A Survey on Mobile Anchor Node Assisted Localization in Wireless Sensor Networks

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***Abstract*—Localization is one of the key technologies in wireless sensor networks (WSNs), since it provides fundamental support for many location-aware protocols and applications. Constraints on cost and power consumption make it infeasible to equip each sensor node in the network with a global position system (GPS) unit, especially for large-scale WSNs. A promising method to localize unknown nodes is to use mobile anchor nodes (MANs), which are equipped with GPS units moving among unknown nodes and periodically broadcasting their current locations to help nearby unknown nodes with localization. A considerable body of research has addressed the mobile anchor node assisted localization (MANAL) problem. However, to the best of our knowledge, no updated surveys on MAAL reflecting recent advances in the field have been presented in the past few years. This survey presents a review of the most successful MANAL algorithms, focusing on the achievements made in the past decade, and aims to become a starting point for researchers who are initiating their endeavors in MANAL research field. In addition, we seek to present a comprehensive review of the recent breakthroughs in the field, providing links to the most interesting and successful advances in this research field.**

***Index Terms*—Wireless sensor network, localization, mobile anchor node, mobility model, path planning.**

I. Introduction

Wireless Sensor Networks (WSNs) consist of a set of physically small sensor nodes deployed in a given monitoring area (region), namely, in two-dimensional (2D) or three-dimensional (3D) environments, to fulfill tasks such as surveillance, biological detection, home care, object tracking, etc., [1]–[3]. The monitoring information is sent to sink nodes via multi-hop communication [4]–[6]. The sink collects the sensing data from the sensor nodes and then processes this information as required by the specific applications [7].

In WSNs, determining unknown nodes' locations is a critical task since it provides fundamental support for many location-aware protocols and applications, such as location-based routing protocols, where the location information is critical for sensor nodes to make optimal routing decisions [8], [9]. The problem of localization is the process of finding location information of the sensor nodes in a given coordinate system. To localize a WSN in the global coordinate system, some special nodes should be aware of their positions in advance either from Global Position System (GPS) or by virtue of being manually placed, which are called anchors (beacons). Other nodes, which are usually called unknown nodes, calculate their positions by using special localization algorithms [10]. Sensor nodes localization usually consists of two steps: (i) distance measurement between neighboring nodes, and (ii) geometric calculation based on measured distances. Based on the distance measurement techniques used, localization algorithms can be classified into range-based localization algorithms and range-free localization algorithms. Range-based localization means that distances between sensor nodes are estimated by using some physical properties of communication signals, i.e., Received Signal Strength Indicator (RSSI), Time of Arrival (ToA), Time Difference of Arrival (TDoA) and Angle of Arrival (AoA) [11], [12]. Range-free localization algorithms estimate sensor node's coordinates using connectivity information between sensor nodes without ranging (i.e., distance or angle) information.

It is costly to equip each sensor node with a GPS unit, especially for large-scale WSNs. A feasible method to localize unknown nodes is to use several mobile anchor nodes (MANs) which are equipped with GPS units moving among unknown nodes and periodically broadcasting their current locations (anchor points) to help nearby unknown nodes with localization [13]–[15], as shown in Fig. 1. A considerable body of research has addressed the Mobile Anchor Node Assisted Localization (MANAL) problem. This kind of architecture offers significant practical benefits, since the mobile anchor node is not as energy constrained as an unknown node and the localization accuracy also can be improved by carefully designing movement trajectory of the mobile anchor nodes. Moreover, the size of a robot is much larger than the size of a sensor node and thus it is much easier to install a GPS unit on the robot [16]. Therefore, this is a viable solution that could be used.

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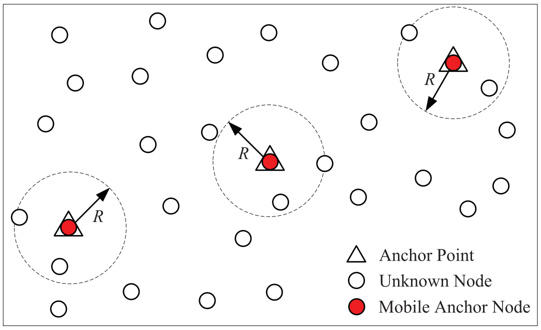

Fig. 1. Mobile anchor node assisted localization.

A fundamental research issue of MANAL algorithms is to design movement trajectories that mobile anchor nodes should move along in a given monitoring area (region) in order to improve localization performances of WSNs.

Another research issue of MANAL algorithms is the localization methods by which unknown nodes calculate their positions based on the beacon packets received from location-aware mobile anchor nodes, as they move through the monitoring area (region). These algorithms employ either only mobile anchor nodes (a single mobile anchor node or a group of mobile anchor nodes) or mobile anchor nodes together with reference nodes to help unknown nodes with localization.

Generally, MANAL algorithms involve three stages: (i) mobile anchor nodes traverse the monitoring area (region) while periodically broadcasting beacon packets which include their current positions; (ii) unknown nodes within the communication ranges of the anchors receive the beacon packets and estimate distances to the anchors by using the physical properties of communication signals when needed; and (iii) unknown nodes calculate their positions if they fall inside the overlapping communication ranges of at least three (four) non-collinear (non-coplanar) anchor nodes by the use of appropriate localization algorithms in 2D (3D) WSNs.

There is plenty of literature discussing the MANAL problem. However, there is no recent review discussing MANAL algorithms in the past few years. This paper's objective is to fill this gap and provide a comprehensive review of the recent breakthroughs in the field, focusing on the achievements made in the past decade, and aims to become a starting point for researchers who are initiating their endeavors in the MANAL research field. In addition, we seek to present a comprehensive review of the recent breakthroughs in the field, providing links to the most interesting and successful advances in this research field. We survey the current works on the above two issues, namely, movement trajectories and localization methods.

Resulting from these considerations, the remainder of this article is organized as follows. Section II introduces backgrounds and basic localization methods for WSNs. Section III presents related work about existing survey papers for localization algorithms in WSNs. Section IV introduces the classification of MANAL algorithms. Section V and VI review two categories of MANAL algorithms in detail. Section VII illustrates existing problems and future research issues in the MANAL research field. Finally, conclusion including a summary table is given in Section VIII.

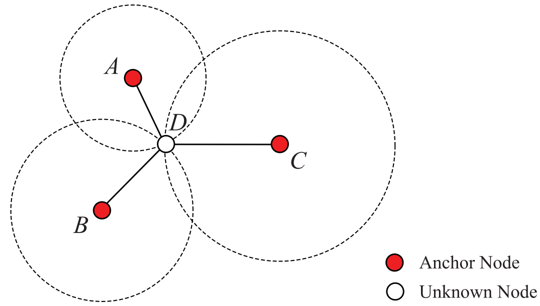

Fig. 2. An example of trilateration.

II. Background Knowledge and Basic Localization Methods

A. Basic Terminologies

Anchor (Beacon) Node: To localize a WSN in the global coordinate system, some special sensor nodes should be aware of their positions in advance either from GPS or by virtue of being manually placed, which are called *anchor nodes* or *beacon nodes*.

Unknown (Ordinary) Node: Sensor nodes that do not know their positions and need to calculate them with the help of anchor nodes.

Static Anchor (Beacon) Node: The anchor (beacon) node which cannot move automatically after initial deployment.

Mobile Anchor (Beacon) Node: The anchor (beacon) node which can move automatically after initial deployment.

Reference Node: The sensor node which already knows its coordinates and works as anchor node to help other unknown nodes with localization.

Anchor (Beacon) Packet: The data packet broadcasted by mobile anchor nodes periodically.

Anchor (Beacon) Point: Virtual coordinates broadcasted by mobile anchor nodes periodically, which is part of the anchor packet.

Broadcast Interval: The time period a mobile anchor node takes to broadcast beacon packets.

Node's Speed: The mobility features that capture node movement speed in mobility models.

Node's Direction: The mobility features that capture node movement direction in mobility models.

Pause Time: The time period that a node is steady in a specific position, i.e., the interval of time when the node's speed is zero or close to zero.

Inter-contact Time: The time interval between two consecutive contacts of the same two nodes.

Contact Duration: The time period two nodes attain while within the same radio range.

B. Basic Methods of Calculating Sensor Nodes' Location

1) Trilateration: Trilateration is the process of finding the position of an unknown node based on its distances to three anchors, as shown in Fig. 2. Assume that the coordinate of an unknown node D is (x, y). The coordinates of three anchor nodes A, B, C are (x_a, y_a), (x_b, y_b), and (x_c, y_c). The distances

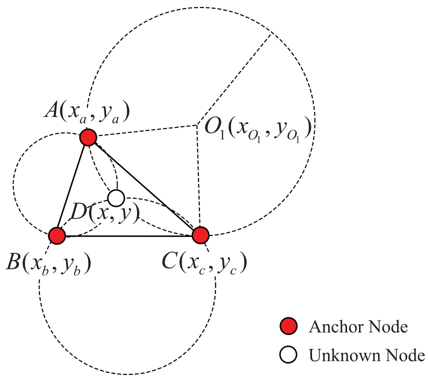

Fig. 3. An example of triangulation.

between D and A, B, C are d_a, d_b and d_c, respectively. These geometric constraints can be expressed by the following system of equations [17],

$$\begin{cases} \sqrt{(x-x_a)^2+(y-y_a)^2}=d_a \\ \sqrt{(x-x_b)^2+(y-y_b)^2}=d_b \\ \sqrt{(x-x_c)^2+(y-y_c)^2}=d_c \end{cases}. \tag{1}$$

By solving Eq. (1), we can get the matrix $AX = B$, where

$$X = \begin{bmatrix} x & y \end{bmatrix}^T,$$
$$A = 2\begin{bmatrix} (x_a-x_c) & (y_a-y_c) \\ (x_b-x_c) & (y_b-y_c) \end{bmatrix},$$
$$b = \begin{bmatrix} x_a^2-x_c^2+y_a^2-y_c^2+d_c^2-d_a^2 \\ x_b^2-x_c^2+y_b^2-y_c^2+d_c^2-d_b^2 \end{bmatrix},$$

2) Triangulation: Triangulation, unlike trilateration, computes the position of an unknown node based on the angular distance between three different pairs of anchor nodes. Consider the example depicted in Fig. 3, suppose that the coordinate of an unknown node D is (x, y). The coordinates of three anchor nodes A, B, C are (x_a, y_a), (x_b, y_b) and (x_c, y_c), respectively. If we know the angles between the line segments connecting D and the anchors, then the unknown node's coordinates must be calculated using triangulation instead of trilateration.

Let $\angle ADB$, $\angle ADC$, $\angle BDC$ denote the angles between the line segments connecting D to the anchors, respectively. D is the intersection point of the three circles. If the angular distance between the anchor nodes is known, the centers of the circles can be obtained. For anchor nodes A, C and the angle $\angle ADC$, if the arc AC is within the scope of the $\triangle ABC$, the circle can be uniquely identified. Assume that the center of the circle is $O_1(x_{O_1}, y_{O_1})$, the radius is r_1, thus, $\alpha = \angle AO_1C = 2(\pi - \angle ADC)$. O_1 and r_1 can be calculated using Eq. (2) [18],

$$\begin{cases} \sqrt{(x_{O_1}-x_a)^2+(y_{O_1}-y_a)^2}=r_1 \\ \sqrt{(x_{O_1}-x_b)^2+(y_{O_1}-y_b)^2}=r_1 \\ (x_a-x_c)^2+(y_a-y_c)^2=2r_1^2-2r_1^2\cos\alpha \end{cases}. \tag{2}$$

Similarly, anchor nodes A, B, the angle $\angle ADB$ and anchor nodes B, C, the angle $\angle ADB$ can determine $O_2(x_{O_2}, y_{O_2})$, r_2 and $O_3(x_{O_3}, y_{O_3})$, r_3, respectively. Thus, knowing the coordinates of $O_1(x_{O_1}, y_{O_1})$, $O_2(x_{O_2}, y_{O_2})$ and $O_3(x_{O_3}, y_{O_3})$, the coordinate of $D(x, y)$ can be calculated by using of Eq. (1).

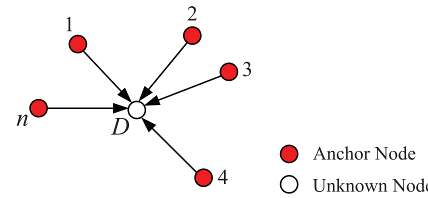

Fig. 4. An example of the maximum likelihood estimation.

3) Maximum Likelihood Estimation: When the number of anchor nodes $n > 3$, we use the maximum likelihood estimation to calculate the coordinate of the unknown node $D(x, y)$. Assume that the coordinates of anchor nodes are respectively (x_1, y_1), (x_2, y_2), (x_3, y_3),..., (x_n, y_n), and the distances between D and the anchor nodes are $d_1, d_2, d_3, \ldots, d_n$, respectively, as shown in Fig. 4. Then the equations can be obtained as follows [17], [18]:

$$\begin{cases} (x-x_1)^2+(y-y_1)^2=d_1^2 \\ (x-x_2)^2+(y-y_2)^2=d_2^2 \\ (x-x_2)^2+(y-y_2)^2=d_2^2 \\ \vdots \\ (x-x_n)^2+(y-y_n)^2=d_n^2 \end{cases}. \tag{3}$$

By subtracting the last equation from the first $n-1$ equations, we can obtain

$$\begin{cases} 2(x_1-x_n)x+2(y_1-y_n)y= \\ \quad d_n^2-d_1^2+x_1^2-x_n^2+y_1^2-y_n^2 \\ \vdots \\ 2(x_{n-1}-x_n)x+2(y_{n-1}-y_n)y= \\ \quad d_n^2-d_{n-1}^2+x_{n-1}^2-x_n^2+y_{n-1}^2-y_n^2 \end{cases}. \tag{4}$$

With some proper transformations, the above equation can be rewritten as $AX = b$, where

$$X = \begin{bmatrix} x & y \end{bmatrix}^T,$$
$$A = 2\begin{bmatrix} (x_1-x_n) & (y_1-y_n) \\ \vdots & \vdots \\ (x_{n-1}-x_n) & (y_{n-1}-y_n) \end{bmatrix},$$
$$b = \begin{bmatrix} d_n^2-d_1^2+x_1^2-x_n^2+y_1^2-y_n^2 \\ \vdots \\ d_n^2-d_{n-1}^2+x_{n-1}^2-x_n^2+y_{n-1}^2-y_n^2 \end{bmatrix}.$$

Then, we can obtain $X = (A^TA)^{-1}A^Tb$.

Actually, the maximum likelihood estimation is the extension of the trilateration method.

III. Related Work

Recently, a large number of localization techniques and algorithms have been proposed for WSNs, and simultaneously many studies have been done to survey and analyze existing localization techniques and algorithms. For example, in [17], Mao *et al.* first provide an overview of measurement techniques that can be used for WSN localization, e.g., distance related measurements, angle-of-arrival (AOA) measurements and RSS profiling techniques. Then the one-hop and the multi-hop localization algorithms based on the measurement techniques are presented in detail, respectively, where the connectivity-based or "range free" localization algorithms and the distance-based multi-hop localization algorithms are particularly discussed due to their prevalence in multi-hop WSN localization techniques. In addition, based on the analysis, the open research problems in the distance-based sensor network localization and the possible approaches to these problems are also discussed.

In [18], Amundson *et al.* present a survey on localization methods for mobile wireless sensor networks (MWSNs). First, the authors provide a brief taxonomy of MWSNs, including the three different architectures of MWSNs, the differences between MWSNs and WSNs, and the advantages of adding mobility. The MWSN localization discussed in [18] is consists of three phases: 1) coordination, 2) measurement, and 3) position estimation. In the coordination phase, sensor nodes coordinate to initiate localization, including clock synchronization and the notification that the localization process is about to begin. In the second phase, the measurement techniques, e.g., the angle-of-arrival (AOA) and the time-difference-of-arrival (TDOA) methods are presented. The measurements obtained in the second phase can be used to determine the approximate position of the mobile target node based on localization algorithms, e.g., the Dead Reckoning, the maximum likelihood estimation (MLE) and the Sequential Bayesian estimation (SBE). To the best of our knowledge, the reference [18] is the first survey focusing on MWSNs localization.

In [19], an overview of localization techniques is presented for WSNs. The major localization techniques are classified into two categories: centralized and distributed based on where the computational effort is carried out. Based on the details of localization process, the advantages and limitations of each localization technique are discussed. In addition, future research directions and challenges are highlighted. This paper point out that the further study of localization technique should be adapted to the movement of sensor nodes since node mobility can heavily affect localization accuracy of targets. However, the localization techniques proposed for mobile sensor nodes are not discussed in [19].

In [20], localization algorithms are classified into target/source localization and node self-localization. In the target localization, Single-Target/Source Localization in WSNs, Multiple-Target Localization in WSNs and Single-Target/Source Localization in Wireless Binary Sensor Networks (WBSNs) are mainly introduced. Then, in node self-localization, range-based and range-free methods are investigated. With the widespread adoption of WSNs, the localization algorithms are very different for different applications. Therefore, in the paper, the localization in some special scenarios are also surveyed, e.g., localization in non-line-of-sight (NLOS) scenarios, node selection criteria for localization in energy-constrained network, cooperative node localization, scheduling sensor nodes to optimize the tradeoff between localization performance and energy consumption, and localization algorithm in heterogeneous network. Finally, the evaluation criteria for localization algorithms are introduced in WSNs.

In [21], the distance-based localization techniques are surveyed for WSNs. It is impossible to present a complete review of every published algorithm. Therefore, ten representative distance-based localization algorithms that have diverse characteristics and methods are chosen and presented in detail in [21]. The authors outline a tiered classification mechanism in which the localization techniques are classified as distributed, distributed-centralized, or centralized. Generally, centralized localization algorithms produce better location estimates than distributed and distributed-centralized algorithms. However, much more energy is consumed in the centralized algorithms due to high communication overheads for packet transmission to the base station. Distributed-centralized localization algorithms are always used in cluster-based WSNs, which can produce more accurate location estimates than distributed algorithms without significantly increasing energy consumption or sacrificing scalability.

In [22], the classification of localization algorithms is first studied based on three categories: range-based/range-free, anchor-based/anchor-free, distributed/centralized. Then, the localization algorithms are compared in terms of node density, localization accuracy, hardware cost, computation cost, communication cost, etc. Based on the analysis of exiting localization algorithms, the authors try to find positions of mobile nodes in harsh environments by designing a distributed RSSI based, range-based and beacon-based localization technique.

In [23], a survey on multidimensional scaling (MDS)-Based Localization is presented for WSNs. Several typical MDS-based localization algorithms, e.g., MDA-MAP(C) [24], MDS-MAP(P) [25], Local MDS [26], dwMDS(G) [27] and HMDS [28] algorithms, have been introduced and analyzed. MDS-MAP(C) is a centralized and the earliest usage algorithm of MDS in node localization for WSN. MDS-MAP(P), Local MDS, and dwMDS(G) are distributed algorithm. They are improved localization algorithms based on MDS-MAP(C). HMDS is a localization scheme for cluster-based WSNs. HMDS consists of three phases: clustering phase, intra-cluster localization phase, and merge phase. In the first phase, the WSN is partitioned into multiple clusters by a clustering algorithm. In the second phase, distance measurements from all cluster members are collected by cluster heads and local MDS computation is performed to form a local map. Finally, in the merge phase, the local map is calibrated to a global map.

In [29], sensor node architecture and its applications, different localization techniques, and few possible future research directions are presented. Localization techniques are classified as anchor based or anchor free, centralized or distributed, GPS based or GPS free, fine grained or coarse grained, stationary or mobile sensor nodes, and range based or range free. All the classification methods are briefly introduced, but the details of localization algorithm are not discussed. In the paper, only some traditional localization algorithms, e.g., GPS, RSSI, ToA, TDoA, AoA, Dv-hop and APIT are compared without considering new improved algorithms.

Existing localization algorithms are always classified into two major categories: range-based and range-free. However, it is difficult to classify all the localization algorithms as range-based or range-free. Therefore, in [30], range-based and

TABLE I
COMPARISON OF RELATED WORKS

Reference	Scenario	Research target	Classification
Ref.[17]	Static WSNs	Localization algorithms	One-hop and multi-hop localization algorithms
Ref.[18]	Mobile WSNs	Localization algorithms	Three phases: coordination, measurement, and position estimation
Ref.[19]	Static WSNs	Localization algorithms	Centralized and distributed
Ref.[20]	Static WSNs	Localization algorithms	Target/source localization and node self-localization
Ref.[21]	Static WSNs	Distance-based localization algorithms	Distributed, distributed-centralized, or centralized
Ref.[22]	Static WSNs	Localization algorithms	Range-based/rangefree, anchor-based/anchor-free, distributed/centralized
Ref.[23]	Static WSNs	MDS-Based Localization	MDA-MAP(C), MDSMAP(P), Local MDS, dwMDS(G) and HMDS
Ref.[29]	Static WSNs	Localization algorithms	Anchor based or anchor free, centralized or distributed, GPS based or GPS free, fine grained or coarse grained, stationary or mobile sensor nodes, and range based or range free.
Ref.[30]	Static WSNs	Localization algorithms	Fully-range-based, hybrid-range-based, fully-range-free, and hybrid-range-free
Ref.[31]	Static and mobile WSNs	Localization algorithms	Static landmarks with static nodes, static landmarks with mobile nodes, mobile landmarks with static nodes, mobile landmarks with mobile nodes
Ref.[32]	Static WSNs	Localization algorithms	Known location based localization, proximity based localization, angle based localization, range and distance based localization
Ref.[33]	Static and mobile WSNs	Range-based localization algorithms	Centralized versus distributed, range free versus range based, anchor based versus anchor free, mobile versus stationary node localization
Ref.[34]	Static WSNs	RSSI based Localization Schemes	No classification
Ref.[35]	Static WSNs	Range free localization techniques	No classification
Ref.[36]	Mobile WSNs	Mobility-assisted localization techniques	Range-based and range-free

range-free schemes are further divided into two sub-categories: fully schemes and hybrid schemes. That is fully-range-based, hybrid-range-based, fully-range-free, and hybrid-range-free. It is pointed out that hybrid localization algorithms can achieve a better localization performance compared with fully localization ones. However, in hybrid localization algorithms, large computations are required to estimate locations and the time complexity of them is relatively high.

In [31], the localization algorithms in WSNs are surveyed and reclassified with a new perspective based on the mobility state of sensor nodes. A detailed analysis of the representative localization algorithms are presented according to the following four subclasses: 1) static landmarks, static nodes, 2) static landmarks, mobile nodes, 3) mobile landmarks, static nodes and 4) mobile landmarks, mobile nodes. However, only anchor-based localization algorithms are studied in the paper without considering any anchor-free localization algorithms.

In most localization algorithms, localization is carried out with the help of neighbor nodes. Therefore, in [32], the localization algorithms are classified as known location based localization, proximity based localization, angle based localization, range and distance based localization. In known location based localization, sensor nodes can obtain their locations in prior either by manually configuring or using GPS. While in proximity based localization, a WSN is always divided into several clusters, and each sensor node can find out the nearness or proximity location by using Infrared (IR) or Bluetooth. All the algorithms studied in [32] are used in 2D static WSNs. They are not suitable for 3D scenarios or mobile WSNs.

In [33], range-based localization techniques are discussed in detail. They are classified into four categories as follow: 1) centralized versus distributed algorithm, 2) range free versus range based localization techniques, 3) anchor based versus anchor free localization techniques, and 4) mobile versus stationary node localization. Some authors have proposed algorithms in which mobile anchor nodes are used in order to improve localization accuracy of stationary sensor nodes. In addition, there are only mobile anchor nodes in WSNs, but also mobile unknown nodes or targets. Therefore, some mobile node localization algorithms are proposed to locate or track mobile sensor nodes. However, in the paper, the details of mobile node localization algorithms are not discussed.

In [34], RSSI based Localization Schemes in WSNs are discussed in terms of localization methods, performance, future scopes, etc. The cost and hardware limitation on sensor nodes preclude the use of range based localization algorithms. In many WSN applications, coarse accuracy is sufficient so range free localization algorithms are considered as a substitute to range based ones. In [35], range free localization techniques are discussed, including APIT, DV-hop, Multi-hop, Centroid and Gradient. And they are compared in terms of localization accuracy, communication and computation cost, coverage information, computational model, node density, and scalability.

In [36], a survey on mobility-assisted localization techniques is presented for WSNs. First, Key issues and inherent challenges faced by mobility-assisted localization techniques are analyzed. Then, mobility-assisted localization techniques are discussed based on two typical categories: range-based and range-free based localization approaches. Furthermore, the well known mobile anchor trajectories presented in existing localization algorithms are also reviewed, including SCAN, HILBERT, CIRCLES and DREAMS. Mobility-assisted localization is a kind of efficient approach that significantly reduces implementation cost by using limited number of mobile anchors instead of a large number of static anchor nodes. However, only the four mobile anchor trajectories are discussed in [36]. Nowadays, many mobility-assisted localization have been proposed for WSNs, and quite a number of path planning schemes have been proposed for mobile anchor nodes. Therefore, in this paper, we further study Mobile Anchor Node Assisted Localization (MANAL) based on the movement of mobile anchor nodes.

As compared in Table I, most existing survey papers concentrate on static WSNs. Only the references of [18], [31], [33], and [36] discuss localization algorithms in mobile WSNs. The reference [18] was studied in 2009 without containing recent localization algorithms. In [33], the localization algorithms for mobile WSNs are mentioned but they are not presented in detail. In [36], only the four typical anchor trajectories, named SCAN, HILBERT, CIRCLES and DREAMS, are analyzed. In our previous work in [31], localization algorithms for mobile

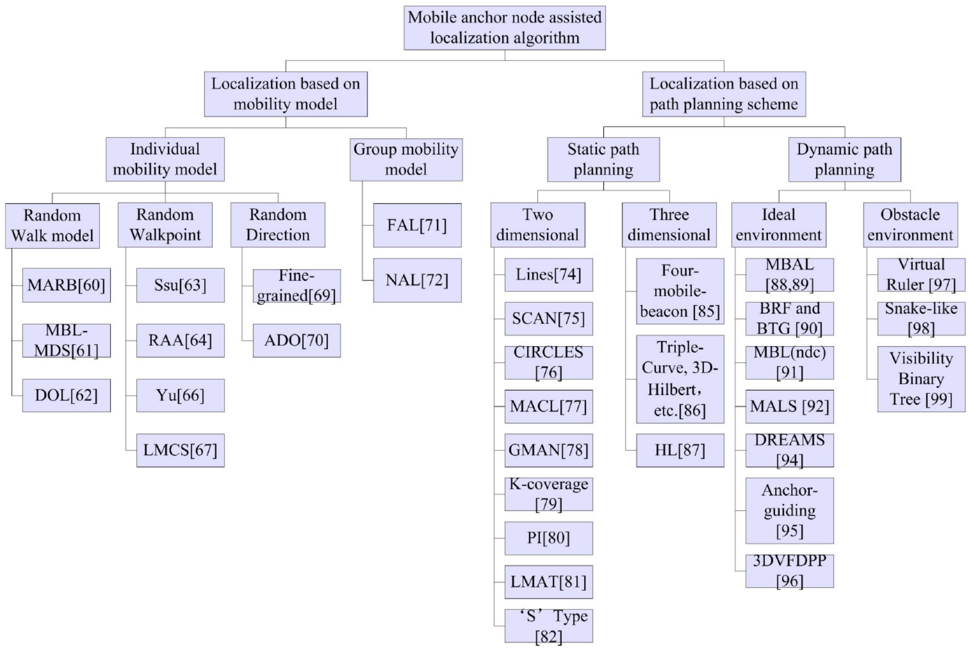

Fig. 5. Classification of mobile anchor node assisted localization algorithms.

WSNs are discussed based on the mobility state of sensor nodes, which mainly focus on the localization process of unknown nodes. In a word, there are few researches on anchor node's movement trajectory. While in the process localization, the positions and the movement trajectories of mobile anchor nodes heavily impact localization accuracy of unknown nodes. Therefore, in this paper, we study the mobile anchor node assisted localization algorithms based on different movement trajectories.

IV. Classification of MANAL Algorithms

The localization process of an unknown node can be described as the unknown node that can determine its position by limited communication with several anchor nodes using some specific localization technologies. On the basis of the characteristics of the localization algorithms, various classification algorithms can be found in the literature, e.g., range-based and range-free localization algorithms; centralized computation versus distributed computation localization algorithms; anchor-based and anchor-free localization algorithms; fine-grained and coarse-grained localization algorithms; incremental and concurrent localization algorithms, etc., [39]–[42].

However, those classifications are not distinct enough for further research of the localization algorithms without considering the mobility state of sensor nodes. Efficient mobile localization methods can change anchor node densities on demand, potentially reducing the number of anchor points needed comparing to static WSNs. Furthermore, mobile anchor nodes can cooperate with the static sensor nodes to make up the limitation of localization in static WSNs. Thus, this paper presents a review of the most successful MANAL algorithms. Fig. 5 provides a global perspective on existing MANAL algorithms, in which a mobile anchor node or a group of anchor nodes move according to certain movement trajectories to localize unknown nodes. There are mainly two types of movement trajectories in existing MANAL algorithms. The first type of movement trajectory is that anchor nodes move with some already existing mobility models without considering network parameters and localization conditions. The second one is that anchor nodes move with some path planning schemes which are particularly designed for WSN localization. Therefore, based on the different movement trajectories, existing MANAL algorithms can be classified into two categories: localization based on mobility model and localization based on path planning scheme, as shown in Fig. 5. The mobility models are further classified into individual mobility models and group mobility models. The path planning schemes are further classified into static path planning schemes and dynamic path planning schemes. The typical algorithms of each category will be analyzed and summarized in the following sections.

V. Localization Based on Mobility Model

A. Mobility Model

Node mobility is one of the inherent characteristics of mobile ad hoc networks (MANETs). A variety of mobility models are proposed for MANETs, which are used to describe the movement patterns of mobile nodes (MNs) [43]. And some mobility models also have been widely used in WSNs in recent ten years. In WSNs, mobile anchor nodes work as MNs moving among unknown nodes and periodically broadcasting their current positions to help nearby unknown nodes with localization. Different localization methods can be built based on these mobility models for WSNs. We classify mobility models into individual mobility models and group mobility models, according to whether or not the position and movement pattern of a mobile node is independent of others.

Individual mobility modeling attempts to mimic the mobility pattern behavior of a specific node and from a temporal time frame [44]. The simplest case of mobility model considers MNs moving randomly and independently of each other, which are called individual mobility models [45]. Individual mobility model can be classified into three sub-categories: 1) memoryless mobility model, e.g., Random Way (RW) [46] and Random Waypoint (RWP) [47], 2) memory mobility model, e.g., Gauss-Markov (GM) [48] and Boundless mobility model [49], 3) Geographic Mobility Model [50], [51].

In group mobility model, a group of MNs share a common mobility pattern, i.e., aggregation of the movements [52]. Often, mobility models try to imitate real mobility patterns, as well as analyze the properties of MNs from a statistical point of view. In this paper, group mobility models are classified into synthetic and hybrid mobility models. Synthetic mobility models are analytical models based on the analytical analysis of specific scenarios [53], [54]. Hybrid mobility models are synthetic mobility models which have features extracted from mobility models based on traces [55]–[59]. Traces give us the possibility to understand realistic movement patterns. However, trace based mobility models are normally limited, given that most of them are only applicable in specific scenarios.

As mentioned above, many mobility models have been proposed for MANETs and widely used in UWSNs. However, not all the mobility models are suitable for WSN localization. In mobile anchor node assisted localization in WSNs, only several mobility models are adopted, such as Random Waypoint (RWP) [46] and Random Waypoint (RWP) [47]. Then, based on different used mobility model, localization based on mobility model can be further divided into the following subclasses: 1) Localization based on Random Walk model, 2) Localization based on Random Waypoint model, 3) Localization based on Random Direction model and 4) Localization based on group mobility model.

B. Localization Based on Random Walk Model

The Random Walk (RW) mobility model is an individual mobility model which imitates the erratic movement of various entities in wireless mobile networks and a simple mobility model based on random directions and speeds. An MN moves from its current location to a new location by randomly choosing the speed distributed in the range $[v_{min}, v_{max}]$ and the direction distributed in the range $[0, 2\pi]$, where v_{min} and v_{max} are respectively the minimum and maximum speed [60]. Each movement in the RW mobility model occurs in either a constant time interval or a constant distance interval, at the end of which a new direction and speed are calculated. If an MN moving according to the RW mobility model reaches the simulation boundary, it "bounces" off the simulation border with an angle predefined at the beginning. Then, the MN continues along this new path. The RW is a memoryless mobility model because the current speed and direction of an MN is independent of its past speed and direction [61]. Thus, the RW is prone to have sudden changes of direction and speed, as depicted in Fig. 6.

1) MARB: Caballero *et al.* [62] proposed the use of a randomly moving aerial robotic beacon (MARB) with GPS

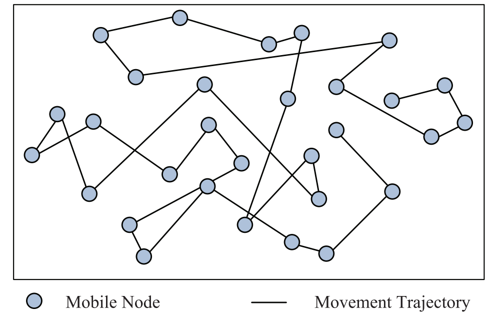

Fig. 6. An example of the RW mobility model.

for the localization of unknown nodes based on RSSI technique. A Bayesian framework is employed for the estimation of the localization of the unknown nodes. Experimental results show that there exists a correlation between the distance to the emitter and the RSSI value. The estimated position of the unknown nodes will be represented by a conditional probability distribution $p(x_k|z_{1:k})$. This distribution (the posterior) can be estimated online while running the network. Therefore, the position will be estimated and updated recursively. The proposed algorithm is very suitable for data-mule systems.

2) MBL-MDS: Kim *et. al* [63] presented a mobile beacon-based localization using classical multidimensional scaling (MBL-MDS) by taking full advantages of MDS with connectivity and measurements. In MBL-MDS, the mobile anchor node flies over sensor nodes. While traveling every beacon distance, the mobile anchor node broadcasts a beacon packet that contains its current position at the sending point (beacon point) to localize unknown nodes. MBL-MDS adopts two rules to improve localization performance: (i) a selection rule to select sufficient sets of reference points; and (ii) a decision rule to determine which of the two symmetrical candidates is the correct node position. The MBL-MDS is suitable for large-scale 3D WSNs. Localization in 3D WNSs does not simply add one extra dimension to the localization problem; it is more complex than 2D localization. Thus, it is necessary to design 3D localization methods specially instead of simply modify 2D localization methods.

3) DOL: Galstyan *et al.* proposed a distributed online localization method (DOL) [64] based on a randomly moving anchor node. It is a coarse-grained range-free localization method to lower the uncertainty of unknown nodes' positions by using radio connectivity constraints. Every time an unknown node receives a beacon packet from the mobile anchor node, the unknown node's location is bounded in the communication range of the mobile anchor node. After receiving several beacon packets from the mobile anchor node, the unknown node approximates the overlapping area by a rectangular bounding box. This way, DOL guarantees that the actual position of the node is always within the bounding box and considerably simplifies the computation of the bounding box. Then, an unknown node uses the centroid of intersection area of several beacon messages as its location as shown in Fig. 7. Even though DOL does not need complex technologies for the distance estimation, the localization accuracy is low.

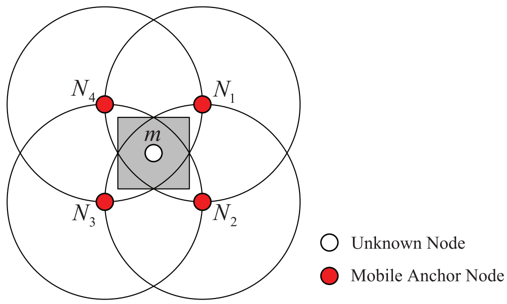

Fig. 7. The possible area of m in DOL.

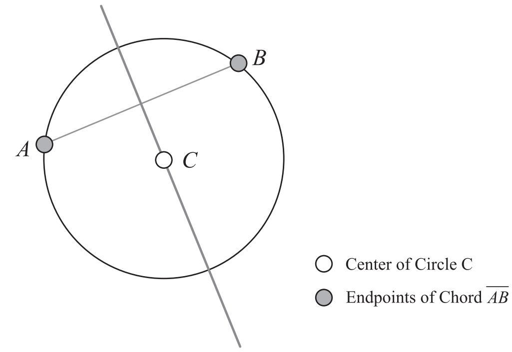

Fig. 8. Perpendicular bisector of a chord conjecture.

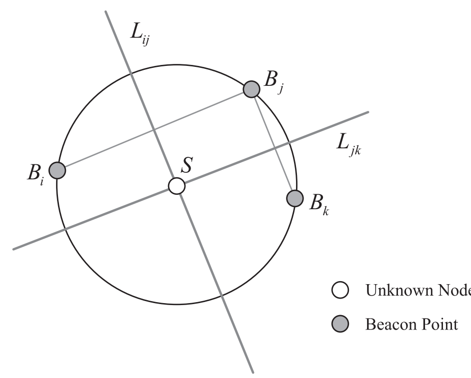

Fig. 9. Localization with mobile anchor node.

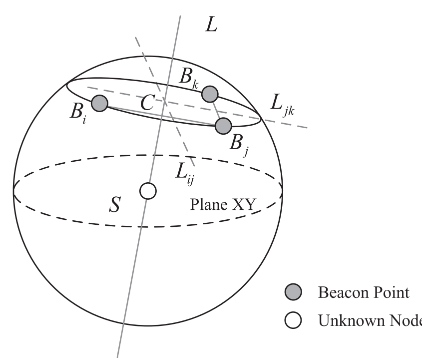

Fig. 10. Localization with aerial anchor.

C. Localization Based on Random Waypoint Model

The Random Waypoint (RWP) [46] mobility model is an extension of RW mobility model which considers pause time between changes in direction and speed. In this model, the selection of a waypoint is random within a given simulation area and does not take a certain behavioral rule or rationale into consideration. The RWP consists of five steps: (i) select a new random destination; (ii) select a speed uniformly distributed in the range $[v_{min}, v_{max}]$, where v_{min} and v_{max} are respectively the minimum and maximum speeds; (iii) move until arriving at the destination; (iv) wait in the destination position for a period of time which is uniformly distributed (i.e., a pause time); (v) go back to step one and repeat the process [49].

In RWP mobility model, the maximum speed and pause time are the two key parameters that determine the mobility behavior of an MN. If v_{max} is small and the pause time is long, the topology of the mobile network is restricted to a small portion of the simulation area. On the contrary, if the node moves fast (i.e., v_{max} is large) and the pause time is small, the topology of the mobile network is expected to be highly dynamic.

1) Ssu: In [65], Ssu *et al.* proposed a range-free localization method based on mobile anchor nodes using the geometry conjecture (perpendicular bisector of a chord) to determining the position of the unknown nodes. The mobile anchor nodes moved with the RWP model, and The conjecture describes that the perpendicular bisector of any chord passes through the center of the circle. The center of the circle is the location of an unknown node. As shown in Fig. 8, the chord ($\overline{AB}$) of a circle is a segment whose endpoints are on the circle. At least three endpoints on the circle should be collected for establishing two chords, the intersection point of two perpendicular bisectors of the chords will be the position of the unknown node, as depicted in Fig. 9. Besides, randomized beacon scheduling, chord selection, obstacle tolerance and enhanced beacon selection mechanisms are introduced for performance improvement. This paper determines two chords that pass through an unknown node and use the intersection point of the two chords as its position. Based on the principles of elementary geometry, unknown nodes can calculate their positions without additional interactions.

2) RAA: A Range-free localization mechanism with Aerial Anchor nodes (RAA) was proposed by Ou *et al.* [66]. Based on the mathematical inference that claims a perpendicular line passing through the center of a sphere's circular, each unknown node selects the appropriate anchor points broadcasted by the mobile aerial node for forming a circular cross section of the sphere. As illustrated in Fig. 10, the position of the unknown node can be obtained by calculating the intersection point of L and plane XY. Thus, the center of the sphere can be calculated by estimating the intersection point of the perpendicular line and the ground. As improvements, the authors made in [65], a jittered beacon scheduling, a chord selection, and a circular cross section selection are proposed to enhance the localization performance. In 2008, Ou *et al.* then presented that the position of an unknown node can be determined by calculating the intersection point of the two perpendicular lines passing through the centers of the two circles which are formed by two circular cross sections [67]. As shown in Fig. 11, the position of the unknown node can be obtained by calculating the intersection point of L and L'.

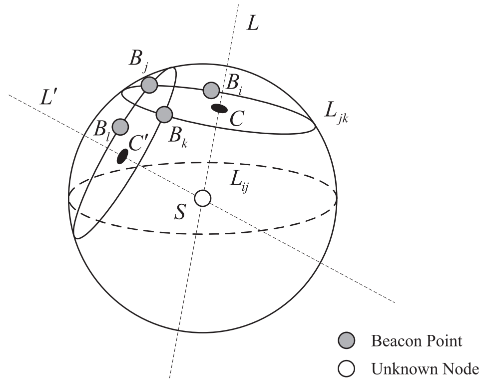

Fig. 11. Localization with flying anchor.

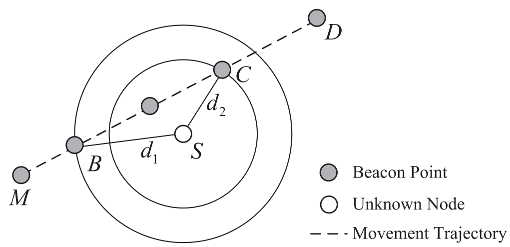

Fig. 12. Communication between unknown node S and mobile anchor node in noisy wireless environment where each circle has a certain error probability for S to receive a beacon package from the mobile anchor node.

3) Yu: Since Ssu *et al.* [65] did not consider wireless channels in their algorithm, Yu *et al.* [68] proposed a new algorithm using a flying beacon to help unknown nodes to determine their positions. Yu *et al.* gave a new view of the conventional definition of reception-range under a noisy wireless environment. The error probability of receiving a packet decreases with the increase of signal to noise ratio. Therefore, many concentric circles can be drawn whose center is the location of the unknown node, as shown in Fig. 12. Once an unknown node receives a beacon packet without error, a hemisphere can be obtained. The center of all hemispheres is the position of the unknown node. The proposed algorithm can achieve localization without using any distance or angle information. They concluded that the proposed algorithm is more energy efficient and has higher localization accuracy than Ssu's localization method.

4) LMCS: A mobile beacon assisted and range free localization method, localization with a mobile beacon based on compressive sensing (LMCS), was proposed by Zhao *et al.* [69]. LMCS utilizes compressive sensing (CS) to get the related degree of the unknown nodes and all the beacon points. According to the related degree, LMCS decides the weight value of each beacon point for the mass coordinates and estimates the unknown nodeł location by weighted centroid. However, extensive communication among neighboring sensor nodes is required to obtain the connectivity information. CS only needs fewer noisy measurements to recover the signal, which is sparse or compressible under a transform basis and can reconstruct exactly the original sparse signal with high probability by dealing with a minimization problem. Besides, the obstacles and degree of irregularity have little effect on LMCS.

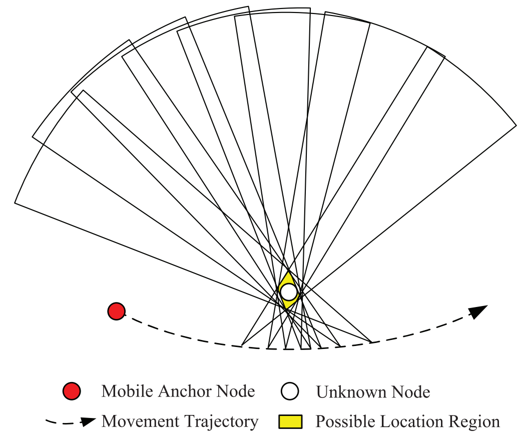

Fig. 13. Estimation of an unknown node's position.

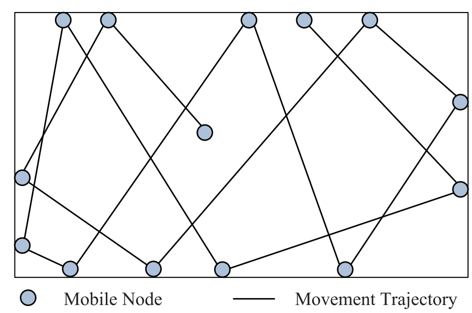

Fig. 14. An example of the RD mobility model.

Another range free localization algorithm named an azimuthally defined area localization (ADAL) is proposed in Guerrero *et al.* [70], which utilizes a beacon with a rotary directional antenna to send messages in a determined azimuth periodically. The area measurement determines the intersection of all overlapping coverage regions. An unknown node uses the centroid of intersection area of several beacon points as its position as shown in Fig. 13. Therefore, it is a distributed and energy efficient algorithm. However, this paper just assumes that the mobile anchor node is capable of moving across the whole network and broadcast the beacon messages to the sensor nodes during the localization process. The movement trajectory of the mobile anchor node is not analyzed in detail.

D. Localization Based on Random Direction Model

The Random Direction (RD) mobility model is a model that forces an MN to travel to the edge of the simulation area before changing direction and speed [47] and was created to overcome the clustering of MNs in the average number of neighbors produced by the RW mobility model. In the RD mobility model, an MN chooses a direction randomly and travels to the border of the simulation area in that direction, as shown in Fig. 14. When the MN arrives at the simulation boundary, it pauses for a period of time, and then, selects a new direction between 0 and 180 degrees and continues the process.

1) Fine-Grained: Liu *et al.* [71] presented a fine-grained localization method using a mobile beacon node, which is based on geometric constraints as an extension of Ssu's [65] algorithm. In [71], the four mobility models, RW model, RWP model, RD model and Gauss-Markov (GM) model are compared. The first three mobility models have been introduced in detail, while the GM mobility model is discussed as follows: the GM model was first introduced by Liang and Haas [48] and designed to adapt to different levels of randomness via one tuning parameter. The GM mobility model provides smoothness to the movement trajectory and eliminates sudden stops and sharp turns. Moreover, the GM mobility model considers past speeds and directions to influence future movement trajectories. Assume that (x_n, y_n) and (x_{n-1}, y_{n-1}) are the x and y coordinates of the MN's position at the nth and $(n-1)\,th$ time intervals, respectively. A random variable using the following equations,

$$S_n = \alpha S_{n-1} + (1-\alpha)\overline{S} + \sqrt{(1-\alpha^2)}\,Sx_{n-1}, \tag{5}$$

$$d_n = \alpha d_{n-1} + (1-\alpha)\overline{d} + \sqrt{(1-\alpha^2)}\,dx_{n-1}, \tag{6}$$

where s_n is the new speed and d_n is the new direction of the MN at time interval n; $\overline{S}$ and $\overline{d}$ are constants which stand for the average value of speed and direction, respectively. $\alpha(0 \le \alpha) \le 1$ is a tuning parameter. Sx_{n-1} and ds_{n-1} are random variables following the Gaussian distribution.

The next location can be calculated based on the current location, speed and direction at each time interval. An MN's position at time interval n can by calculated by the following equations,

$$x_n = x_{n-1} + S_{n-1}\cos d_{n-1}, \tag{7}$$

$$y_n = y_{n-1} + S_{n-1} + S_{n-1}\sin d_{n-1}. \tag{8}$$

Based on the compassion of RW, RWP, RD and GM models, the RD mobility model is selected for the mobile anchor node in [71]. The algorithm consists of two steps: (i) localization by a mobile anchor node; (ii) localized unknown nodes serves as stationary beacon nodes to help uncovered unknown nodes with localization. They introduced ten localization models, which describe the localization relationship between the mobile beacon and the stationary unknown node. Thus, two possible positions of the unknown nodes can be obtained according to the mathematical formula. Then, by moving the mobile beacon and calculating the distances between the mobile beacon and the two possible positions, the true coordinates of the unknown node can be confirmed. The proposed algorithm outperforms Ssu's [65] and Yu's [68] localization methods in terms of average overhead and average localization error.

2) ADO: A distributed localization method using the arrival and departure overlap (ADO) of beacon points was proposed by Xiao *et al.* [72]. In the ADO, three different mobility model, the Sparse-Straight-Line (SSL) movement pattern, the Dense-Straight-Line(DSL) movement pattern, and the random movement pattern, are compared. In the random movement pattern, the anchor node travels along a predefined straight line and after a certain distance, randomly changes its direction. That is, the RD mobility model is adopted. In addition, ADO uses *arrival and departure constraint area* to decide each node's location. As shown in Fig. 15, suppose that a beacon is moving from left to right along the x-axis; unknown node G receives the beacon package for the first time when the mobile beacon moves to point B, which forms an *arrival constraint area* in the left-hand crescent; when the mobile beacon moves forward, the unknown node G receives the beacon package for the last time when the mobile beacon moves to point C, which forms a *departure constraint area* in the right-hand crescent. Thus, the *arrival constraint area* and *departure constraint area* will create an ADO. Unknown node G must be in ADO. According to the different movement trajectories of the mobile beacon, sensor nodes should apply the correspondingly proposed algorithms to efficiently compute their positions.

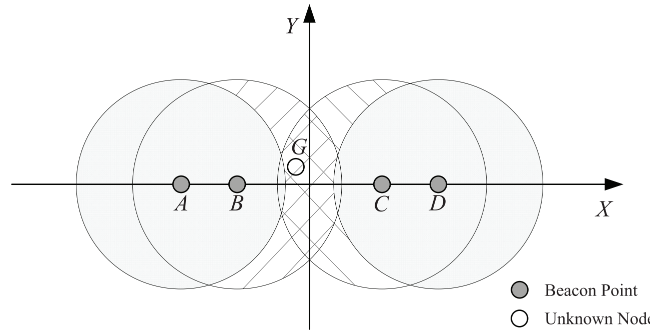

Fig. 15. Localization using the arrival and leaving information of the beacon.

E. Localization Based on Group Mobility Model

1) FAL: Liu *et al.* [73] proposed a five anchors localization method (FAL) without using distance or angle information to balance the complexity of distance measurement with localization accuracy. Based on the comparison of RSS transmitted by five mobile anchor nodes and the principles of elementary geometry, unknown nodes can estimate their positions without additional interactions. Five anchor nodes $N_i(i = 0, 1, \ldots, 4)$ form a square with one located at the centre of the square. The square is divided into four equal regions. Since the distances between N_i and N_{i+1} $(i = 1, 2, 3)$ are equal, they assume that the RSS between N_i and N_{i+1} $(i = 1, 2, 3)$ are the same. According to the RSSI model, the shorter distance between node m and node N_i is, the larger RSS_i m acquires. Therefore, unknown node m chooses one of the four regions where it is located based on the RSS_i. By this way, the possible position of unknown node m can be slowly constructed after four steps, as shown in Fig. 16. FAL algorithm does not need a complex technology for distance estimation, thus it reduces the complexity of the hardware equipment.

2) NAL: In [74], Zhang *et al.* presented a nine anchors localization method (NAL) for WSNs. Nine mobile anchor nodes form a circle. Unknown nodes inside the circle will record the RSS from mobile anchor nodes and estimate their locations by comparing the RSS. The positional relationship of the nine mobile anchor nodes is shown in Fig. 17. Similar to DOL, an unknown node uses the centroid of intersection area of several beacon messages as its location. NAL algorithm can achieve high accuracy compared with DOL. However, it requires more mobile anchor nodes.

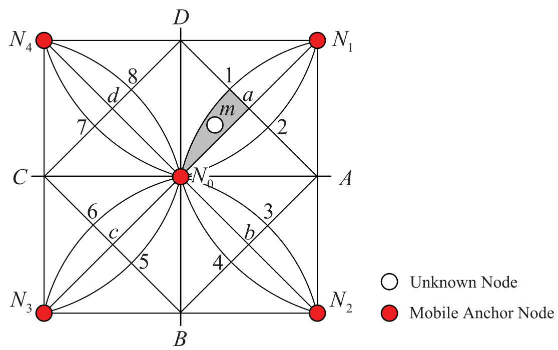

Fig. 16. The possible area of m in FAL.

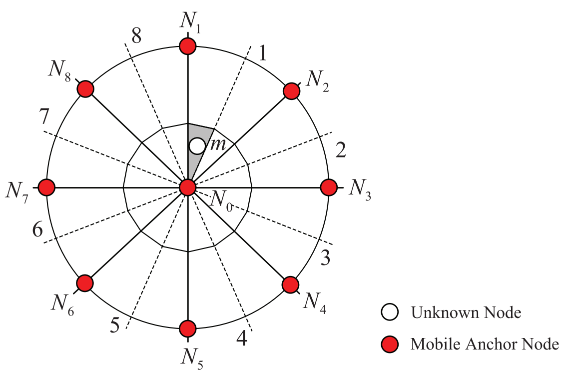

Fig. 17. The possible area of m in NAL.

Multiple mobile anchor nodes assisted localization methods usually arrange mobile anchor nodes into regular geometric patterns and make mobile anchor nodes moving together in the network. The relative positions of mobile anchor nodes remain the same during the movement. Thus, unknown nodes can estimate their locations based on the RSS and geometric relationship of the mobile anchor nodes. This kind of range-free localization methods does not require technology for distance estimation. Unknown nodes estimate their locations without any information exchange with other unknown nodes. Therefore, this kind of range-free localization methods consumes less energy compared with conventional range-based localization methods.

F. Comparison of Localization Based on Group Mobility Model

Table II summarizes the above-mentioned localization based on mobility model in terms of the used mobility model, pause time, the number of mobile anchor nodes, the area coverage, the beacon utilization, the advantages and disadvantages. From the comparison, we can conclude that:

- In most localization algorithms based on mobility model, mobile anchor nodes need a period of pause time to broadcast localization beacons, which introduce longer localization delay. Otherwise, the anchor nodes continually send beacons while traveling through the localization area. In this case, much more energy is consumed for sending localization beacons.
- In the adopted mobility models, e.g., Random Way (RW), Random Waypoint (RWP) and Random Direction (RD) models, it is always assumed that the trajectories of the mobile anchor node are straight lines between two stop points, while the details of the mobility models are not discussed. The trajectories of the mobile anchor node or the positions of sending localization beacons heavily impacts the localization accuracy and localization ratio of unknown nodes, thus a more realistic mobility model for the anchor node needs further study.
- Compared with the localization algorithms using single anchor node, the localization algorithms using multiple anchor nodes can obtain high ratio of beacon utilization. This is because in localization algorithms which use single anchor node, a lot of collinear beacons and insufficient number of beacons cannot be used to localize unknown nodes; while in the localization algorithms which use multiple anchor nodes, all the beacons can be used in the localization process.
- In addition, we can see from the Table II that, all the localization algorithms based on mobility model cannot ensure full coverage of network, because all the mobility models used in the localization process are random movement without considering localization parameters in WSNs, such as network size, node density, node distribution etc. In this case, not all the unknown nodes can be successfully localized by mobile anchor nodes. In order to improve localization ratio and localization accuracy of MANAL algorithms, many path planning schemes are proposed in WSNs, which will be carefully discussed in the next section.

VI. Localization Based on Path Planning Scheme

Recently, researchers' interest on autonomous vehicles has increased with the development of electronic techniques [75]. One of the main subjects in autonomous vehicle research is path planning. In mobile anchor node assisted localization algorithms, path planning tries to find a feasible movement trajectory for mobile anchor nodes in a given monitoring area (region) with the objective of improving localization performances.

The problem of path planning for mobile anchor nodes is to design the movement trajectories satisfying the following properties: (i) It should pass closely to as many potential node positions as possible, aiming at localizing as many unknown nodes as possible; (ii) It should provide each unknown node with at least three (four) non-collinear (non-coplanar) anchor points in a 2D (3D) WSN to achieve an unique estimation of unknown node's position; (iii) It should be as short as possible to reduce the energy consumption of mobile anchor nodes and time of localization.

Path planning schemes can be either static or dynamic. Static path planning scheme designs movement trajectory before starting execution, mobile anchor node follows a predefined trajectory during the localization process. Dynamic path planning scheme designs movement trajectory dynamically or partially

TABLE II
COMPARISON OF LOCALIZATION BASED ON MOBILITY MODELS

Algorithm	Reference	MM	PT	MANs	AC	BU	Advantages	Disadvantages
MARB	Ref.[60]	Random Walk	No	Single	No	Low	Localization accuracy is improved by taking into account the uncertainty of RSSI values.	Due to the random movement of the beacon, not all the unknown nodes can be localized.
MBL-MDS	Ref.[61]	Random Walk	No	Single	No	Low	Localization performance is improved by selecting sufficient sets of reference points.	The details of the mobility model are not discussed.
DOL	Ref.[62]	Random Walk	No	Single	No	Low	No complex technology is needed for the distance estimation.	Localization accuracy and localization ratio are low.
Ssu	Ref.[63]	Random Waypoint	Yes	Single	No	Low	As a range-free localization scheme, no extra hardware or data communication is needed.	Coarse positioning accuracy and low localization ratio.
RAA	Ref.[64]	Random Waypoint	Yes	Single	No	Low	As a range-free localization scheme, no extra hardware or data communication is needed.	Coarse positioning accuracy and low localization ratio.
Yu	Ref.[66]	Random Waypoint	Yes	Single	No	Low	Noise wireless channels are considered; Localization is achieved without using any distance or angle information.	It assumed that the trajectories of the mobile anchor node are straight lines within the sensor area, but the details are not discussed.
LMCS	Ref.[67]	Random Waypoint	Yes	Single	No	Low	Has better localization performance under irregularity of radio range or obstacle environment.	Using connectivity information needs extensive communication and exhausts more energy.
Fine-grained	Ref.[69]	Random Direction	Yes	Single	No	Low	Outperforms [63] and [66] in terms of average overhead and average localization error.	The two step localization introduce inevitable cumulative localization error.
ADO	Ref.[70]	Random Direction	Yes	Single	No	Low	Using the arrival and departure information of the beacon to localization unknown nodes.	Location accuracy depends on the choice of the RSS model.
FAL	Ref.[71]	Group mobility	Yes	Five	No	High	Does not need a complex technology for distance estimation.	The details of the group movement are not discussed.
NAL	Ref.[72]	Group mobility	Yes	Nine	No	High	Does not require distance estimation; Consumes less energy.	Requires more (about 9) mobile anchor nodes. They should be move together.

1 MM-Mobility model; PT-Pause Time; AC-Area full Coverage; BU-Beacon Utilization.

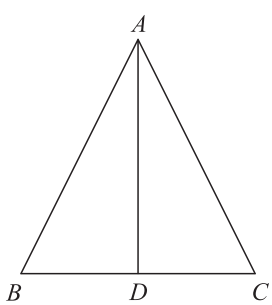

Fig. 18. Abscissa identify of node A.

according to the observable environments or deployment situations, etc.

A. Static Path Planning Scheme

1) Two-Dimensional: First, static path planning schemes in two-dimensional WSNs are discussed, which includes: path planning based on lines [76], SCAN, DOUBLE-SCAN and HILBERT [77], CIRCLES and S-CURVES [78], MACL [79], GMAN [80], K-coverage [81], PI [82], LMAT [83], 'S' Type [84], SCAN Based [85], [86].

(i) Path planning based on lines

A range-free layered localization method with a sleep/wake mechanism named as sensor sleep-time forecasting to save energy consumption during localization was presented by Zhang *et al.* [76]. The mobile anchor node travels the monitoring area along the x-axis and transmits gradient signals, i.e., the mobile anchor node transmits different communication range information to different layers. Abscissa identify algorithm of node A is shown in Fig. 18. The $\triangle ABC$ is an isosceles triangle. The line $\overline{AD}$ is the vertical bisection line of the hemline $\overline{BC}$. The position of nodes $B(x_B, y)$ and $C(x_C, y)$ can be known by the mobile anchor node. Node A's abscissa can be calculated by using of $x_A = (x_B + x_C)/2$. Each unknown node in the monitoring area maintains a visit list which stores received beacon messages. With the mobile anchor node moving along the x-axis, unknown sensor S cannot receive beacon messages for this layer. Then, the unknown node S will calculate its location. The mobile anchor node moves along the x-axis back and forth transmitting gradient signals to help unknown nodes in different layers with localization. Thus, unknown nodes in all layers can be localized completely. If the unknown nodes have located their localization, they would switch to the sleep state. The proposed localization method is independent of unknown nodes density and communication range.

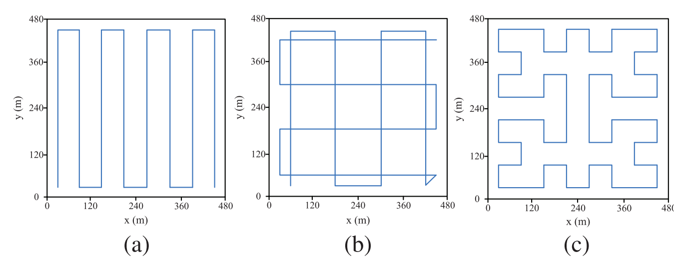

Fig. 19. Movement trajectory of SCAN, DOUBLE-SCAN and HILBERT: (a) SCAN, (b) DOUBLE-SCAN, (c) HILBERT.

(ii) SCAN, DOUBLE-SCAN and HILBERT

Koutsonikolas *et al.* [77] studied the design of mobile anchor node movement trajectories aiming at maximizing the localization accuracy of WSNs. Three movement trajectories, SCAN, DOUBLE-SCAN and HILBERT, are proposed to satisfy network coverage and provide good quality anchor points. The distance between two successive segments of the trajectories is defined as the resolution. SCAN is the simplest and the most easily among the three movement trajectories, the mobile anchor node travels along the y axis, as shown in Fig. 19(a). However, SCAN provides a large amount of collinear anchor points. To overcome the collinearity problem, DOUBLE-SCAN was proposed which scans the monitoring area along both

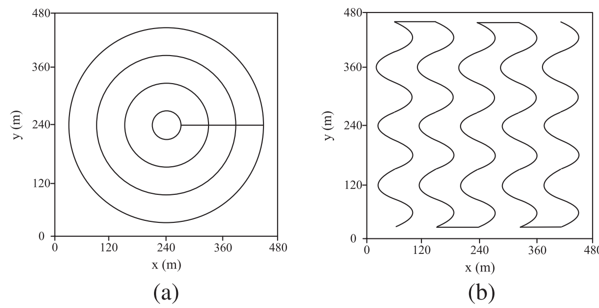

Fig. 20. Movement trajectory of CIRCLES and S-CURVES: (a) CIRCLES, (b) S-CURVES.

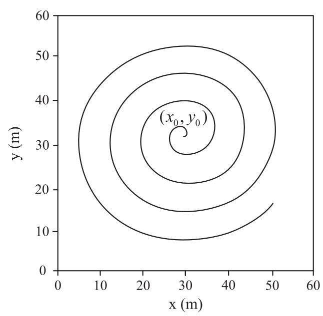

Fig. 21. Movement trajectory of MACL.

directions, as shown in Fig. 19(b). However, DOUBLE-SCAN requires the mobile anchor node to travel doubled distance compared with SCAN. A level-n HILBERT curve divides the 2D area into 4^n square cells and connects the centers of those cells using 4^n line segments, each of length equal to the length of the side of a square cell. The resolution of HILBERT curve is defined as the length of each line segment, as shown in Fig. 19(c). Compared with SCAN and DOUBLE-SCAN, the HILBERT can provide more non-collinear anchor points for unknown nodes. When the mobile anchor node traverses the monitoring area at a fine resolution, SCAN has the lowest localization error and smallest path length among the three trajectories, followed closely by HILBERT. However, when the resolution of the trajectory is larger than the communication range, the HILBERT achieves significantly better localization accuracy than the others.

(iii) CIRCLES and S-CURVES

To reduce the collinearity during localization, Huang *et al.* [78] proposed CIRCLES and S-CURVES static path planning schemes, as depicted in Fig. 20. CIRCLES consists of a sequence of concentric circles centered within a given monitoring area. S-CURVES is based on SCAN, which progressively scans the monitoring area form left to right taking an 'S' curve. Both of CIRCLES and S-CURVES can provide non-collinear beacon potions. The authors concluded that the CIRCLES has significantly shorter path length than SCAN, HILBERT and S-CURVES. However, CIRCLES and S-CURVES leave the four corners of the square monitoring area uncovered.

(iv) MACL

Hu *et al.* [79] proposed a mobile anchor node centroid localization (MACL) algorithm. The mobile anchor node traverses the monitoring area following a spiral trajectory while periodically broadcasting beacon packets which contain its current position, etc., as shown in Fig. 21.

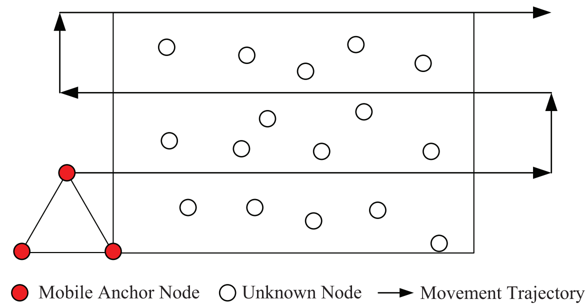

Fig. 22. Movement trajectory of a GMAN.

(v) GMAN

In [80], Zhang *et al.* proposed a collaborative localization algorithm using a group of mobile anchor nodes (GMAN). A GMAN is composed of three mobile anchor nodes, which form an equilateral triangle and each anchor node is located at one of the three vertexes, as shown in Fig. 22. They assume that a two-tier network architecture with unknown nodes randomly deployed in a given area (region). A GMAN moves through (or flies over) the monitoring area with a certain or random speed. If an unknown node is in the coverage of a GMAN, it can receive anchor packages from the mobile anchor node and estimate its location.

(vi) K-coverage

In [81], Fu *et al.* proposed a k-coverage trajectory to reduce beacon density and trajectory length. The k-coverage trajectory consists of two periods, finding a virtual beacon deployment and obtaining the shortest trajectory to tour virtual beacons. In the first period, an optimal 3-coverge is illustrated. In the second period, the Ant Colony Algorithm (ACA) is used to solve the Traveling Salesman Problem (TSP), i.e., to design a movement trajectory for the mobile anchor node to traverse the virtual beacons using a shortest path length. Since the static trajectory does not work well in non-uniformly deployed sensor networks, they proposed a virtual force trajectory which will be discussed in the following section.

(vii) PI

A mobile-assisted localization algorithm called perpendicular intersection (PI) was presented in [82]. Instead of mapping RSSI values into physical distances directly, PI utilizes the geometric relationship of a perpendicular intersection to compute node positions. The mobile anchor node starts at point P_1, changes its direction at point P_2 and stops at point P_3. The lengths of P_1P_2 and P_2P_3 should be shorter than R. Meanwhile, the angle θ should satisfy $0 < \theta \leq \pi/3$. $N(x, y)$ can be calculated by using coordinates of P_1, P_2, P_3, A and B, as shown in Fig. 23.

To use PI, the trajectory should include at least two intersecting lines, which are not longer than the commutation range of the mobile anchor node, and the angle between them should satisfy $0 < \theta < \pi/3$. Since the equilateral triangle will minimize the path length while maximizing the area for a given perimeter, they conclude that the optimal trajectory of the mobile anchor node consists of multiple equilateral triangles, as depicted in Fig. 24.

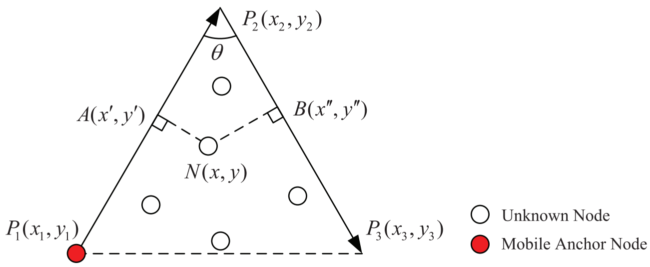

Fig. 23. An example of PI

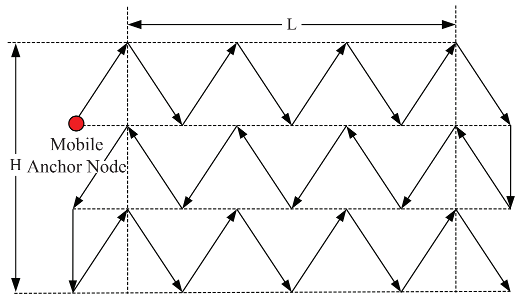

Fig. 24. Movement trajectory of PI.

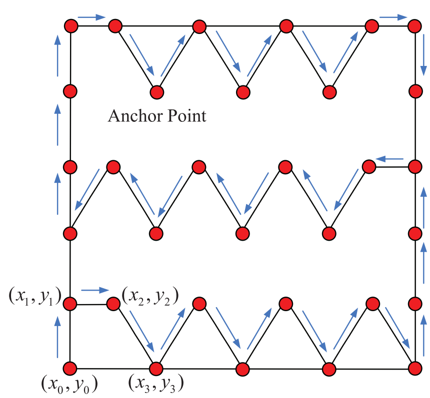

Fig. 25. Movement trajectory of LMAT.

(viii) LMAT

Han *et al.* studied the optimized movement trajectory with objectives of maximizing localization coverage and localization accuracy of unknown nodes [83]. They proposed a localization algorithm with a mobile anchor node based on trilateration (LMAT) which requires the mobile anchor node travelling the monitoring area following a regular triangle trajectory. In LMAT, anchor points compose regular triangles to insure the localization accuracy, as depicted in Fig. 25. The distance between the unknown node and the anchor can be measured based on RSSI. The main advantage of the triangle trajectory is to solve the collinearity problem.

(ix) 'S' Type

Two attractive movement trajectories for the mobile anchor node were proposed by Chen *et al.* [84] to reduce the total path length and improve movement efficiency of mobile anchor node while satisfying the expected location performance, which can efficiently extend the lifetime of the mobile anchor node and optimize the anchor distribution. The authors use an 'S' type as

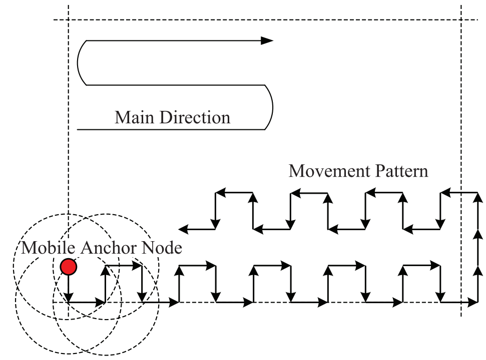

Fig. 26. Movement trajectory of 'S' type.

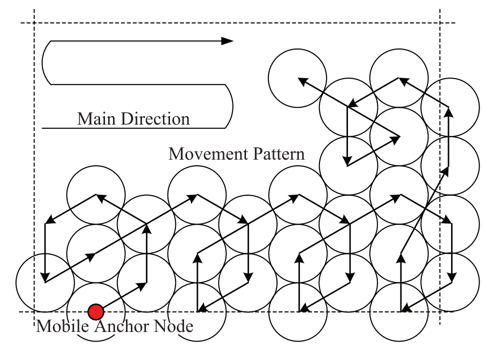

Fig. 27. Movement trajectory of 'S' type.

macro movement trajectory for mobile anchor node. The monitoring area can be divided into small squares with the length of $R/\sqrt{2}$ by anchor points, as illustrated in Fig. 26. Thus, the unknown nodes can receive four uniformly distributed anchor packages in a little square area, which can reduce the solution of the collinearity problem. They also proposed a spiral movement trajectory for mobile anchor node in some emergent environments, such as fire alarm. The monitoring area can be divided into small circulares developed by anchor points, as shown in Fig. 27. The radius of the circular is dependent on the communication range of the mobile anchor node.

(x) SCAN Based

To meet the specific requirements of the localization algorithm proposed in [85], Ou *et al.* presented a new path planning scheme based on the SCAN algorithm [86]. The path planning scheme guarantees that (i) all sensor nodes are able to identify three or more anchor points so as to form two non-parallel chords and (ii) the length of each chord should exceed a certain threshold value so as to minimize the localization error. The distance between two successive vertical segments of the movement trajectory (i.e., the resolution) is specified as $R - X$ (R is the communication range of the mobile anchor node, $0 < X \leq R/3$), as shown in Fig. 28. Thus, by extending the sensing field and choosing an appropriate value of X, the proposed path planning scheme can ensure that the mobile anchor node passes through the circle of each sensor node either two or three times. Besides, the obstacle problem has been carefully handled by using the enhanced anchor point selection mechanism. When the mobile anchor node discovers an obstacle while moving along the proposed movement trajectory, the mobile

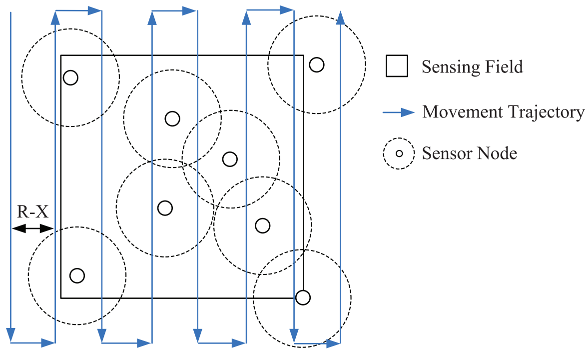

Fig. 28. SCAN based Mobile anchor node path planning.

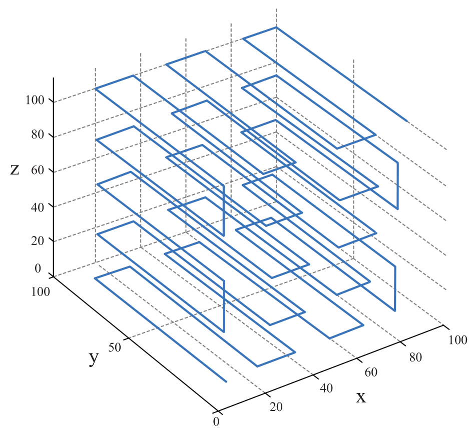

Fig. 29. Movement trajectory of four-mobile-beacon assisted localization.

anchor node will detour around the obstacle toward the right-hand direction. After detouring, the mobile anchor node returns to the original proposed movement trajectory.

2) Three-Dimensional: In this subsection, static path planning schemes in three-dimensional WSNs are discussed, which includes: Four-mobile-beacon [87], Layered-Scan, Layered-Curve, Triple-Scan, Triple-Curve and 3D-Hilbert [88], HL [89].

(i) Four-mobile-beacon

In [87], Cui *et al.* proposed a four-mobile-beacon assisted weighted centroid localization (WCL) algorithm. The four mobile beacons form a regular tetrahedron and traverse the given monitoring region following the LAYERED-SCAN trajectory which consists of several parallel layers of SCAN, as illustrated in Fig. 29. The distance between two adjacent layers is defined as vertical resolution. The distance between two successive lines, parallel to y axis is defined as horizontal resolution.

(ii) Layered-Scan, Layered-Curve, Triple-Scan, Triple-Curve and 3D-Hilbert

In [88], Cui *et al.* introduced Layered-Scan, Layered-Curve, Triple-Scan, Triple-Curve and 3D-Hilbert movement trajectories for 3D WSNs. Layered-Scan and Layered-Curve divide the 3D monitoring region into several layers along one axis and regard each layer as a 2D monitoring area. Thus, in each layer of Layered-Scan and Layered-Curve, the mobile anchor node traverses along one dimension using SCAN and S-CURVES, respectively. To avoid collinearity or coplanarity of anchor

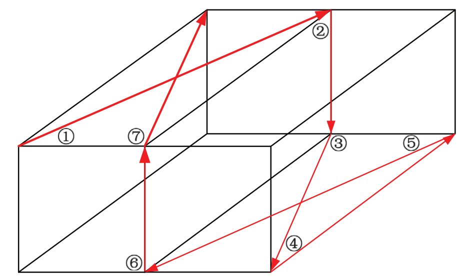

Fig. 30. Movement trajectory of HL.

points, they proposed Triple-Scan and Triple-Curve which are the triple of Layered-Scan and Layered-Curve, respectively (i.e., divide the morning region into several layers along three axes). Both of Triple-Scan and Triple-Curve can overcome coplanarity problem, but some parts of the paths are scanned several times which increase the path length of the mobile anchor node. 3D-Hilbert derived from Hilbert space filling curve which has more turns compared with Layered-Scan and Triple-Scan to overcome collinearity and coplanarity problems, but has shorter path length compared with Layered-Curve and Triple-Curve.

(iii) HL

In [89], Liu *et al.* presented a hexahedral localization (HL) algorithm. The space is divided into a lot of hexahedrons. Then, all the unknown nodes can be located by utilizing the perpendicular properties of the trajectory. The mobile beacon moves along the given trajectory and broadcasts its positions periodically, as shown in Fig. 30. To ensure the coverage of mobile beacons, the point in the hexahedron which is the furthest from the trajectory should be covered in the extension. Thus, they calculate the distance between the furthest point and the trajectory. However, they concluded that the mobile beacon's trajectory may be uncontrollable, and the trajectory may not be the ultimate one. They will devote to studying the model optimization in their future work.

Discussion: In brief, using a single mobile anchor node would be more economical. However, it may bring collinearity or coplanarity problem into localization, while using a group of mobile anchor nodes could reduce the localization time and is more suitable for 3D environments. However, static path planning scheme cannot make full use of the real-time information during localization.

B. Dynamic Path Planning Scheme

Static path planning scheme works well when the unknown nodes are assumed to be uniformly deployed. However, in the cases where such assumption is not valid, static path planning scheme might not be the best solution. All the above-mentioned static path planning schemes take the entire area (region) into consideration, that is to say, the mobile anchor node follows the predefined trajectory and traverse the whole area (region) during the localization process. Thus, static path planning schemes will result in long path length, long localization time and low utilization rate of the beacon messages. Therefore, some research focuses on the study of dynamic path planning schemes to make full use of the distribution information of

WSNs and minimize the path length and energy consumption of the mobile anchor node. We classify dynamic path planning schemes into two groups, with obstacle and without obstacle, since many dynamic path planning schemes focus on obstacle detection and avoidance issues, and most of the relative researches are designed for 2D WSNs.

1) Ideal Environment: In this subsection, dynamic path planning schemes in ideal environment of WSNs are discussed, which includes: MBAL [90], [91], BRF and BTG [92], MBL(ndc) [93], Virtual Force [81], MALS [94], Six Possible Next Positions [95], DREAMS [96], Anchor-guiding [97], 3D-VFDPP [98].

(i) MBAL

In [90], Kim *et al.* presented mobile beacon-assisted localization (MBAL) which consists of three sub-processes, a reference movement phase, a sensor localization phase and a movement path decision phase. The mobile beacon moving according to a regular triangle with the length of its communication range first broadcasts three beacon messages. The unknown nodes that do not know their own positions then request the mobile anchor node to deliver more beacon packets. The mobile beacon determines the movement trajectory with all requests from remaining unknown nodes with the objective of minimizing the total length of the mobile anchor node. At each step, the mobile beacon chooses the nearest target among candidate points and receives additional request messages from new request node. Similarly, Kim *et al.* [91] considered candidate areas for both ground and aerial beacons, the mobile beacon chooses the nearest position in candidate areas as a next anchor point iteratively.

(ii) BRF and BTG

Connectivity in WSN inherently indicates that we can take advantage of the graph structure inherent in the network. Li *et al.* [92] regarded a WSN as a connected undirected graph. They proposed a breadth-first (BRF) algorithm and a backtracking greedy (BTG) algorithm to transform the path planning issue into seeking spanning trees of the undirected graph and traversing through the graph. Thus, the movement trajectory of the mobile anchor node changes dynamically accordingly to the distribution of unknown nodes.

(iii) MBL(ndc)

Most existing mobile beacon-assisted localization algorithms do not make effective use of the node distribution information, which results in low utilization ratio of anchor points. Zhao *et al.* [93] proposed a mobile beacon-assisted localization algorithm based on network-density clustering (MBL (ndc)) which combines node clustering, incremental localization and mobile beacon assisting together. The MBL (ndc) chooses the node with the highest local density as a cluster head and forms a cluster using improved density based spatial clustering of application with noise (DBSCAN) algorithm. Then, it combines global path planning for all cluster heads and local path planning for every cluster together to determine the movement trajectory of the mobile beacon. The mobile beacon firstly traverses all the cluster heads employing the genetic algorithm. Then, the mobile beacon moves along regular hexagon trajectory in each cluster with the cluster head located in the center of the regular hexagon. The global and local path planning achieve an optimal movement trajectory which not only guarantees localization ratio and accuracy, but also reduces energy consumption.

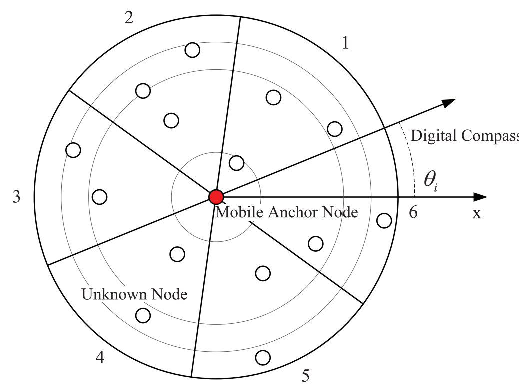

Fig. 31. The mobile anchor node is equipped with multiple directional antennas and digital compass can receive feedback messages in 6 directions.

(iv) Virtual Force

Inspired by artificial potential field, Fu *et al.* proposed a novel dynamic movement trajectory based on virtual force, which is constructed by interaction force between mobile anchor node and unknown nodes [81]. The virtual force trajectory was presented for the non-uniformly (i.e., “U” type, “L” type) deployed WSNs. Each sensor node is equipped with an omni-directional antenna. The mobile anchor node uses directional antennas with ID 1, 2, . . . , N ($N = 6$ is shown in Fig. 31) to receive feedback messages from sensor nodes and calculates the total virtual force on a mobile anchor node. Then, the mobile anchor node moves to a new position according to the total virtual force and then starts a new cycle.

(v) MALS

A mobile assisted localization by stitching (MALS) which is designed to accommodate non-uniform and irregular deployment scenarios was proposed by Wang *et al.* [94]. By employing rigidity theory, the original large-scale network is partitioned into several localization units, of which each can be uniquely localized by given three non-collinear anchor points. The movement trajectory is formed by “stitching” all localization units together in the shortest path to traverse only areas with unknown nodes and avoid blank areas. The mobile anchor node follows the designed path step by step from one localization unit already localized to the next one yet to be localized.

(vi) Six Possible Next Positions (SPNP)

Li *et al.* [95] presented a dynamic movement trajectory according to the real-time information of unknown sensors. Six optional positions are provided to be chosen based on geometry as illustrated in Fig. 32. The first three anchor points are random but they must construct an equilateral triangle whose length of side is R_m (mobile beacon’s maximum coverage radius). Then, the mobile anchor node finds a new position among the six optional positions. The unknown node with most neighbors has the most chance to be the next position of the mobile beacon. The algorithm is designed to be both “thrifty” in both energy consumption and economical cost, and lightweight in terms of computation load.

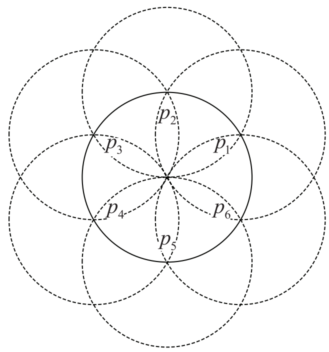

Fig. 32. Six possible next positions of a mobile beacon.

(vii) DREAMS

Li *et al.* proposed a deterministic beacon mobility scheduling (DREAMS), of which each mobile beacon first visits an unknown node by performing a random movement, and then performs a Depth-First Traversal (DFT) on the network graph under currently visiting unknown node's instruction embedded in the beacon packet [96]. During DFT, the mobile beacon performs intelligent distance-based heuristic movement. The heuristic movement relies on the measurement of relative distance of a mobile beacon and a target sensor. To shorten the path length, DFT may be performed on a Local Minimum Spanning Tree (LMST) sub-graph, where edges are weighted by RSSI, unvisited but localized known nodes may be excluded from DFT if the exclusion does not affect discovery of unlocalized unknown nodes. They also extended the algorithm to multi-beacon cases. Each mobile beacon traverses a portion of the network and produces a traversal tree. Neighbor nodes that belong to different traversal trees negotiate on behalf of their localizing mobile beacons for the coordinate system that these mobile beacons will use for localization. The negotiation and coordinate transformation process takes place distributively only when the traversal trees of two mobile beacons meet.

(viii) Anchor-guiding

In [97], Chang *et al.* proposed an anchor-guiding mechanism according to the size of the estimate region of each static unknown node. They assume that each static unknown node has an initial rectangle estimative region $ER_{s,t} = [(x_{s,1}, y_{s,1}), (x_{s,2}, y_{s,2})]_t$ of its location at time t, where coordinates $(x_{s,1}, y_{s,1})$ and $(x_{s,2}, y_{s,2})$ denote the locations of left-up and right-down points of $ER_{s,t}$. The mobile anchor node broadcasts a beacon packet $b(x_m, y_m)_{t'}$ at t' will create a new range-constraint region named as *broadcasting rectangle* $R_{t'}(x_m, y_m)$. Upon receiving the beacon packet, the unknown node s will recalculate its estimative region by $ER_{s,t'} = ER_{s,t} \cap R_{t'}(x_m, y_m)$, as shown in Fig. 33. The authors designed the movement trajectory aiming to minimize $ER_{s,t'}$ and path length. The promising region $PR_{s,t}$ can be determined by $PR_{s,t} = [(x_{s,1} - r, y_{s,1} - r), (x_{s,2} + r, y_{s,2} + r)]$. Thus, the shortest path will be built during the *beacon locations selection phase* passing through all promising grids.

(ix) 3D-VFDPP

A Three-Dimensional Dynamic Path Planning based on Virtual Force (3D-VFDPP) algorithm was put forward by Lv *et al.* [98]. This paper assumes that there exists *gravitational force or repulsive force* between sensor nodes. Since the sensing region of a mobile anchor node is divided into eight parts, the mobile anchor node should calculate the virtual force between unknown nodes and itself in all directions and move according to the magnitude and direction of an aggregate virtual force. The larger the virtual force in a direction is, the more probably the mobile anchor node will move along that direction.

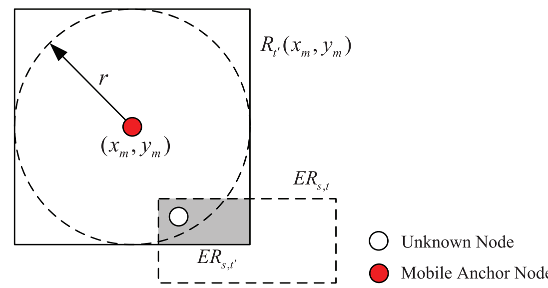

Fig. 33. An example to illustrates the calculation of new estimative region.

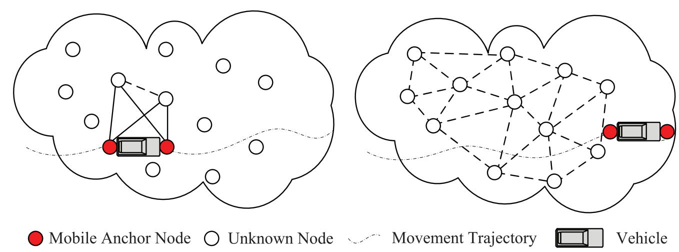

Fig. 34. The virtual ruler moves through monitoring area and measures pair-wise distances between unknown nodes.

2) Obstacle Environment: In this subsection, dynamic path planning schemes in obstacle environment of WSNs are discussed, which includes: Virtual Ruler [99], Snake-like [100], Visibility Binary Tree [101].

(i) Virtual Ruler

In [99], mobile beacon is fixed with a pair of ultrasound transmitters. They assume that each unknown node is equipped with an ultrasound receiver (or beacons) to the two ends of a vehicle. Thus, the mobile beacon behaves as a *virtual ruler* that wanders in the monitoring area to provide distance measurement services to pair-wise unknown nodes, as illustrated in Fig. 34. During the movement, the virtual ruler can measure the distance between a pair of unknown nodes from different perspectives to obtain different values. In order to identify correct distance measurements, Ding *et al.* assigned confidence C to a distance measurement $C = N + \lambda \times k_{max}$, where N is the total number of measurements to the same pair of unknown nodes, k_i is the number of measurements of value d_i, λ is the weighting coefficient. The mobile beacon based distance measurement can be further combined with the recursive approach so that distance measurements with higher confidence are selected with higher priority.

(ii) Snake-like

In [100], a mobile anchor node which has the ability to face and detour obstacles moves in a snake-like algorithm as illustrated in Fig. 35. When the mobile anchor node faces the obstacle, it changes its direction and stores the information of circulating point for future movements.

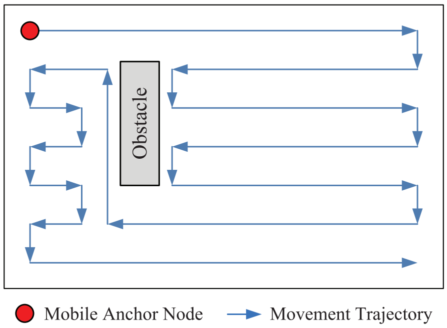

Fig. 35. Snake-like movement of the mobile anchor node when facing an obstacle.

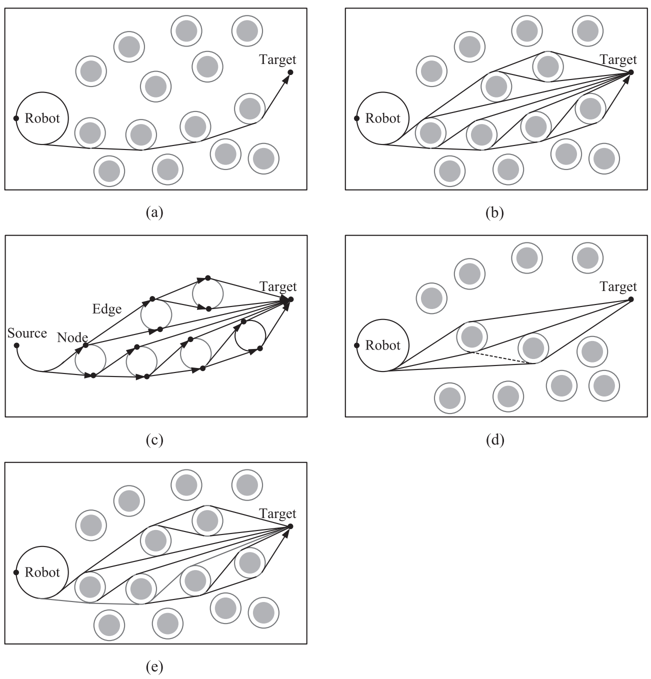

Fig. 36. (a) First path from source to target, (b) Set of complete paths, (c) Representation of the set of complete paths by the visibility binary tree, (d) Optimized binary tree, (e) The shortest path (in red lines) in the optimized binary tree.

(iii) Visibility Binary Tree (VBT)

A visibility binary tree algorithm was introduced in [101]. The algorithm relies on the construction of the set of all complete paths between robot and target considering inner and outer visible tangents between robot and circular obstacles as shown in Fig. 36. The visibility binary tree is built starting from all possible paths between the robot position and the target and optimizing the structure by reducing redundant edges. Then, an ad hoc searching algorithm is run on this graph to this optimized binary tree to find the shortest path between the source and the target.

Discussion: No matter whether indoor or outdoor scenes of real environments, sensor nodes may be deployed randomly or in irregular monitoring areas. Thus, movement trajectories should be designed dynamically or partially according to the observable environments or distribution density of sensor nodes rather than beforehand. Generally, the major problems for dynamic path planning of mobile anchor nodes are computational complexity, existence of local optima and adaptability. The existing dynamic path planning schemes in obstacle environments generally assumed that the sensor nodes are equipped with some form of onboard hardware such as radar, sonar, laser, infra-red, cameras, etc. to detect nearby obstacles. In brief, dynamic path planning schemes can make full use of the real-time information during the movement and is more suitable for irregular monitoring area.

C. Comparison of Localization Based on Path Planning Scheme

Table III summarizes the above-mentioned path planning schemes. The first column presents each of the introduced path planning scheme. The second column compares the number of mobile anchor nodes used in each algorithm. Then, the parameter area full coverage stands for whether the mobile anchor node travels the entire monitored area (region), that is to say, whether the boundary of the movement trajectory is no smaller than the boundary of the monitored area (region). Another parameter is beacon utilization, as shown in fifth column. In addition, the advantages and disadvantages are compared. As shown in Table IV, we can conclude that:

- In general, movement trajectory of MNs in an individual mobility model is completely independent of each other, movement trajectory of MNs in a group mobility model is based on a function depending on the relationship between MNs or attraction of an RP or a community. Using single mobile anchor node would be more economical but can bring collinearity or coplanarity problem while using a group of mobile anchor nodes could reduce localization time and is more suitable for 3D WSNs.
- Compared with static path planning schemes, dynamic path planning schemes can make full use of real-time information of environment and distribution density of sensor nodes. Thus, the localization algorithms based on dynamic path planning schemes can obtain better localization performance, e.g., localization ratio and localization accuracy. In addition, they are much more suitable for no-uniformly WSNs, since the trajectory of the anchor node can change dynamically with node distribution. However, they will also introduces much more localization delay and higher algorithm complexity.
- Since extensive communication among neighboring sensor nodes is required, computational complexity and energy consumption of range-free localization methods are larger than that of range-based localization methods. However, range-free localization methods are more economical due to the fact that they do not require technology for distance or angle estimations.
- During node movement, turning motion also consumes energy, and even consumes more energy than linear motion does. However, in most localization algorithm based on path planning scheme, the energy consumption for turns is not taken into account in the design of path planning. In addition, in the study of localization for obstacle environment, the obstacle is always assumed to

TABLE III
COMPARISON OF PATH PLANNING SCHEMES

	Reference	MANs	AC	BU	Advantages	Disadvantages
Lines	Ref.[74]	Single	No	Low	Path planning is simple; All the nodes can be localized.	Changing communication range needs extra hardware.
SCAN, DOUBLE-SCAN, HILBERT	Ref.[77]	Single	No	Low	SCAN is the simplest. DOUBLE-SCAN solves the collinear problem. HILBERT provides more non-collinear beacons.	Energy consumption for turns is not consider. Many collinear anchor beacons are wasted.
CIRCLES, SCURVES	Ref.[78]	Single	No	Low	Provide non-collinear anchor beacons with shorter path length than [75].	Sensor nodes on the four corners of the square monitoring area cannot be localized.
MACL	Ref.[79]	Single	No	Low	Provide non-collinear beacons with shorter path length.	Sensor nodes on the corners cannot be localized.
GMAN	Ref.[80]	Multiple	Yes	Low	Higher localization accuracy.	Three anchor nodes must move together synchronously.
K-coverage	Ref.[81]	Single	Yes	Low	Ensure k-coverage.	Repetitive movement and long trajectory length.
PI	Ref.[82]	Single	Yes	Low	Minimize path length while maximizing traversing area.	Energy consumption for turns is not consider.
LMAT	Ref.[83]	Single	Yes	Low	Maximize localization coverage and accuracy.	Energy consumption for turns is not consider.
'S' Type	Ref.[84]	Single	Yes	Low	Reduce the solution of the collinearity problem.	Much energy is consumed for turns.
SCAN Based	Ref.[86]	Single	Yes	Low	All the nodes can be localized.	The path length is relatively longer.
WCL	Ref.[87]	Multiple	No	Low	Suitable for 3D localization.	Existing the beacon collinear problem as SCAN.
Layered-Scan etc.	Ref.[88]	Single	No	Low	Suitable for 3D localization.	Increase the path length of the mobile anchor node.
HL	Ref.[89]	Single	Yes	Low	All the nodes in 3D space can be localized.	Increase the path length and waste a lot of energy.
MBAL	Ref.[90]	Single	No	High	A dynamic path planning works well in no-uniformly WSNs.	Does not consider the obstacle environment.
BRF, BTG	Ref.[92]	Single	No	High	High utilization ratio of anchor beacons.	Low localization accuracy.
MBL(ndc)	Ref.[93]	Single	No	High	The trajectory of the anchor node can change dynamically with node distribution.	The algorithm complexity is increased with the number of nodes.
Virtual Force	Ref.[81]	Single	No	High	A dynamic path planning works well in no-uniformly WSNs.	Directional antennas are required.
MALS	Ref.[94]	Single	No	High	Suitable for large-scale WSNs.	Clustering introduces longer localization delay.
SPNP	Ref.[95]	Single	No	High	Lightweight in terms of computation load.	Long traveling time and localization delay.
DREAMS	Ref.[96]	Single	No	High	Without requiring any prior knowledge of the sensory field.	Does not work well in the presence of node failure.
Anchor-guiding	Ref.[97]	Single	No	High	Balancing the location inaccuracies of all sensor nodes.	High algorithm complexity.
3D-VFDPP	Ref.[98]	Single	No	High	Avoid the movement in the areas with no unknown nodes	Need to calculate the virtual force in all directions.
Virtual Ruler	Ref.[99]	Multiple	No	High	Suitable for obstructed WSNs.	Ultrasound transmitters are required.
Snake-like	Ref.[100]	Single	No	High	Localize unknown nodes with minimum number of beacons.	Only regular obstacles are considered.
VBT	Ref.[101]	Single	No	High	The shortest traveling path can be found.	Long localization delay.

1 AC-Area full Coverage; BU-Beacon Utilization.

be a regular object for simplicity. The relevant research of how to deal with obstacles, especially the irregular obstacles in real applications is still in the initial stage.

VII. EXISTING PROBLEMS AND FUTURE RESEARCH ISSUES

Many innovative ideas and solutions have been used to design efficient mobile anchor node assisted localization algorithms. All the survey localization algorithms are compared in Table IV. From the Table IV, we can summarize the existing problems and the possible future research issues of MANAL algorithms from two aspects: 1) existing problems and future research directions for Localization Based on Mobility Models; and 2) existing problems and future research directions for Localization Based on Path Planning Schemes.

A. Localization Based on Mobility Models

In the Table IV, we first compare the computation complexity of localization algorithms. Since the sensor nodes in WSNs are with limited storage space and computing power. All the localization algorithms designed for WSNs should be simple and lightweight enough. From the Table IV, we can find that most localization algorithms based on mobility model are with higher computation complexity, while the algorithm complexity of localization algorithms based on path planning scheme are relatively lower.

Second, the energy consumption of MANAL algorithms is compared in Table IV. Relatively, the localization algorithms based on path planning scheme consumes less energy than that based on mobility model. In addition, using the localization algorithms based on path planning scheme consumes, a higher localization ratio and localization accuracy can be obtained. That is, the localization algorithms based on path planning scheme are much more suitable for WSNs compared with that based on existing mobility model. Furthermore, using multiple anchor node collaborate with each other to localize unknown nodes are much more energy efficient than using single one anchor node. In this case, it is difficult to assign several anchor nods with mobility models to achieve considerable localization performance, while designing path planning schemes for them is much more practical. That is why more and more researchers began to study the path planning problem in recent years instead of the research of mobility model.

B. Localization Based on Path Planning Schemes

As shown in Table IV, most existing mobile anchor node assisted localization algorithms focus on either a movement trajectory which employs an existing localization method to calculate coordinates of unknown nodes or a localization method which is based on an existing movement trajectory. A specifically designed localization method which corresponds to the movement trajectory should be proposed in a paper to embody the interactions. In addition, some other research problems needs further study:

- Most existing localization algorithms based on path planning schemes do not make effective use of the distribution information of sensor nodes. Let mobile anchor nodes traverse the entire network following a predefined movement trajectory is energy consumption and results in low utilization of beacon points. Thus, it is necessary to design movement trajectories based on the distribution density of unknown nodes to achieve a proper balance between localization performance and energy consumption.

TABLE IV
SUMMARY OF MANAL ALGORITHMS

Algorithm	Reference	Computation Complexity	Energy Consumption	Environment	Remarks
MARB	Ref.[60]	High	High	3D, without obstacle	A Bayesian framework is employed for the estimation of the localization of the unknown nodes.
MBL-MDS	Ref.[61]	High	High	3D, without obstacle	Using MBL-MDS by taking full advantages of MDS with connectivity and measurements.
DOL	Ref.[62]	High	High	2D, without obstacle	Guarantees that the actual position of the node is always within the bounding box and simplifies the computation.
Ssu	Ref.[63]	High	High	2D, without obstacle	Uses the geometry conjecture to determining the position of the unknown nodes.
RAA	Ref.[64]	High	High	3D, without obstacle	Based on the mathematical inference that claims a perpendicular line passing through the center of a sphere's circular cross section passes through the center of the sphere.
Yu	Ref.[66]	High	High	3D, without obstacle	Gives a new view of the conventional definition of reception-range under noisy wireless environment.
LMCS	Ref.[67]	High	High	2D, without obstacle	Utilizes CS to get the related degree of the unknown nodes and all the beacon points.
Fine-grained	Ref.[69]	High	High	3D, without obstacle	Based on geometric constraints as an extension of Ssu.
ADO	Ref.[70]	High	High	2D, without obstacle	Uses the arrival and departure overlap of beacon points.
FAL	Ref.[71]	High	Low	2D, without obstacle	Based on the comparison of RSS and the principles of elementary geometry.
NAL	Ref.[72]	High	Low	2D, without obstacle	Nine mobile anchor nodes form a circle. Unknown nodes estimate their locations by comparing the RSS.
Lines	Ref.[74]	Low	Low	2D, without obstacle	The simplest path planning scheme.
SCAN, DOUBLE-SCAN, HILBERT	Ref.[77]	Low	Low	2D, without obstacle	HILBERT can achieve better localization accuracy than SCAN and DOUBLE-SCAN.
CIRCLES, SCURVES	Ref.[78]	Low	Low	2D, without obstacle	Reduce the collinearity.
MACL	Ref.[79]	Low	Low	2D, without obstacle	A spiral movement trajectory.
GMAN	Ref.[80]	Low	High	2D, without obstacle	A collaborative localization algorithm using a group of mobile anchor nodes.
K-coverage	Ref.[81]	Low	Low	2D, without obstacle	Reduces beacon density and trajectory length.
PI	Ref.[82]	Low	Low	2D, without obstacle	Minimizes path length and maximizes the area for a given perimeter.
LMAT	Ref.[83]	Low	Low	2D, without obstacle	Maximizes localization coverage and localization accuracy.
'S' Type	Ref.[84]	Low	Low	2D, without obstacle	Reduce the total path length and improve movement efficiency.
SCAN Based	Ref.[86]	Low	Low	2D, obstacle	Ensure that the mobile anchor node passes through the circle of each sensor node either two or three times.
Four-mobile-beacon	Ref.[87]	Low	High	3D, without obstacle	Four mobile beacons form a regular tetrahedron.
Layered-Scan etc.	Ref.[88]	Low	High	3D, without obstacle	Divides the morning region into several layers.
HL	Ref.[89]	Low	High	2D, without obstacle	Divides the morning region into several hexahedrons.
MBAL	Ref.[90]	Low	Low	2D, without obstacle	Chooses the nearest target among candidate points and receives additional request messages.
BRF, BTG	Ref.[92]	High	Low	2D, without obstacle	Transform the path planning issue into seeking spanning trees of the undirected graph and traversing through the graph.
MBL(ndc)	Ref.[93]	High	Low	2D, without obstacle	Combines node clustering, incremental localization and mobile beacon assisting together.
Virtual Force	Ref.[81]	High	Low	2D, without obstacle	Constructed by interaction force between mobile anchor node and unknown nodes.
MALS	Ref.[94]	Low	Low	2D, without obstacle	Designed to accommodate non-uniform and irregular deployment scenarios.
Six Possible Next Positions	Ref.[95]	Low	Low	2D, without obstacle	Six optional positions are provided to be chosen based on geometry.
DREAMS	Ref.[96]	High	Low	2D, without obstacle	Performs a DFT on the network graph under currently visiting unknown node's instruction.
Anchor-guiding	Ref.[97]	High	Low	2D, without obstacle	According to the size of the estimative region of each static unknown node.
3D-VFDPP	Ref.[98]	High	High	3D, without obstacle	Assumes that there exists gravitational force or repulsive force between sensor nodes.
Virtual Ruler	Ref.[99]	Low	High	2D, obstacle	Behaves as a virtual ruler to provide distance measurement services to pair-wise unknown nodes
Snake-like	Ref.[100]	Low	Low	2D, obstacle	Has ability to face and detour obstacles moves in a snake-like algorithm.
Visibility Binary Tree	Ref.[101]	High	Low	2D, obstacle	Relies on the construction of the set of all complete paths between robot and target.

- In the real applications of WSNs, sensor nodes are always deployed in large-scale environment. It is necessary to enlarge the monitoring area amid nodes. In this case, the scalability of localization techniques is required to meet the localization requirements in large-scale WSNs. However, existing mobile anchor node assisted localization algorithms are mainly designed for small-scale WSNs. Therefore, it is essential to design new path planning schemes and mobile anchor node assisted localization algorithms for large-scale WSNs to meet the requirements of real applications.
- Most existing MANAL algorithms are designed for single mobile anchor node. Few researchers focused on the path planning of a group of mobile anchor nodes. However, using multiple mobile anchor nodes to collaboratively help unknown nodes with localization can significantly improve localization ratio and reduce localization time. Therefore, study on the path planning for a group of mobile anchor nodes is another research problem needed to be solved.
- Sensor nodes could have different sensing and communication ranges according to different roles they play in the network. Thus, future research could focus on designing mobile anchor node assisted localization algorithms for heterogeneous WSNs. In this case, different nodes require for different path planning schemes according to their own characteristics and dynamic environment parameters. That is, designing path planning schemes in heterogeneous WSNs is much more challenging than homogeneous ones.

- Most existing MANAL algorithms are designed for ideal WSNs without considering obstacle, while in real applications, obstacles are inevitable. Therefore, designing MANAL algorithms for obstacle environment is essential. However, it is difficult to obtain the information of obstacles in advance, and the obstacles in real application are always irregular. Thus, designing a simple and generic path planning to avoid the obstacles autonomously is interesting and challenging.
- A majority of the current mobile anchor node assisted localization algorithms are based on a credible environment. However, in real applications, sensor nodes may be deployed in an unsafe and complex environment. Thus, the security issue of MANAL algorithms should be considered. Especially in the process of path planning, protecting the anchor nodes' trajectories from potential malicious attacks is important. On another side, getting trustable and meaningful localization beacons to make the right position calculation is also extremely important. However, there are not many efforts had already been made for path planning reliability, security and availability issues. Due to the high requirement of localization, e.g., less energy consumption, high localization ratio and localization accuracy, maintaining a reliable path planning is presenting a huge and urgent challenging issue.
- To the best of our knowledge, there is no solid standard metrics to evaluate path planning schemes or MANAL algorithms. In order to further carefully and deeply study the mobile anchor node assisted localization problem, it is important to design systematic evaluation criteria to analyze the performance of different mobile anchor node assisted localization algorithms. This is also one of the important research directions in the future.

VIII. Conclusions

Localization algorithms provide fundamental support for many location-aware protocols and applications. Localization accuracy is closely related to the quality of service of WSNs [102]. In this paper, we investigated mobile anchor node assisted localization algorithms in WSNs and presented a comprehensive review of the recent breakthroughs in this field. We classified MANAL algorithms into two categories: localization based on mobility model and localization based on path planning schemes, and gave a comprehensive survey for the most interesting and successful advances. In the future, we will further study the mobile anchor node assisted localization problem, including analyzing the impact of anchor mobility on localization, design an optimal path planning for anchor nodes to improve localization performance, etc.

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Appendix

Table V summarizes abbreviations used in this survey.

TABLE V
List of Abbreviations

Abbreviations	Full names
WSNs	Wireless Sensor Networks
GPSs	Global Position Systems
MNs	Mobile Nodes
MANs	Mobile Anchor Nodes
MANAL	Mobile Anchor Node Assisted Localization
2D	Two-Dimensional
3D	Three-Dimensional
RSSI	Received Signal Strength Indicator
ToA	Time of Arrival
TDoA	Time Difference of Arrival
AoA	Angle of Arrival
MWSNs	Mobile Wireless Sensor Networks
MLE	Maximum Likelihood Estimation
SBE	Sequential Bayesian Estimation
WBSN	Wireless Binary Sensor Networks
NLOS	Non-Line-Of-Sight
MDS	Multidimensional Scaling
IR	Infrared
MANETs	Mobile ad hoc networks
RW	Random Way
RWP	Random Waypoint
RD	Random Direction
GM	Gauss-Markov

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