A Survey on Mobility and Mobility-Aware MAC Protocols in Wireless Sensor Networks

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***Abstract*—In wireless sensor networks nodes can be static or mobile, depending on the application requirements. Dealing with mobility can pose some formidable challenges in protocol design, particularly, at the link layer. These difficulties require mobility adaptation algorithms to localize mobile nodes and predict the quality of link that can be established with them. This paper surveys the current state-of-art in handling mobility. It first describes existing mobility models and patterns; and analyzes the challenges caused by mobility at the link layer. It then provides a comparative study of several mobility-aware MAC protocols.**

***Index Terms*—MAC protocols, mobility, handover, wireless sensor networks, survey.**

I. INTRODUCTION

WIRELESS sensor networks are one of the technologies of the future. These networks consist of a large number of small size nodes which can sense a variety of physical phenomena, partially process the raw data locally, and deliver the result over a wireless multi-hop link [1]. The nodes are able to self-organise in order to establish and maintain the network. Due to the small size of the nodes and the wireless communication, the networks exhibit several attractive features. For example, the nodes can be easily installed in places which can otherwise be inaccessible or expensive to wired systems. Likewise, deployment and maintenance operations can take place without disrupting the normal operation of the structure or process they monitor.

A large number of applications have been proposed for wireless sensor networks. Mainwaring et al. [2] deploy wireless sensor networks to monitor the activities of sea birds by gathering data from humidity, temperature, barometric pressure, and light sensors. Kim et al. [3] use wireless sensor networks for structural health monitoring in which the structural integrity of bridges and buildings is inspected using accelerometer sensors. Werner-Allen et al. [4] deploy wireless sensor networks that employ seismic and infrasonic sensors to monitor active volcanoes. The authors report capturing 230 volcano events in three weeks time. Stoianov et al. [5] use hydraulic and acoustic/vibration sensors to monitor large diameter, bulk-water transmission pipelines. Similar applications include precision agriculture in which temperature, humidity, and pH are extracted from the environment using wireless sensor networks to efficiently utilise irrigation, herbicide, pesticide, and fertiliser [6], [7].

Some of the above networks may experience a change in topology due to some reasons, for example, when new nodes join the network and when existing nodes experience hardware failure or exhaust their batteries (and, therefore, become inaccessible to their neighbors). This type of change in the topology of the network occurs seldom and is described in the literature as a change in the topology due to a **weak mobility** [8]. Almost all of the medium access control protocols in wireless sensor networks are able to deal with a slow change in a network's topology. For example, in SMAC [9] and TMAC [10], nodes update their knowledge about their neighbors by exchanging synchronization packets. Likewise, preamble-based protocols such as BMAC [11], XMAC [12] and WiseMAC [13] avoid the need for periodic synchronization (because it is expensive) by enabling transmitting nodes to send a burst of preambles. The duration of the preamble is longer than the sleeping duration of a node[1]. This way, a receiver is able to respond to a preamble when it wakes up. In receiver-initiated MAC protocols such as RI-MAC [14], each time a receiver wakes up from a sleep state, it broadcasts a beacon to all its neighbors to inform them that it is now ready to receive packets.

However, all of these protocols enable nodes to perceive a change in their surrounding only at the beginning of each active period. Consequently, there is a delay in packet transmission whenever a topology change has occurred and the delay can be high in multi-hop networks. Since weak mobility takes place infrequently, the delay it introduces may be tolerable, nevertheless.

In contrast, a **strong mobility** is characterized by concurrent node joins and failures as well as physical movement of nodes [8]. Physical mobility is caused by the deliberate movement of objects or persons to which sensor nodes are attached. Similarly, it can occur when nodes are carried by external forces such as wind, water, or air [8]. In some applications, strong mobility plays a key role. For example, biomedical sensor nodes can be attached to the bodies of patients [15] and nurses [16] to monitor their activities; workers in disaster recovery scenes [17] and oil extraction and refinery areas [18] can carry sensing devices to avoid dangerous situations; mobile sensor nodes can also be employed to report or debrief soldiers the events encountered during a mission [19]. Strong mobility results in a frequent topology change which in turn introduces the following problems:

Manuscript received 30 March 2011; revised 10 August 2011 and 8 November 2011.

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Digital Object Identifier 10.1109/SURV.2012.013012.00051

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[1] Almost all MAC protocols in wireless sensor networks enable nodes to periodically sleep. In fact the sleeping duration is longer than the active duration. The aim is to avoid idle listening and overhearing, and to achieve an optimal network lifetime.

- Mobility leads to a deterioration in the quality of an established link and, therefore, data transmission is prone to failure, which in turn increases the rate of packet retransmission.
- Mobility leads to frequent route changes, which result in a considerable packet delivery delay.
- A mobile node cannot immediately begin transmitting data upon joining a network, because its neighbors should first discover its presence and decide how to collaborate with it. This requires sometime.
- In contention-based MAC protocols, mobility may increase packet collision while in schedule-based MAC protocols, two-hop neighborhood information becomes inconsistent once nodes enter or leave, leading to schedule inconsistencies.

This paper surveys mobility related issues and mobility-aware medium access control protocols in wireless sensor networks. Whereas the problem of mobility has extensively been addressed in the context of mobile and wireless communications as well as mobile ad hoc networks, a comprehensive survey with regard to wireless sensor networks is lacking. Therefore, this paper makes the following contribution:

- It discusses various mobility patterns and models in wireless sensor networks.
- It presents state-of-the-art mobility estimation techniques which are relevant for wireless sensor networks.
- It provides a comprehensive and comparative investigation into the proposed mobility-aware medium access control protocols. And,
- It outlines some outstanding issues pertaining to the design of mobility-aware communication protocols.

The remaining part of this paper is organised as follows: Sections II and III discuss different mobility patterns and the proposed models thereof. Section IV introduces and evaluates several mobility estimation techniques. Section V presents proposed mobility-aware MAC protocols and how they estimate and handle mobility. Section VI provides a comparative discussion with regard to the mobility-aware MAC protocols. Section VII discusses some outstanding research issues concerning mobility in wireless sensor networks. Finally, the paper closes in Section VIII by providing concluding remarks.

II. MOBILITY PATTERNS AND MODELS

Understanding the mobility patterns of nodes is essential to design realistic models and resource efficient mobility estimation mechanisms. Based on the expected mobility patterns, protocol design can make plausible assumptions in dealing with communication handover. This section deals with higher-level mobility patterns in wireless sensor networks and the abstract models that can represent them. In Section III, mobility will be treated in terms of sink mobility and node (source) mobility. The former mainly affects network protocol design, since individual nodes should be able to determine the routes to the ultimate destination of the information they transmit. The latter mainly affects MAC protocol design, since individual nodes should be able to dynamically and seamlessly use shared communication media without affecting their neighbours.

A. Mobility Patterns

A mobility pattern is the movement pattern of real-life objects, such as vehicles, and people, which can be characterized by properties such as dimension, limitation, group behavior and predictability. There are mainly three mobility patterns relevant to wireless sensor applications.

1) Pedestrian mobility pattern: It describes the motion characteristics of people. Sensor nodes are attached to the body of people when they walk around. This pattern is manifested by its limited speed, obstacle avoidance, and chaotic nature. The movement in this pattern is two-dimensional, and may or may not show a group behavior [20].

2) Vehicular mobility pattern: It describes the movement of vehicles which are equipped with sensor nodes. Vehicles can communicate with each other conveniently by capturing traffic conditions and other information. Vehicle movement is one-dimensional and characterizes a group behavior at a high speed [20].

3) Dynamic medium mobility pattern: It occurs when nodes move through a medium, such as wind, water or other fluids. This mobility can be one-, two- or three-dimensional depending on the type of the medium. The difference between the pedestrian and dynamic medium mobility patterns lies in the nature of the medium. The medium is factitious in the former pattern whereas it is natural in the latter pattern.

B. Mobility Models

A mobility model is a formal mathematical description generalizing the characteristics of mobility patterns. A mobility model falls into one of the two categories, namely, trace-based and synthetic models [21]. In a **trace-based** model, real-life mobility patterns are collected from a large number of participants for a long observation period. However, the real movement trajectory of mobile nodes is difficult to capture even when sufficient historical data are obtained and recurrent mobility patterns occur. **Synthetic** models, on the other hand, attempt to represent the behaviors of real-world mobile objects. However, they cannot produce the precise description of mobile patterns. There are several synthetic mobility models, but here only two of them are considered.

1) Entity mobility models: A typical example is the Random Walk Mobility Model. It expresses the mobility of a node as it travels from its current location to a new location within a pre-defined time period or distance, by randomly choosing a direction and speed. A node changes its direction and speed once the time expires or the maximum permitted distance is reached. It is proven that a random walk on a one- or two-dimensional surface returns to the origin with complete certainty [22]. A similar model is the Random Waypoint Mobility Model, which includes pause time between changes in the direction and/or speed. Mobility is greatly affected by the pause time and speed of nodes. For example, a fast movement of nodes and a long pause time results in a more stable network than a slow movement of nodes and a short pause time [23].

2) Group mobility models: In these models the movement of nodes with respect to other nodes is of primary interest [24]. For example, the Exponential Correlated Random Mobility

Model creates a motion function to predict the new location of mobile nodes in the next time slot so as to mimic an erratic movement. In the Nomadic Community Mobility Model, a set of mobile nodes collectively roam from one place to another according to the location of a reference node. Individuals move randomly within their own spaces following a random entity mobility model. Unlike the Nomadic Community Mobility Model in which the mobile nodes share a common reference point, the Column Mobility Model requires a one to one mapping of the anchor and the mobile subjects [23].

III. SINK MOBILITY AND NODE MOBILITY

A number of approaches exploit the mobility of nodes for data collection. The focus of these approaches can be mainly classified into two types: sink mobility and node mobility. In sink mobility, the sink, which is the ultimate destination of sensed data in wireless sensor networks, moves and routes itself in the network to collect data from static nodes. However, a more complicated and challenging case is node mobility, where individual sensor nodes actively move from place to place and during their movement they attempt to maintain an end-to-end communication link.

A. Sink Mobility

Many have argued that the concept of a stationary sink can introduce a number of drawbacks. For example, the nodes placed around a base station can easily become bottlenecks by quickly depleting their energy reserve [25]. One way to deal with this problem is to deploy multiple mobile sinks, so that the load can be evenly distributed among nodes and the lifetime of the network can thus be increased [26]. Nevertheless, a high network dynamics due to mobile sinks can degrade the performance of the network. It has been shown that the end-to-end packet delivery ratio dropped down to 50% when nodes moved at $0.5m/s$ on average (the maximum speed was $1m/s$); this figure dropped to less than 20% when the maximum speed was greater than $5m/s$ [27].

In existing or proposed MAC and routing protocols, sink mobility can be categorized into three types, according to the movement pattern of mobile sinks and their manners of data collection.

1) Mobile base station: The position of a mobile base station changes during its operation time. Data generated by sensors are relayed to the mobile base station without long term buffering [28]. The communication load distribution studied in [29] shows that a network's lifetime can be improved even if an optimally placed fixed sink is replaced by a randomly moving mobile base station. The idea is to enable relay nodes to evenly consume energy and, thereby, optimize the overall energy consumption of the network. The study also shows that the optimal movement strategy is to follow the periphery if the deployment area is circular. A similar result is obtained when the sensor nodes are placed in grids [30]. The base station relocation method [31] periodically recalculates the ideal position of a mobile base station along the periphery of a sensing field.

2) Mobile data collector: Employing many relay nodes or long-range communication interfaces to maintain connectivity can be very expensive. A potential solution to this problem is to use mobile data collectors (data mules [32]) that gather buffered information from the source nodes over a single-hop communication link [28]. Proposed approaches can be classified into three classes, with respect to the pattern of the sink mobility.

Random mobility: The mobile data collectors move randomly and collect the buffered samples opportunistically. The received data from the one-hop sensors are transferred to a wireless access point. Since the trajectory of mobile data collectors is random, the message transmission delay can be high [32].

Predictable mobility: In the predictable mobility pattern, the static nodes are assumed to know the moving route of the mobile data collector, and this information will be used to predict the time that data transfer may take place. Based on this predicted time and location, nodes schedule their sleep and listen periods. In this way, the network can optimize its energy consumption [33].

Controlled mobility: In some circumstances, data may be transmitted at different rates due to the change of events or event occurrence interval. This may lead to the loss of data if a transmitter cannot finish the transmission to the mobile data collector before its buffer overflows. In order to accommodate variable transmission rates, a heuristic solution called Earliest Deadline First [34] is proposed. The aim is to actively control the movement of the mobile data collector in real time. The node to be visited next by the mobile data collector is chosen as the one that has the earliest buffer overflow deadline. However, the approach does not work well if nodes with consecutive deadlines are located far away from each other.

3) Rendezvous-based mobility: The rendezvous-based approach is a hybrid solution that shares some properties of a mobile base station and a mobile data collector. In this mobility pattern, sensor nodes deliver data to rendezvous points which are close to the path of mobile devices and the sampled data will be buffered at rendezvous points until they are relayed to the mobile sinks [28]. For example, the autonomous mobile router-based scheme [35] enables nodes which are out of the communication range of a mobile sink to buffer their data at those which can be visited directly by the mobile sink.

The difference between the three sink mobility patterns is displayed in Figure 1. The use of relay nodes in the mobile-base-station pattern implies that the distance between source nodes and the sink can be larger than a single hop. Therefore, the area that the mobile sink moves is limited. On the contrary, there is no extra relay nodes in the mobile-data-collector pattern. This indicates that source nodes need only forward their data to the sink directly (one-hop distance). As a result, the mobile sink has to pass along all the source nodes to collect samples, leading to a long moving range and a long communication cycle. The rendezvous-based mobility pattern, however, is a hybrid solution. It reduces the number of relay nodes to save energy, but at the same time increases energy due to the incremental sink mobility scope and data collection cycle.

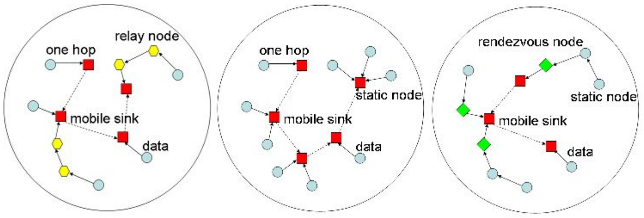

Fig. 1. Comparison between mobile base station, mobile data collector, and rendezvous-based mobility pattern

B. Node Mobility

Instead of the sink, individual nodes can be mobile either continuously or intermittently; and intentionally or accidentally, depending on the nature of the application. Node mobility can have additional merits besides the ones discussed in Section I, such as improving coverage in situations in which nodes occasionally become disconnected due to initial uneven or random deployments as well as unpredictable failures; or when they run out of battery [36].

If the mobile subjects upon which the nodes are attached are human beings, mobility can be considered as either a macroscopic or microscopic aspect. As a **macroscopic** aspect, it reflects the mobility habit based on everyday activities (for example, going back and forth from home to office; taking a break; going to a meeting or working with colleagues). As a **microscopic** aspect, it reflects the way humans interact with their surrounding environment (for example, indoor, outdoor, road, or network) [37]. Since only the movements observed at the radio range of wireless interfaces are of interest, they are more influenced by the microscopic mobility.

IV. MOBILITY ESTIMATION

A. Mobility Estimation Technique

Mobility patterns and models establish the basis for designing self-organizing algorithms and communication protocols that deal with mobile nodes. A mobility estimation technique employs a mobility model to predict a link quality, reserve resources, and facilitate a handover process [38]. A large number of estimation approaches utilize one or more of the following models:

1) Linear model: A linear model predicts a node's future state based on its current and past states, and can be static or dynamic. A static model usually forecasts a mobile node's position based on GPS information, by assuming it moves with the same speed and in the same direction [39]. By employing Kalman filters and extended Kalman filters [38], it is possible to deal with the dynamic aspects of mobility.

2) Information theoretic model: A node in this model maintains the history of base stations or nearby mobile individuals it encounters and applies a compression algorithm [40] to generate a dictionary of the recurrent observed paths [41].

3) Markov chain based model: A calibrated Markov chain is produced with states and active/inactive cycles representing the access points and the behavior of mobile nodes, respectively. State conditions describe obstacles or restrictions in the environment [42].

4) Pattern matching model: A node first searches for patterns similar to the current scenario in its stored history and the one with the highest cross-correlation [43] is selected as a base for the link prediction [37].

B. Data Source for Mobility Estimation

The scope and usefulness of a mobility estimation technique depend on the way the raw data are acquired and processed. In some cases, multiple sources can be utilized to generate the raw data for mobility estimation. In the following subsections, some of the mobility estimation techniques and the data sources are briefly discussed.

1) Global positioning system (GPS): GPS gives the absolute coordinates of a mobile node, but it is expensive and energy consuming [44]. It also suffers from frequent satellite disconnections in indoor environments [45].

2) Pedometers: A pedometer is a portable and electronic/electromechanical device that counts each step a person takes by detecting the motion of the person's hips. Algorithms for navigating a mobile node by using the hop-count based metric is simple and scalable [46]. This method, however, is highly dependent on the network density and path length, and thus is coarse-grained and error-prone [47].

3) Robotics: A robot can localize itself in both mapped and unmapped terrains by employing the method which represents the posterior distribution of possible locations via a set of weighted samples. New measurements such as observations of new landmarks are incorporated to filter the previous mobility prediction and update the data of location [48]. However, such estimation suffers from rotational and translational errors [49], even if a map of the environment and sensory information is given.

4) Radio frequency identification (RFID): RFID is a technology that employs radio frequency signals to exchange data between a reader and an electronic tag attached to an object for the purpose of identification and tracking. RFID readers are located strategically in the field [50]. One of its drawbacks is the relative short communication range $(1 - 2m)$ and the inhibition to future extensions.

5) Anchor node: Anchors are a set of static nodes with globally known or unknown positions. In the literature, they are also referred to as reference nodes or seeds [48]. Anchor nodes periodically broadcast beacon messages. By receiving beacons from enough sources, mobile nodes can localize themselves. In some cases, robots equipped with GPS are deployed into a wireless sensor network to act as reference nodes, so that sensors can localize themselves with the information given by the robots [51]. The accuracy of the localization depends on the distance between the mobile and the reference points as well as the number of the anchor nodes [52]. If the distance is too long or the anchor nodes are too less, the location estimation errors can be high. Moreover, the loss or malfunctioning of anchor nodes can affect the estimation mechanism [53].

6) Time of arrival (TOA): TOA finds the distance between a transmitter and a receiver via a one way propagation time by exploiting the relationship between the light speed and the carrier frequency of a signal [54]. However, all the nodes, with no information when messages will come, have to keep awake all the time.

7) Angle of arrival (AOA): AOA is usually employed as prior-knowledge for the triangulation localization method [55]. The information of the arriving angle can be obtained by using either goniometers, gyroscopes or compass.

8) Received signal strength indicator (RSSI): RSSI [56] represents the relationship between a transmission and a received powers. It can be employed to compute the distance of separation between a transmitter and a receiver when a good portion of the electromagnetic wave propagates in a line-of-sight (LOS) link. It has been used in a number of mobility-aware MAC protocols. However, the measure of RSSI fluctuates significantly due to deleterious effects of fading and shadowing and thus provides a lower accurate result than GPS.

9) Signal-to-Noise ratio (SNR): Deriving connectivity information from position information is not straightforward, since it requires a one-to-one mapping between distance and signal quality. Hence, alternative to RSSI, SNR is utilized as a measure of a node's link state. It is easy to be monitored and does not require any special hardware [37].

10) Ultrasound: A mobile node with an ultrasonic sensor measures the distance to a node by exploiting the ultrasonic signal propagation time. However, the transmission range of an ultrasound signal is small as it cannot propagate further than radio frequency wave [46]. It also adds size, cost, and energy supply to each device. Therefore even though ultrasound based localization approach can achieve high accuracy, it is not suitable for wireless sensor networks.

11) Accelerometers: Accelerations are generated due to both translational and rotational movements of an object. An accelerometer-based mechanism is shown to be an accurate, robust and practical method for objectively monitoring the free movement of objects and persons. The mechanism responds to both frequency and intensity of movement [53]. However, these devices increase the cost and size of a node and may not always be available or deployable. Moreover, accelerometer readings are sensitive of the node placement [57].

12) Triangulation and trilateration: The localization of mobile nodes can also be accomplished through triangulation in a one-hop neighborhood [58]. Once a local estimation is made for each node, a global localization can be established by calculating differences in terms of the distance and direction between each node and a particular central node, or a dense group of nodes [58]. However, this mechanism requires the use of isotropic antennas, which is expensive and less practical.

A trilateration requires priori-knowledge of the location of at least three nodes. The distance between nodes can be determined only within a certain degree of certainty [55].

13) Hybrid: Instead of directly using one of the above techniques, one can make use of the combinations of two or more localization measurement schemes. For example, mobile nodes can be aware of the relative distance between anchor nodes and themselves through RSSI values [59], through beacons broadcasted by anchor nodes, or through hop-based techniques [47]. However, the latter approach does not perform well in non-uniform topology where the position estimation can be coarse. Likewise, by reading records from both an odometer and a compass [49], a node can determine its translation as well as orientation at each particular time.

A comparison of the localization techniques is summarised in Table I.

V. MOBILITY-AWARE MAC PROTOCOLS

Node mobility causes, among other things, the deterioration of existing communication links. Once such a deterioration in a link quality is detected, one of the following strategies can be adopted to maintain an end-to-end data transmission [60]:

- The transmitting node continues with the data transmission if it realises that it can complete data transmission before the link eventually breaks.
- The transmitting and receiving nodes negotiate for a dynamic rate adaptation, so that data can be transmitted at a higher speed before the link breaks.
- The transmitter initiates a seamless handover without breaking the existing one to transfer transmission to a better link.

These decisions require the link layer to interact with the application, network and physical layers, since these layers provide information pertaining to the data size, the transmission rates supported by the transceivers, and the transmission power range that can be adapted. In the following subsections, a few mobility-aware MAC protocols which support strong node mobility are investigated.

A. MS-MAC

The mobility-aware MAC protocol for sensor networks (MS-MAC) [61] extends SMAC to support mobility. It introduces coordinated sleep/listen duty cycles and periodically synchronizes the schedule of nodes. The synchronization is done by broadcasting a SYNC packet at the beginning of the listen phase every predefined number of cycles (for example, 10 seconds every 2 minutes). A node first tries to follow the existing schedules by listening for a certain amount of time. If no SYNC packet is received, the node will randomly choose a time to go to sleep and immediately broadcasts this information. However, if a node receives a different schedule after it selects one, it will adopt both schedules. Therefore, the border nodes in a virtual cluster may have two or more different schedules, where a virtual cluster is formed by nodes with the same schedule.

Even in the situation where mobility is detected inside a virtual cluster, SMAC can perform well, since nodes have no difficulties in communicating with each other by having the same schedules, even though the cluster topology is changed due to this **intra-cluster mobility** [62]. However, if mobility is detected across virtual clusters, SMAC is unable to handle it, since before a connection with a new cluster can be set up, a node has to wait for a long time (as much as 2 minutes in our example) to receive the SYNC packet from the new cluster and updates its own schedule accordingly. In the meantime, it cannot communicate with its old neighbors once it moves out of the cluster range. The member and topology changes of a virtual cluster caused by the **inter-cluster mobility** leads to the disconnection of the mobile node from the network [62].

TABLE I
COMPARISON AMONG THE DATA SOURCES FOR MOBILITY ESTIMATION

Localization Technique	**Characteristics**	**Advantages**	**Disadvantages**
GPS	Measures absolute coordinate	Precise; simple	High price; unavailable in enclosed space; additional hardware is needed
Pedometers	Employ hop-count approaches	Simple; scalable	Coarse-grained; error-prone
Robotics	Employ the Monte Carlo method	Support localization in both mapped and unmapped terrains	Prone to rotational and translational errors
RFID	Data are exchanged via radio waves	Capable of identification and tracking	Short communication range; passive; difficult for future extensions
Anchor node	Pre-existing nodes with globally known or unknown positions	Nodes can be accurately localized if anchors are enough	Cumulative estimation errors; may be unavailable
TOA	Employs a propagation time	No additional cost	Error prone; energy inefficiency
AOA	Employs Goniometers, gyroscopes or compass	Uses as prior-knowledge for the triangulation localization method	Inaccurate; can not be used alone
RSSI	Measures relative distance	No additional cost	Subjects to effects of fading and shadowing; the signal has a large variation
SNR	Reflects a node's current connectivity	Can be monitored by off-the-shelf devices; no hardware is needed	SNR is not sufficient to express link quality. SINR (interference included in the ratio) is a better expression.
Ultrasound	Employs a propagation time of ultrasonic signal	Accurate	The receivable range is limited; adds size and cost to devices
Accelerometers	Responds to both frequency and intensity of movement	Accurate; robust; practical	Adds cost and size of equipments; may not be available or deployable
Triangulation & trilateration	Calculates global coordinate based on local coordinate	No additional cost	Recalculation may be done; a few nodes' locations should be prior known

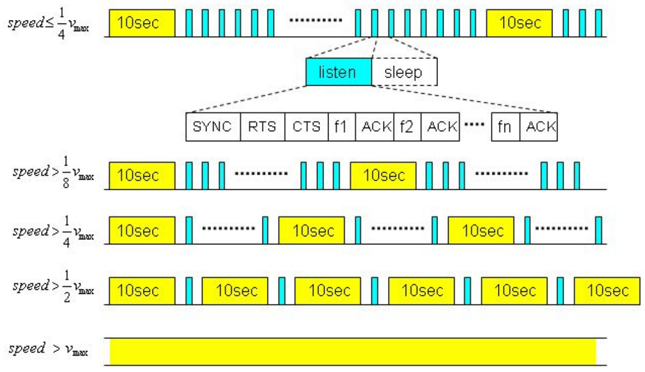

Fig. 2. Synchronization frequency adjustment in MS-MAC

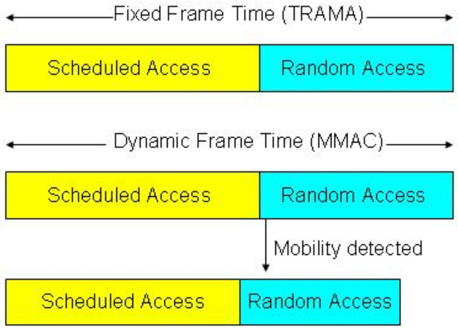

Fig. 3. Dynamic frame time in M-MAC

To expedite the connection set up process, MS-MAC enables each node to discover the presence as well as the level of mobility within its neighborhood, based on the RSSI values obtained from the SYNC messages transmitted by its neighbors. If the RSSI value from one and the same neighbor changes during a time interval, it realizes that either this neighbor, the node itself, or both of them are moving, since a one-to-one mapping between the distance and the RSSI values is assumed. Depending on the change of the RSSI values, the relative moving speed of the mobile individual can be deduced. Based on this information, the node broadcasts a SYNC message containing its own schedule and additional mobility information (the maximum estimated speed in the neighborhood). Upon receiving this packet, all the neighbors create an active zone by adjusting the synchronization frequency if the node is to move from one virtual cluster to another. The synchronization frequency, however, depends on the maximum speed of the surrounding neighbors. As can be observed in Figure 2, the faster the speed is, the higher the synchronization frequency will be. Therefore, by making the mobile node awake as much as possible, the connection with a new virtual cluster will be quickly set up before the node losses all its neighbors.

However, if a node does not detect any change in the coming RSSI values or if the node is not a border node, the mobility information in the SYNC message is set to be empty and thus no active zone will be created.

B. M-MAC

The mobility-adaptive, collision-free medium access control protocol (MMAC) [8] is a schedule-based MAC protocol following the design principle of TRAMA [63]. Instead of the fixed frame length in TRAMA, M-MAC introduces a flexible frame time that enables the protocol to dynamically adapt to mobility, making it suitable for wireless sensor environments, as Figure 3 describes.

In M-MAC, time is divided into rounds and each round is composed of k frames (k is an integer larger than 1). At the beginning of each frame, all the nodes in the network predict their mobility states at several different time points of the next frame based on the $AR-1$ mobility estimation model [64]. The average of these location estimations is regarded as a node's location prediction for the next frame. This information

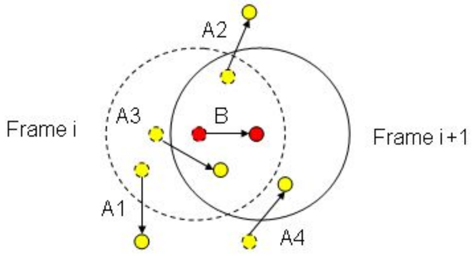

Fig. 4. Mobility estimation for the next frame in M-MAC

is transmitted to the node's corresponding cluster head. Since the cluster head never goes into sleep, it is able to collect the values of all its members and broadcasts them in the last slot of a frame. This ensures that all the nodes in the cluster have the best knowledge of the predicted mobility states of its current and potential two-hop neighbors. A node calculates the relative distance between the center node (node B in Figure 4) and itself, in order to learn whether it will enter or leave the cluster in the next frame (the cluster is the collection of the 2-hop neighbors of node B). For example, the big circle in Figure 4 represents the cluster range. In frame i, nodes $A1$, $A2$ and $A3$ are initially within B's two-hop neighbor range. However, both their absolute and relative locations change with respect to B's position in frame $i+1$, since $A1$ and $A2$ move out of B's two-hop range. In contrast, $A3$ still lies beside B due to its similar movement speed and direction with B. A new node $A4$ moves into B's view in the next frame.

According to this comparison, a node independently proposes a new frame duration and transmits it to the cluster head. The head, by averaging the duration estimations from all the members, produces the mean frame size and broadcasts it to all the nodes. If this value is less than the previous one stored at a node, it increases the random access interval and decreases the scheduled access interval while keeping the frame time constant. The frame time, however, can only be changed at the end of a round by employing Global Synchronization Period (GSP). The GSP averages the predicated frame durations from all the cluster heads and disseminates this mean value in the network as the frame size for the next round.

C. M_TDMA

The mobility-aware TDMA-based MAC protocol for mobile sensor networks (M_TDMA) [62] has been proposed to extend the TDMA mechanism for adapting to the changes in a network topology. Unlike a pure TDMA, M_TDMA partitions the network into non-overlapping clusters using the FLOC algorithm [65], with each cluster having its own head. Each node within a cluster is assigned a unique slot. To deal with mobility, some of these slots are shared across clusters and some of them are kept free for future allocation. To this end, M_TDMA splits a given round into two parts, namely, the control part and the data part. The control part is used to adapt to mobility, whereas nodes transmit packets in the data part. Some of the slots at the end of the data part are reserved for the future entering nodes as well as the message retransmissions.

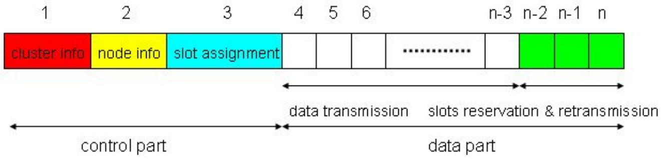

Fig. 5. Work principle of M_TDMA

As shown in Figure 5, the control part is composed of the first three slots. In the first slot, the head broadcasts cluster information, such as the ID, the head status, the cluster schedule and the round number. If a node receives this information, it knows that it is still in the original cluster, and therefore, it only updates its state in the second slot. If the node does not receive any massage, it notices that it has left the original cluster but has not entered into any new cluster. In this case, it has to wait until the cluster information is received in a future round. But if the node receives cluster information from a different head, it then learns that it has joined a new cluster and informs its presence in the second time slot.

On receiving a new ID, the head checks whether any unassigned slot is left in the data part. If more than one is free, the head directly assigns one to the new node in the third slot and updates the cluster schedule. However, if only one slot is free, instead of fully allocating the slot to the new node, the head halves the bandwidth by doubling the period in which the new node transmits, as the other half is kept for further entering nodes. In this case, the head updates the schedule by maintaining a sequence of IDs, with the last element serving as a place holder. If no slot is left, the head checks the place holder and further halves the remaining bandwidth.

The head, however, may not receive any information in the second slot when two or more nodes simultaneously announce their appearance in the second slot or no node joins in the cluster. Similarly, a new node may not receive the slot assignment in the third slot if the cluster head is out of range or its packet had collision with other packets in the second slot. In both cases, the node has to randomly back-off and retransmits its ID in the next round. In the data part, nodes transmit and receive based on a normal TDMA mechanism.

D. MA-MAC

The light-weight mobility-aware medium access control protocol (MA-MAC) [60] is an extended version of XMAC. Similar to all the low duty cycle MAC protocols, MA-MAC enables a node to sleep most of the time and switch on the radio for receiving the incoming packets periodically. In the static scenario, MA-MAC performs similar to XMAC by dividing a preamble into multiple strobes and enabling an early ACK packet to save energy. However, if mobility is detected, MA-MAC initiates a seamless handover by relaying the remaining data to a new node before the link breaks. Each node can be found in one of the five states, namely, sleep, receive, send, discover, and handover.

Initially, a node is in a sleep state, after being successfully booted. It may enter into a wake up state if it has data to transmit or when its normal active period begins, or when a handover process is triggered. To support mobility, MA-MAC defines two distance thresholds. The first threshold prompts a node to initiate a seamless handover, whereas the

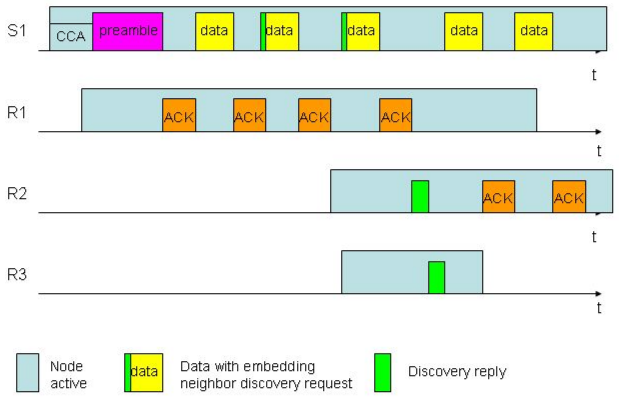

Fig. 6. Handover mechanism in MA-MAC

second threshold sets an upper limit to the distance that should be travelled before the mobile node has established a link with a new relay neighbor. During mobility, if a transmitter detects that the distance between the receiving node and itself exceeds the first threshold, it enters into a discovery state and begins to search for an intermediate neighbor along the way to the base station. To do so, the transmitter broadcasts data packets in which handover requests are embedded. If it receives at least one of ACK packet from a new node before it completes the second distance threshold, the transmitter enters into a handover state to resume data transmission to the newly discovered node. The transmitter enters into a sleep state otherwise.

Figure 6 illustrates a handover process in which a mobile sender ($S1$) evaluates the RSSI values of incoming ACK packets from a receiver ($R1$). If it realises that the distance of separation between the two of them exceeds the first threshold, it begins to embed handover requests in the outgoing data packets and transmits them in a broadcast mode. Up on receiving broadcast packets (since the communication with $S1$ hitherto has been unicast), $R1$ realizes that the transmitter wishes to change a link. Thus it will refrain sending ACK packets for a short interval, to enable $S1$ to collect handover replies from its surrounding. In case of no answer, $S1$ resumes communicating with $R1$ while keeping sending handover requests. Once $R2$ and $R3$ wake up and hear the neighbor discovery messages, they will send back handover replies. $S1$ will select the node from which it receives the first reply as a relay node ($R2$) and communicates with it. Meanwhile $R3$, by overhearing the data packet from $S1$, realizes that it has not been selected and thus goes back to sleep to save energy.

E. MobiSense

MobiSense [66] is a cross layer architecture that combines the MAC and routing layers to achieve energy efficient communication in a micro-mobility scenario. Here nodes are organized into clusters, in which strategically placed static nodes act as cluster heads and mobile nodes move between them. To increase the network throughput and to simplify the network management, MobiSense adopts multi-channel communications by requiring adjacent cluster-heads to operate in different channels. The aim is to reduce the interference between the clusters and to allow the cluster-heads to dynamically schedule traffic locally.

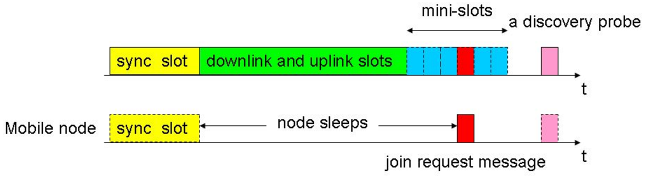

Fig. 7. Work mechanism of MobiSense

MobiSense organizes a super-frame into a synchronization slot, downlink and uplink data transmission slots, admission mini-slots, and discovery slots. All the cluster heads send synchronization packets at the beginning of each frame to inform mobile nodes about the changes in their uplink and downlink transmission. Each cluster head sends a probe in the discovery slots on a common channel to advertise the information about the channel it uses for communication, the current cluster size, and the timing of its access window. As a result, by listening to these slots, mobile nodes that want to join the network or handover from one cluster to another can rapidly gather network information and build the prioritized lists of access points. Since the size of the discovery slots is fixed, nodes only listen for a fixed duration. After determining the new cluster, a mobile node randomly selects an access mini-slot and sends its own join request message. Since the collision probability is low under moderate contention scenarios, MobiSense achieves a low admission delay and a fast network convergence. The downlink and uplink slots are used for two-way data communications. The working mechanism of MobiSense is explained in Figure 7.

F. MCMAC

The mobile cluster MAC (MCMAC) [67] is a schedule-based MAC protocol which extends LMAC [68] and GMAC [69] to support cluster mobility. Unlike most of the proposed mobility-aware MAC protocol, MCMAC is optimized for those nodes which travel in group. This is particularly the case in Body Area Networks, such as in healthcare applications, where a number of biomedical sensors are travelling together, being attached to the body of a patient.

MCMAC categorizes the sensor nodes into a static network and a mobile cluster. The protocol defines a Reference Point Group Mobility (RPGM) model and a Random Waypoint Mobility (RWM) model to mimic the movement characteristics of mobile clusters and the individual node movement within a cluster. A frame in MCMAC is divided into an active and a sleep period. Since the slot assignment method is different for static and mobile nodes, the active period is further divided into static active slots (SAS) and mobile cluster slots (MCS). Static nodes communicate with each other in the SAS part by dynamically occupying a unique transmission slot in its two-hop neighborhood. A static node can only transmit data in the specific slot it chooses and receives data in the remaining part of SAS. A guard time is inserted at the start and the end of every transmission slot to compute a node's phase difference with its direct neighbors for synchronization. The working principle of static nodes is described in Figure 8 (a).

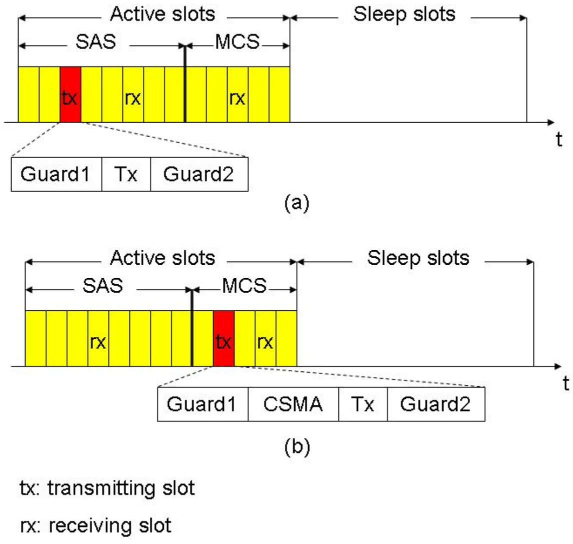

Fig. 8. Architecture of MCMAC

The MCS part is used for nodes in a mobile cluster to communicate with each other. Since the size of a cluster can be small (a human body) and all enclosed nodes are typically within each other's one- or two-hop neighborhood, each slot in this part is assigned to exactly one node. In case of multiple clusters, a transmission slot is extended to include a CSMA period to avoid collision between two mobile nodes in two different clusters which share the same transmission slot. A mobile node selects a random time in CSMA period to sense the medium before data transmission, as Figure 8 (b) illustrates. Static and mobile nodes also listen to the MCS and SAS parts, respectively, to enable a communication between them.

VI. DISCUSSION AND COMPARISON

In the previous section, the protocols that support strong mobility were introduced. In this section, the corresponding merits and demerits of these protocols will be discussed and compared in detail.

For MS-MAC protocol, one obvious advantage is that a mobile node can keep transmitting and receiving data packets with its original neighbors while establishing connection with the nodes in a new virtual cluster. However, frequent synchronization can lead to high energy consumption. And such energy consumption is not limited to the mobile node itself, but also to all the neighbors which are two-hops away from it. Therefore, the neighbors may deplete their energy quickly even if they are stationary. From this point of view, the handover mechanism of MS-MAC is actually implemented by trading-off a higher energy expenditure of the neighbors around a mobile node for a lower latency in setting up a connection with a new virtual cluster.

M-MAC deals with mobility-related delays by adjusting the size of a frame and the proportion of the scheduled access interval to the random access interval within a frame. However, it has several inherent limitations. Being computationally intensive is one of the limitations of M-MAC. The accuracy of the mobility handling mechanism depends on the accuracy of the predicted size of the next frame, which is estimated by all individual mobile nodes in the current round. This estimation, however, is made according to the change of the relative distance between nodes obtained by employing the $AR-1$ location evaluation model. Furthermore, the adjustment of the size of both the scheduled access interval and the random access interval for the next frame as well as the size of the frame for the next round is only managed according to the historical statistics. Therefore, the node movements, which still occur in the current frame and round, are not taken into consideration after mobility is predicted, leading to latency and inaccuracy of mobility estimation.

Unlike MS-MAC which aims at decreasing the connection time by creating an active zone around a mobile node, M_TDMA targets at the absence of collision while supporting mobility. Unlike M-MAC which introduces the mobility adaptive frame by predicting the future position of all the nodes, M_TDMA does not rely on any localization service and the frame size is never changed. Instead, M_TDMA divides a frame into a control part to learn about mobility and a data part to allocate time slots to the newly entering nodes. However, M_TDMA has its own drawbacks, not least of which is its making several assumptions. To start with, it assumes that any individual node remains within a cluster for at least one round unless it crashes. This, however, depends on the moving direction and speed a mobile node chooses. Secondly, it assumes that a node may not stay for more than one period without hearing from a head. This actually related with the state of the head and the network topology. Thirdly, it assumes that heads would not collide for more than two consecutive rounds, even though it depends on the network partitioning algorithm and network density. In addition to these assumptions, M_TDMA introduces a big latency, since mobility can only be detected in the second slot and thus a node which enters the cluster after this time has to wait until the next round comes. This implies that during this time, the node is disconnected from the entire network. Furthermore, a new node may not receive the slot allocation in the third slot, because either a collision occurs among the new nodes in the second slot; or a collision occurs among the heads in the third slot. In both cases, the new node has to re-announce its presence in the future round, leading to an increased energy consumption and latency.

Unlike all the protocols discussed so far, MA-MAC seamlessly handovers a communication to a better link whenever the quality of an existing link deteriorates. One advantage of this approach is that mobility can be handled in time, since the handover technique will be triggered once the distance between a transmitter and a receiver exceeds the lower threshold. However, the mobility estimation technique functions under the assumption that the deterioration of a link quality is a gradual and steady process, which implies that there is no sudden crash of nodes and/or the speed of nodes is constant. Similarly, MA-MAC assumes that the nodes which surround the mobile individuals are quasi-stationary. This means that the quality of a link between the mobile node and the selected relay node will not be decreased until the second threshold is reached. Moreover, the efficiency of MA-MAC highly depends on the network density and the nodes'

TABLE II
COMPARISON AMONG THE MOBILITY-AWARE MAC PROTOCOLS

MAC Protocols	**Estimation techniques**	**Characteristics**	**Advantages**	**Disadvantages**
MS-MAC	Information theoretic model	1. A contention-based protocol extends SMAC. 2. A mobile node can connect with a new virtual cluster by running synchronization frequently.	1. It can communicate with the original neighbors while setting up connection with a new virtual cluster. 2. The synchronization frequency can adapt to the speed of a mobile node's neighbors.	1. It trades-off a higher energy cost for a less delay. 2. A neighbor of the mobile node consumes a significant amount of energy even if it is stationary.
M-MAC	Auto-regression model/Kalman Filter	1. A schedule-based protocol designed from TRAMA. 2. It adjusts the frame size and the proportion within a frame.	1. The time slot can be dynamically allocated by changing a frame's size and the proportion within a frame. 2. The proportion within a frame is changed more frequently than the frame size.	1. Computational intensive. 2. The accuracy depends on the AR-1 model. 3. Mobility is estimated based on historical statistics.
M_TDMA	Information theoretic model	1. A schedule-based protocol on top of TDMA. 2. It uses the control part to learn mobility information and the data part to allocate slots to new nodes.	1. It guarantees collision-freedom. 2. It does not rely on any localization algorithm. 3. It uses the control and data parts to adapt to mobility without changing the frame size	1. Several assumptions are made. 2. Disconnection with the network may occur. 3. Energy and latency are increased.
MA-MAC	Pattern matching model	1. A contention-based protocol based on XMAC. 2. It defines two thresholds for handling mobility.	1. Mobility can be handled in time. 2. Relay nodes can be discovered during the data communication.	1. Several assumptions are made. 2. It depends on network density and nodes' schedules. 3. The decision of two thresholds is critical.
MobiSense	Information theoretic model	1. A schedule-based MAC protocol. 2. It uses mini-slots, discovery slots and multi-channel communication for handling mobility.	1. The discovery slots allows rapid network information gathering. 2. The multi-channel communication enables local scheduling. 3. The mini-slots ensure rapid admission and fast network convergence.	1. Multi-channel requires careful management of the media resource. 2. The order of the discovery slots and the access mini-slots is critical. 3. Mobility cannot be handled in time. 4. Collision may occur.
MCMAC	Linear model	1. A schedule-based MAC protocol designed based on LMAC and GMAC. 2. It avoids adaptation time by using different slot assignment scheme for static and mobile nodes.	1. Guard time introduction ensures decentralized frame synchronization. 2. Transmission slot is dynamically selected in the SAS part. 3. Flexible slot assignment scheme avoids adaptation time once cluster moves.	1. Collision cannot be avoided due to state switching delay. 2. Collision can also happen due to hidden terminal problem. 3. Single channel limits the bandwidth and makes the throughput unscalable.

schedule arrangement. If the number of neighbors around the transmitter is small, it may not discover any relay candidate, and, hence, the transmitter can do nothing but keep sending data to the original receiver until the link eventually breaks. If all the neighbors except the current receiver are sleeping during the time the transmitter broadcasts handover requests, no relay node can be found for future communication. Finally, the determination of the two distance thresholds is critical to the performance of MA-MAC.

MobiSense proposes a multi-channel medium access mechanism to provide reliable data transfer and fast handover as well as dynamic and distributed transmission scheduling in micro-mobility environments. By enabling clusters to operate in different channels, interference between them is reduced and traffic demands can be adapted to the need of individual mobile nodes. In addition, it allows some of the clusters to multiplex data to the sink while others serve their mobile nodes. The use of the discovery slots on a predetermined common channel allows mobile nodes to rapidly gather network information, prevents unsuccessful join attempts, and maintains a constant network discovery delay. Moreover, the well-defined access mini-slots avoid collision between data transmissions and join requests and enables distributed network formation and faster network convergence.

Along with some of its merits, MobiSense has some demerits as well. Firstly, it assumes the presence of some fixed static nodes. Secondly, the use of multi-channel is expensive, since it requires careful management of the channel resource and a more advanced receiver design. Thirdly, the order of the discovery slots and the access mini-slots is critical for handover, since a mobile node cannot send a join request before knowing the cluster information in the discovery slots. Fourthly, mobility cannot be handled instantaneously, since nodes can only handover during the access mini-slots. Even worse, the handover request may not be processed in case of a collision.

MCMAC supports continuous cluster mobility. Instead of using a synchronization slot, it inserts guard times in a node's transmission slot to indicate the phase difference to its direct neighbors. This mechanism ensures decentralized frame synchronization. MCMAC also enables a node to dynamically select its transmission slot based on its neighbors' occupancy bit-sets. In addition, the different active slot assignment for static and mobile nodes avoids the need for an adaptation time after a cluster movement. Several static nodes can share one and the same transmission slot if the distance between any two of them is larger than two hops. This improves the channel capacity. The size of the SAS part, therefore, depends on the network density. Unlike the SAS part, each slot in the MCS part is allocated to exactly one mobile node in a cluster to avoid interference between mobile nodes, since a cluster can be small and mobile nodes are usually within each other's one- or two-hop distance. The MCS part, however, can also be shared in case of multiple mobile clusters in the network, by using a hybrid contention-based and schedule-based channel access mechanism. A simple Carrier Sense Multiple Access (CSMA) period is adopted for sensing the channel status before the real data transmission. As a result, the size of the MCS part is equal to the maximum number of nodes in the biggest cluster.

Even though the CSMA mechanism is introduced, collision cannot be completely avoided, since there is a switching delay between the carrier sensing mode and a data transmission. Therefore, it may happen that a node senses a free channel while another competing node is preparing for data transmission. Collision can also happen due to the hidden terminal problem.

A comparison summary of the six mobility-aware MAC protocols is given in Table II.

VII. LESSEN LEARNED AND OPEN ISSUES

Wireless sensor networks that support mobile nodes have a large number of applications in areas such as healthcare, supply-chain, toxic gas detection in disaster areas, etc. Due to the criticality of the applications, the way mobility should be captured and handled requires a careful planning. Most of the proposed MAC protocols investigated in this paper assume a mixed deployment in which both static and mobile nodes are present. In fact, most approaches implicitly assume that the number of static nodes is significantly larger than the number of mobile nodes. We believe that this is a realistic assumption.

Experiment and simulation results indicate that accurate mobility estimation is essential to avoid unnecessary oscillation in link establishment (or node associations in cluster-based networks) [8], [60]. However, the results also indicate the existence of a strong trade-off between estimation accuracy, estimation time, and signal processing cost (both in terms of energy consumption and computing resources). Therefore, mobility estimation techniques that optimize this trade-off are required. Moreover, estimation techniques that are based only on RSSI values perform poorly, leading to frequent oscillations even when nodes are not mobile. Unfortunately, most of the proposed approaches rely on this technique. The limited size of a sensor node and its limited resources put significant constraints on the type of data sources that can be used for mobility estimation.

We believe that the mobility patterns discussed in Section II can help to improve estimation accuracy and reduce the cost of mobility estimation. For example, knowledge of the pattern of mobility of the object or person can significantly reduce both false positives and false negatives. We realise that most of the proposed MAC protocols do not fully take advantage of this knowledge. Finally, work still remains to quantify the cost of mobility. Strong mobility requires that neighbour nodes (static nodes) should remain awake when a request to join comes from a mobile node. Research questions such as (1) how many of these nodes should remain awake? and (2) for how long should nodes remain awake? depend on the mobility patterns, the energy reserve of the static nodes, the acceptable end-to-end delay in data communication, and the node density. These issues have to be carefully studied and their significance with respect to network lifetime should be quantified.

VIII. CONCLUSION

In this paper, a survey of mobility estimation and mobility supporting protocols in wireless sensor networks was given. The paper began by introducing the difficulties caused by mobility at various layers, particularly, at the MAC layer. To efficiently address the problem of mobility, a classification of mobility patterns and models was described and several mobility estimation techniques were discussed. Finally, the paper investigated six mobility-aware MAC protocols and compared their merits and demerits.

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