizes the invalidation report by including all recent update information contained in a special group in the database, which can make the mobile nodes be disconnected to save energy regardless of the database update, and [77] centers on adjusting the size of the invalidation report dynamically by using the bit sequence.

### 3.2.2. Multiple hop data replication issues.

Assuming multihop communication, [78] proposes three replica allocation methods taking the access frequency and 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 method eliminates the replica duplication owned by mobile hosts with less access frequencies, if there are replica duplications 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. Extension of the aforementioned three methods are presented in [79] and [80], checking the data update in database and stability of radio links among mobile hosts, respectively. Accounting for the data correlation between data items, another extension method [81] replicates data at mobile hosts with data priority. Considering the access frequency, network topology, data update, and user profile, the latest extension is in [82]. Moreover, given the access frequencies, the number of replicas and the remaining power of mobile hosts, another extension is in [83]. In addition, [84] presents several metrics (e.g., average size of partitions, distribution of partition sizes) to fully investigate the impact of mobility on data replication in MWSNs.

**Summarization:** Data replication is a very powerful way to deal with network partitions and improve query processing in MWSNs. Also, data replication is quite helpful for strengthening data accessibility. Table VI shows the comparison of the data replication methods discussed earlier. Access frequency is the most basic and commonly considered factor during data replication. Apart from access frequency, other elements (e.g., network topology, data update, data correlation, user profile) are also explored for data replication. Potential unexplored internal factors (e.g., replicated sensor memory size) should also be researched when replicating data.

### 4. OPEN RESEARCH PROBLEMS

**Holes avoiding base station repositioning.** Random aerial deployments 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 to fix 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 cannot 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. The way to find one or a set of locations outside the hole which...

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**Table V.** Data gathering methods comparison.

<table>
<thead>
<tr>
<th>Method name</th>
<th>Mobile entity</th>
<th>Mobility paradigm</th>
<th>Communication hop</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chakrabarti'03 [62]</td>
<td>Mobile base stations</td>
<td>Predictable</td>
<td>Single</td>
<td>Queuing system</td>
</tr>
<tr>
<td>Song'06 [63]</td>
<td>Mobile base stations</td>
<td>Predictable</td>
<td>Single</td>
<td>Scheduling</td>
</tr>
<tr>
<td>Tacconi'07 [64]</td>
<td>Mobile base stations</td>
<td>Predictable</td>
<td>Multiple</td>
<td>Query-based routing</td>
</tr>
<tr>
<td>Cheng’09 [65]</td>
<td>Mobile base stations</td>
<td>Predictable</td>
<td>Multiple</td>
<td>Query-based routing</td>
</tr>
<tr>
<td>Wang’05 [66]</td>
<td>Mobile base stations</td>
<td>Controllable</td>
<td>Multiple</td>
<td>Linear programming</td>
</tr>
<tr>
<td>Luo’05 [67]</td>
<td>Mobile base stations</td>
<td>Controllable</td>
<td>Multiple</td>
<td>Joint mobility and routing</td>
</tr>
<tr>
<td>Gao’11 [68]</td>
<td>Mobile base stations</td>
<td>Controllable</td>
<td>Multiple</td>
<td>Shortest path</td>
</tr>
<tr>
<td>Shah’03 [69]</td>
<td>Mobile relay nodes</td>
<td>Unpredictable</td>
<td>Multiple</td>
<td>Mule structure</td>
</tr>
<tr>
<td>Jain’06 [70]</td>
<td>Mobile relay nodes</td>
<td>All</td>
<td>Multiple</td>
<td>Mule structure</td>
</tr>
<tr>
<td>Shinjo’08 [71]</td>
<td>Mobile sensor nodes</td>
<td>Controllable</td>
<td>Multiple</td>
<td>Moving distance and throughput</td>
</tr>
<tr>
<td>Shinjo’09 [72]</td>
<td>Mobile sensor nodes</td>
<td>Controllable</td>
<td>Multiple</td>
<td>Moving distance and throughput</td>
</tr>
<tr>
<td>Taeprapin’09 [73]</td>
<td>Mobile sensor nodes</td>
<td>Controllable</td>
<td>Multiple</td>
<td>Moving distance and throughput</td>
</tr>
</tbody>
</table>
Table VI. Data replication methods comparison.

<table>
<thead>
<tr>
<th>Method name</th>
<th>Mobile entity</th>
<th>Mobility paradigm</th>
<th>Communication hop</th>
<th>Characteristics</th>
<th>Cache invalidation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huang’94 [74]</td>
<td>Mobile base stations</td>
<td>All</td>
<td>Single</td>
<td>Read and write frequency</td>
<td>Yes</td>
</tr>
<tr>
<td>Barbará’94 [76]</td>
<td>Mobile base stations</td>
<td>All</td>
<td>Single</td>
<td>Access frequency</td>
<td>Yes</td>
</tr>
<tr>
<td>Wu’96 [76]</td>
<td>Mobile base stations</td>
<td>All</td>
<td>Single</td>
<td>Access frequency</td>
<td>Yes</td>
</tr>
<tr>
<td>Jing’97 [77]</td>
<td>Mobile base stations</td>
<td>All</td>
<td>Single</td>
<td>Access frequency</td>
<td>Yes</td>
</tr>
<tr>
<td>Hara’01 [78]</td>
<td>Mobile base stations</td>
<td>Unpredictable</td>
<td>Multiple</td>
<td>Access frequency (AF), network topology (NT)</td>
<td>No</td>
</tr>
<tr>
<td>Hara’03r [79]</td>
<td>Mobile base stations</td>
<td>Unpredictable</td>
<td>Multiple</td>
<td>AE NT, data update</td>
<td>Yes</td>
</tr>
<tr>
<td>Hara’03d [80]</td>
<td>Mobile base stations</td>
<td>Unpredictable</td>
<td>Multiple</td>
<td>AE NT, radio link</td>
<td>No</td>
</tr>
<tr>
<td>Hara’04 [81]</td>
<td>Mobile base stations</td>
<td>Unpredictable</td>
<td>Multiple</td>
<td>AE NT, data correlation</td>
<td>No</td>
</tr>
<tr>
<td>Hara’06 [82]</td>
<td>Mobile base stations</td>
<td>Unpredictable</td>
<td>Multiple</td>
<td>AE NT, data update, user profile</td>
<td>Yes</td>
</tr>
<tr>
<td>Shinohara’07 [83]</td>
<td>Mobile base stations</td>
<td>Unpredictable</td>
<td>Multiple</td>
<td>AF replica number, host remaining energy</td>
<td>No</td>
</tr>
<tr>
<td>Hara’10 [84]</td>
<td>All</td>
<td>All</td>
<td>Multiple</td>
<td>Quantifying mobility impact</td>
<td>No</td>
</tr>
</tbody>
</table>

can also improve network lifetime or capacity is a very valuable issue.

**Mobility supported localization technologies.** Localization methods in MWSNs generally take mobile base stations or mobile sensor 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, whereas 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 methods (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 query-based data replication.

**Duty-cycling in mobile WSNs.** Duty-cycled WSNs have great advantage of saving energy consumption, by selecting only a subset of sensor nodes to be awake according to some sleep scheduling algorithms. However, almost all current duty-cycling researches focus on static WSNs rather than MWSNs. Sleep scheduling algorithms which consider the mobility of sensor nodes (e.g., [85]) are very innovative and should be explored.

**Mobile multimedia sensor networks (MMSNs).** The availability of low cost hardware (e.g., CMOS cameras and microphones) will enable a new MMSN [7,86,87]. It has great potential for utilizing a number of mobile multimedia sensor nodes (e.g., the Mobile Sensor Platform from AICIP laboratory at the Electrical Engineering and Computer Science Department of the University of Tennessee shown in Figure 6) to enhance the network capacity to retrieve multimedia (e.g., video, audio stream, image). For MMSNs, the large size of the multimedia stream need multiple and stable paths for transmission. This is also a rather tough but interesting issue.

**Healthcare with mobile WSNs.** Healthcare is always a hot research topic in WSNs [88]. In mobile WSNs, because sensors can move, mobile sensors (e.g., mobile robots) can be utilized to collect multimedia data (body signal, video, etc.) for human health monitoring. Also, mobile robots can be used to assist patients with respect to their living (e.g., drinking and walking). This is a very worthy issue and research attention should be paid to explore this aspect.

![Figure 6.](image_url) Mobile Sensor Platforms have both mobility and multimedia functions; they can be considered as mobile multimedia sensor nodes.
5. 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 is more, a lot of new and more intelligent applications appeal the WSN to be mobile. However, about the research on MWSNs, no comprehensive survey about communication and data management is provided. In this paper, we survey the communication and data management issues with respect to MWSNs. Particularly, we research the topology control, coverage, localization, target tracking for communication issue of MWSNs, as well as data gathering and data replication about data management issue of MWSNs. Further, quite interesting and valuable open research areas about MWSNs are also proposed. We believe that our work can offer a useful overview about the research and development of MWSNs.

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REFERENCES

distributed, scalable solution to the area coverage problem, In Proceedings of DARS, 2002; 299–308.
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