ISSN 2278-3091
Volume 10, No.1, January - February 2021
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse131012021.pdf
https://doi.org/10.30534/ijatcse/2021/131012021

Cooperation Between Mobile and Static Nodes in Mobile Wireless Sensor Networks

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ABSTRACT

Mobile wireless sensor networks (MWSNs), a special class of WSN in which one or more component of the network is mobile, have recently grown popularity. In MWSNs, mobility plays a key role in the operation of the network. Cooperation between mobile and static nodes in MWSNs has gained significant importance in recent years. These nodes can cooperate in a number of ways to increase the efficiency and performance of the network. Mobile nodes, in cooperation with other static nodes in MWSN can provide important benefits in sensor deployment, localization, route planning and navigation, connectivity prediction and repair, routing and data collection. The aim of this paper is to characterize different cooperation techniques in different stages of MWSNs operation. First, we provide a general introduction followed by an overview to the roles and types of mobile nodes in MWSNs. Then we present basic taxonomy and brief review on cooperation between mobile and static nodes in different phases of MWSNs operation. Finally, the paper is concluded with hints to open problems.

Key words: Wireless sensor networks; mobile sensor networks; cooperation

1. INTRODUCTION

Mobile wireless sensor networks (MWSNs) are a special and versatile class of WSN, in which one or more than one component of the network is mobile. Mobile nodes increase the capabilities of the MWSNs in many ways, including connectivity, coverage, channel capacity, and lifetime [1]. For instance, a mobile node can visit different regions in the network to collect data, thus reducing the burden of data forwarding task by nodes. As a result, it spreads the energy consumption more uniformly throughout the network [2].

Allowing the sensor nodes to be mobile increases the number of possible applications beyond the limits of those for which static sensors can be used. Sensors can be attached to people for monitoring [3], and to animals for tracking their movements [4]. Sensors may also be attached to unmanned aerial vehicles (UAVs) for surveillance or environment mapping [5].MWSNs can be classified into three types architecture wise [6].

Planer MWSN: In planar architecture, heterogeneous devices, whether stationary or mobile, communicate in an ad hoc manner. In this case the sensed data is being routed to a remote sink or base station in a multi-hop ad hoc fashion. For example navigation systems presented in [7] have a planner architecture.

Two Tiered MWSN: This architecture also consists of heterogeneous devices, where the mobile nodes construct an overlay network or act as data mules to help moving data through the network. These mobile nodes also help establishing network connectivity and ensuring that network packets reach their intended destination. For example, the NavMote system in [8] has a two tier architecture.

Three Tiered WSN: In this architecture, a set of stationary sensor nodes pass data to a set of mobile nodes (mobile relays), which then forward that data to a set of access points. For example, consider a sensor network application that monitors the availability of parking space in some area. The sensors (first layer devices) broadcast the parking space updates to mobile nodes (second layer devices e.g., smartphones) that are in their coverage range. Finally, the mobile nodes forward this data to the access points (third layer devices) where the data is stored in a centralized database, which can then be accessed to locate an available parking spot. An example of three tier architecture has been considered in [9] in which mobile relays moves around the sensor network and pick up messages from the sensors when in their coverage range, buffer them, and then transfer them to base stations.

A. Roles of Mobile Nodes in MWSNs

Mobile Sensors: These are theordinary or regular sensor nodes which are mobile in a sensor network. These mobile nodes are the sources of information and they perform sensing as their main task. In addition they may also forward data coming from other nodes which they have been previously in contact with [10]. Mobile sensor nodes can be used to sense, learn, and share information about people, objects, and their surrounding for personal, industrial, and military use [11].

Mobile Sinks: Mobile **s**inks or mobile base station are those nodes which are the destination or consumer of messages originated by sensors. They represent the endpoints of collected data in MWSNs. Mobile sinks collect data either directly (i.e., by visiting sensors and collecting data from each of them) or indirectly (i.e., through relays or other nodes) [12].

Mobile Relays: Mobile relays are neither producer nor consumer of information in a sensor network. They perform specific task by collecting messages from sensor nodes when in their coverage range, possibly carry the data to a different location with them and eventually pass it to the base station when in contact. In a sensor network, mobile relays might be present or not, depending on the application and scenario. An example of three tiered architecture has been proposed in [9] where the middle tier being represented by mobile relays.

B. Paper contribution and organization

This paper aims at characterizing different cooperation techniques in different stages of MWSNs operation. It must be noted that a detailed review covering all issues have not been presented due to space constraints. Interested readers should target detailed surveys on particular topics. The rest of the paper is organized as follows. Section II introduces cooperation in Mobile Wireless Sensor Networks (MWSNs). Subsections (from A to F) in Section II presents particular explanation and brief review on cooperation between mobile nodes and WSN in different stages of WSN Operation. Specifically, cooperation in sensor node deployment and localization are discussed in Subsection A and B, respectively. Subsection C presents network connectivity, Subsection D is about route planning and navigation, Subsection E explain mobile node discovery while routing is covered in Subsection F. Finally, Section III o□ers concluding remarks, with directions on open research issues.

2. COOPERATION

In this section we discuss cooperation in relation with MWSNs. Each subsection highlights important details and taxonomy of cooperation approaches, striving to identify the development trend behind them.

According to Oxford dictionary cooperation can be defined as the *willingnessto assist*; an act or instance of working or acting together for a common purpose or benefit. Hence cooperation is the process of working or acting together in order to achieve a common goal or mutual benefit. Mobile and static nodes can cooperate in a number of ways to increase the efficiency and performance of the network [13]. Mobile nodes, in cooperation with other static nodes in MWSN can provide important benefits in sensor deployment, localization, route planning and navigation, connectivity repair, mobile node discovery and routing. Details of each of these phases is discussed in the subsequent subsections.

A. Cooperation in Nodes Deployment

The deployment stage addresses the issues such as how to deploy the network in the sensing field. Good network node deployment can not only reduce the node redundancy and the network costs, but also can enhance the service life and data collection in the network. Sensor nodes are either deployed to cover specific area/locations or to improve connectivity.

1. **To Improve Connectivity**

In order to work efficiently it is important for a sensor network to maintain some degree of connectivity (the ability of the sensor nodes to reach the data sink). There are situations when we (re)deploy or move existing deployed sensors to change their location to better characterize the sensing area and to maximize connectivity. Different algorithms [14] are in use to maximize or re-establish network connectivity in case of holes and faulty links by using mobile nodes in MWSN.

2. **To Cover Specific Area or Location**

Area based deployment requires the sensing field to be covered by sensor nodes and mainly address how to deploy the sensor nodes to achieve sufficient coverage of the region of interest. Area based coverage may consist of *non-uniform coverage* (the coverage requirements of different points in the region of interest are different) and *uniform coverage* (uniform coverage for all the region of interest).

Non-Uniform Coverage: Whensampling rate, data producing capability or coverage priorities are different for certain locations in the area of interest then we need a non-uniform sensor coverage. For example a non-uniform sensor deployment is considered in [15], where the coverage priority of different points in the area is not same and are specified by a weighted function. Each sensor identifies coverage holes within its Voronoi polygon, and then moves in a proper direction, using the weighted function, to reduce them. Similarly, the work in [16] propose two sets of distributed protocols (one favoring communication and other favoring movement) to control the movement of mobile sensors in order to cover specific points. Both of the protocols use Voronoi diagrams to detect coverage holes and specific algorithms to find target locations of sensors.

Uniform Coverage: In this case it is assumed that the coverage priority for different points in the field is uniform or same. Uniform deployment can be achieved using *static deployment strategies* or *dynamic deployment strategies* [17]. In *static deployment strategy* best locations for static sensor nodes are chosen in advance according to the scenario either in a *deterministic or random way*. However, in order to maximize the performance of a sensor network, sensor nodes need to automatically move to proper optimal positions in the area and that's where *dynamic deployment* strategies, backed by mobile nodes or mobile robot, come in handy.

An efficient and self-deployed MWSN is discussed in [18], using a distributed motion coordination algorithm where mobile sensors autonomously form a sensor barrier between two given landmarks to achieve the barrier coverage. In [19] Virtual Force Algorithm, a solution to area coverage for WSN, is improved with random distribution of mobile sensor nodes. Here the MWSN autonomously adjust node deployment according to the location and importance of the region of interest. Similarly in [20] two bidding protocols are designed for guiding the movement of mobile sensors in MWSN to increase coverage to a desirable level. Static sensors identify coverage holes locally by using Voronoi diagrams and bid mobile sensors to move. Mobile sensors accept the highest bids and try to heal the largest coverage gaps.

B. Cooperation in Nodes Localization

Accurate and low-cost sensor localization in WSN is considered important in a wide variety of applications [21]. In cooperative localization, sensors nodes work together to make measurements and then form a map of the network. A detailed review of location estimation algorithms have been presented in [22]. Localization algorithms for WSNs can be divided into *Ranged-based Algorithms* and *Range-free Algorithms*[23].

Ranged-based Algorithms: These types of algorithms need to measure the distance or angle between each node in order to determine its geographical position. The ranging knowledge can be obtained using a number of different techniques. For example: RSS [24] , TOA [25], AOA [26] etc.

1. **RSS:** Received Signal Strength (RSS) is defined as the measured voltage or power (i.e., the squared magnitude of the signal strength) by a receiver circuit. RSS measurements are relatively simple and inexpensive but unpredictable and can be done by each node receiver during normal data communication without consuming additional resources [21].
2. **TOA:** Time of Arrival (TOA) is the time at which a signal first arrives at a receiver. It is the time of transmission plus a propagation delay and is equal to the transmitter-receiver separation distance divided by the propagation velocity. Receivers can accurately estimate the arrival time for line-of-sight (LOS) signal, but this estimation is spoiled both by additive noise and multipath signals [21].
3. **AOA:** Angle of Arrival (AOA) is the information about the direction to neighboring sensors [21]. The most common method to estimate AOA is to use an array of antennas and employ array signal processing techniques at the sensor nodes. The AOA is estimated from the differences in arrival times for a transmitted signal at each of the sensor array elements. This approach requires multiple antenna elements, increasing sensor device cost and size.

Range-free Algorithms: Range freeAlgorithms use network constraints such as connectivity or anchor nodes information to estimate the coordinates of the nodes instead of real ranging. A details survey of algorithms proposed to estimate the sensor nodes geographical positions based on range free methods is presented in [27].

A distributed sensor network and mobile robots has been discussed in [28] where the static sensors process all broadcasts they hear from a mobile robot, including GPS data and estimate their location using simple averaging procedure of received signal strength. Other methods discussed in [29] include taking just the strongest received signal, a signal strength weighted mean, and a median. Another range-free base cooperative localization is proposed in [30] considering the existence of obstacles in WSNs. In this scheme, a mobile anchor node cooperates with static sensor nodes and moves actively to refine its location performance, while, at the same time, taking into account the relay node availability to make the best use of beacon signals. The scheme effectively maximize accuracy and minimize the effects of obstacles on node localization by using a relay node and a novel convex position estimation algorithm.

Localization algorithms can also be divided into *centralized algorithms* and *distributed algorithms*[21]. Centralized algorithms collect measurements at a central processor before any calculation and estimation is done while distributed algorithms require sensors to share information only with their neighbors, but possibly repeatedly. Distributed algorithms are useful in case where no central processor is available to handle the calculations or when the sensor network is large enough. In case of large network sensors will forward all measurement data to the central processor, possibly resulting in a communication bottleneck and higher energy drain at and near the central processor. Performance of localization algorithms mainly depends on the size and density of sensor network, the measurement and localization algorithms used and possibly the environment under consideration [21].

C. Cooperation in Connectivity Prediction and Repair

Connectivity tells us whether or not two devices are in communication range of each other (in other words connected) and is regarded as a binary measurement or binary quantization of RSS. Typically for each device there is a minimum received power (threshold) below which it is highly unlikely that a packet will be correctly received [21]. Connectivity is the basic requirement for the proper operation of any wireless network. In a mobile wireless sensor network, it is a challenge to deal with connectivity problems, as links might get up and down frequently. Several approached are used to improve and predict connectivity in MWSNs.

A GPS is used in[31], where authors provide a Markov Chain to predict the connectivity between the mobile nodes and some fixed base stations. Similarly the solutions presented in [32], [33] and [34] use link quality information instead of GPS data to predict the link connection states. In [32] a Birth-death Markov Model is proposed, which uses Signal-to-Noise Ratio (SNR) information to characterize and predict link quality. Similarly RSSI is employed in [33] as a Markov Model in order to predict the signal variation while in [34] authors used a time series to model the changes on link quality due to node mobility. A drawback of using Markov Chain or Time series is that previous history as well as a large amount of memory is needed to make use of the model.

In [35] Genetic Machine Learning Algorithm is used to estimate the remaining connectivity time between neighbor nodes by combining Classifier Systems with a Markov chain model of the RF link quality. This scheme uses link quality information such as SNR, RSSI etc. and does not require any location information to compute the connectivity prediction.

The paper in [36] in presents a method for linking disjoint segments of WSNs using an UAV. The approach connects network segments using a limited number of mobile nodes. In this case the UAV becomes a data mule, carrying physically packets across the network when moving. Each disjoint segment elects a cluster head which is responsible for interaction with the UAV. The system is effective in moderate traffic with enough data buffers with a very small packet loss. Several other proposals tackle the same problem of disjoint network segments using redundant deployment or using mobile nodes as relay stations.

D. Cooperation in Route Planning and navigation

The mobility pattern followed by a mobile node has a significant impact on the data collection process [37]. Mobility can be either *uncontrollable or controllable*. In case of uncontrolled mobility sensor nodes can learn the mobility patterns of mobile nodes to improve network performance. In this case the more the randomness in mobility the harder it is to learn and predict. On the other hand, in *controlled mobility* the mobility (speed and path) of the mobile node is controllable. By controlling mobility of the mobile nodes in MWSNs we can enhance the performance to a desired level. For instance, mobile nodes can visit static nodes at specific times, while at the same time can move slow or stop at nodes until they have collected all buffered data. However, different problems arise in this context, mainly how to control and schedule mobile nodes arrivals at sensors, optimizing both the trajectory and the speed of the mobile node. Interested readers may refer to [37] for a detail survey.

1. **Optimizing Path**

Path or trajectory of mobile nodes needs to be dynamically optimized and updated as soon as an event or activity is detected by the static nodes. For example an approach is discussed in [38], where a mobile node moves along a default route. If a static node wants to be visited it can send a visit request to the mobile node. The mobile node makes necessary changes in its trajectory by visiting the requesting node and then resumes its default route back. Another example is the iMouse[39] where static sensors inform the base station when they detect an anomaly. A mobile node equipped with cameras can then be sent by the base station to visit the location for further data collection.

In [40], [41] and [42] the problem of monitoring a large area using WSNs is considered where a set of mobile nodes cooperate with the static nodes in order to reliably detect and locate an event without any GPS or prior maps of the environment. In this case when static nodes detect a suspicious activity or event, they report it to a mobile node that can move closer to the suspected area and can confirm whether the event has occurred or not. In [40] mobile nodes decide their path based on their own information and measurements as well as information collected from the static sensors in a neighborhood around them. While in [41] the concepts of credit based approach (in which nodes are assigned credit values according to their distance from the event) and navigation force from the neighboring static nodes are used in optimizing the path. Similarly [42] propose two navigation algorithms. The first uses the distance between the mobile node and each sensor node and the second uses the metric calculated from one-hop neighbors' hop-counts. The mobile node periodically measures the distance or metric and move toward a point where these values become smaller and finally it reach the destination.

In [43], [44] and [45] cooperation between an UAV and WSN have been discussed where a dynamic path/route has been estimated for the flight of UAV. In [43] the sensor network employ mapping algorithms to compute adaptive, time-varying paths to events. Here a set of localized sensor nodes facilitate UAV's navigation by encoding path information and provides point-by-point navigation directions. The work in [44] ensures that the UAV passes through some predefined zones and avoids forbidden zones. It uses particle filters to predict the UAV trajectory taking into account the UAV model, UAV kinematic and dynamic constraints of the UAV flight. The same issue is tackled in [45] by proposing a heuristic solution by decoupling the problem into four sub-problems. First of all, clusters of sensors are determined and then efficiently connected. Thirdly route inside the cluster is designed so that the information collection is maximized. Finally, a path planner for the UAV to collect data is designed.

Similarly a two way cooperation between WSN and UAV in large scale network is proposed in [13]. In this case the WSN deployed on the ground organize autonomously in clusters. As a routine operation in cluster based WSN the role of the cluster head in each cluster is usually rotated periodically in order to conserve energy of the cluster head. In the proposed scheme the new cluster head is selected according to the available energy of the candidate node, connectivity with other nodes and current UAV trajectory (in communication range for how much time). Similarly, the radio transmission coverage zones of the new cluster heads are used to update the UAV flight plan.

2. **Optimizing Speed**

Speed can be optimized in two ways [37]. The first one which is the simplest form of speed control is called *stop and communicate*. In this technique when the mobile node enters the communication range of a static node that has some data to send, it stops there and collects all buffered data. The duration of the stop depends on the data generation rate of the source node. Kansal et al in [46] propose a solution in which the speed of the mobile node can be controlled in a manner similar to stop and communicate. The second way to optimize speed is called *adaptive speed control*[46] in which the speed of mobile node is changed according to the number of encountered nodes and the percentage of collected data with respect to buffered messages. Different group of nodes are made according to the amount of data collected, such as low, medium or high. The mobile node moves slowly in the group with a low percentage of collected data, while it moves faster when it is in communication range with the nodes with a high level of collected data.

E. Cooperation in Mobile Node Discovery

Static nodes must efficiently and accurately detect the presence of mobile nodes before starting any sort of communication. The contact time, time for which mobile and static nodes are in communication range, consists of detection time (the time required for detecting the presence of a mobile node) and actual data transfer time. It is also equally important to minimize the detection time in order to increase the actual data transfer time.

Strictly Scheduled Discovery Protocol: In this case the mobile and static nodes agree on a specific time at which the data transfer may initiate. This is feasible only when the mobile node follows a very strict schedule or the mobility is strictly controllable. For example in [47] mobile nodes are assumed to be on board of public transportation shuttles that visit static sensor nodes according to a tight schedule. In this way the sensor nodes could calculate the exact data transfer time and wake up accordingly. These types of protocols are usually simpler to implement and are very energy efficient because they only need to exchange schedules only. However, it requires strict synchronization or tightly controlled mobility, an assumption which is usually difficult to hold in practice.

Loosely Scheduled Discovery Protocol: If themobile node does not follow a strict schedule, sleep/wakeup patterns can still be defined and nodes can still communicate without explicitly agreeing on a specific time table. One of the most common protocol in this context is based on periodic listening [48]. In this case the mobile node sends periodic beacons messages, while the static node periodically wakes up and listens from mobile node for a short time. If it does not hear any beacon message from a mobile node it can return to sleep, otherwise it can start transferring data to the mobile node.

Predictive Discovery Protocols: The efficiency of the discovery process can be further improved by exploiting some knowledge regarding the mobility pattern of the mobile node [37]. In this case the static nodes try to learn and predict the arrival of mobile nodes to start the discovery process. The degree of learning and prediction greatly depend on the type and nature of mobility of mobile node.

In case of *deterministic mobility* static nodes can easily learn and predict the arrival time of mobile node. For example in [49] the authors proposed, as a first step, a learning phase where the static nodes follow a loosely scheduled scheme to check the presence of mobile nodes. Once a mobile node is detected, static nodes then save its schedule for later use. In case of *random mobility*, sensor nodes still can learn the arrival time of mobile nodes but in this case the learning ability depends on the mobility randomness. The more the randomness in mobility the harder it is to learn and predict. In case of *dynamic mobility* wherethe mobility pattern is non periodic and continuously changing, static nodes need continuous learning.

F. Cooperation in Routing

Routing is the process of selecting the best path(s) for transferring data in a network from source to destination. The route of each message sent to the sink is crucial in terms of consuming different network resources. Routing protocols for

MWSNs are generally based on static WSN and mobile ad hoc networks (MANETs). Static WSN protocols provide the required functionality but cannot handle mobility. Whereas, MANET protocols can deal with mobility but they are not designed for sensor data having one way communication [50]. For MWSNs routing protocols can be mainly classified based on their network structure or mobility. Interested readers may refer to [51] for a detailed survey.

1. *Classification based on Network Structure*

Flat Routing: In flat routing, also called data centric routing, all the sensor nodes in the network behave in equal manner. Nodes collaboratively perform routing by sending queries, and hence collecting data from close sensors.

Hierarchical Routing: In hierarchical routing the nodes in the network are organized into clusters on the basis of distance, energy, resources etc. In this case some of the nodes have more responsibilities (relaying, management etc.) in the network. Each cluster head manages and controls all the nodes within the cluster and is responsible for communication outside the cluster. This helps reducing the organization complexity and increases energy efficiency. For instance in Geocast proposed in [52] one of the mobile sinks, called a master sink, acts as data collector. All nodes send messages to the master sink by using simple geographic routing.

2. *Classification based on mobility*

MWSNs with Mobile Sink(s): Mobile sink in a sensor network can visit different region of the area for data collection thereby balance the consumption of energy and prolong the network life time. Mobile Sink can follow three types of mobility patterns. In Elastic routing [53] all sensors are static except the sinks which move freely in the network following *random mobility*. The mobile sinks periodically announce its current location to the neighbor sensor nodes. In case of an event the nodes first try for any available sink in their neighbor's list, and if found the packet is sent directly to the sink without further calculation. Routing protocol in [54] discusses a mobile sink with *predictable mobility* (along a known fixed path), in a sensor network. The data collector node collects and stores the data from the sensors in the mini sink, which is later collected by the mobile sink, since it periodically visits the mini sinks for data collection. The work in [55] use *controlled mobility*for increasing life time of WSNs. In this case heuristics are defined for controlled sink movements that are fully distributed and localized which obtain remarkable network lifetime improvements.

MWSNs with Mobile Relay(s): Mobile relays or data forwarder in MWSNs has been considered in [9]. In this case mobile relays moves around the sensor network and pick-up messages from the sensor nodes when in close range, buffer them, and then transfer them to base stations.

All Nodes Mobile: A variant of geometric routing protocol (M-Geocast[52]) considers the case of fully mobile sensor network where all nodes are mobile. Here one of the sinks is a designated as master sink which acts as a data collection and dissemination server. It exploits simple geographic routing protocol to send messages to the master sink.

3. Discussion and Conclusions

In this paper we have characterized cooperation techniques in different stages of MWSNs operation. First, we provided a general introduction to MWSNs followed by an overview of the roles of mobile nodes in MWSNs. Then we presented basic taxonomy and brief review on cooperation between mobile and static nodes in different phases of MWSNs operation. Finally, the paper is concluded with hints to open problems.

As a general remark, there are only few solutions implemented in real world scenarios. Experimental evaluation and real-world applications need to be further studied. It is also important to investigate sensor nodes fault tolerance jointly (whether it is deployed to enhance coverage or to maximize connectivity) in order to increase network lifetime. In most of the solutions proposed for mobile node navigation in the literature the authors assume a linear path for the mobile node, which is not usually the case in real world. In most of the cases, physical obstacles are not considered, which is also not very similar to the real-world scenarios. Two other future directions for cooperative localization research are mobile sensor tracking and the use of connectivity measurements. Moreover, complete solutions that can be applied out-of-box (immediately, without configuration efforts) to specific application scenarios have not yet been proposed.

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