Distributed Mobile Sink Routing for Wireless Sensor Networks: A Survey

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***Abstract*—The concentration of data traffic towards the sink in a wireless sensor network causes the nearby nodes to deplete their batteries quicker than other nodes, which leaves the sink stranded and disrupts the sensor data reporting. To mitigate this problem the usage of mobile sinks is proposed. Mobile sinks implicitly provide load-balancing and help achieving uniform energy-consumption across the network. However, the mechanisms to support the sink mobility (e.g., advertising the location of the mobile sink to the network) introduce an overhead in terms of energy consumption and packet delays. With these properties mobile sink routing constitutes an interesting research field with unique requirements. In this paper, we present a survey of the existing distributed mobile sink routing protocols. In order to provide an insight to the rationale and the concerns of a mobile sink routing protocol, design requirements and challenges associated with the problem of mobile sink routing are determined and explained. A definitive and detailed categorization is made and the protocols' advantages and drawbacks are determined with respect to their target applications.**

***Index Terms*—Mobile Sinks, Distributed Routing, Wireless Sensor Networks**

I. Introduction

ENERGY efficiency is the most important issue for wireless sensor networks (WSN) since sensor nodes have limited batteries. Replacing the batteries of sensor nodes is likely to require significant effort; therefore, WSNs have to be able to operate without human intervention for an adequately long time. In WSNs with static (immobile) sinks, the nodes close to the sinks are more likely to deplete their battery supplies before other nodes due to the intersection of multi-hop routes and concentration of data traffic towards the sinks. This problem is referred to as the hotspot problem [1], [2]. Node deaths would lead to disruptions in the topology and reduction of sensing coverage. Moreover, sinks could become isolated and sensor data generated across the network would no longer be obtained. Therefore, routing protocols designed for immobile sinks have to incorporate load-balancing in order to achieve uniformity of energy consumption throughout the network. The usage of mobile sinks is proposed and explored as a possible solution to this problem [3]–[7].

Mobile sinks implicitly provide load balancing without extra effort [8]. The hotspots around the sink change as the sink moves, and the increased energy drainage around the sink is spread through the network which helps achieving uniform energy consumption and thereby extending the network lifetime.

Sparse and disconnected networks can be better handled with mobile sinks [9]. Mobile sinks could obtain sensor data from isolated portions of the network which might otherwise be inaccessible in a static sink case, thus enhancing the connectivity of the network. Acquiry of data from loosely connected portions of the network can be achieved by mobile sink routing protocols with much less effort than the conventional static sink routing protocols which spend excessive resources to cope with such topologies [10]. Sink mobility also reduces the number of hops on data routes, especially in delay-tolerant applications, where data aggregation nodes are utilized which wait and disseminate data when the sink gets closer at a cost of increased delays. Shorter data dissemination paths lead to increased throughput and reliability together with decreased energy consumption. Other advantages of sink mobility include security benefits. Compromise of mobile sinks are much more difficult than static sinks [9]. An adversary would have to locate and chase a mobile sink carrier to damage the sink or retrieve any sensitive information. Attacks relying on intercepting the wireless transmissions are more difficult as well, since such an interception device have to catch up with the sink and follow it in order to overhear data packets received by the sink.

The advantages of mobile sinks do however come at a cost. Advertising the changing location of the sink freshly across the network is not trivial. The overhead of this operation should not exceed a certain limit in order not to diminish the advantages of the energy savings due to the usage of mobile sinks. Some approaches support the sink mobility by disseminating data redundantly through multiple nodes rather than advertising the sink's location to the source nodes, which may result in a similarly critical overhead. The routing protocols designed for WSNs with mobile sinks should minimize the energy overhead of such operations while avoiding an extreme increase in the sensor data delivery latencies which is especially important for real-time WSN applications.

An example usage scenario for WSNs with mobile sinks is fire detection systems [11]. A fire detection system consists of numerous sensor nodes deployed on a forest area and one or several mobile sinks. Sensor nodes report temperature or humidity in a periodic manner. In case of a fire, the sensors detecting a drastic change of sensor values go into alarm mode and increase their reporting frequency. The mobile sink(s) could be placed on a motorized vehicle or be carried by a

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human. The sink could then be moved across the forest to gather the periodic reports generated by the sensors or around the forest if the terrain is not suitable for navigation. Mobile sinks carried by fire-fighters would assist them in their efforts towards extinguishing the forest fire by providing them with fresh and detailed information about the area of interest.

Other application scenarios of mobile sinks include habitat monitoring. The mobile sink might be deployed on a robot that collects information from the sensors deployed on different areas of a large field [12]. Battlefield surveillance, where sensors detect and monitor enemy troop or vehicle movements, is also an applicable scenario. In such a scenario static sinks are not preferred since they can easily be located and compromised by an adversary [9]. Unmanned aerial vehicles (UAV) may also be used to collect the harvested intelligence. Traffic monitoring, smart houses and hospitals, pollution control and rescue missions are other example scenarios [10].

The problem of mobile sink routing is a promising research field with unique challenges. A comprehensive and effective solution must attempt to solve many inherent problems associated with WSNs together with the new problems associated with mobile sinks. Mobile sinks extend the dynamic property of WSNs (node deaths, ad-hoc topology) with frequent topological changes introduced by the sink mobility.

In this paper, we provide a survey of the existing distributed mobile sink routing protocols. Distributed approaches do not rely on a central entity to manage routes and make decisions; therefore, they are applicable to pure WSN applications where the network consists of mono-type sensor devices. In order to provide an insight to the rationale and concerns of a mobile sink routing protocol, design requirements and challenges associated with the problem of mobile sink routing are highlighted and explained. The existing protocols are categorized into detailed and definitive classes and their advantages and drawbacks are determined.

Other surveys on the subject of mobile sink routing in WSNs exist in the literature: [9], [13]. In this paper, we present a more comprehensive review of the existing protocols, and aim to provide the state-of-the-art in the subject by including the most recent approaches and proposals. We also believe that the categorization devised in this paper introduces a more detailed and accurate perspective on the subject.

The paper is organized as follows: In Section II, the design requirements of the distributed mobile sink routing protocols and the associated challenges are explained. In Section III, the protocols belonging to a widely adopted class, hierarchical mobile sink routing protocols, are presented. In Section IV, the non-hierarchical approaches are reviewed. The open research issues and future research directions are outlined in Section V. The paper is concluded in Section VI with discussion on the existing approaches and final remarks about the problem of distributed mobile sink routing.

II. Design Issues and Challenges

In this section, we present important design issues which should be considered for an effective mobile sink routing protocol, and point out the related challenges. We first explain naive, extreme approaches which may serve as rough design guidelines; then put forward the performance requirements of a protocol in terms of various WSN related performance criteria; give the typical properties and the patterns of the sink mobility, and finally present the sensor capabilities which pose additional challenges or enable various underlying mechanisms aiding or restricting the operation of the mobile sink routing protocols.

A. Extreme Approaches

The problem of mobile sink routing can be evaluated and defined with respect to two extreme cases. At one end stands the naive approach of periodically flooding the mobile sink's position to the network. While this approach enables all nodes in the network to acquire the fresh position of the sink regularly, the overhead of global flooding is immense since it requires all the nodes in the network to relay routing control packets frequently and redundantly.

At the other end, simply the lack of a routing protocol stands. In this case, the sink collects data as it passes along the communication ranges of the sensor nodes. This approach is the most energy-efficient since it has absolutely no overhead to construct data routes [14]. The energy consumption could be further decreased by utilizing a sleeping mechanism (turning the radio off) which allows nodes to wake up only when the sink is nearby [15]. Regardless of its energy-efficiency, this approach is infeasible because of the large delays introduced by the need to wait for the sink to disseminate data. Moreover, the delivery of data might not even be guaranteed in cases where the sink does not travel through the whole network. Also the nodes' buffers might overflow and data packets might be dropped when the sink fails to come nearby within reasonable time limits.

An effective mobile sink routing protocol stands gracefully between these two extremes. It has to support frequent delivery of the fresh sink position information to the source nodes to minimize data reporting delays while also limiting the energy overhead of this operation to prolong the network lifetime. Achieving these two contradicting goals is a significant challenge especially considering the unique properties, capabilities and requirements of WSNs.

B. Performance Requirements

An efficient mobile sink routing protocol has to deal with several performance criteria. Different applications require maximization of different performance indicators, thus a protocol aiming to be applicable to a wide range of situations has to meet the following performance requirements. It should be noted that, even though these criteria are common for all WSNs, mobile sinks pose new challenges which render general routing solutions inefficient.

- Energy: Protocols designed for WSNs, regardless of their aim or operation layer, have to take actions to maximize the lifetime of the network. Lifetime is directly affected by the durability of the sensors' batteries. Achieving uniform energy consumption across the network extends the network lifetime, since it prevents early deaths in specific zones of the network due to hotspots which can cause topology disruptions and disconnectivity. The mobile sinks alleviate hotspots implicitly since the possible high energy consumption zones around the sinks shift as the sinks move. However, the challenges associated with the mobile sink routing may cause the overall energy consumption in the network to increase. The need of frequent advertisement of the sink's position (or its placement in the topology) to the network is a possible energy drainage. An efficient routing protocol should minimize the overhead of this operation in order to preserve the energy savings due to the usage of mobile sinks.

- Latency: The time between the sensor data generation and its reception by the sink is defined as latency. The sensor data generated in a WSN are subject to varying latencies depending on the network conditions (congestion, queueing delays, retransmissions due to channel errors etc.) and the distance to the sink. The mobile sinks introduce another source of latency in case the sink's position is unknown to the data generating sensors or the known position of the sink is outdated. In these cases, the sensor should acquire the sink's position or data has to be sent through an indirect route respectively. An efficient routing protocol has to offer a low-latency mechanism to acquire the sink's position whenever needed by a sensor. Especially in real-time applications, minimization of latency has the utmost importance.
- Reliability: A routing protocol's reliability depends on the delivery ratio of the data packets to the sink. Even though avoiding packet losses generally are in the scope of the underlying medium access control (MAC) protocol, sink mobility poses a reliability challenge that the routing protocol must address. The data packets that are forwarded towards an outdated sink position are destined to be lost since the sink will not be found in the estimated location. Successful mobile sink routing protocols must employ mechanisms to avoid such packets losses. Another important issue regarding reliability is the possibility of sudden load changes along data dissemination routes when the sink relocates. The route reconfigurations might cause reliability fluctuations in small periods of time leading to unexpected losses of data [16]. Such fluctuations might also affect the above-mentioned criteria in forms of high jitter or decreased energy consumption uniformity. Lastly, actions should be taken to accommodate control packet losses which might hinder the operation of the protocol.

C. Sink Mobility Patterns

Depending on the application requirements and the WSN deployment area characteristics (terrain, roads, area size, navigability, etc.), the sinks may follow different mobility patterns. The sink mobility could be viewed through the sink's perspective and the sensors' perspective. The sink's perspective reflects the true motion pattern of the sink while the sensors' perspective reflects the sink's mobility estimated through the limited knowledge of the sensors.

We classify the sink's mobility through the sink's perspective into two different patterns: continuous and nomadic. In the continuous sink mobility pattern, the sink moves continuously with constant or variable speed with absolutely no pauses during its motion. In this pattern, the sink's placement in the network topology is expected to change frequently; therefore, the routing protocol should be able to perform frequent topology control, and maintain the availability of fresh sink position to the source nodes. In the nomadic sink mobility pattern, the sink has movement and waiting phases during its motion. These two phases follow each other in a cyclic manner. This pattern might be thought of as the combination of the static sink case and the continuous sink mobility case. The routing protocol must act as a static sink routing protocol in the sink's waiting phase, minimizing topology control and thus decreasing the overhead of sink mobility accommodation mechanisms. Moreover, the sink's intermittent movement should not lead to packet losses and the packet latencies should be bounded in both the waiting and the movement phases of the sink's motion. It should also be noted that the continuous sink mobility pattern is a special case of the nomadic pattern with zero waiting time.

Regardless of the sink mobility pattern, the routing protocol's capabilities depend on whether the sink's path can be predicted. In this retrospect we can classify the sink's mobility from the sensors' perspective into two divisions: predictable and random. In the predictable sink mobility, the routing protocol exploits the predictable nature of the sink's movement to optimize data delivery performance, while in the random sink mobility the routing protocol cannot make any estimations on where the sink will be, hence it relies only on the current state of the topology.

The mobile sink routing protocols which are able to operate with random sink mobility are applicable to a wider range of scenarios since the predictability of sink mobility might not be available in many cases.

A third class of sink mobility from the sensors' perspective is the controlled sink mobility. This case denotes a property of the routing protocol rather than the property of the sink's motion. The protocols employing controlled sink mobility rely on directing the sink's motion according to the network's needs. For instance, the sink might be summoned to a congested area or to the vicinity of nodes which have the oldest data packets in their queues.

The sink mobility patterns through the perspective of the sensors directly influences the assumptions and the capabilities of a mobile sink routing protocol. For instance, a routing protocol which relies on predicting the sink's trajectory would be rendered ineffective or dysfunctional in a scenario where the sink does not traverse a predictable or learnable path. On the other hand, the sink mobility patterns through the sink's perspective do not pose such serious constraints as most of the protocols in the literature can operate under both the continuous or the nomadic pattern. These patterns generally influence only the efficiency of the protocols. Therefore, in this paper, while classifying the protocols in the literature, we focus more on the sink mobility patterns through the sensors' perspective.

Not only the type of the sink's mobility but also the sink's speed affects the operation and the performance of a routing protocol. In high sink speed cases, the sink travels through a

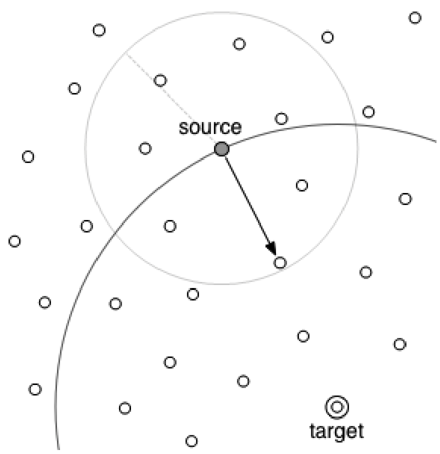

Fig. 1. Greedy geographic routing

relatively large portion of the network in a short time period; nonetheless, it would have less time to collect data from the nodes it comes in contact with. Hence the packets generated and aggregated on the nodes along the sink's path might not all be delivered [17]. For low sink speed cases, the opposite of this situation is observed. Even though the sink has enough time to obtain all the data aggregated on the nearby nodes, the nodes on the distant portions of the network have to wait more for the sink to come closer so that they can disseminate their data through reasonably shorter routes.

D. Sensor Capabilities and Underlying Mechanisms

Sensors are low-powered devices with limited batteries and computational constraints. Hence the assumptions of the mobile sink routing protocols about the capabilities of the sensors and the underlying mechanisms (e.g. physical, MAC layer properties, underlying routing protocols) have to be reasonable.

An important assumption commonly made by numerous existing mobile sink routing protocols is position-aware sensors. The problem of determining the position of the nodes is referred to as localization. The position information may be based on a global or a virtual local coordinate system. Using a satellite based localization system such as global positioning system (GPS) stretches the sensor hardware constraints well beyond; however, energy-efficient localization methods which are specifically proposed for WSNs exist [18]–[20]. Such methods operate well within the sensor hardware constraints and render the assumption of position-awareness fair.

Position-aware sensors provide some crucial advantages. First, the advertised sink position information may simply be reduced to the geographic coordinates of the sink. Topological information need not be transmitted, which saves a significant amount of bits. Second, once a source node with sensor data acquires the geographic coordinates of the sink, it can relay its data using greedy geographic routing.

Greedy geographic routing is regarded as highly scalable and energy-efficient; therefore, it is an attractive routing solution for WSNs with position-aware sensors [21], [22]. Geographic routing only requires local knowledge to operate. Nodes, at each hop, forward data to the neighbors that are the closest to the destination position. Geographic routing is illustrated in Figure 1. To overcome the difficulties in finding routes in case of topology defects, for instance routing around voids, many protocols which extend geographic routing have been proposed [23]–[25]. Mobile sink routing protocols that employ geographic routing as the underlying routing solution eliminate the energy and latency cost of route establishment in addition to the mentioned advantages.

A routing protocol's (either a static sink or a mobile sink protocol) applicability to a wide range of different sensor devices depends also on its MAC layer requirements. Recently, many low-power MAC protocols suitable for WSNs have been proposed [26]. Duty-cycling is the primary approach adopted in these protocols. Sensor transceivers cycle trough active (idle) and inactive (sleep) phases in a synchronous or asynchronous manner. These characteristics may force some constraints on the higher layer protocols. For instance, issuing an extensive number of broadcasts might hinder the energy savings of an asynchronized MAC protocol since broadcasts by their nature require the receiving parties to be simultaneously awake at the time of transmission. The routing protocols should mind these restrictions and be as independent from the lower layers as possible, unless it is a cross-layer protocol.

III. Hierarchical Mobile Sink Routing Protocols

There are many approaches to the problem of routing in WSNs with mobile sinks; the most important and the most widely adopted one being the hierarchical mobile sink routing protocols. Hierarchical approaches aim to decrease the load of advertising the sink's position to the network by establishing a virtual hierarchy of nodes which imposes different dynamic roles on the sensors. The constructed hierarchy might be composed of two or more tiers. The nodes in the overlay virtual structure (high-tier nodes) obtain the sink's position while the remaining nodes (first-tier nodes) query the high-tier nodes to acquire the sink position information whenever necessary. A successful hierarchical approach should employ an easily reachable virtual high-tier structure and propose countermeasures against possible hotspots on the high-tier nodes.

The hierarchical approaches could be further classified with respect to the virtual structures imposed: grid, clusters, tree, backbone or simply a specified area. Protocols utilizing a combination of these structures also exist in the literature.

In this section, the most prominent hierarchical mobile sink routing protocols are reviewed and classified. Their advantages, drawbacks and applicability in real WSN scenarios are determined.

A. Grid-based Approaches

Protocols of this class employ a grid structure as the higher level of the virtual hierarchy. Selected high-tier nodes constitute the crossing-points of the grid. Various shapes could be used to make up the grid: rectangles, triangles, hexagons etc. Since the grid is usually a geometric structure, geographic coordinates of the sensors are required, hence position-aware sensors are preferred.

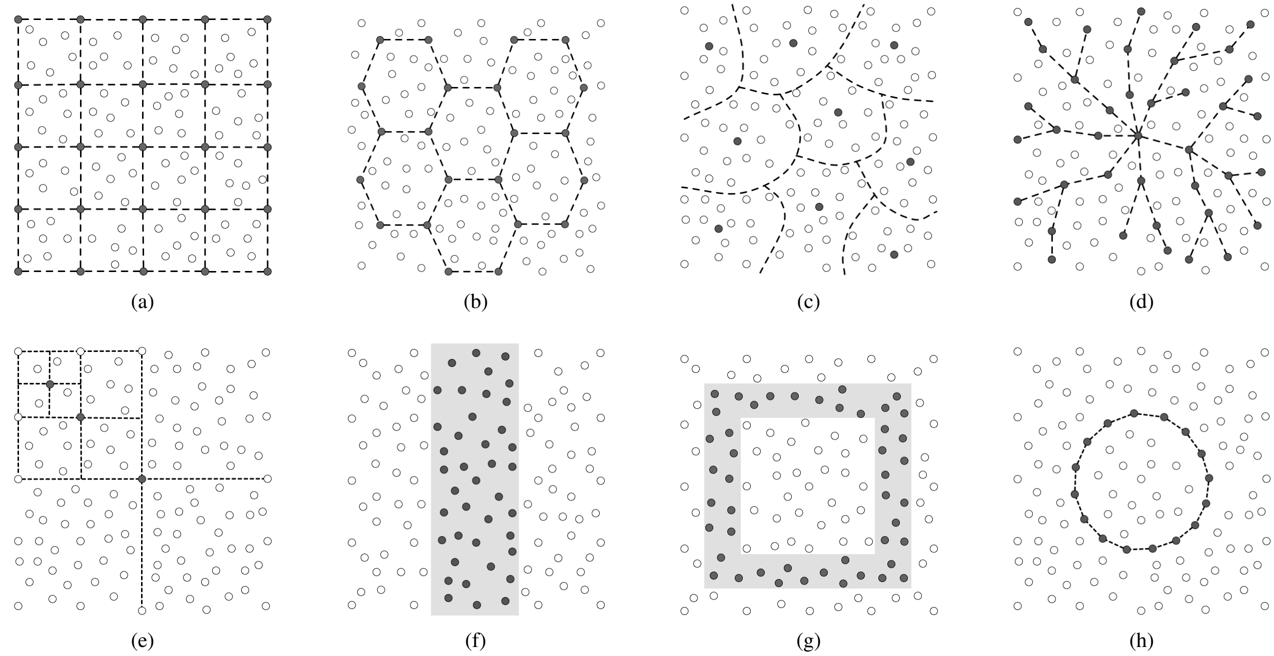

Fig. 2. Various Hierarchical Structures: (a) Rectangular grid (e.g. TTDD, GBEER, CMR), (b) Hexagonal grid (HPDD), (c) Clusters (e.g. HCDD, EEMSRA, MSRP), (d) Tree (SEAD), (e) Quadtree (QDD), (f) Line (LBDD), (g) Rail (Railroad), (h) Ring (Ring Routing)

1) TTDD: Two-Tier Data Dissemination in Large Scale WSNs (TTDD) [27] is one of the predecessors of the hierarchical approach. It is a virtual grid based approach which is source-oriented in the sense that each source node with valid sensor data proactively constructs a grid around itself and becomes a crossing point of this grid. The grid covers the whole network (Figure 2a). For grid construction to be possible, position-awareness of sensor nodes is required. Whenever sinks require data, they query the network by local flooding within a cell (defined by the grid constructed by a source) and these queries are relayed to the source node. Data is then forwarded to the sink using the reverse of the path taken by the data request. Progressive footprint chaining strategy [28] is used to make the mobility of the sink within a cell transparent to the network. For periodic data reporting applications where every sensor in the network report data, the overhead of constructing grids (one grid for each node) is immense. In order to lighten this burden, nodes may select aggregation nodes among themselves to decrease the number of source nodes constructing grids.

Advantages and Drawbacks: Grid-based protocols are advantageous for the easy-accessibility of the grid structure. Both the source nodes and the sinks can reach the grid with minimal number of hops. However, construction of the grid is non-trivial. TTDD suffers from the high overhead of constructing a separate grid for each source node especially in applications where numerous sensor nodes generate data.

2) GBEER: Grid-Based Energy-Efficient Routing From Multiple Sources to Multiple Mobile Sinks (GBEER) [29] is a hierarchical virtual grid-based method similar to TTDD. However, unlike TTDD, it constructs a single combined grid structure for all possible sources. To build the grid structure location-awareness of sensor nodes is necessary. Both data requests originated from the sink and data announcements originated from the source are propagated through the grid structure. The concept of Quorums is proposed to ensure that these different types of packets intersect at a header (grid-point). Data announcements are propagated horizontally along the grid while data requests are propagated vertically, ensuring that these packets intersect at a crossing point. The position of the sink is then delivered to the source node, and data is delivered directly to the sink. Like TTDD, progressive footprint chaining is used to render the mobility of the sink transparent at the grid.

Advantages and Drawbacks: GBEER aims to eliminate the high overhead of constructing separate grids for each source (as in TTDD) by establishing and maintaining a common grid structure, but the nodes making up the grid are likely to be hotspots and die quicker than other nodes. To overcome this problem the grid have to be changed from time to time which is cumbersome. Even changing a single crossing point requires informing the four neighboring crossing points which will introduce extra traffic on numerous nodes residing between the crossing points.

3) CMR: Coordinate Magnetic Routing (CMR) [30] constructs a virtual rectangular grid similar to GBEER. Magnetic diffusion strategy is used to create a magnetic field over the nodes where the nodes knowing the sink's position have negative polarity and the nodes knowing about the source nodes have positive polarity. The sink position advertisements are sent in the horizontal direction along the grid while the sensor data are sent in the vertical direction as in GBEER. A node encountering one of these packets changes its polarity accordingly. When a data packet is received by a node with negative polarity, which is aware of the sink's position, it is relayed to the sink. As an effort towards increasing the reliability of the protocol against the possibility of packet losses, the vertically and horizontally sent packets are duplicated and sent along two parallel lines of the grid.

Advantages and Drawbacks: CMR suffers from the same drawbacks of GBEER. An advantage of CMR is the duplication of packets travelling on the grid to increase reliability; however, the redundancy of packets might further increase the energy consumption of the nodes on the grid crossing points and amplify the severity of the hotspot problem.

4) HPDD: In place of a rectangular grid, Hexagonal Path Data Dissemination (HPDD) [31] utilizes a common grid structure composed of hexagons (Figure 2b) which is shown to outperform rectangular grid based approaches. The remaining properties of the protocol resemble GBEER.

Advantages and Drawbacks: HPDD suffers from the same hotspot problem on the second-tier structure as GBEER, even though a hexagonal grid structure is better than a rectangular grid in providing shorter data and sink advertisement routes.

5) HexDD: A Virtual Infrastructure Based on Honeycomb Tessellation (HexDD) [32] constructs a hexagonal grid structure similar to HPDD. HexDD aims to prevent redundant propagation of the sink's data queries over the whole grid by defining query and data rendezvous lines (border lines) along the six directions following the edges of the hexagons. The border lines intersect on a predefined center hexagonal cell. Sensor data are sent towards the closest border line and then propagated towards the center cell. The nodes on the border lines replicate and store the data. Queries are forwarded towards the center cell via the same mechanism. When a query meets a corresponding data stored on a border line node, the data is sent towards the sink through the reverse path.

Advantages and Drawbacks: The total overhead of HexDD is lower than HPDD due to the border lines confining the sink's queries within a subset of the grid. However, the nodes on the border lines and especially on the center cell which is the intersection of these lines are likely to become hotspots. No countermeasure against such hotspots is proposed.

B. Cluster-based Approaches

Protocols belonging to this class employ clustering mechanisms to partition the network and employ the cluster head nodes as the high-tier nodes (Figure 2c). Formation of clusters is more complicated than the construction of a grid; however, since clustering is a topology-aware mechanism which considers the distribution of nodes in the field, a more efficient virtual hierarchy is achieved.

1) HCDD: Hierarchial Cluster-based Data Dissemination (HCDD) [33] is a hierarchical approach which uses clustering to determine second-tier nodes. Like GBEER and HPDD a combined hierarchical structure for all data sources is constructed. The cluster heads are called Routing Agents which are responsible for propagation of data requests. Max-Min D-Cluster Formation Algorithm [34] is used for determining cluster heads. The advantage of this algorithm is its ability to operate without position-information of sensor nodes. Other aspects of this approach resemble TTDD.

Advantages and Drawbacks: HCDD's advantage is that it employs a distributed clustering algorithm which can operate without position-awareness of the sensor nodes. Clustering allows a better choice of second-tier nodes; however, the distributed algorithm's overhead is high and running it again in case the batteries of the cluster head nodes are about to deplete is very inefficient.

2) EEMSRA: Energy-Efficient Mobile Sink Routing Algorithm (EEMSRA) [35] is another clustered routing protocol based on LEACH [36]. LEACH proposes a method to randomly select cluster-heads. These clusterheads are used as gateways to the sink. The cluster heads change periodically in order to mitigate the hotspot problem. A key feature of EEMSRA is that the cluster heads create a TDMA (time division multiple access) schedule informing each node in the cluster of when they can transmit data. In this sense, EEMSRA is a cross-layer protocol which operates coordinated with the MAC layer. The cluster heads also perform aggregation before transmitting data to the sink. The sink broadcasts its next projected cluster visit in order to enable the network to update routes prior to the sink's actual arrival at the cluster. This approach, while saving significant amounts of energy, requires the sink to at least have knowledge about its short-term trajectory. Moreover, a sink movement scheme which takes the clusters' energies into account has been proposed. The sink always selects the neighboring cluster with the maximum remaining energy as the next visiting location. Considering these approaches, EEMSRA employs controlled sink mobility.

Advantages and Drawbacks: EEMSRA forms clusters with enforced TDMA schedules to increase energy-efficiency. This approach has MAC layer requirements, so it might not be applicable to a wide range of devices. Another limitation of EEMSRA is the need for controlled sink mobility. Other than these drawbacks, EEMSRA is a beneficial protocol in terms of energy efficiency. The authors proposed a mechanism to change the cluster heads in order to mitigate the hotspot problem.

3) MSRP: Mobile Sink-based Routing Protocol (MSRP) [37] employs cluster heads as data aggregation centers where the sensor data of the corresponding clusters are gathered. The mobile sink determines the cluster heads in its specified vicinity and attempts to obtain the data aggregated in these cluster heads. A TDMA schedule, similar to EEMSRA, is set up between the neighboring cluster heads and the sink to coordinate data dissemination. Sink mobility is controlled considering the residual energy of the near cluster heads.

Advantages and Drawbacks: MSRP is very similar to EEMSRA with one key difference: The sensor data aggregated in the cluster heads may be obtained only when the sink comes closer than a specified distance threshold; therefore, MSRP is only suitable for delay-tolerant applications. Moreover, the protocol does not guarantee that the sink will visit all the cluster heads within a bounded time, hence it is possible that some portions of the network may not be well served. However, the proposed controlled sink mobility scheme is well-defined and efficient in extending the network lifetime, thus rendering this protocol suitable for applications favoring energy-efficiency rather than fast data delivery.

C. Tree-based Approaches

This class of protocols construct an overlaying virtual tree structure (Figure 2d). The sink advertisement is usually dissipated from the root towards the leaves.

1) SEAD: Minimum-Energy Asynchronous Dissemination to Mobile Sinks in WSNs (SEAD) [38] utilizes minimum-cost weighted Steiner trees as the high-tier structure which selects replicas at intermediate points. Like TTDD, separate trees are constructed for each source. SEAD also uses progressive footprint chaining to make the sink mobility transparent to the overlaying structure. Position-awareness of the sensor nodes is required for construction of the Steiner tree and data dissemination.

Advantages and Drawbacks: SEAD defines and establishes a more intelligent second-tier structure which is a Steiner tree. Even though the accessibility of this structure is better, the overhead of establishing separate trees rooted on sources is very high.

2) QDD: Quad-tree Based Data Dissemination Protocol (QDD) [39] partitions the network into successive quadrants (Figure 2e). The center point of each quadrant becomes a second-tier node. The quadrants are recursively divided further into smaller quadrants until the resolution of the second-tier nodes are sufficient for quick access to the virtual structure. Data announcements and queries are sent to the center points of quadrants in a recursive manner until they rendezvous.

Advantages and Drawbacks: The overhead of constructing the quad-tree structure in QDD is minimal compared to most of the other hierarchical approaches; however, no countermeasure against the hotspot problem is proposed.

D. Backbone-based Approaches

The protocols of this class establish a backbone covering the network which typically consists of nodes with different multiple roles.

1) DDB: Dynamic Directed Backbone (DDB) [40] constructs a backbone as the second-tier structure. The backbone is composed of leader and gateway nodes. Leader nodes form clusters of nodes in their own neighborhoods and coordinate data traffic associated with all nodes in their clusters. Leader nodes communicate with each other by gateway nodes which complete the connectivity of the backbone structure. The sink connects to the backbone which extends through the network, and data dissemination is performed over the backbone.

Advantages and Drawbacks: Changing the proposed backbone structure to avoid hotspots has relatively low overhead since only the immediate neighbors have to be informed if a backbone node switches roles with a regular node. However, in order to cover the whole network, a large backbone with many branches have to be established, which will cause redundancy of routing control packets (sink data queries and data announcements) and thus increase the overall energy consumption in the network.

2) DQM: Data Quality Maximization (DQM) [41] is another routing protocol based on a backbone consisting of gateways. This protocol assumes predictability of the sink movement and selects gateways adjacent to the predicted path of the sink. The sensors establish shortest path routes with the gateways using Floyd-Warshall algorithm. Gateways aggregate incoming data and wait for the sink to arrive.

Advantages and Drawbacks: DQM is only applicable in delay-tolerant applications since the selected gateways disseminate the aggregated data only when the sink is nearby. Moreover, the gateways might never be visited by the sink; therefore, a predictable sink movement scheme has to be employed which enables gateways to be selected along the projected path of the sink. Another drawback of DQM is the difficulty of mitigating the hotspot problem. Changing gateways would introduce a large overhead since the aggregated data must also be transferred to the newly selected gateway.

E. Area-based Approaches

These approaches designate the nodes in an area of specific boundaries as the high-tier nodes rather than establishing complicated structures. The hierarchy construction cost of these protocols is minimal. To mitigate the hotspot problem, rather then changing the structure, the size of the area is specified large enough to spread and lessen the extra load on the high-tier nodes.

1) LBDD: Line-based Data Dissemination (LBDD) [42] defines a vertical strip of nodes which divide the field of deployment into two equal portions (Figure 2f). The nodes on this strip are referred to as in-line nodes. Sensor data are sent to the line and the first in-line node encountered stores the data. The sink sends a data query to the line and the query is propagated through the line until the in-line node storing the data is reached. The in-line node then forwards the data directly to the sink, and data dissemination is completed.

Advantages and Drawbacks: LBDD proposes an area-based line structure which is very simple to determine and establish. The line structure is easily accessible by the source nodes and the sink, thus the overhead of these operations are low. Despite of these advantages, LBDD still relies on broadcasts for propagating data queries along the line. The line has to be wide enough to mitigate hotspots; therefore, especially for large networks, the flooding on the line will cause a significant increase in the total energy consumption.

2) Railroad: Railroad [43] constructs a virtual infrastructure called the rail. The rail is a closed loop of a strip of nodes which has the shape defined by the outline of the network (Figure 2g). The nodes on this rail are called rail nodes. When a node has sensor data, it sends information about this data (meta-data) to the nearest rail node. The rail node receiving the meta-data constructs a station which is a portion of the rail centered on the rail node with minimum width of communication range. The meta-data is shared among the nodes residing on the station. The sink queries the rail for meta-data and when a station node is reached it informs the source of the sink's position and then the source node can send the corresponding data directly to the sink. One key difference of Railroad from LBDD is that queries issued by the sink travel on the rail by unicasts rather than broadcasts. To ensure that a query encounters a node with meta-data, stations must cover the width of the rail.

Advantages and Drawbacks: Railroad alleviates the need for extensive broadcasts on the rail structure by the construction of stations, which provides an advantage against LBDD and contributes towards the protocol's scalability. However, the expected data delivery delays of Railroad are higher than LBDD since the sink's queries have to travel through a much longer structure. Also, once the queries reach a station, the source node must be informed of the sink's position to initiate data dissemination due to the storage of meta-data in place of data in the stations. Even though the usage of meta-data provide energy savings, increased delays are expected.

3) Ring Routing: Ring Routing [44] proposes a ring structure which is a closed loop of single-node width (Figure 2h). The ring encapsulates a globally predetermined network center. The sink advertises its position to the ring by forwarding packets towards the network center via geographic routing. Hence the ring nodes conserve the fresh position of the sink at all times. The source nodes query the ring to acquire the fresh sink position information by a similar mechanism. Even though the ring structure is not comprised of an area, the area encapsulated by the ring constitutes a rendezvous direction for queries and advertisements. Hence Ring Routing is considered to be an area-based approach. A local structure change mechanism is proposed to mitigate hotspots on the ring. Each ring node independently selects new ring nodes among their neighbors when their batteries nears depletion, while conserving the closed loop and the encapsulation of the network center properties.

Advantages and Drawbacks: The ring structure is easily accessible and the proposed hotspot mitigation mechanism has low overhead, which makes Ring Routing an efficient protocol. The quick and straightforward acquiry of fresh sink position information from the ring allows fast data delivery. The drawback of Ring Routing is its questionable scalability. For large or sparse networks, the overhead of the initial ring construction is expected to be high.

F. Agent-based Approaches

This class of protocols select one or more agents to relay the traffic between sources and the sink. Agents take on the role of representatives for the sources or the sink. Contrary to the other hierarchical approaches, the agents do not form an infrastructure. With these properties, agent-based approaches can be considered as primitive versions of other complicated hierarchical protocols, employing few disorganized agents as high-tier nodes. These protocols usually utilize infrequent flooding to advertise the location of the agents. An agent-based system with a single agent is depicted in Figure 3.

1) DHA: Data Dissemination Protocol Based on Home Agent and Access Node (DHA) [45] extends and generalizes the progressive footprint chaining mechanism to handle both sink position advertisement and data dissemination. Two specialized nodes, referred to as Home Agent and Access Node, are employed. The home agent represents the mobile sink to the sensor nodes, thus making the movement of the sink transparent to the network. On the other hand, the access node represents the mobile sink to the home agent. Only the home agent and the access node are affected by the movement of the sink. As the sink moves, it selects new access nodes which inform the home agent of their new roles. The home agent aggregates and relays data packets to the access node which relays them directly to the sink. Therefore, source nodes only need to know the position of the home agent to disseminate data. The home agent is changed occasionally to avoid hotspots, and the position of the new home agent is flooded across the network.

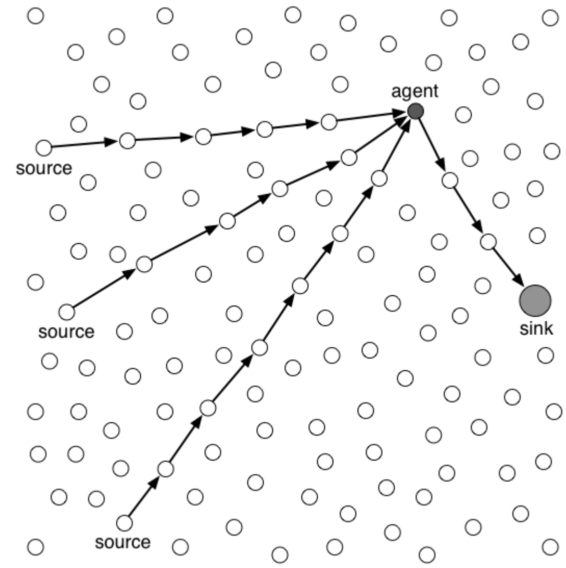

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Fig. 3. Agent-based data dissemination

Advantages and Drawbacks: DHA selects a home agent as a data aggregation and dissemination point. The load on the home agent is immense, and changing the home agent requires global flooding. Even though such drawbacks render DHA very energy inefficient, the simplicity of the protocol is a significant advantage.

2) OAR: Optimized Agent-based Routing Protocol (OAR) [46] employs a single agent which is constantly replaced to be in the neighborhood of the mobile sink. Initially, the agent floods the network to advertise its position. The sources deliver their data to the sink via the agent. Progressive footprint chaining strategy is utilized to select new agents and maintain a relay path. When the relay path gets too long, the current agent constructs direct paths with the recent sources by informing them of its position. Overhearing is also used as an additional mechanism to share this information with nodes near the agent to source path.

Advantages and Drawbacks: Like DHA, OAR is a simple to implement protocol; however, it suffers from the same drawbacks. The relay path between the formerly advertised agent and the current agent is likely to carry large amounts of traffic which would lead to hotspots and inefficiencies in data transmissions. Since the protocol relies on informing only the recent sources about the agent change, the sources which have become active after a long time of inactivity would have difficulty delivering data to the sink.

G. Hybrid Approaches

As the name of the class suggests, these protocols employ a combination of two or more virtual structures.

TABLE I
SUMMARY AND COMPARISON OF HIERARCHICAL MOBILE SINK ROUTING PROTOCOLS

Protocol	**Position-awareness**	**Sink mobility pattern**	**Virtual structure type**	**Data aggregation**	**Multi-sink support**	**Protocol overhead**	**Structure accessibility**	**Hotspot mitigation strategy (strength)**
TTDD [27]	Yes	Random	Rectangular grid	Yes	Yes	High	Easy	Separate grid for each source (strong)
GBEER [29]	Yes	Random	Rectangular grid	No	Yes	Medium	Moderate	Structure change (moderate)
CMR [30]	Yes	Random	Rectangular grid	No	Yes	Medium	Moderate	Structure change (moderate)
HPDD [31]	Yes	Random	Hexagonal grid	No	Yes	Medium	Moderate	Structure change (moderate)
HexDD [32]	Yes	Random	Hexagonal grid	Yes	Yes	Low	Moderate	N/A
HCDD [33]	No	Random	Max-Min D-Clusters	No	No	High	Hard	Structure change (weak)
EEMSRA [35]	Yes	Controlled	TDMA clusters	Yes	No	Medium	Hard	Structure change (strong)
MSRP [37]	Yes	Controlled	Clusters	Yes	Yes	Medium	Hard	Structure change (moderate)
SEAD [38]	Yes	Random	Steiner tree	No	Yes	High	Easy	Separate tree for each source (strong)
QDD [39]	Yes	Random	Quad-tree	No	Yes	Low	Moderate	N/A
DDB [40]	Yes	Random	Backbone	No	Yes	High	Easy	Structure change (strong)
DQM [41]	Yes	Predictable	Backbone	Yes	No	High	Easy	N/A
LBDD [42]	Yes	Random	Line (wide)	No	Yes	Low	Hard	Large structure (strong)
Railroad [43]	Yes	Random	Rail (wide)	No	Yes	Medium	Moderate	Large structure (strong)
Ring Routing [44]	Yes	Random	Ring (one-node width)	No	No	Low	Moderate	Structure change (strong)
DHA [45]	Yes	Random	Two agents	Yes	No	Low	Easy	Agent change (weak)
OAR [46]	Yes	Random	Single agent	No	Yes	Low	Easy	Agent change (weak)
MGRP [47]	Yes	Random	Grid & clusters	Yes	No	High	Easy	N/A
EGRR [48]	Yes	Predictable	Expect areas & grids	No	No	High	Moderate	Structure change (strong)
EADA [49]	No	Predictable	Grid & on-demand trees	Yes	No	High	Moderate	Structure change (strong)
Shared Tree [50]	No	Random	Clusters & tree	No	Yes	Medium	Hard	N/A

1) MGRP: Multi-tier Grid Routing (MGRP) [47] combined the grid based approach with clustering. A recursive grid is constructed similar to the quad-tree approach of QDD. However, the crossing points are not data dissemination centers. Within each grid cell, a distributed clustering algorithm is executed and the clusterheads are selected as data aggregator nodes. Grid cells have binary addresses, hence the recursive structure of the multi-tier is clearly represented and cells are easily accessible by the sink.

Advantages and Drawbacks: MGRP constructs a grid structure combined with clusters which is easily accessible. However, the overhead of constructing such a complex structure is high. Also, no countermeasure against the hotspot problem is proposed.

2) EGRR: Real-Time Routing Protocol Based on Expect Grids (EGRR) [48] is a grid-based routing protocol which extends Expect Area Based Real-Time Routing Protocol (EAR2) [51]. In EAR2 the source nodes calculate Expect Areas (EA) using the current speed and position of the sink and send data to the closest node in the EA. The closest node then floods data within the EA, and data is disseminated to the sink. The authors of [48] aim to minimize the flooding overhead of EAR2 by introducing Expect Grids (EG) in addition to EAs. The closest node in an EA receiving data forwards it through the EG constructed in the EA. The sink retrieves data from the closest crossing point of the grid. With this mechanism, extensive broadcasts are avoided.

Advantages and Drawbacks: EGRR depends on predicting the sink's movement. The sink advertisement broadcasts are minimized by using expect areas combined with expect grids. The hotspot problem is mitigated by the constant change of second-tier structure; however, the overhead of the frequent re-establishment of expect grids in case the sink moves to a different EA is high.

3) EADA: Energy Aware Data Aggregation (EADA) [49] combines a grid structure with on-demand data dissemination trees. In each grid cell, the node with the maximum residual energy is selected as the gateway node which is responsible for aggregating the data generated within the grid cell. The mobile sink floods data queries through gateways restricted on a circle sector towards the interest zone. Once the query enters the interest zone, the entry gateway becomes the root of a newly constructed tree which covers all the nodes in the interest zone. The aggregated data are then disseminated through the reverse of the query route to the sink. If the energy of the root gateway goes below a certain threshold, the gateway with the maximum remaining energy in the interest zone is selected as the new root and a new tree is formed.

Advantages and Drawbacks: The load on the grid is alleviated by the construction of trees in the interest zones; however, establishing and maintaining a separate tree for each interest zone are likely to increase the overall energy consumption in the network. A mechanism to prevent hotspots in the tree roots have been proposed, hence the possible energy holes along the branches towards the root due to the concentration of data traffic are mitigated.

4) Shared Tree: This protocol organizes a cluster-based infrastructure into a common shared tree [50]. A distributed clustering method not requiring position-aware sensors is utilized. The mobile sink frequently sends its topological position to the root of the shared tree, and the source nodes send requests to the root to obtain it. The cluster heads periodically share their routing tables with their sibling cluster heads. Employing this information, the data dissemination is performed through shorter routes rather than traversing the whole tree.

Advantages and Drawbacks: The main advantage of Shared Tree is that it does not require position-awareness. The utilized clustering method is cumbersome but once the clusters are established, by the advantage of shorter routes due to the inherent shared tree routing table sharing mechanism, the overall energy consumption of the network is expected to be low. However, the protocol still faces the hotspot problem on the cluster heads, and a localized mechanism to change cluster heads when their batteries are near depletion is not proposed.

The above-mentioned hierarchical mobile sink routing protocols are summarized and compared in Table I. The virtual hierarchical structures and the hotspot mitigation strategies along with their strengths are also provided. It should also be noted that the comparison of the protocols under the performance criteria we have discussed in Section II-B is often not possible due to the lack of analyses or comprehensive simulation studies performed for all the protocols under similar scenarios. Therefore, we did not include the discussed performance criteria in Tables I and II, since we do not have quantitative indicators which would enable us to accurately compare the protocols under such criteria. Instead, these criteria are discussed individually for each protocol in the respective analysis sections. The criteria we included in the tables, such as protocol overhead and possible hotspots, are more general and deducible from the mere properties of the protocol.

IV. Non-hierarchical Mobile Sink Routing Protocols

The non-hierarchical mobile sink routing protocols do not utilize a high-tier structure. A hierarchy is not imposed on the sensor nodes. This approach eliminates the overhead of constructing a virtual structure and eliminates the possibility of hotspots on such a structure; however, these protocols lack the benefits of the hierarchical routing protocols such as the easy acquiry of sink position from the high-tier nodes. Various mechanisms are employed to advertise the mobile sink's position to the network: flooding, overhearing, selection of agents and exploitation of geometric properties.

A. Flooding-based Approaches

This class of protocols rely on propagation of broadcasts across the network to advertise the sink or to deliver data to the sink. This is referred to as flooding. Since flooding is costly in terms of energy due to the characteristics of wireless communication, these approaches propose mechanisms to restrict it to confined areas or decrease its frequency and try to avoid unnecessary broadcasts. This class constitutes the most widely used approach among the non-hierarchical mobile sink routing protocols.

1) GRAB: In Gradient Broadcast (GRAB) [52], the sink builds a cost field by flooding advertisement packets across the network. The cost of a node is defined as the estimated energy overhead to forward a packet from this node to the sink. The authors assume that a node can estimate the energy cost of sending data to its neighbors by observing the signal-to-noise ratios of the neighbors' transmissions. Nodes include their own costs in the advertisement packets, and hence nodes can update their costs by accumulating the cost encoded in the advertisement packet and the local cost for communicating with the transmitting neighbor. The cost field implicitly designates the global direction towards the sink. When a source node has data, it does not select a single recipient. Rather, data packets are broadcast and the nodes with costs lower than the transmitter continue propagation. Data packets are funnelled down to the bottom of the cost field where the sink resides (Figure 4). The sink observes the success ratios of the received packets and the average consumed energies and compares them with the past values in order to determine if the cost field needs to be rebuilt, which involves global re-flooding across the network.

Advantages and Drawbacks: The gradients constructed via an energy-considering cost metric provide efficient routes; however, the redundancy of packets along the data dissemination tree is likely to increase the overall energy consumption

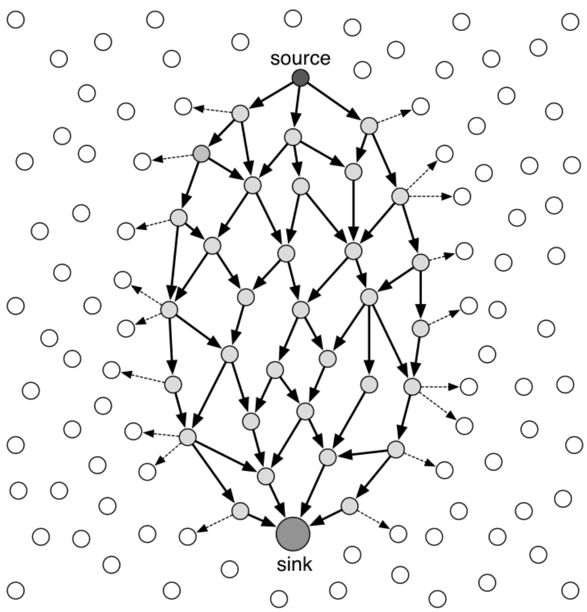

Fig. 4. Multicast data dissemination through cost field (e.g. GRAB, ER). Data packets are rebroadcasted only by the nodes with lower cost values.

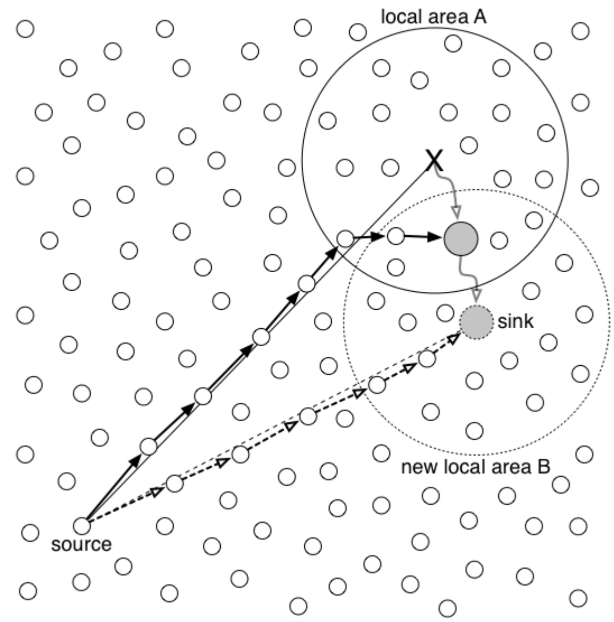

Fig. 5. Operation of ALURP. Sources forward data towards local area center. Sink leaves area A, global flooding is performed, new area B is specified.

in the network. The sink intelligently decides whether to re-flood the network which avoids extensive flooding, but since the establishment of gradients is a complicated operation, the energy overhead of rare global floods is still significantly large.

2) ER: Efficient Routing (ER) proposed by Fodor et al. [53] is another flooding-based approach which maintains a data dissemination tree centered on the sink which is constructed and updated in accordance with a cost metric. The protocol aims to restrict broadcasts by only updating the routes of the nodes which undergo a significant cost change. The underlying motivation is that the nodes closer to the sink are affected more by the sink's mobility compared to the farther away nodes. Therefore, the closer nodes update their routes more frequently while other nodes attempt to do so only when the cost of a new route is significantly lower than their current routes. The sink periodically broadcasts advertisement packets, and the recipients continue flooding only when they accept the new route (which is observed to have a significantly lower cost), hence the flooding is restricted to a portion of the network.

Advantages and Drawbacks: The protocol is able to operate without position-awareness. The cost metric can be redefined considering the network's needs (it can simply be taken as the hop count or as some quality of service related metric), thus making ER a widely applicable and tunable protocol. The flood restriction mechanism is simple and intuitive; however, the need for floods extending to a large portion of the network are still frequently needed, especially for scenarios where the sink moves fast.

3) TwinRoute: TwinRoute [54] provides a hybridization of two basic routing approaches: proactive and reactive schemes. Proactive scheme exploits the predictability of sink mobility. It keeps record of sink visits at each sensor node to choose storage-nodes. The storage delay threshold parameter is used to determine the storage-nodes. Storage-node rooted dissemination trees are constructed to relay data to these nodes rather than the sink itself. As a mobile sink passes a storage-node, it collects the aggregated data. Reactive Scheme is similar to flooding, but it is limited by the parameter tree depth. Also nodes having participated in a tree construction previously do not participate in upcoming attempts within a specific interval defined by a tunable timer. TwinRoute forces a hybridizing condition by introducing an additional parameter called scheme preference parameter which denotes the distance gain necessary to switch from proactive scheme to reactive scheme. Storage nodes exist, however nodes could choose to send their packets directly to the sink whenever appropriate. TwinRoute is suitable for delay-tolerant applications. Position-awareness of sensor nodes is not required.

Advantages and Drawbacks: Since TwinRoute employs storage nodes along the predicted path of the sink, it is suitable for delay-tolerant applications. The predictable sink mobility requirement also restricts the applicability of the protocol. Despite these limitations, the tunable hybridizing parameter constitutes a useful setting which can be modified according to the application requirements. The protocol's operability without node position information is another advantage.

4) ALURP: Adaptive Location Updates for Mobile Sinks (ALURP) [55] is a protocol which also does not require position-aware sensors. When the network is deployed, the mobile sink advertises itself to the entire network by global flooding. Nodes forward data packets to a local area (defined by a specified radius around the sink) rather than the sink itself, while nodes within this local area route data packets directly to the sink. As the sink moves, it re-advertises itself by flooding only inside this local area, which is a few hops wide. When the sink moves out of this area, it needs to advertise itself to the whole network again by global flooding. The operation of ALURP is depicted in Figure 5.

Advantages and Drawbacks: ALURP defines a local area around the sink to restrict broadcasts; however, the need for global flooding is not altogether eliminated. The frequency of global flooding is decreased at the expense of increased data delivery delays caused by the usage of suboptimal routes to the sink.

5) Mobile RPL: A Hybrid Routing Protocol for WSNs with Mobile Sinks (Mobile RPL) [56] is the adaptation of the static sink routing protocol RPL [57] to support mobile sinks. Mobile RPL is similar to ALURP in the sense that the sink periodically advertises itself to the network by global flooding and the frequency of global floods is reduced by defining a few hops wide area in which broadcasts are confined. However, RPL defines the local area around the source nodes rather than around the sink. The global flooding of sink advertisement packets creates a directed acyclic graph (DAG). Members of an active DAG can disseminate data to the sink. A source node which is not a member of an active DAG issues a route request which is propagated in the defined local area to reach a DAG member node. If such a node is not found after a maximum number of retries, the request is flooded to the entire network. The intermediate nodes forwarding the reply to the source node record the sink position information and become DAG members for future data dissemination.

Advantages and Drawbacks: Mobile RPL can be considered as a source-oriented variant of ALURP. This approach is only efficient when there are only a few number of active sources in the network. A large number of sources lead to numerous local floods which would introduce an even greater overhead than global flooding.

6) DEEP: Density-based Proactive Data Dissemination Protocol (DEEP) [58] utilizes probabilistic flooding to limit extensive rebroadcasts. The data packets are propagated in a randomly selective manner and aggregated by nodes across the network. Each sensor node has a partial view of the network which corresponds to the source nodes from which data packets have been received. To further decrease unnecessary propagation of data packets, the duplicate packets are detected and discarded. The aggregated data on each sensor also undergo compression to increase bit efficiency. The protocol can operate with random sink mobility where the sink travels unpredictably to collect aggregated data from the sensors in its neighborhood. When a sink collects information from a node, it acquires the data from the partial view of that node which corresponds to a significant portion of the network. Position-aware sensors are not required for the operation of DEEP.

Advantages and Drawbacks: DEEP utilizes an efficient mechanism to restrict flooding. Flooding of data packets introduces a high redundancy of information in the network; however, it helps the mobile sink to collect data generated by a large portion of the network through minimal movement. The protocol's ability to work without position-awareness is another advantage. As for all flooding-based protocols, the scalability of DEEP poses a concern, but the probabilistic mechanism can be tuned to be more selective in order to reduce the total number of broadcasts in the network which is bound to increase as the network size increases.

7) QBDCS: Query-Based Data Collection Scheme (QBDCS) [59] relies on predictable sink mobility. The sink inserts queries into the network towards its interest areas. The queries contain the sink's position, speed and direction. Upon reception of a query, the data aggregation nodes in the interest area estimate the sink's future position and direct data packets accordingly. Once the packets reach the estimated sink position, they are flooded in a local area in order to accommodate estimation errors and guarantee reaching the sink. Moreover, the sink tries to determine the optimal time to inject its queries to the network in order to minimize the total length of the query and data routes with respect to a specific interest area.

Advantages and Drawbacks: The requirement of predictable sink mobility limits the applicability of the protocol to a wide range of scenarios. In case the sink faces an obstruction in its path and is unable to reach the predicted position, there is a significant chance that the sink will not be found in the local flooding area, which would cause a large amount of data to get lost. Even though such drawbacks exist, for cases where a consistent and truly predictable sink mobility is observed, QBDCS successfully confines flooding to a small area and thus achieves high energy-efficiency.

8) REDM: Robust and Energy-efficient Dynamic Routing (REDM) [60] employs a controlled sink mobility scheme. Global flooding is utilized for initial sink advertisement. The routes are established considering the hop count and the average residual energy of the paths. Also, routes are updated in case a node on the path nears battery depletion. The sink mobility is controlled by a power-aware heuristic which leads the sink to the vicinity of the nodes with low remaining energies. When the sink moves by a certain distance threshold from its former position, global flooding is repeated.

Advantages and Drawbacks: Since global flooding is the base mechanism of REDM, it is suitable for nomadic sink mobility pattern. The protocol proposes efficient mechanisms for achieving uniform energy consumption along the data routes when the sink is in its stationary phase; however, the cost of global flooding required to accommodate to the movement phase of the sink is too large to make this protocol efficient in case of rapid and frequent sink mobility.

9) RM: Efficient Route Maintenance Scheme (RM) [61] enforces different states on the nodes according to their closeness to the sink. The nodes in the sink's vicinity change states as the sink moves and thus the portions of the routes close to the sink are updated. By such local route updates (in two hop range of the sink) , RM aims to decrease the frequency of global flooding. The updates also include a route shortening mechanism to reduce hop counts in case the sink moves towards a source node. The protocol is mainly targeted for scenarios where some sources in the network are active and have continuous data streams.

Advantages and Drawbacks: The local update mechanisms in the vicinity of the sink are well defined and are expected to be successful when the sink moves slowly. For cases where the neighborhood of the sink changes rapidly, the advantages of RM would diminish since global flooding would dominate the overall operation of the protocol.

10) E-TRAIL: Energy-Efficient Trail-based Data Dissemination (E-TRAIL) [62] combines local flooding with a trail-based approach to reach the sink when it moves. The sink advertises itself by flooding its vicinity in a specific hop count range. The nodes receiving such advertisements now have a route to the sink. When the sink starts to move and thus leaves the root of the local dissemination tree it has constructed, it continuously broadcasts beacons in two hop range to make sure that a trail is formed behind it. Following this trail, the source nodes in the local tree may still reach the sink. After some time, the local flooding is repeated and a new tree is constructed, thus the routes are re-established and over-lengthy routes are avoided. E-TRAIL also proposes a sleep scheduling mechanism within the dissemination trees to conserve more energy in an intelligent manner.

Advantages and Drawbacks: Since the sink advertises itself via local flooding, the nodes which are not in the range of the flooding cannot establish routes to the sink. Therefore, E-TRAIL is suitable for numerous multiple mobile sinks which are enough to cover the whole network by dissemination trees. If this condition is met, E-TRAIL is an efficient protocol and it successfully decreases the amount of broadcasts required for the sink advertisement by employing the local floods in rare intervals due to the help of the utilized trailing mechanism.

11) Termite-hill: The analogy of termites constructing hills from pebbles drives the motivation behind Termite-hill [63]. The basis of the protocol is that the nodes on the data routes from sources to the sink remember the routes for some time, as in termites excreting pheromones when carrying pebbles. When a source node does not know the sink's location, it floods the data until it reaches a node which remembers a previously taken route to the sink. The data then follows the pheromone trail to reach the sink. Termite-hill does not require position-aware sensors.

Advantages and Drawbacks: Global flooding is avoided by the route remembering property; however, the validity of the remembered routes would decay rapidly in case of fast sink mobility. Hence there is a possibility of data packets traveling over extremely long and indirect routes.

12) SinkTrail: SinkTrail [64] constructs and utilizes a logical coordinate space which does not require position aware sensors. The sink's mobility is assumed to be nomadic. The sink re-floods the whole network whenever it pauses. The nodes store trail references which basically represent their logical coordinates in the network. The trail reference is a vector containing a specific number of previous hop counts to the sink obtained via the flooded messages. The sink also has a trail reference referred to as the destination reference. Source nodes utilize a mechanism similar to the geographic routing to greedily forward their data towards the sink. The trail references of the neighbors are used as coordinates to determine the recipient logically closest to the sink's destination reference. Through the use of these logical coordinates, data are funneled and delivered to the sink. Frequent global floods are averted since the logical coordinate space designates an approximate global direction towards the sink even if the information about the sink's position has decayed.

Advantages and Drawbacks: SinkTrail decreases the frequency of global floods by utilizing an effective logical coordinate system which enables simple data dissemination by logical greedy geographic routing. However, the requirement of nomadic sink mobility limits the applicability of the protocol.

13) GMRE: Greedy Maximum Residual Energy (GMRE) [65] protocol employs controlled sink mobility to better achieve uniform energy consumption. The sink divides the area of deployment into sites. At each site, a sentinel node is selected to gather the residual energy levels of the nodes and report to the sink. The sink nomadically travels to the adjacent site that has the maximum residual energy and floods its location to the network upon its arrival. This process is repeated when the sink decides to move again.

Advantages and Drawbacks: The retrieval of the sites' residual energies is a costly operation involving numerous nodes and thus should be performed infrequently. This overhead limits the mobility of the sink and forces it to spend adequately long sojourn times for the protocol to be efficient. Even though the protocol proves to be energy-efficient under certain scenarios, the nomadic and controlled sink mobility assumptions hinder the protocol's applicability.

14) SIMPLE: Swarm Intelligence Methodology to Design Data Acquisition Protocol (SIMPLE) [66] employs a flooding-based sink advertisement mechanism that sets up gradients which favor the paths with higher residual energies. At each source node, the path that contains the node with the highest minimum residual energy is selected as the data dissemination path. The swarm intelligence technique is utilized to set up gradients with minimum global knowledge about the network. In order to decrease the frequency of the global floods, a probabilistic mechanism that regulates the re-broadcasting of the advertisements is proposed. The nodes with higher residual energies and the nodes closer to the sink have higher chance of re-broadcasting the sink advertisements. The multiple sink adaptation of the protocol is also specified.

Advantages and Drawbacks: The proposed probabilistic sink advertisement scheme is energy-aware. Moreover, the distance to the sink consideration ensures that the nodes close to the sink, which are affected mostly by the sink mobility, have freshly updated routes. These properties contribute towards the protocol's energy-efficiency, scalability and reliability. However, as the residual energies of the nodes decrease throughout the network, the overall frequency of sink advertisement re-broadcasts are expected to decrease, which would degrade the establishment of fresh routes and lead to suboptimal paths.

B. Overhearing-based Approaches

The protocols belonging to this class exploit the overhearing property of wireless communications. Overhearing is an unwanted but inevitable property which describes the reception of transmitted packets by the neighboring nodes in addition to the intended recipient. In these approaches the sink is advertised by the information contained in the overheard packets. Figure 6 demonstrates the sink advertisement by overhearing.

1) DDRP: An Efficient Data-Driven Routing Protocol (DDRP) [67] exploits overhearing of data packets for the

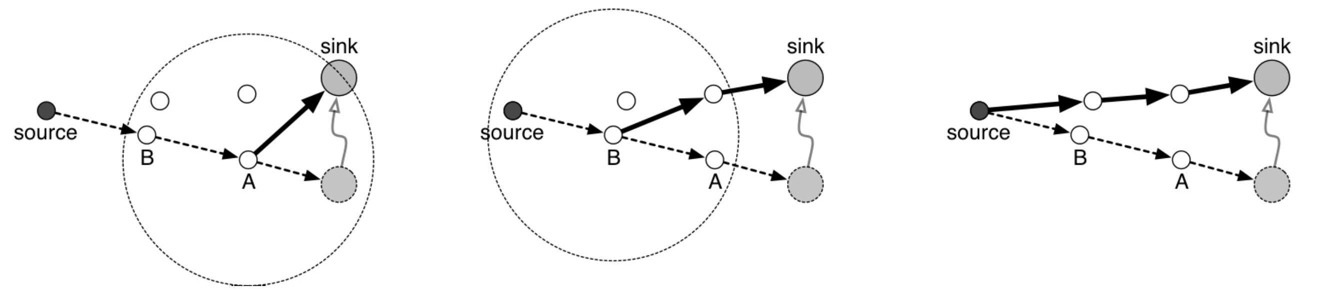

Fig. 6. Sink advertisement by overhearing. (a) Node A transmits packet containing sink position information, node B overhears it, (b) node B transmits, source overhears sink position information, (c) source forwards data towards acquired sink position (old path is denoted by dashed arrows; updated path is denoted by solid arrows).

sensor nodes to gratuitously learn the routes toward the sink. Each data packet carries an additional information on the hop distance of the sender node to the sink. The overhearing of such a packet will provide other nodes in the communication range with a route to the sink. As data packets are generated and transmitted, the knowledge of routes to the sink propagates across the network. If a sensor node has not yet learned of a valid route to the sink, it uses the random walk mechanism to forward its data towards a random direction until the packet encounters a node with a route to the sink or the sink itself. To reduce the frequency of the random walk procedure, which is inefficient, DDRP enforces data packets to be buffered for a certain amount of time before they are transmitted, in order to take the chance that a route is learned in the meantime.

Advantages and Drawbacks: DDRP exploits the broadcast nature of wireless communications to acquire routes to the sink by overhearing other nodes' transmissions. Even though DDRP is straightforward and very simple to implement, overhearing increases the energy consumption significantly. Moreover, since overhearing requires all nodes in a neighborhood to listen to the medium synchronously, DDRP cannot be used with a duty-cycling low-power MAC protocol.

2) Elastic Routing: As in DDRP, overhearing is the primary mechanism for the sink position advertisement in Elastic Routing [68]. The sink position information is recursively updated on each node on a data route starting from the node closest to the sink. Additionally, when the sink moves and its neighborhood changes, it informs the last source it has received a data packet from of its new position. This notification is also overheard by nodes near its path, hence also enabling numerous other nodes to learn the sink's new position.

Advantages and Drawbacks: The drawbacks of overhearing limit the applicability of Elastic Routing significantly, but its ability to propagate the sink's position to a large number of sensors with very few data propagations makes it an effective protocol in applications where MAC protocols suitable to overhearing are employed. Its easy-to-implement design is also an advantage.

C. Approaches Exploiting Geometric Properties

Since sensors are usually deployed on a nearly flat field which can be considered as a two-dimensional plane, geometric properties might be utilized to ensure the intersection of different kind of packets. The rationale behind this class of protocols is to exploit these properties in order to realize sink advertisement to source nodes.

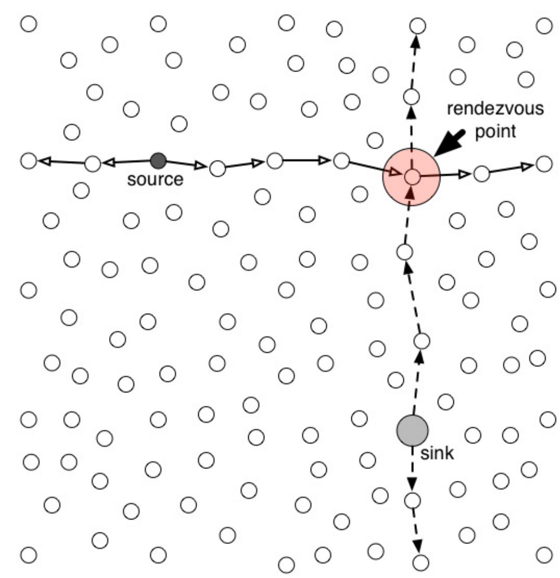

Fig. 7. Operation of XYLS. Sink sends queries vertically, source sends data horizontally. Data and queries meet at rendezvous point.

1) GHT: Geographic Hash Table (GHT) [69] hashes the data type into geographic coordinates. Nodes deliver their data to the nodes closest to the resulting geographic positions, and sinks may retrieve data by sending a query towards the geographic position determined by using the same hash function with the requested data type.

Advantages and Drawbacks: GHT has minimal overhead to select query-data rendezvous nodes since such nodes are defined by the utilized geographic hash function. However, the number of rendezvous nodes is likely to be small, thus causing hotspots due to the concentration of data traffic on a few nodes. Changing these nodes is practically impossible unless the hash function is changed.

2) XYLS: Column-Row Location Service (XYLS) [70] uses a similar approach to GBEER in the sense that the data queries by the sink are propagated vertically while the data announcements are propagated horizontally across the network. However, it does not utilize a grid structure, so that there is no

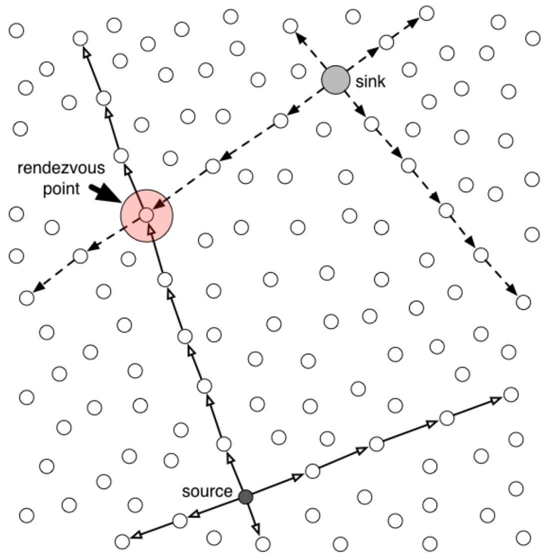

Fig. 8. Operation of Double Cross. Queries and data are sent along two pairs of orthogonal lines which are bound to intersect.

virtual infrastructure and all nodes contribute in distribution of routing information packets. In order for packets to travel along vertical and horizontal paths, position-awareness of sensor nodes is required. The rendezvous mechanism of XYLS is shown in Figure 7.

Advantages and Drawbacks: XYLS utilizes a straightforward mechanism to enable the rendezvous of data and query packets. Once a data packet intercepts a node with information of the sink's position, the data can be disseminated with no overhead. However, in order to ensure the intersection of data and queries, they have to be propagated along two opposite directions which causes redundancy. For queries this is not a severe problem since they are likely to be small packets, but for data which are expected to be composed of many bits, such a redundancy causes an energy inefficiency. Moreover, the problem of whether the information available in the first intercepted node which is aware of the sink's position is fresh has not been resolved.

3) Double Cross: Double-Blind Data Discovery Using Double Cross [71] is a mobile sink routing protocol based on Random Line Walk (RLW) [72]. In RLW, when a sensor node has data, it forwards it towards a random direction which is maintained in the successive hops, thus forming a line. In order for this mechanism to function, the relative direction information of the neighboring nodes is sufficient. This information can be derived by the simple cosine rule in case the distances of the neighbors are known. Therefore, RLW does not require position-awareness of sensor nodes, and distances may be inferred by observing the signal-to-noise ratio. RLW ensures that a data packet propagates along a straight line; however, it cannot guarantee for the paths of two separately generated data packets to have a predetermined angle between them, which would require position-awareness of sensor nodes (e.g. vertically and horizontally propagated packets in XYLS). Double Cross extends the idea of RLW by exploiting the simple geometric property of a plane: The intersection probability of two pairs of orthogonal lines on a plane is more than 99%. When a node has data, it sends it along two orthogonal lines which correspond to four directions. The queries issued by the sink are sent in four directions in the same manner. Due to the geometric property given above, data and queries are bound to meet (Figure 8), thus data dissemination can be initiated by taking the reverse path of the query.

Advantages and Drawbacks: Double Cross employs a much more complicated mechanism compared to XYLS to ensure that queries and data meet. The significant advantage of this mechanism is that it can operate without position-awareness. However, the high redundancy of packets is still a drawback.

The above-mentioned non-hierarchical mobile sink routing protocols are summarized and compared in Table II. The sink advertisement mechanisms and the possible hotspot regions are also provided.

V. Open Issues and Research Challenges

With its unique challenges and various aspects, the mobile sink routing problem still harbors many issues to be resolved. The routing aspect is tightly dependent on the mobility characteristics of the sink(s), and more efficient and comprehensive solutions which address the whole system are favorable. The issues presented in this section provides a variety of perspectives which could enhance a routing protocol, rendering it more applicable, broad and effective.

Application Type. Mobile sink mechanisms are mostly used for time-driven applications in which the sink moves across the network and collects the data from cluster heads [37], designated gateways [14] or source nodes themselves [3], [10], [73]. However, there are a lot of applications that employ event-driven paradigms [74] for data forwarding. Therefore, mobile sink strategy should be improved for data gathering in these kinds of networks [44].

Distributed Data Storage Capability. Distributed data storage capability is an important issue in WSNs with mobile sink. In particular when and where to store collected data should be considered in the context of data routing depending on the QoS constraints of generated WSN data. For example, delay-tolerant data can be routed and stored in nodes on the path of the mobile sink whereas delay-intolerant data can usually be required to be directly forwarded to the mobile sink. This issue should be further investigated by incorporating other parameters like node density, speed of mobile sink, etc. Moreover, the presence and the number of multiple mobile sinks impose extra challenges to select the position of data storage.

Speed of Mobile Sink. There is also an influence of speed of mobile sink on data routing which determines the destination of the forwarding. If the speed of the sink is low, the data can be directly forwarded to its last-known current location, since the sink is mostly in the vicinity of the forwarded position. As its speed increases, the knowledge of sink location becomes outdated and as a consequence the number of packet losses increases or the energy consumption and

TABLE II
SUMMARY AND COMPARISON OF NON-HIERARCHICAL MOBILE SINK ROUTING PROTOCOLS

Protocol	Position-awareness	Sink mobility pattern	Data aggregation	Multi-sink support	Protocol overhead	Sink advertisement mechanism	Possible hotspots (severity)
GRAB [52]	No	Random	No	No	High	Global flooding	None
ER [53]	No	Random	No	Yes	High	Global flooding	None
TwinRoute [54]	No	Predictable	No	Yes	Medium	Hop-limited local flooding	Data storage nodes (medium)
ALURP [55]	No	Random	No	No	Medium	Local flooding in limited area	Nodes in local area (low)
Mobile RPL [56]	No	Random	No	Yes	High	Hop-limited local flooding around sources	None
DEEP [58]	No	Random	Yes	No	Medium	Probabilistic flooding	None
QBDCS [59]	Yes	Predictable	Yes	Yes	Medium	Global flooding limited by predictability	Data aggregation nodes (low)
REDM [60]	No	Controlled	No	No	High	Global flooding	None
RM [61]	No	Random	No	No	Medium	Two-hop limited flooding	None
E-TRAIL [62]	No	Random	No	Yes	Medium	Hop-limited local flooding	Nodes on trail path (medium)
Termite-hill [63]	No	Random	No	No	Medium	Global flooding & route remembering	Nodes on pheromone trail routes (low)
SinkTrail [64]	No	Random	No	Yes	Medium	Global flooding	None
GMRE [65]	Yes	Controlled	No	No	High	Global flooding	Sentinel nodes (low)
SIMPLE [66]	No	Random	No	Yes	Medium	Probabilistic flooding	None
DDRP [67]	No	Random	No	Yes	Low	Overhearing	Overhearing nodes near data paths (low)
Elastic Routing [68]	Yes	Random	No	No	Low	Overhearing & recent sources notification	Overhearing nodes near data paths (low)
GHT [69]	Yes	Random	No	No	Low	Geo-hashed coordinates	Query-data rendezvous nodes (medium)
XYLS [70]	Yes	Random	No	No	Low	Geometric intersection of query and data paths	Query-data rendezvous nodes (low)
Double Cross [71]	No	Random	No	Yes	Medium	Geometric intersection of query and data paths	Query-data rendezvous nodes (low)

delivery delay increases in case of foot-print chaining. If the trajectory of the sink is known or estimated, depending on the sink speed, more accurate estimation of destination location can be possible.

Sink Traversal Pattern. Sink trajectory optimization coupled with routing is a difficult problem which have been addressed in numerous studies from a centralized perspective. However, a central entity that is aware of the conditions in the whole network at all times might not exist. In such cases, distributed solutions can be integrated into a routing solution to achieve efficient data collection. Some of the existing routing protocols utilize controlled sink mobility in a greedy manner; however, a comprehensive solution does not exist. Moreover, multiple sinks are rarely considered in existing sink path optimization studies. The pattern of the sink traversal in the network is critical for timely and efficient data delivery. The node density and the topology of the network are the determinant factors of the traversal pattern. In sparse and/or partitioned networks, the trajectory should be deterministic and the sink should visit each partition in a timely and fair fashion depending on the data generation characteristics of each partition. In dense and/or connected topologies, the mobility pattern is not required to be deterministic and random mobility can be tolerated. Moreover in some topologies hybrid pattern can result with better delivery performance. Hence, selection of a proper traversal pattern is an important challenge. Studying random sink mobility patterns is another open issue which attracts attention. Mobile sink routing protocols designed for random sink mobility could operate differently under various stochastic mobility patterns. Solutions which operate efficiently and reliably under a variety of such conditions may be explored. A problem of mobile sink methods is that in practice, due to the presence of obstacles and boundaries of the application area blocking the trajectory of the sink, the mobile sink may not be allowed to move along straight lines. The solution of this problem is known as obstacle avoidance methods [75]. More research should be done to overcome this problem.

Number of Mobile Sinks. Multiple mobile sinks are considered superficially by many of the existing routing protocols. The solutions supporting multiple sinks are merely adaptations of the single sink targeted designs. Routing protocols which are designed to exploit the advantages of multiple sinks to the full extent are rare. It is not certain that the schemes that only support single mobile sink will work efficiently in the presence of multiple mobile sinks. So investigating the impact of multiple mobile sinks is an open research issue. The selection of the destination sink directly affects the delivery performance and the lifetime of the network. An inefficient sink selection mechanism may lead to a degraded network performance and decreased operational lifetime.

Security. There are applications where data integrity and security is crucial in military applications like border surveillance or battlefield monitoring applications. Although the mobility of the sink is beneficial due to the difficulty in compromising and sniffing, in multiple mobile sink strategy, the probability that a malicious node plays the role of sink node and collects the data is very high [76], [77]. In this way, it can negatively manipulate the identity of data. Hence, the establishment of secure communication environment in terrains such as behind the enemy lines or inhospitable terrains needs to addressed, which is not considered in current energy-efficient mechanisms that are proposed to prolong network lifetime since their final goal is not satisfying this matter.

Network Assisted Sink Mobility. Instead of determining a mobility pattern, the traversal of the mobile sink(s) may be assisted by the network itself. For example, in event driven WSNs, a mobile sink can be directed to the regions of hotspots in the network due to high amount of data generation or bottleneck areas leading to accumulation of data. Sink navigation is a challenging issue especially in the presence of multiple concurrent data generation regions and in the existence of multiple mobile sinks to determine the optimal guidance strategy for reliable and fast data delivery.

Reliable Routing. In order to provide reliable data delivery, rate control and cross layer rate adaptation techniques should be developed that are specifically designated for the WSNs with mobile sinks. Depending on the speed of the sink(s), mobility pattern(s) and the routing distance(s) between the source and the sink(s) can be used to determine the feasible/optimal data rate. In addition, implementing multiple paths towards multiple mobile sinks for reliable data delivery with the help of path optimization techniques is an open issue. Moreover, the design of a decision mechanism to switch among single or replicated data delivery modes to establish a more reliable and energy efficient WSN containing any number of mobile sinks is a challenging task. On the other hand, using power control scheme accompany with multi-path mechanism helps the protocol to conserve much more energy [78]. It seems using a hybrid form of multiple and mobile sinks is a smart choice for more lifetime elongation [10]. The dual-sink [74] protocol, for example, is a novel scheme in which one of the sinks is mobile and collects the data packets from one or a few hops neighboring nodes while the other one is stationary at the center of field and receives data from far away source nodes without any localization overhead. In this way, the algorithm could benefit the advantages of both static and mobile sink approaches. Therefore, the hybrid multiple mobile sinks is an open issue for future trends.

Packet Level Simulation of Optimal Solutions. In the mobile sink routing literature, there are numerous works that analyze the routing problem and provides an optimal routing strategy under the constraints of some specific network and node characteristics. The packet level simulation of these optimal solutions and the performance evaluation compared with the analytical solutions can be regarded as another candidate research opportunity. Moreover, there is a lack of real life experiments with WSNs with single/multiple mobile sinks. The proposal of a new routing protocol for WSNs with mobile sinks and the implementation of it in real motes to evaluate the operation and the delivery performance in real WSN setups provides a valuable contribution.

Cross Layer Issues (Physical/MAC Layers). Cross-layer approaches using the physical and MAC layers usually utilize power and transmission control mechanisms to conserve more energy and therefore prolong network lifetime. The transmission range adaptation can be used in the physical layer as the power management scheme to restrict transmission range at the time of packet forwarding. This can reduce the energy consumed by a transmitter dramatically [78]. With this transmission range adaptation, the usage of mobile sinks could affect and change the basic assumptions and system properties of WSNs in general. Here, the connectivity enhancement provided by the mobility of the sinks leads to relaxations on the connectivity constraint of the WSN topologies based on the mobility pattern of the mobile sink given that the sink traverses through each disconnected partition of the network. In such cases, a sparse topology might perform similar to a dense topology with a static sink. In a similar way, the mobility of the sink can lead to lowering the number of nodes required to maintain data retrieval the operation of the WSN based on the application and sensing coverage requirements of the WSN application. The degree of extra sparseness allowed by a specific number of mobile sinks is a factor yet to be determined. In some cases, it is possible to exploit the knowledge on the mobility pattern to further optimize the detection of mobile sinks. In fact, if visiting times are known or can be predicted with certain accuracy, sensor nodes can be awake only when they expect the mobile sink to be in their transmission range. This behavior can be further enhanced by using additional low power wakeup radios on the sensor nodes to sense the presence of the sink in the neighborhood of the sensor node [79].

QoS Constraints. Imaging and video sensors in real-time applications pose issues like Quality of Service (QoS). In QoS algorithms some metrics such as delay and bandwidth should be guaranteed during the network functionalities. Satisfying these metrics, especially in mobile sink scenarios, may be in conflict with achieving more energy-efficiency [80]. Improving sink mobility methods or using multi-path routing approaches [81], [82] in QoS algorithms is needed to conserve much more energy.

System Overheads. Most of the static multi-sink approaches [83], [84] suffer from control overhead caused by sinks advertisement flooding in the gradient field construction phase. Mitigating the negative effect of such overhead on energy-efficiency is an open research issue. The main drawback of power control schemes is the execution cost due to calculating the RSSI/LQI parameters [85]–[87]. Therefore, mitigating the overhead caused by such calculation could be an open issue for future trend.

VI. Conclusions and Discussions

In this paper, we have presented a comprehensive review of the existing distributed mobile sink routing protocols. The unique challenges associated with mobile sinks and the design requirements of a mobile sink routing protocol are discussed in detail to provide an insight into the motivations and the inherent mechanisms. An accurate classification of the protocols is given and the advantages and drawbacks of the protocols are individually determined with respect to the performance requirements.

The determined classes of protocols have different benefits which may provide motivations for new solutions. The hierarchical approaches exploit a virtual structure which serves as a rendezvous region for the sink advertisement and data packets. The virtual structure reduces the overhead of the sink advertisement by confining it to a subset of the network; however, the high-tier nodes constituting the structure are susceptible to becoming hotspots since they are likely to carry and process more traffic.

Different virtual structure types have varying degrees of accessibility and hotspot susceptibility. Grids, clusters and backbones have high accessibility since they provide a uniformly distributed structure which covers the whole network, but the hotspot mitigation strategy requires more effort since modifying such complex and dense structures have relatively more overhead. The tree structure simplifies the sink advertisement process by employing the root as a relay node for messages; however, such an approach alleviates the severity of hotspots on the nodes close to the root. Area-based approaches mitigate the hotspot problem by distributing the load on the high-tier nodes to numerous nodes on specific geographical regions at the expense of reduced accessibility.

Non-hierarchical approaches forsake both the benefits and the drawbacks of a virtual hierarchy. The lack of a structure also eliminates the overhead of constructing it. Moreover, most of the non-hierarchical approaches are able to operate without position-aware sensors since the employed mechanisms rarely rely on a geographic coordinate space. In spite of these advantages, the mechanisms employed by the non-hierarchical approaches are usually inefficient or costly.

Flooding has a very high overhead, and the protocols employing this mechanism are aware of this overhead, hence they take actions to either reduce the frequency or the propagation area of the floods. Overhearing-based approaches are efficient only when the utilized MAC mechanism allows overhearing at will. For MAC protocols employing radio sleep mechanisms, overhearing might eliminate the energy savings of the MAC layer or simply be unrealizable due to asynchronous sleep-wake cycles of nodes. Agent-based approaches are very simple-to-implement and have low overhead; however, the hotspots on the agents pose a serious problem. The approaches exploiting geometric properties generally require position-aware sensors contrary to the other classes of the non-hierarchical protocols. They are quite efficient, but the geometric mechanisms might require complex calculations or lead to packet transmission redundancies which hinder the effectiveness of these protocols.

Mobile sinks have significant advantages to enhance the performance of the existing WSN architectures; therefore, developing efficient distributed routing solutions is a promising research effort. In this work, we also provide a detailed review of the open issues and the associated challenges to motivate and guide future researchers.

Acknowledgment

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