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ORIGINAL RESEARCH

A comprehensive survey on trajectory schemes for data collection using mobile elements in WSNs

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Abstract
Mobile elements trajectory optimization is one of the most important and efficient ways to enhance the performance of wireless sensor networks (WSNs). In the last 15 years, extensive research has been done in this area, but less effort has been devoted to providing a concise review of the broader area. This article surveys the role of mobile elements trajectory optimization in the performance improvement of WSNs. The complete survey has been done based on three major aspects: applications, trajectory techniques and domains used to formulate the trajectory. Under these three aspects, large numbers of schemes are discussed, along with their sub-aspects. A comparative analysis using eight important parameters, like trajectory pattern, number of mobile elements, speed, mobile element type, etc., is presented in a chronological fashion. The paper also points out the merits and demerits of each scheme described. Based on the current research, we have identified some research domains in this area that need more attention and further exploration.

Keywords Wireless sensor network · Mobile elements · Path planning · Trajectory · Energy-efficient · Mules

1 Introduction

A wireless sensor network (WSN) is a collection of sensor nodes that can sense surrounding environmental factors, like temperature, pressure, humidity, pollution, etc (Akyildiz et al. 2002). Sensors are tiny electronic devices that can communicate with each other to form a large network. A sensor node has three main tasks: sense the data, process it and transfer it to other nodes or a base station (BS). Among these three jobs, the most energy is consumed in transmitting the data to their neighbouring nodes in the network. Sensor nodes are generally battery-operated devices and hence energy-efficient operations are needed. Energy is the main resource in a WSN; hence, a dearth of energy creates a severe problem in a network. In a conventional WSN, there is a static BS located either outside or inside the network, and all sensor nodes send their sensed data towards the BS through single-hop or multi-hop communication. The packet reaches the BS in both communication types, but the routing can suffer from hotspot problems. In multi-hop communication, the nodes nearer the BS have higher traffic loads compared to the more-distant nodes, which results in fast energy dissipation, leading to hotspot problems (Li and Mohapatra 2007). In the case of single-hop communication, the more-distant nodes from the BS experience this energy hole problem, as the energy depletion of a node is directly proportional to its distance from the BS. If any part of the network suffers from this energy hole problem, the whole network is affected. Having a mobile element in the WSN is a prominent solution for such hotspot problems. Apart from the hotspot solution, there are a number of other areas where mobile elements have been used to improve the overall performance of WSNs, like energy efficiency, connectivity, reliability, end-to-end delays, etc. Several researchers have proposed the use of different kinds of mobile elements in WSNs to improve the overall performance of the networks (Shah et al. 2003; Di Francesco et al. 2011; Wu et al. 2008; Singh et al. 2016b). Mobile elements are considered a mechanical data carrier and a major tool to extend the network lifetime, which can establish connectivity between isolated networks

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and the BS. The mobile elements travel throughout the network and collect sensor data, store it and drop off to access points or sinks. Based on the movement patterns of mobile elements, the trajectory is classified into three categories: random, controlled and uncontrolled.

In a random trajectory, the mobile elements are randomly moved with some probability in any direction, like an animal's movement. In this type of trajectory, we cannot control the trajectory of the mobile elements, and its schedule prediction is very low.

A controlled trajectory is the most suitable trajectory for WSNs, where the mobile elements are totally under the control of users, like robots and controlled vehicles. In a controlled trajectory, we can control the speed, direction and schedule of the mobile elements, which makes this trajectory type the most efficient.

In an uncontrolled trajectory, the mobile elements always move on a fixed and predefined route and the schedule is known in advance, like buses, trains, etc. In a controlled trajectory, path planning is an important issue, and the main focus of researchers is to optimize the trajectory path of the mobile elements.

A lot of path-planning approaches have been proposed by researchers based on different techniques, but there is still scope for improvement. Khan et al. (2013); Matsuo et al. (2015) make a comparison between a static sink and a mobile sink and prove that a mobile-sink-based WSN has a longer lifetime compared to one with a static sink. Depending on the network's components and data collection behaviour, it can be classified into three groups.

i. A mobile base station (MBS)
ii. A mobile data carrier
iii. A normal sensor node

(i) *A mobile base station (MBS)* An MBS is like a general BS but is capable of moving throughout the entire network and collecting data. An MBS is the final destination for all sensed data and has sufficient energy and storage. The number of MBSs depends on the applications and size of the sensing network. If the sensing area is very large, then more than one MBS will need to be deployed because a single MBS would take a long time to collect data from the entire network, causing data loss and delays. In most scenarios, MBSs are IP enabled and can communicate directly with the real world.

(ii) *A mobile data carrier* In some scenarios, it is not possible to make the BS mobile due to the harsh environment where the sensor nodes are deployed. A mobile sink requires an IP address to communicate with the rest of the world, and it is not possible to provide IP addresses in such scenarios. In these scenarios, the sink or BS is static and is generally placed outside the network. Here, a special node is used, known as a 'mobile data carrier' or 'relay node'. It is neither the source nor the final destination of the sensed packets but works as a carrier between sensor nodes and the BS.

(iii) *A normal sensor nodes* Normal or regular nodes are the major components of WSNs, and their main task is to sense the environment. Mostly, these nodes are static in nature, but, depending on the applications, they may move and relay their sensed data to the access point or BS, but all mobile sensor nodes must have mobilizer hardware for mobility. The overall network cost and energy consumption will increase if we use mobilizers because extra hardware comes with additional costs and energy usage.

A lot of research has already been done on path-planning issues and techniques in WSNs. Some surveys have been conducted related to mobility management and data collection, as shown in Table 1. Anastasi et al. (2009b) present the results of an energy conservation survey in WSNs with some mobility management issues. In this survey, their main focus was on energy conservation, not on the mobile elements' trajectories. Wang et al. (2012) summarize mobile WSN protocols and issues in detail but focus on path planning, with limited discussion. Reports of a few more surveys are available, but these are very limited and general in nature (Sayyed and Becker 2015; Mukherjee et al. 2015), while others Dong and Dargie (2013) have focused on mobility-aware MAC schemes only. The survey results presented by Di Francesco et al. (2011) are comprehensive in nature and discuss the phases of data collection by mobile elements, like discovery, data transfer and routing. The surveys of Khan et al. (2014) and Gu et al. (2016) only explored sink mobility. By contrast, our survey dealt with all types of mobile elements and included both application-based and domain-based schemes.

This paper discusses the different types of methodologies used in the recent past for the path planning of mobile elements in WSNs for data collection. In previous surveys, authors have mainly focused on data collection issues like data transfer, mobile element scheduling, contact detection, routing, etc. Some important issues associated with the use of mobile elements for data collection, like application areas, challenges, path-planning approaches, the different domains used for various protocols, etc., have not yet been discussed. In this paper, we cover these issues in different sections. For better understanding, we have split the discussion of path-planning approaches into two primary sections, each categorized into different sub-sections based on trajectory schemes, as shown in Fig. 2. This paper mainly focuses on the application areas of mobile elements, data gathering and

Table 1 List of the previous surveys on mobility of mobile elements

References	Major focus	Trajectory coverage	Topic discussed
Anastasi et al. (2009b)	Energy-efficiency	Narrow	How to minimize energy consumption by using mobile sink?
Di Francesco et al. (2011)	Mobility and data collection	Substantial	Mobile elements architecture based on their role, data collection process and its issues with solutions
Wang et al. (2012)	Mobility Management	Substantial	Mobile WSN with coverage and connectivity
Dong and Dargie (2013)	Mobility management	Narrow	MAC layer protocols with existing mobility models and movement patterns
Khan et al. (2014)	Sink mobility	Substantial	Data collection using sink mobility and their issues
Sayyed and Becker (2015)	Data collection	Narrow	Data collection in mobile WSN
Mukherjee et al. (2015)	Mobility of sensor nodes	narrow	Mobile nodes based data gathering
Gu et al. (2016)	Sink mobility	Substantial	Sink mobility management with taxonomy and development flow in all category
Our work	Path planning of mobile elements	Substantial	Applications of mobile elements, Trajectory path for data collection, different domains used

the challenges. The different domains that are used to formulate trajectory techniques are also discussed in detail. Apart from these, some major areas for future research are also suggested regarding the exploitation of mobility in WSNs.

The rest of the paper is structured as follows: Sect. 2 states the specific application areas of mobile elements in WSNs. Static path trajectories are discussed with their classifications and features in Sect. 3. Section 4 explores the main characteristics of dynamic path trajectories. The major challenges are introduced with their priorities in Sect. 5. The different domains used in the trajectories of mobile elements is provided in Sect. 6. A comparative analysis based on two different tables is presented in Sect. 7. Some important future areas for research are proposed in Sect. 8. The overall article is summarized in Sect. 9. Finally, Sect. 10 concludes the article.

2 Application areas of mobile elements in WSN

Mobile elements are used for many different reasons in WSNs. The different fields of WSNs where mobile elements play an important role in enhancing network performance are shown in Fig. 1. Based on the uses of mobile elements, we ranked and explored the different application areas.

2.1 Data collection

In all WSNs, data collection from the end devices (sensors) is the prime objective. In most scenarios, data collection is event based, and sensor nodes only respond when abnormal events occur, like fire, avalanche, flood, etc. However, in some cases, data is collected periodically, like medical diagnosis, border surveillance, environment monitoring, etc., where sensor nodes store all data and send it to the BS. As sensor nodes have limited memory, it is a very tough task for them to accommodate all packets and transmit them to

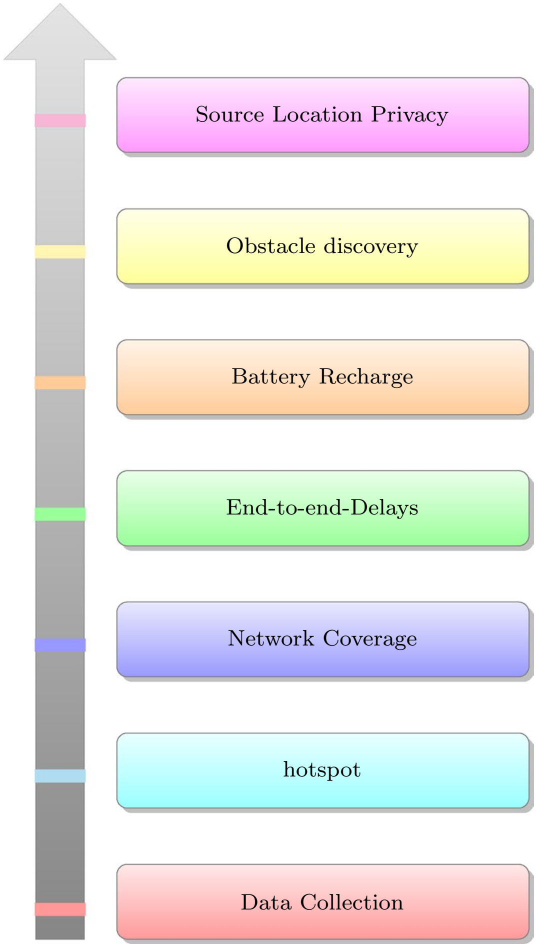

Fig. 1 Priority-wise area where Mobile Elements are used in WSN

the BS on time. Here, mobile elements play a key role due to their mobile nature and sufficient storage. Mobile elements frequently travel the network and collect data directly from sensor nodes or from relay nodes. If the network size is large, more mobile sinks or mobile carriers are required for data collection to prevent packet dropping (Gao et al. 2011; Ghaleb et al. 2014). Kumar and Dash (2019) have proposed an new approach for maximizing the data collection and minimizing the energy consumption using a mobile sink. In their scheme, a mobile sink is moving with a constant speed in a predefined path.

2.2 Hotspot

In large area networks, hotspots are a major problem, where an energy hole is created around the BS due to the large amount of data traffic on the sensor nodes of that area (Olariu and Stojmenovic 2006; Li and Mohapatra 2007; Wu et al. 2008; Asharioun et al. 2015). As a result, the overall performance of the network degrades, and the network gets partitioned into isolated networks. Several researchers have used mobility and mobile elements as tools to reduce such hotspot problems. They have exploited mobility to minimize the amount of communication in the network, especially near the BS. In this type of network, sensor nodes directly send their data to the mobile elements or relay nodes near a sojourn point. Mobile elements roam throughout the network periodically based on certain conditions, and when they reach sensor nodes' radio ranges, the elements transmit their data to them. As sensor nodes do not send their data directly or through multi-hop communication to the BS, the traffic load is normal on the nodes that are closer to the BS. Mobile sinks and mobile carriers (or mules) are frequently used in WSNs to minimize hotspot problems (Jain et al. 2006; Thanigaivelu and Mururgan 2012; Marta and Cardei 2009; Jannu and Jana 2016; Singh et al. 2016b).

2.3 Network coverage

Coverage is an important issue in WSNs, including in isolated WSNs. An isolated WSN is a group of several small WSNs where the group has no connectivity (Tseng et al. 2013; Singh and Kumar 2018). Coverage ensures the connectivity between the sensor nodes throughout the sensing area. Coverage is measured on the basis of the throughput and lifetime of the network (Ghosh and Das 2008; Abo-Zahhad et al. 2014; Das and Roy 2014; Vecchio and López-Valcarce 2015; Wang et al. 2017b; Elhoseny et al. 2018). To achieve an efficient network, the network must have good connectivity among nodes, as well as with the BS. In addition to connectivity, node deployment is another important issue for coverage. Generally, two types of node deployment are popular in WSNs: random and uniform. In random deployment, nodes are randomly thrown (like drops from aeroplanes, helicopters, etc.) in the area of interest; in uniform deployment, nodes are placed manually at predefined locations (Sharma et al. 2016). In random deployment, coverage is a major concern because nodes can be placed anywhere in the network; in some cases, an isolated network is created. By contrast, in uniform deployment, coverage is not a major issue. In a WSN, the BS is the final destination of all sensed data, and such data is transmitted through an efficient route. Based on the communication range, the node establishes a path; if there is no path from a sensor node to the BS, then the packets will not reach the BS. Mobile elements are the best solution for coverage problems (Somasundara et al. 2006; Mohamed et al. 2017). They can travel anywhere in the network, as well as outside the network, and they make connectivity and data transmission routes among the nodes and connect with isolated networks. One of the major advantages of using mobile elements is the cost-effectiveness. If there are mobile elements in the network, then fewer nodes are required to cover the entire sensing area, which ultimately reduces costs. To make a trade-off in between cost and coverage, Saukh et al. (2014) have proposed a novel idea by using public transport. Here, public transport is working as a mobile sink and due to this less number of sensors has been deployed which reduces the overall cost of the network.

2.4 End-to-end delays

The use of mobile elements can reduce the overall delay in networks, but not in every scenario. If the terrain is large and only one mobile element [either a mobile BS or a mobile carrier (mule)] is collecting data, then delays will increase. Network delays also depend on the data collection mode: whether the mobile elements are collecting data directly from sensor nodes or from rendezvous nodes or points (Thanigaivelu and Mururgan 2012; Khan et al. 2015; Akbar et al. 2017). The different trajectory schemes also influence the end-to-end delays in a network. The overall delay can be minimized by using a greater number of mobile elements, but this will increase the overall cost and complexity of the network. Therefore, a trade-off will be essential between delays and costs. To minimize the delays and energy consumption of an overall network, a novel approach has been developed: the delay-intolerant data routing scheme (DRS) (Ghosh et al. 2017b). In this scheme, a mobile sink is used to collect data from the sensor network, which follows a Moore curve trajectory, and sensor nodes use anycast forwarding to minimize the delays. Here, nodes follow a strict duty cycle and save a significant amount of energy. The delay-intolerant DRS shows an improvement of 25–29% over existing schemes in terms of network lifetime. Another scheme has been developed by considering delay optimization and energy consumption minimizing using three different heuristic methods (Yang et al. 2013). To reduce the overall delay, using multiple mobile sinks is an effective technique. Kumar and Kumar (2018) developed an location aware routing for controlled mobile sinks (LARCMS) which minimizes the delay as well as it increases the lifetime of the network.

2.5 Battery recharge

In traditional WSNs, a sensor node's life is measured by its battery life. In most scenarios, if the sensor's battery is completely dissipated, then that sensor node is considered dead. Recently, wireless charging has emerged as the best technique to give extra life to sensors (Wu et al. 2013; Lakhal et al. 2013). If sensor nodes are deployed randomly in a sparse network manually, it is not possible to recharge all the nodes. Therefore, mobile elements are the best option to recharge low-energy nodes in the network and make them more energy efficient. A few researchers have proposed new schemes using wireless recharging to enhance the lifetime of a network (Lin et al. 2016; Zhong et al. 2017; Tu et al. 2017).

2.6 Obstacle discovery

Generally, in the past, the physical obstacles in networks were totally ignored by researchers. However, in practical scenarios, obstacles are an essential part of the network that cannot be pushed aside. Recently, a few papers have been published contemplating the physical obstacles in networks. Conventional routing with obstacles does not perform well due to the low signal strength and energy constraints of nodes. Obstacle detection is also very tough, mainly in random deployment (Wang and Ssu 2013). By contrast, mobile elements handle these situations more efficiently due to their mobility and lower energy constraints. The latest trends in WSNs show a great swing towards addressing obstacles by using mobile sinks or mobile carriers (Chang et al. 2009; Chanak and Banerjee 2014; Chu and Ssu 2014; Xie and Pan 2016).

2.7 Source location privacy

As the number of applications of sensor networks in our day-to-day lives increases substantially, this raises a fundamental question of source privacy. In certain applications of WSNs, source location privacy is an important issue. For instances, in animal sanctuaries or managed forests, the nodes are attached to the bodies of animals for observing their social behaviour, movement monitoring, etc (Ozturk et al. 2004). Here, the sensor-equipped animals work as mobile sensor nodes, and the sensors communicate with the BS using flooding or other routing protocols. A poacher can easily find a target animal by using backtracking routing, which is a serious issue for the protection of these animals. Several source location privacy techniques have been suggested (Li et al. 2009; Roy et al. 2015; Kumar et al. 2015; Roy et al. 2016) but these are not very efficient due to their complexity and high energy consumption (Gupta et al. 2016). A few schemes have been designed with mobile mules and sinks that are less complex and consume a low amount of energy (Li et al. 2012; Singh et al. 2016a). In these schemes, extra mobile elements divert the attention of intruders by transmitting beacon messages that protect the actual location of the source.

3 Static path trajectory of mobile elements

In a static path trajectory, the mobility patterns are mostly periodic, so the mobile elements move on a fixed path, which is repeated at set increments. After the deployment of static sensor nodes, the mobile elements require only a one-time learning phase due to the uniform path. This type of trajectory can be classified into two types, as shown in Fig. 2, (i) direct contact and (ii) Sojourn point.

3.1 Direct contact

In a direct-contact-based trajectory, mobile elements are used to collect data from each node with a maximum of a one-hop communication link, as shown in Fig. 3. If the mobile elements are IP enabled, then they directly communicate with the rest of the world; otherwise, they carry the collected data to a fixed BS. This type of data collection approach is generally very useful for small area networks but in the case of a large sensor network, it fails to deliver better performance due to the significant delays and data losses. Hence, it is not feasible for a single mobile element to collect data individually from each node in the case of a large-scale sensor network. To achieve better performance, more than one mobile element needs to be deployed. The number of mobile elements needed depends on the applications and size of the sensing area. Another important factor in a direct contact trajectory is the movement pattern of the mobile elements, which should be discussed in detail. Depending upon the movement pattern of the mobile elements in the direct contact trajectory, three different approaches can be determined: (1) random, (2) the travelling salesman problem and (3) label covering.

3.1.1 Random

In a random trajectory, the mobile carrier moves randomly in the network and collects data from individual sensor nodes or polling points. Polling points are points from where mobile carriers collect data. This type of trajectory is mainly suitable for wildlife monitoring, where sensing

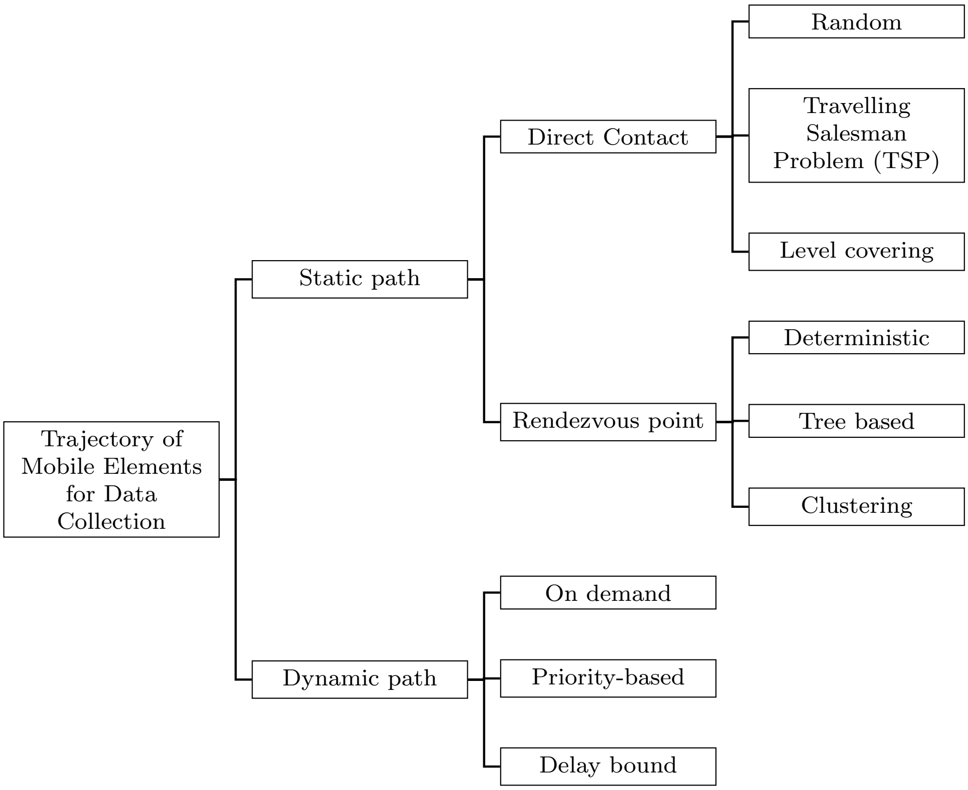

Fig. 2 Taxonomy of the approaches for the trajectory of mobile elements in WSN

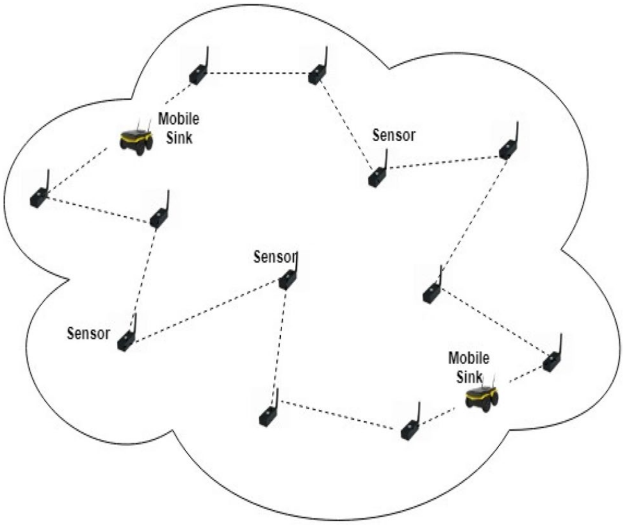

Fig. 3 Direct contact-based trajectory for data collection

devices are fixed on the animal's body. These devices sense their surroundings based on the animal's movement in the environment. Several polling points are selected because we cannot predict the movement of the animal. Polling points have wireless sensor nodes that can receive the other sensors' data and transmit it to the BS. When an animal comes close to a polling point, the sensing device on that animal transfers the sensed data to the polling point. The Zebranet project was the first random-trajectory-based data collection scheme, which was developed at the Mpala Research Centre in central Kenya (Juang et al. 2002). If delays are not a constraint, then a random trajectory is the best suited and most efficient data collection method for the network. Shah et al. (2003) propose a three-tier architecture using mobile elements (data mules) for data collection. Here, the data mules work as carriers between sources and destinations. They collect data from the sensor nodes and deliver it to the static BS. In this three-tier architecture for data collection, the bottom layer is the sensors; the data mules are the middle layer, which can be humans, animals, robots or vehicles; and access points or BSs are the top layer. In their work, each mule moves in a grid-based network with a random walk based on probability during data collection. This feature increases the overall data delivery delay in the network. The performance of this scheme has been improved by using mule-to-mule communication (Jain et al. 2006).

3.1.2 Travelling salesman problem (TSP)

The travelling salesman problem (TSP) is a classical algorithm in the field of graph theory for visiting all the nodes with the shortest path. This algorithm has been exploited by several WSN researchers for data collection using mobile sinks. Nesamony et al. (2007) mapped and formulated a TSP algorithm for visiting sensor nodes by using a mobile sink. They reduced the number of mobile sink trajectory problems by using neighbourhoods. Rao and Biswas (2008) present a data collection scheme based on RPs with multi-hop communication. This scheme does not require location information because it works on a network-guided data collection (NGDC) framework. They used a mobile sink for data collection, and the path of the mobile sink was constructed based on a TSP algorithm. The main focus of this work was to provide a trade-off between energy efficiency and data delivery delays by restricting the maximum hop in multi-hop communications. Another TSP-based data-gathering scheme using mobile sinks was proposed by Cheng and Yu (2016). The main contribution of this scheme is that it shortens the distance between data collection points by considering the overlapping areas of the sensors' communication ranges. This method reduces the number of visiting points and the computational costs required in path planning, which results in a great improvement over existing protocols in terms of the lifetime of the network.

3.1.3 Label covering

Label covering relaxes the requirement of visiting each node during the data collection, which reduces the data delivery delays. Label covering is basically a vertex-to-vertex movement by the mobile sink, where the search space for the data collection is reduced due to the implied trajectory path. Based on the indegrees of the vertices, the data collection points are selected like rendezvous points. The higher indegree vertices get first chance to serve as sojourn points during the data collection. In these types of data collection trajectories, the main motive is to cover the label set (sojourn points) in the shortest path. Several researchers have proven that the label-covering problem is an NP-hard; therefore, they have solved it using approximation algorithms. Xing et al. (2008a). propose a tree-based data collection scheme where RPs are formed based on the label covering. The optimal RPs are selected using greedy methods during label covering of the tree. This scheme minimizes the overall path length for the mobile elements. Kumar et al. (2017) suggest a new data collection scheme based on label covering, where some subset vertices are selected as the RPs from where the mobile sink collects data. Both schemes perform well but have a major issue: hotspots.

3.2 Sojourn point

Sojourn points (SPs) are the centroid point of the sub-networks in a WSN, where the mobile data collector stops and collects data. In each sub-network, most of the sensor nodes are covered using single-hop communication from this point. This relaxes the mobile data collector's need to visit each node during the data collection, as shown in Fig. 4. Hence, the total data delivery time is kept to a minimum. Xing et al. (2008b) propose an SP-based data collection scheme, where a subset of nodes are considered SPs. These nodes collect data from their neighbours' source nodes; after aggregation, they wait for the mobile data collector. The mobile collector periodically visits all the SPs. When it comes near to an SP, it receives the aggregated data from the SP node. This scheme improves energy efficiency and minimizes network delays. It also increases the throughput of the network. Besides these advantages, it also has various challenges, such as mobility patterns, the mobile collector's speed, the selection of SPs, etc. In a similar way to direct contact schemes, we can divide SP-based data collection into three different groups: (1) deterministic, (2) tree based and (3) clustering.

3.2.1 Deterministic

In deterministic SP-based data collection, the mobile data collector visits all the SPs on a fixed route with controlled mobility. The simple and controlled mobility of the mobile collector makes this scheme efficient for data collection. The major challenges in this approach include simple path selection, finding SPs and controlling the mobility speed. Several approaches have been proposed to tackle the challenges of fixed track schemes (Kansal et al. 2004). In deterministic SP-based data collection, the mobile data collector visits all the SPs on a fixed route with controlled mobility. The simple and controlled mobility of the mobile collector makes this scheme efficient for data collection. The major challenges in this approach include simple path selection, finding SPs and controlling the mobility speed. Several approaches have been proposed to tackle the challenges of fixed track schemes. Singh et al. (2016b) present grid-based clustering with even-odd round-based data collection from

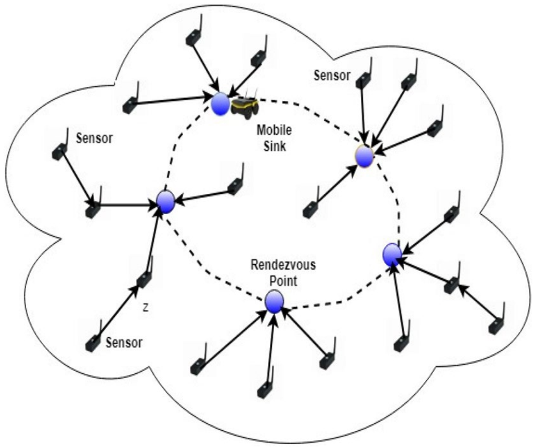

Fig. 4 Rendezvous point-based trajectory for data collection

the left-most and right-most cluster heads (CHs) of each level. Here, SPs are fixed at each level on both sides of a rectangular area. The selected CH sends its aggregated data to its neighbouring CH at the same level but based on a round number. When the data reaches the left-most or right-most CH, it transfers the final aggregated data to the mobile mule. The mobile mule periodically visits both the sides on a fixed route and stops at each SP for a predefined length of time. This scheme reduces the occurrence of energy holes and increases throughput. Centralized CH selection is the main drawback of this scheme.

3.2.2 Tree-based

In tree-based approaches, several trees are formed based on the node density, and the root nodes of each tree are considered the SPs. Multi-hop routing is used for the formation of these trees and data transmission towards the roots. A distributed and energy-efficient data dissemination protocol is presented by Kim et al. (2003) named 'SEAD' (scalable energy-efficient asynchronous dissemination). This protocol uses multiple mobile sinks to reduce end-to-end delays. Under the SEAD protocol, a minimum-weight Steiner tree is constructed from the source node to the mobile sink, which is also called a 'dissemination tree' (d-tree). To reduce the load of an intermediate node from a tree between the source and the sink, a replica node is selected; from that point, a different d-tree is constructed, where a replica node works as an access point. Based on the sink trajectory, the d-tree updates its access and replica nodes. Although the SEAD protocol improves the lifetime of the network, it fails to minimize end-to-end-delays and costs. Xing et al. (2007) present a novel scheme for large area networks by using a tree-based SP method. The authors propose two different techniques for selecting SPs; based on these SPs, the data collection path of the mobile sink changes. A hotspot region is created near the SPs, which degrades the overall network performance.

3.2.3 Cluster-based

In cluster-based approaches, each cluster or group of clusters acts as an SP, and the CH works as the data supplier's node during the data collection. The mobile element moves on a predefined path but based on the CH's position, it changes its route in that round. For a particular round, the mobile element does not change its route. In centralized clustering, like in grid-based methods, clusters are fixed for the whole lifetime of the network; therefore, the trajectory path will also be fixed due to having the same SPs. However, in distributed clustering, most of the clusters change every round, so the trajectory path also changes due to having different SPs. Thanigaivelu and Mururgan (2012) suggest grid-based clustering (GBC) with a predefined trajectory for the mobile sink. Equal-sized square grids are formed; in each grid, there is a CH whose job it is to transfer the aggregated data to the secondary CH. The mobile sink moves on a predefined path with uniform speed and stops at the four middle corners of the square area; it collects data from the secondary CH directly. This scheme reduces the hotspot problem but due to the centralization of the clustering, it is not suitable for large area networks. A new clustering algorithm with multiple mobile sinks has been proposed for heterogeneous WSNs (Krishnan and Kumar 2016). Singh et al. (2016b) propose an CH-based data collection scheme where odd-even level routing for data forwarding at each level is used, with the mobile mules collecting data from the boundary CHs at each level. Two mules at a time are used in this scheme, but only one mule visits the levels based on the round numbers. Due to the centralized clustering, this approach is not suitable for large area networks. Further, Singh et al. (2018) extended their previous scheme (Singh et al. 2016b) by using unequal clustering and mobile mules with different trajectory patterns. In this scheme, a near-optimal CH change factor is calculated, alongside a reduction factor for the cluster size. An optimal CH selection works as an SP is the major challenge in this area.

4 Dynamic path trajectory

In a dynamic path trajectory, the mobile elements change their normal path and select a new path based on certain restrictions, like delay bound during data collection. In most data collection trajectories, the mobile elements' path is determined before the journey; however, in dynamic path planning, the mobile elements' path can change at any time according to a particular demand or priority. Therefore, on the basis of the constraints due to which dynamic path planning is used, we can divide this trajectory type into three different sub-types: (1) on request, (2) priority based and (3) delay bound.

4.1 On-request

On-request trajectory control protocols primarily change the default route when they receive a request from a source node. On the occurrence of any unusual events, the terminal node sends a request packet to the mobile element to visit it. Zhao et al. (2004) propose a message ferrying (MF) scheme for data collection in sparse WSNs. The MF is assisted by mobile nodes, which build connectivity between disconnected networks. There are two variants of the MF approach, based on the non-random trajectory initiated by the node or ferry. In the first, the mobile nodes move on a predefined path in the deployed area and collect data from the regular nodes, delivering it to the disconnected networks. The second approach, known as ‘ferry-initiated MF’, is mainly based on an on-demand trajectory model. The mobile nodes move on their default route but when they receive any requests from the regular nodes, they reroute from their normal path, visit the requested nodes and exchange the data. In this scheme, the regular nodes are considered mobile instead of static, as in previous schemes developed for mobile ad-hoc networks (Zhao and Ammar 2003). The iMouse (Tseng et al. 2007) system was developed by using mobile nodes with extra features, like a webcam to take snapshots, WLAN for data transmission and a mobilizer to move. This was mainly designed for the emergency services. The mobile nodes move on a predefined path to collect data and send it to the BS. In the case of an emergency, like a fire, the mobile nodes immediately visit that location, take a snapshot and transfer accurate data to the BS. A new data collection scheme based on the on-demand approach was developed (He et al. 2014). In this scheme, mobile elements visit the data collection points when they get requests from nodes. The data collection method is modelled on the M/G/1/c-NJN queuing system with a service process of the nearest job next (NJN). This work was theoretically analysed and simulated, with the results compared with a first come first serve (FCFS) scheme, it performed better than FCFS. Khan et al. (2015) present a dynamic-trajectory-based on-request data dissemination protocol. In this scheme, the whole network is divided into square grids, and a mobile sink moves on a predefined circular path. Based on the demand, the mobile sink stops near the source grid, and a virtual path is formed from the source node to the mobile sink. The main aims of this scheme are the minimization of delays and energy consumption. This scheme has more overheads due to the creation of a virtual path at each sojourn point of the mobile sink. An efficient data collection method has been developed for an on-demand fuzzy-based clustering network (Ghosh et al. 2017a). Here, clustering is performed with the help of a fuzzy rule-based system using the location of the sensor nodes and based on demand the CH is changed. To find the optimal CHs, the PSO algorithm is used to optimize the node degree, node centrality and packet drop probability. A mobile collector moves throughout the network and collects data from the CH personally. The mobile collector’s route is optimized by using a TSP algorithm with ant colony optimization. Simulation results prove the superiority of this scheme compared to existing protocols in terms of energy efficiency and packet drops.

4.2 Priority-based

A priority-based dynamic trajectory works on a predefined data priority, where mobile elements usually move on a default path and change their route when they receive any high-priority data messages. Partition-based scheduling has been proposed by Gu et al. (2005) for a different rate of data generation sensor nodes. In this method, the whole network is partitioned into different regions based on the rate of data generation, and nodes are visited according to the node’s buffer status so that data will not be lost due to overflow. This scheme suffers from higher delays due to the individual data collection by mobile elements from the nodes in single-hop communication, which inspired the authors to improve and extend the scheme. They came up with an extension that uses multi-hop transmission to the mobile elements (Gu et al. 2006). They also propose differentiated message delivery for normal and urgent (priority-based) messages by the mobile elements, which collect data based on these priorities to minimize data loss. Juvvalapalem and Rao (2016) present a priority-based trajectory method for data collection. Initially, rendezvous points and sub-rendezvous points are selected based on the positions of the CHs. A SenCar (mobile element) with multiple radio channels always monitors all the rendezvous points and collects data based on the priority. Say et al. (2016) developed a novel method for the data collection trajectory using an unmanned aerial vehicle (UAV), which visits locations based on the priority. The priority is set based on the different frame sizes created after the division of the coverage area. The proposed scheme performed better but required a dedicated data transfer protocol from nodes to the UAV or vice versa because the UAV flies on a 3D plane.

4.3 Delay bound

In a delay-bound dynamic trajectory, the mobile element changes its default route based on the restricted time. In these types of scenarios, a fixed time is allotted for the complete journey. During that time, the mobile element has to collect data and transfer it to the BS. Therefore, the mobile element always maintains the time bound. If it has less time based on parameters such as distance, residual energy, the priority of data, etc., it decides the new route and collects data. Nitesh et al. (2017) present a dynamic delay-aware path-planning scheme for a mobile sink that is based on energy density. Rendezvous points are calculated based on the energy density of each sensor node. They propose two different methods: the first one is called an ‘energy-density-based trajectory’ (EDT), where the delay bound is not considered. The second method is named a ‘delay-aware energy-density-based trajectory’ (DAEDT), which similar to the EDT but path planning occurs based on the delay bound. In the EDT, the impact of every other node that is in the communication range of a sensor node is calculated. The nodes with the lowest impact are considered RPs. A set of RPs that covers all the deployed nodes are separated, and a TSP path covering all these RPs is constructed. The EDT does not consider the delay bound associated with the application and hence is not suitable for application areas where the responsiveness of the network is expected to be high. Its worst-case time complexity is $O(n^3)$, where n is the number of nodes deployed. In the DAEDT, the TSP path is bound by some user-defined delay limit. The number of RPs will decrease, resulting in a greater communication distance. Thus, when delays are considered, the sensors are not restricted to communicating only over single-hop distance.

5 Mobile elements trajectory challenges

The mobile element with efficient path planning improves the lifetime of the WSN, in spite of advantages, there are several major challenges arises that required a proper attention. These challenges are illustrated in Fig. 5 based on their priorities and also discuss these in details. The priority is calculated depending on the published literature on these topics.

5.1 Load balance

One of the major factors for which the mobile element has been introduced in WSN is load balancing. The use of mobile element reduces the energy consumption of sensor nodes but its consumes energy in uneven mode. This is the major challenge while we are using the mobile element trajectory for data collection. Mai et al. (2011) have proposed a load balancing rendezvous points (RPs) trajectory scheme for the mobile sink named as RPS-LB. They used the approximation algorithm for selecting the load-balance RPs which ensures the optimal trajectory path of the mobile element during data collection. Due to the predefined trajectory, fewer numbers of RPs are selected which increases the burden on the network. A similar type of work has been done using linear programming and heuristic algorithm (Li and Park 2015). They have also calculated the optimal RPs for the trajectory path which resolves the energy hole problem and balances the energy consumption of the network. The main problem with this scheme is complexity which restricts to use this in a large area network.

5.2 Schedule pattern

The scheduling problem is generally related to the controlled mobility where a user can control the mobile element. In the control trajectory, the target of mobile elements is to visit each node or RPs in such a way that it avoids the data overflow of the nodes. To achieve this, scheduling is the main process which assigns a predefined scheduling chart to all mobile elements or they schedule dynamically during their trajectory based on certain criteria. Scheduling also plays a major role in the energy harvesting by charging the node's battery using mobile chargers (Rahimi et al. 2003). Somasundara et al. (2004) presented a dynamic scheduling scheme for the nodes which generates data at different rates. Due to the different sampling rate of the nodes, the quantity of the data varies which requires a regular visit for the node containing high quantity data. The frequent visit to these nodes ensures that the data will not lose due to overflow. The authors have proved that this is an NP-complete problem and they have provided a linear programming solution. They have used only one mobile element which increases the overall delay of the network. Hence, they extended their work by using multiple mobile elements and for their scheduling heuristic approach is applied (Somasundara et al. 2007). Gandhi and Narayanasamy (2011) have presented a survey on the schedule pattern of the mobile element during data collection. Their survey is mainly based on the trajectory scheduling between different RPs in the network.

5.3 Speed

The speed is usually related to controlled mobility and it is an important parameter for minimizing network delay and maximizing throughput. The speed of the mobile element depends on the carrier on which the mobile element is attached like an animal, transport vehicle, robot etc. The speed can be vary depending upon the application such as slow (1–5 m/s), medium (5–20m/s) and high (above 20 m/s). The variation in the speed effects on the performance of the network; for example, slow speed causes high network delay and high speed lead to frequently link breaks during communication. Kansal et al. (2004) proposed a speed controlled scheme for the mobile element for efficient data collection. Their protocol works on the stop and communication method where a mobile element is moving with a uniform speed and stops near the sensor nodes and collects data. Based on the stop time the speed is adjusting. They have also presented another scheme in this literature called adaptive motion control (AMC). In AMC, all the nodes of the network are partitioned into different subsets like small, medium and high. The mobile element changes its sojourn time and speed based on these subsets. Sugihara and Gupta (2010) have proposed a new speed control scheme using a heuristic approach by reducing this problem into 1-dimension. They have used three different speed: maximum acceleration, uniform speed, and maximum negative acceleration also known as *accel*, *plateau*, and *decel* interval in the form of time respectively. An optimal speed of mobile sink has been suggested for maximum data gathering by Kumar and Dash (2017). They have used deterministic polynomial time algorithm for their scheme to achieve the maximum data collection within a fixed time.

5.4 Contact detection

During the trajectory, the contact establishment between the mobile element and sensor nodes or the rendezvous node is a major challenge because contact detection directly affects the data gathering. If the contact establishes efficiently (in minimum time) in between the mobile entity and the source node, the maximum data will be collected by the mobile entity. In most of the cases, contact establishes with the help of 3-Way Handshake protocol. In smart contact, the source node detects the presence of a mobile element very fast and established connection with minimum energy. In timely contact detection, the contact period will be fully utilized and maximum data can be transfer. There are three types of contact available in the most of the literature: *scheduled-based*, *on-request* and *periodic listening*.

In *scheduled-based* contact, source nodes have a prior knowledge of the time when mobile element will come in their range. For prior knowledge of exact arrival time of mobile entity needs an efficient time synchronization which is practically very tough to achieve. Rohankar (2015) has presented a mobile agent-based prediction contact where a mobile sink collects the required parameters from a mobile agent like node energy, contact duration and location. Based on these parameters, the sink node visits all source nodes. Singh et al. (2018) applied this contact scheme in their proposed work, they have used a mobile mule with a predefined trajectory path in an unequal grid clustering. The borderline CHs of each level are synchronized with the mule's visiting schedule which efficiently made contact and easily transfers complete data. Most of the uncontrolled trajectory is also scheduled-based where mobile elements scheduled are fixed such as transport vehicles.

On-request contact detection totally depends on the demand or requirement. The mobile element trigger with a radio signal if it wants to contact with any source node. By getting the triggered signal, the source node wakes up and establishes the connection with that mobile element and transfer the required data. Ansari et al. (2008) have proposed a new wake-up scheme by using a radio trigger signal which consumes low energy. They have attached an external wake-up circuit as a extra hardware in the microcontroller of the sensor node which increases the overall cost of the network. A cost and energy effective wake-up scheme needs to be design for WSN.

In *periodic listening* contact, the mobile element periodically transmit the beacon messages during its trajectory. The static source nodes wake-up based on their duty cycle and sense the beacon messages for a short interval. If it receives any beacon message, it established the contact and starts data transmission; else it goes to sleep state again. To increase the contact detection efficiency, the wake-up duty cycle of the source nodes need to be maintained carefully. Anastasi et al. (2009a) have proposed a similar type of wake-up schedules for nodes which ensures the receiving of maximum beacon messages for connection establishment.

5.5 Data transfer

After the contact detection, actual data transfer starts in between mobile element and source node and it totally depends on the communication protocols. In RP-based data collection, the data transfer occurs in an easy way due to sojourn time but while the mobile element is moving and data transfer occurs with the source node, in that case, data losses will be more. A simple stop and wait data transfer protocol has been used during data gathering in (Kansal et al. 2004; Somasundara et al. 2006). For RP-based data transfer it works fine but for other scenarios, it is not suitable because a static source node does not know the exact contact time which results in packet drops. Anastasi et al. (2007) have further explored it by using automatic repeat request (ARQ) protocol. They have used a window frame size data to transmit in each communication where the restricted amount of data present in each node. Some common and efficient data transfer protocols focusing on mobile elements and data transfer from source node must be developed to achieve the best result. All the discussed protocols only follow wireless link capacity as the main tool to transfer data and pay no attention to the power control of sensor nodes. However, Guo et al. (2016) first noticed and developed a new framework which allows concurrent data transfer using a dynamic wireless link as well as it also limits the power control. This problem is analysed under the various constraints like flow conservation, energy conservation, elastic link capacity, transmission compatibility and sojourn time. A sub-gradient iteration algorithm is used for the minimization problem and also proposed a new algorithm to derive the sojourn time at different visiting points.

5.6 Latency

Latency or delay is a key parameter to measure the performance of a mobile element in a WSN. This becomes more challenging when the mobile element moves in a random fashion or in a large area network. In a large area, collecting data from an individual node with the help of mobile element is not a good idea because it takes a long time that means large delay. To minimize this delay several researchers have presented different schemes like multiple mobile elements, CHs-based and RPs-based data collection etc. Yu and Guo (2010) suggested a new delay minimization method where mobile element only visits CHs and collects data from them instead of visiting all nodes. It decreases the overall delay but increases overheads because the CHs are changing every round and due to which in each round mobile element has to search and established contact. An RPs-based data collection scheme has been proposed (Mishra et al. 2016) which resolve the hotspot problem and minimizes the delay due to delay bound nature. The whole area is divided into hexagonal cell and the centroid of these cells selected as RPs from where the mobile sink collects data. The scheme is good but it is mostly similar to CHs-based and not suitable for large area networks. Further, they have extended their previous work (Mishra et al. 2016) by using RPs-based trajectory path with the help of Voronoi diagram. To minimize the delay, if we use multiple mobile elements then the overall network cost will increase and maintaining the scheduling of multiple mobile elements is also a challenging task. Therefore, it requires a trade-off between delay and cost.

5.7 Cost

The overall cost mainly depends on the hardware devices used in the network like sensor nodes, gateway nodes, BS etc. If mobile elements are added into the network then the cost will increase however, due to the many benefits it is suggested to use but in a balanced mode. In large area network single mobile entity is not suitable for the network due to high delay. Therefore, a trade-off is required between the number of mobile entity and the delay.

6 Different domains used for trajectory path

There have been a lot of schemes proposed to build the trajectory path for the mobile element. Among those, most of the trajectory paths are designed by using only two domains: graph theory and optimization based. Graph theory is the most popular area and its algorithms are applied in wired as well as wireless networks to find the shortest and efficient path from source to destination. In WSN, the trajectory paths of mobile elements are also formulated based on the different algorithms of graph theory such as Hamiltonian cycle based, minimium spanning tree (MSP), shortest path algorithms, TSP and tree-based. Optimization is one of the major areas which has been used to optimize the trajectory path of the mobile elements. Several optimization algorithms have been applied to investigate the best path for mobile element. The frequently used optimization schemes in mobile element trajectory will be discussed in this section.

6.1 Graph theory-based

A large number of trajectory path algorithms have been proposed in the different literature. Depending upon the performance parameters and application scenarios, the graph theory algorithms are used for different purpose like for delay minimization, shortest path algorithms are used, for covering all nodes TSP is used etc. The most popular algorithms used to exploit the trajectory path of the mobile element will be discussed next.

6.1.1 Hamiltonian cycle based

The Hamiltonian cycle or Hamiltonian circuit has constructed a path with cycle and finding a Hamiltonian path in a graph is an NP-complete problem. Ha et al. have proposed a mobile sink trajectory with the help of the Hamiltonian cycle in a cluster-based network (Ha et al. 2017). A random deployment scenario with homogeneous sensor nodes is considered by authors, in which a mobile sink is used to collect data from each sensor node individually. Clustering is done using K-means algorithm where the value of k is chosen based on simulation results. The centre of each cluster is the coordinate value obtained by averaging the coordinates of all the member nodes. Mobile sink stops at each of these centres and collects data from all the member nodes by broadcasting a TDMA schedule for all member nodes of that cluster. The choice of the path is mapped to the problem of the Hamilton cycle of graph theory. The set of vertices represent the centre of the cluster and edges represent the connection between these points. Weights of these edges are assigned as the Euclidean distance between the two centres. The Hamilton cycle of this graph is the path followed by the mobile sink for data collection. The main drawback of this method is the use of the k-means algorithm that requires the number of clusters to be formed. Also, each sensor node sends data individually to the mobile sink which consumes a greater amount of time and thus decreasing the throughput.

6.1.2 Minimum spanning tree (MST)

An MST is the subset of low-cost edges of a connected weighted graph. Several researchers have exploited MST according to their use in WSN and especially in path selection. A mobile sink based data gathering scheme has been proposed by Zhao et al. (2015) to enhance the lifetime of large area networks. The mobile sink periodically moves in a predefined path and collects data from the root node of the tree constructed with the help of multi-hop transmission. They have used greedy and dynamic programming to balance the load of the tree during multi-hop communications. Depending upon the minimum residual energy of nodes, a MST is constructed and based on this, mobile sink moves and collects data. In this scheme, hotspot problem arises due to tree-based transmission. Nitesh et al. (2016) presented an MST based trajectory path which reduces the path length and energy consumption of the network. They have formulated two different cost functions and based on these costs, the RPs are selected. Initially, they formed an MST and then 2 sub-MST are formed based on the cost function of each node by removing the low-cost node. The maximum cost function nodes in each sub-MST are selected as RPs and mobile sink visits based on these RPs. The main problem of this protocol is its complexity because many different algorithms are used here like MST and sub-MST then RPs selection and TSP for trajectory.

6.1.3 Shortest path algorithm

Shortest path algorithms are very much important in any network.There are various shortest path algorithms are used in WSN routing and trajectory path construction for data collection such as Bellman-Ford, Dijkstra, Floyd–Warshall, A^* algorithm etc. Vupputuri et al. (2010) have proposed a heterogeneous WSN where data collectors are considered as mobile and more resourceful as compared to normal sensor nodes. They used data collectors as a CH in each cluster and form a connected graph among all data collectors and static BS. They have used Dinics algorithm which gives always a shortest and maximum flow of data. To change the data collectors positions, they have applied average residual energy of one hop nodes. An efficient shortest path algorithm based on the minimum hops is proposed by Ghaleb et al. (2014). They have used a tree-based shortest path towards the centre where static BS is placed. They have also used mobile BS by creating some rendezvous points based on the polling point which have at most *d* levels of the multi-hop path. From these polling points, a mobile BS collects data with the shortest path. The hotspot is the major drawback of this scheme. Singh and Kumar (2018) suggested a data collection scheme for isolated-WSN, where they have used a mobile sink in each isolated-WSN which works as a gateway node to communicate with other isolated networks. The mobile sinks of each isolated-WSN form a connected graph for efficient data transfer to the static BS which is situated at far from these isolated networks. They used Edmonds-Karp algorithms for graph connectivity and shortest path. The shortest path algorithm improves the performance of the networks in terms of delay and energy consumption.

The last two techniques of Figs. 5, 6 have already discussed in Sect. 3, therefore we think there is no need to repeat those again in this section.

6.2 Optimization techniques-based trajectory

Optimization is a technique to find out the most efficient solution from all possible solutions. In WSN, optimization problems are frequently used to optimize the routing path or trajectory path of the mobile elements. The major techniques used in path planning optimization are as follows: approximation algorithms, linear programming, Swarm intelligence algorithms and genetic algorithm.

6.2.1 Approximation algorithms

An approximation algorithm is a technique for finding the optimal solution with NP-completeness. In this optimization algorithm, it does not ensures the best solution, therefore, the main focus of this is to find the best possible optimal value in a short time. Sugihara and Gupta (2008) presented an approximation based optimization scheme to minimize the data delivery delay. They have used controllable mobile element (data mule) for efficient data collection in minimum time. Luo and Hubaux (2010) extended their earlier work (Luo and Hubaux 2005) by using multiple sinks. In their previous work, they have used only one mobile sink for data collection which increases the network delay. In the extended scheme, they explored some primary issues of this joint sink mobility and routing problem by developing an optimization framework. Based on the primal-dual algorithm, authors have developed an approximation algorithm and mathematically formulated.

6.2.2 Linear programming

To solve some complex problems, the linear programming is one of the best and simplest method to achieve optimization by simple assumptions. Gao et al. have presented a new data collection scheme which is based on 0-1 integer linear programming. Gao et al. (2010) called this scheme as maximum amount and maximum lifetime (MAMAL) because their main motto is to collect the maximum amount of data by consuming less energy. The complexity of Integer linear programming is quite high, therefore it is not preferable to use in large area networks. Another linear programming based on trajectory model is proposed by Basagni et al. (2011). They have formulated an upper bound of the network lifetime using linear programming and for trajectory, a heuristic approach has been used. Since linear programming gives the solution for maximum and minimum energy consumption in each round, it is not a global solution. Tashtarian et al. (2016) proposed an optimal trajectory for the mobile sink by using two different approaches. In the first approach, a heuristic convex mathematical optimization model is used to find out the optimal line depending on the current location and speed of the mobile sink. In the second approach, a mixed integer linear programming is used to get the optimal trajectory path with the variable speed of the mobile sink. The main advantages of this scheme are energy-efficiency and less delay but it faces hotspot problem due to multi-hop communications.

6.2.3 Swarm intelligence

Swarm intelligence is the collective behaviour of decentralized, self-organized systems, natural or artificial. It is composed with a community or population of the nature like ant colonies, bird flocking, honey bee etc. and it works on artificial intelligence. There are two groups of swarm intelligence called ant colony optimization (ACO) and particle swarm optimization (PSO). ACO is a type of optimization technique which works on the behaviour of the ant during their food search. It is a probabilistic problem best suited for finding the optimal path from source to destination. Particle swarm optimization (PSO) is a community-based optimization technique inspired by social behaviour of bird flocking or fish schooling. A big number of researchers have exploited different PSO algorithms to optimize the routing in WSN and trajectory path of mobile elements. Wei et al. (2010) presented an ACO-based mobile agent routing algorithm where ant's food searching behaviour used to build the trajectory path for the mobile agent. Based on the ACO, the energy-efficient path is constructed from the location where mobile agent moves and collect data from the source nodes. Due to the dynamic changes in the trajectory path, it has a high delay. A PSO-based clustering scheme with mobile sink is proposed by Wang et al. (2017a). It selects the CH based on residual energy and the node's location coordinates with the help of PSO and mobile sink visits each CH based on the priority given to the CH having maximum average residual energy. For small area network like 100X100 m^2 used by authors works fine but for a large area, it is not suitable because in a large area the numbers of clusters are more which increase the overall delay and energy consumption.

6.2.4 Genetic algorithms

The genetic algorithm is a meta-heuristic optimization technique which is inspired by the process of natural selection. It is based on bio-inspired operations like crossover, mutation and selection which provides best optimize solutions. Lai and Jiang (2013) provided a genetic algorithm based mobile data mule path planning to minimize the trajectory path and energy consumption. Due to visiting each sensor nodes, it does not achieve the required results. A similar type of approach has been proposed for clustering–based genetic algorithm (CBGA) path planning using genetic algorithm by Liu et al. (2013). Further, They have extended their previous work by adding some extra feature such as Traveling Salesman Problem with Neighborhoods (TSPN) and Look-Ahead Locating Algorithm (LLA) (Wu and Liu 2014). They have proposed a CBGA in an innovative way and after that, they optimize the route by using the LLA which reduces the 39% cluster visits. Based on the LLA reduced cluster, TSPN is used to trajectory and collects data. Overall it is a good tour planning algorithm but due to many algorithms, it became complex. A novel genetic algorithm-based clustering algorithm is proposed by Elhoseny et al. (2015) which gives an optimizes the energy consumption of the heterogeneous networks. Further, they have extended their works and presented a framework called genetic algorithm based self-organizing network clustering (GASONeC) (Yuan et al. 2017). In this work, they have used dynamic network structure to optimize the balancing factors which are required for optimal CH selection like residual energy, expected energy consumption, the distance between a node to BS and node degree. This scheme greatly improved the lifetime up to 43.44% as compared to other protocols.

7 Comparative analysis

A comparative analysis of the trajectories for data collection by mobile elements and the major domains where trajectory techniques are used have been summarized in tabular form, as shown in Tables 2 and 3, respectively. These trajectory schemes have been compared based on different parameters, such as trajectory pattern, number of mobile elements, routing scheme, speed, domain deployed in, important metrics, mobility entity and deployed network size. In Table 2, three different categories (direct contact, rendezvous point and dynamic path) schemes are included, whereas in Table 3, two important domains (graph-theory-based and optimization-based protocols) are summarized. Here, the trajectory pattern is the type of trajectory used in the scheme. Usually, three types of trajectories are used: random, controlled and uncontrolled. In the next parameter, we are considering the number of mobile elements used: single or multiple. The routing scheme is an important parameter, where we have single-hop and multi-hop routing in the corresponding schemes. The performance of the trajectory has been measured by the speed in some protocols; therefore, speed is taken as an important parameter here. There are two different speed types mentioned in the tables regarding the trajectories of the mobile elements: uniform and variable. The deployment area and its size are also a major factor that directly affects the performance, as the performance of a densely deployed network is totally different from the performance of a sparsely deployed network. In the comparative tables, we have included the important metrics for which the schemes were developed, such as energy consumption minimization, delay minimization, hotspot mitigation, etc. Different researchers have used different mobile entities, like mules, robots, animals, bus shuttles, mobile sinks, etc. Therefore, it is important to know which type of mobile entity has been used in the corresponding scheme. From the comparative analysis, it can be seen that most schemes have used a controlled trajectory due to its ease of use and better performance. One major result is shown in the important metrics column, where we can see that the main focus of using mobile elements is energy efficiency. Most of the works mentioned in this article generated their results using

Table 2 Comparative analysis of the key parameters of different trajectory schemes

Schemes	Trajectory pattern	# Mobile elements	Routing schemes	Speed	Deployed	Important metrics	Mobile entity	Network size
Direct contact								
Juang et al. (2002)	Random	Multiple	Single-hop	Variable	Sparsely	Energy	Zebra	1000 KM^2
Shah et al. (2003)	Random	Multiple	Single-hop	Variable	Sparsely	Energy	Mule	N/A
Jain et al. (2006)	Random & Deterministic	Multiple	Single-hop	Variable	Sparsely	Energy	Mule	Large
Nesamony et al. (2007)	Controlled	One	Single-hop	Uniform	hostile	Energy & Delay	mobile sink	Large
Rao and Biswas (2008)	Controlled	One	Multi-hop	Uniform	Densely	Hotspot	mobile sink	N/A
Xing et al. (2008a)	Controlled	One	Multi-hop	Uniform	Densely	Energy & Delay	Mobile sink	300 m^2
Kumar et al. (2017)	Controlled	One	Multi-hop	Uniform	Sparsely	Energy	Mobile sink	0.4×0.6 KM^2
Rendezvous points								
Kim et al. (2003)	Controlled	One	Multi-hop	Uniform	Sparsely	Energy	Mobile sink	2 KM^2
Kansal et al. (2004)	Controlled	One	Multi-hop	Uniform	Densely	Energy	Robot	N/A
Xing et al. (2007)	Controlled	One	Multi-hop	Uniform	Densely	Energy	Mobile sink	300 m^2
Thanigaivelu and Mururgan (2012)	Controlled	One	Multi-hop	Uniform	Densely	Hotspot	Mobile sink	500 m^2
Thanigaivelu and Mururgan (2012)	Controlled	Multiple	Single-hop	Uniform	Densely	Energy	Mobile sink	500 m^2
Konstantopoulos et al. (2014)	Controlled	One	Multi-hop	Uniform	Densely	Energy & Delay	Mobile sink	500 m^2
Singh et al. (2016b)	Controlled	Two	Multi-hop	Uniform	Densely	Energy	Mule	N/A
Singh et al. (2018)	Controlled	One	Multi-hop	Uniform	Densely	Energy	Mule	0.5×0.25 KM^2
Dynamic path								
Zhao and Ammar (2003)	Controlled	One	Single-hop	Uniform	Sparsely	Connectivity	Ferry	N/A
Zhao et al. (2004)	Random	One	Single-hop	Uniform	Sparsely	Energy & Delay	Ferry	5 KM^2
Gu et al. (2005)	Controlled	One	Multi-path	Variable	Densely	Data loss	Mobile Sink	100 m^2
Gu et al. (2006)	Controlled	One	Multi-hop	Variable	Densely	Data loss & Delay	Mobile sink	100 m^2
Tseng et al. (2007)	Controlled	Multiple	Single-hop	Uniform	Densely	Energy	Lego car	15 m^2
Khan et al. (2015)	Controlled	One	Multi-hop	Variable	Densely	Delay & Energy	Mobile sink	200 m^2
Juvvalapalem and Rao (2016)	Controlled	One	Multi-hop	Uniform	Densely	Energy	SenCar	N/A
Say et al. (2016)	Controlled	One	Single-hop	Uniform	Densely	Energy	UAV	300 m^2

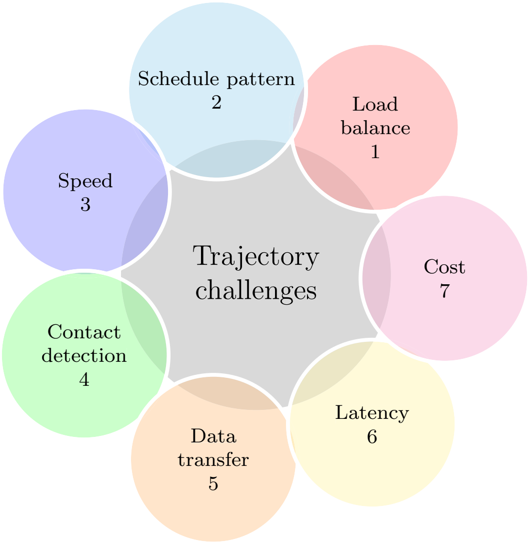

Fig. 5 Trajectory challenges of mobile elements with an increasing priority

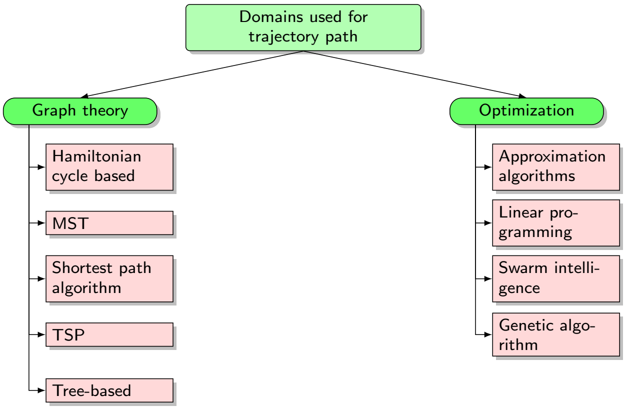

Fig. 6 Different domains used for trajectory path during data collection

simulation tools like NS-2, Omnet++, MATLAB, etc.; in their simulations, they used small-size networks (100m × 100m to 500m × 500m-very small compared to real-life scenarios). Therefore, we have considered network size an important parameter in our comparative tables. In the network size column, the term 'N/A' is used, which means that the network size is not specified in that particular paper.

8 Future directions

Data collection using mobile elements has some common objectives on which most of the researchers have proposed their protocols, like minimum packet loss, minimum delays, hotspot mitigation, increased coverage, etc. However, a few areas are still unexplored and require a lot of research, like security, speed, harvesting and the use of UAVs and drones as mobile elements.

After the introduction of mobile elements in WSNs, security arose as a major challenge that needed serious attention because all the data is stored in the mobile elements. If an attacker compromises the mobile elements, then the whole network's data will not be safe. Therefore, it is essential to develop protocols to secure the data of mobile elements. For conventional WSNs, some security protocols have been developed (Elhoseny et al. 2016a, b), but for mobile-elements-based WSNs, very few protocols have been designed (Rasheed and Mahapatra 2012). This area is totally open and has a lot of scope for future work.

Regarding the trajectory, one important issue that needs more attention is the speed of the mobile elements because delays are directly determined by their speed. In most research, speed has been assumed to be uniform during the evaluation. Based on the situation during the data collection in the network, we can change the speed of the mobile elements. For instance, when a mobile element is in the range of a sensor node, its speed could be lowered, resulting in better data collection; its speed could be raised when it is not in the range of a node. By optimizing the speed of mobile elements, delays and data collection can be optimized. The major challenges in the optimization of speed are environmental and mechanical issues. Due to mechanical limitations, we cannot exceed the threshold speed because harsh environments are not fit for the movement of mobile elements.

The wireless recharging technique provides a new domain for research on mobile-elements-based WSNs. In most WSN scenarios, efficient energy utilization is a major concern because the sensor nodes have limited energy stored in their batteries. If the sensors' batteries are discharged, then the network is considered dead; with wireless recharging, rechargeable batteries can be used, and a mobile charger can recharge those batteries. Until now, only a few schemes (Ren et al. 2015; Mehrabi and Kim 2016) have been proposed in different scenarios for recharging the sensor nodes' batteries, with very little work done in this area. The major drawbacks of wireless recharging include slow charging, limited range, etc. There are a lot of challenges that need to be tackled in research in this area, such as the optimal trajectory path for the mobile charger, fast charging, the range of wireless charging, etc.

WSNs are mainly deployed in harsh environments like forests, mountains, etc., and the assumptions regarding the mobile elements' movement in these types of scenarios are totally impractical. A lot of researchers have assumed the trajectory of the mobile elements in these scenarios in their schemes; in a few scenarios, a helicopter has been used as a mobile element, which is not affordable in all

Table 3 Comparative analysis on key parameters of different trajectory schemes

Schemes	Trajectory pattern	# Mobile elements	Routing schemes	Speed	Deployed	Important metrics	Mobile entity	Network size
Graph theory-based								
Rao and Biswas (2008)	Controlled	One	Multi-hop	Uniform	Densely	Delay	mobile sink	220 m^2
Vupputuri et al. (2010)	Controlled	Multiple	Multi-hop	Uniform	Densely	Hotspot	Data Collector	100 m^2
Ghaleb et al. (2014)	Controlled	One	Multi-hop	Uniform	Densely	Energy	Mobile sink	500 m^2
Khelladi et al. (2014)	Controlled	One	Single-hop	Uniform	Densely	Recharge	Mobile charger	25 m^2
Zhao et al. (2015)	Controlled	Multiple	Multi-hop	Uniform	Sparsely	Energy	Mobile sink	1.5 KM^2
Nitesh et al. (2016)	Controlled	Multiple	Single-hop	Uniform	Hostile	Energy & Delay	Mobile sink	Large
Tu et al. (2017)	Controlled	One	Single-hop	Uniform	Sparsely	Recharge	Mobile charger	200 m^2
Ha et al. (2017)	Controlled	One	Single-hop	Uniform	Sparsely	Energy	Mobile sink	250 m^2
Optimization-based								
Luo and Hubaux (2005)	Discrete	One	Multi-hop	Uniform	Densely	Energy	Mobile sink	N/A
Sugihara and Gupta (2008)	Controlled	One	Single-hop	Uniform	Densely	Delay	Mule	$200 \pi r^2$
Luo and Hubaux (2010)	Controlled	Multiple	Multi-hop	Uniform	Densely	Energy	Mobile sink	10 × 10 off-graph grid
Gao et al. (2010)	Uncontrolled	One	Multi-hop	Uniform	Densely	Energy	Vehicle	0.2 × 0.25 KM^2
Wei et al. (2010)	Controlled	Multiple	Multi-hop	Uniform	Densely	Energy	Mobile agent	200 m^2
Basagni et al. (2011)	Uncontrolled	Multiple	Single-hop	Uniform	Densely	Energy	Mobile sink	475 m^2
Lai and Jiang (2013)	Controlled	One	Multi-hop	Uniform	Densely	Energy and delay	Mule	7 × 7 units square box
Wu and Liu (2014)	Controlled	One	Multi-hop	Uniform	Sparsely	Energy	Mule	2 KM^2
Tashtarian et al. (2016)	Controlled	One	Single-hop	Uniform	Densely	Energy	Mobile sink	N/A
Wang et al. (2017a)	Controlled	One	Multi-hop	Uniform	Densely	Hotspot	Mobile sink	100 m^2

scenarios. Recently, UAVs and drones have grown in popularity as carriers in WSNs (Dong et al. 2014; Say et al. 2016). These light and low-cost flying vehicles can be used in many scenarios easily and efficiently. To date, a lot of research has been done on the communication frameworks of UAVs and drones. In WSNs, fewer efforts have been made to exploit the trajectories of UAVs and drones for data collection. For the efficient use of UAVs and drones in WSNs, researchers need to develop a common routing protocol for efficient data transfer. Handling the trajectories of these aerial vehicles is also a challenging task.

For future research in this area, a framework is presented in Fig. 7. In this figure, all the initial and important areas and sub-areas are mentioned.

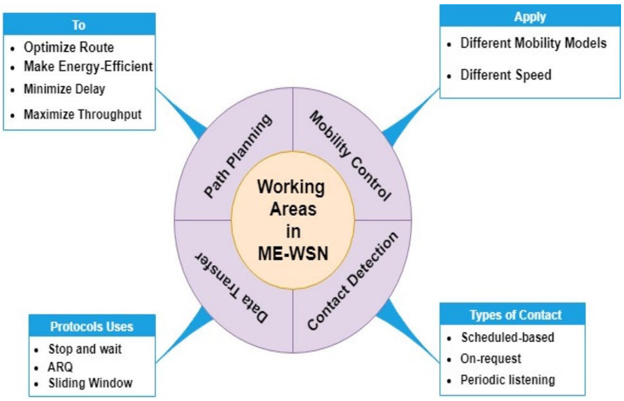

Fig. 7 Working areas to guide future researchers regarding mobile-elements-based WSNs

9 Discussion

Even after 15 years of existence, the use of mobile elements in WSNs for data collection still draws a lot of attention from researchers. This shows the importance of mobile elements in WSNs. Several kinds of research works have been done in this area and many important milestones have been achieved, but certain issues still exist that need to be explored.

As mentioned in Section 2, mobile-elements-based WSNs are widely used for performance enhancement. The primary objective of the mobile elements is data gathering, mainly in large area networks. In small area networks, the conventional routing protocols of WSNs are enough for sending the sensed data to the static BS. By contrast, in large area networks, sending the data to the BS is not an easy task because it takes more energy and time due to the use of multi-hop communication. An additional problem arises due to multi-hop communication, named a 'hotspot'. Many new trajectory schemes have been proposed to mitigate or minimize the hotspot problems of WSNs. Several protocols and schemes have been designed based on different constraints, like hotspots, data delivery delays, coverage, etc., as the field of research has progressed.

End-to-end delays are also a major problem in mobile-elements-based WSNs, and the main reason for such delays is the individual data collection from each sensor node. To resolve this issue, rendezvous-point-based data collection has been proposed, where the data is collected from some predefined point, which is selected based on parameters like node density, residual energy, distance from the BS, etc. Rendezvous-point-based data collection suffers from high delays due to the sojourn time or halt time for data collection. Therefore, the best solution for minimizing delays is to collect data from rendezvous points in a dynamic mode. Some work has been developed in this regard, where the data collection occurs during the trajectory without any pauses. The throughput is affected in this scheme because the complete data may not be transferred when the mobile elements are in motion. Packet drops are greater in this type of data transfer, but the delay will be less due to the absence of pauses. More efforts are required to develop efficient data transfer schemes for when the mobile elements are in motion.

In multiple-mobile-elements-based data collection, scheduling the trajectory and fixing their collection points are major issues that require extra attention. Multiple mobile elements are mainly used in large area networks to minimize the overall network delay and to maximize the throughput. Communication between two or more mobile elements improves the network performance in terms of delays and network lifetime, but little research has been done on this.

Random and uncontrolled trajectories are important types of mobility in WSNs where the interference of any events related to mobility is predicted to be lower. A random trajectory is mainly used in habitat monitoring, where animals are used as mobile elements, which can move in any direction at any time. An uncontrolled trajectory means the mobile entity moves on a fixed, predefined trajectory path but we do not normally have control over it, such as a transport shuttle to which a mobile entity is attached (Huang and Savkin 2017). A random trajectory is also uncontrolled, but the primary difference is in their visiting schedules. In an uncontrolled trajectory, the visiting schedule is known in advance; in a random trajectory, the schedule is totally unknown and very tough to predict. For these types of trajectories, we need to develop new data transfer schemes and prediction models to significantly improve the performance of WSNs. A controlled trajectory is the most popular and efficient trajectory for data collection in WSNs because we can control the visiting schedule, as well as the trajectory path and speed. Due to this full control, the trajectory is not a big issue; the major issue is path planning. Here, the major question is which criteria will determine how the mobile elements will move because there are many parameters associated with sensor nodes, CHs and relay nodes, such as energy, distance from the centroid or BS, node density, etc. Multi-criteria-based path planning is one of the important solutions proposed by researchers. Path planning is a vast topic that requires more attention to develop efficient trajectory schemes.

10 Conclusion

Due to the broader applications and resource constraints of sensor nodes, mobile elements can be considered an extra dimension that could improve the performance of WSNs. This paper has presented an extensive survey on the path-planning schemes used in WSNs for data collection. The survey included all the recent progress made in mobile elements path planning. Initially, the paper suggested some broad application areas where the trajectories of mobile elements play a great role. Further, we presented a level-based classification of the different trajectory schemes used for data collection. At the first level, we classified schemes into two groups: static and dynamic. The key challenges with their priority were discussed in detail. The major domains used in this area to design efficient trajectory paths were also discussed. The analysis of all the trajectory schemes discussed in this article is presented in different tables with some important parameters for easy reference. The findings of the survey show that most schemes used a mobile sink as the mobile element and their major focus was on energy efficiency. Although a mobile sink can improve the overall performance of a network, it cannot be used in all scenarios because it requires Internet access to communicate with the rest of the world. Therefore, we can exploit other types of mobile elements, such as data collectors, data mules and mobile sensor nodes, for data collection in such networks. A great amount of effort has been dedicated to developing the mobility and trajectory paths of mobile elements, while less work has been done on the contact detection and data transfer between mobile elements and source nodes.

All the mobile-elements-related trajectory schemes reviewed in this article provide promising improvements over static schemes for WSNs; however, there are still many areas that demand more attention. A few of these issues have been mentioned in Section 8, and these issues could be considered important areas for the future of mobile-elements-based WSNs.

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