Chapter 5: A Survey on Mobility and Mobility-Aware MAC Protocols in Wireless Sensor Networks

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Abstract

- This chapter 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.

Introductions

- 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 .
- 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.
- 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 .
- Since weak mobility takes place infrequently, the delay it introduces may be tolerable, nevertheless.

Introductions (Cont.)

- Strong mobility results in a frequent topology change which in turn introduces the following problems:
  - 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.

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.
  - Pedestrian mobility pattern
  - Vehicular mobility pattern
  - Dynamic medium mobility pattern

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 .

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.

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.

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.
- 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.

Mobility Models (Cont.)

- 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.
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  - Entity mobility models
  - Group mobility models

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.
- 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.

Group Mobility Models

- In these models the movement of nodes with respect to other nodes is of primary interest.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.

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.

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.
- 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. Nevertheless, a high network dynamics due to mobile sinks can degrade the performance of the network.
- Mobile base station
- Mobile data collector
  - Random mobility
  - Predictable mobility
  - Controlled mobility
- Rendezvous-based mobility

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.
- The communication load distribution studied in 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. The base station relocation method periodically recalculates the ideal position of a mobile base station along the periphery of a sensing field.

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 that gather buffered information from the source nodes over a singlehop communication link.
- Proposed approaches can be classified into three classes, with respect to the pattern of the sink mobility.

Mobile Data Collector-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.

Mobile Data Collector-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.

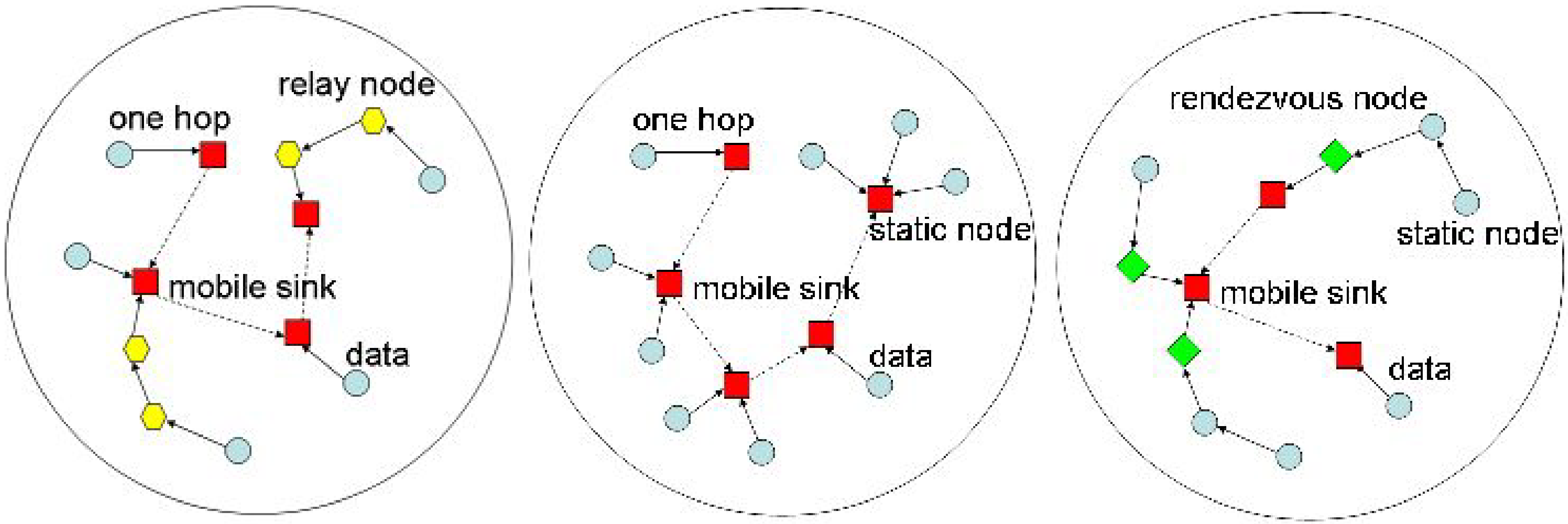
Mobile Data Collector-Controlled Mobility

- 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 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.

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.
- For example, the autonomous mobile router-based scheme 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.

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



Node Mobility

- Nodes can be mobile either continuously or intermittently depending on the nature of the application.
- 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.
- As a microscopic aspect, it reflects the way humans interact with their surrounding environment.

Mobility Estimation Technique

- A large number of estimation approaches utilize one or more of the following models.
  - Linear model
  - Information theoretic model
  - Markov chain based model
  - Pattern matching model

Mobility Estimation Technique-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.
- By employing Kalman filters and extended Kalman filters, it is possible to deal with the dynamic aspects of mobility.

Mobility Estimation Technique (Cont.)

- 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 to generate a dictionary of the recurrent observed paths.
  - 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.
- 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 is selected as a base for the link prediction.

Data Source for Mobility Estimation

Localization Technique	Characteristics
GPS	Measures absolute coordinate
Pedometers	Employ hop-count approaches
Robotics	Employ the Monte Carlo method
RFID	Data are exchanged via radio waves
Anchor node	Pre-existing nodes with globally known or unknown positions
TOA	Employs a propagation time
AOA	Employs Goniometers, gyroscopes or compass
RSSI	Measures relative distance
SNR	Reflects a node's current connectivity
Ultrasound	Employs a propagation time of ultrasonic signal
Accelerometers	Responds to both frequency and intensity of movement
Triangulation & trilateration	Calculates global coordinate based on local coordinate

Data Source for Mobility Estimation(Cont.)

Localization Technique	Advantages	Disadvantages
GPS	Precise; simple	High price; unavailable in enclosed space; additional hardware is needed
Pedometers	Simple; scalable	Coarse-grained; error-prone
Robotics	Support localization in both mapped and unmapped terrains	Prone to rotational and translational errors
RFID	Capable of identification and tracking	Short communication range; passive; difficult for future extensions
Anchor node	Nodes can be accurately localized if anchors are enough	Cumulative estimation errors; may be unavailable
TOA	No additional cost	Error prone; energy inefficiency
AOA	Uses as prior-knowledge for the triangulation localization method	Inaccurate; can not be used alone
RSSI	No additional cost	Subjects to effects of fading and shadowing; the signal has a large variation
SNR	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	Accurate	The receivable range is limited; adds size and cost to devices
Accelerometers	Accurate; robust; practical	Adds cost and size of equipments; may not be available or deployable
Triangulation & trilateration	No additional cost	Recalculation may be done; a few nodes' locations should be prior known

MS-MAC [61]

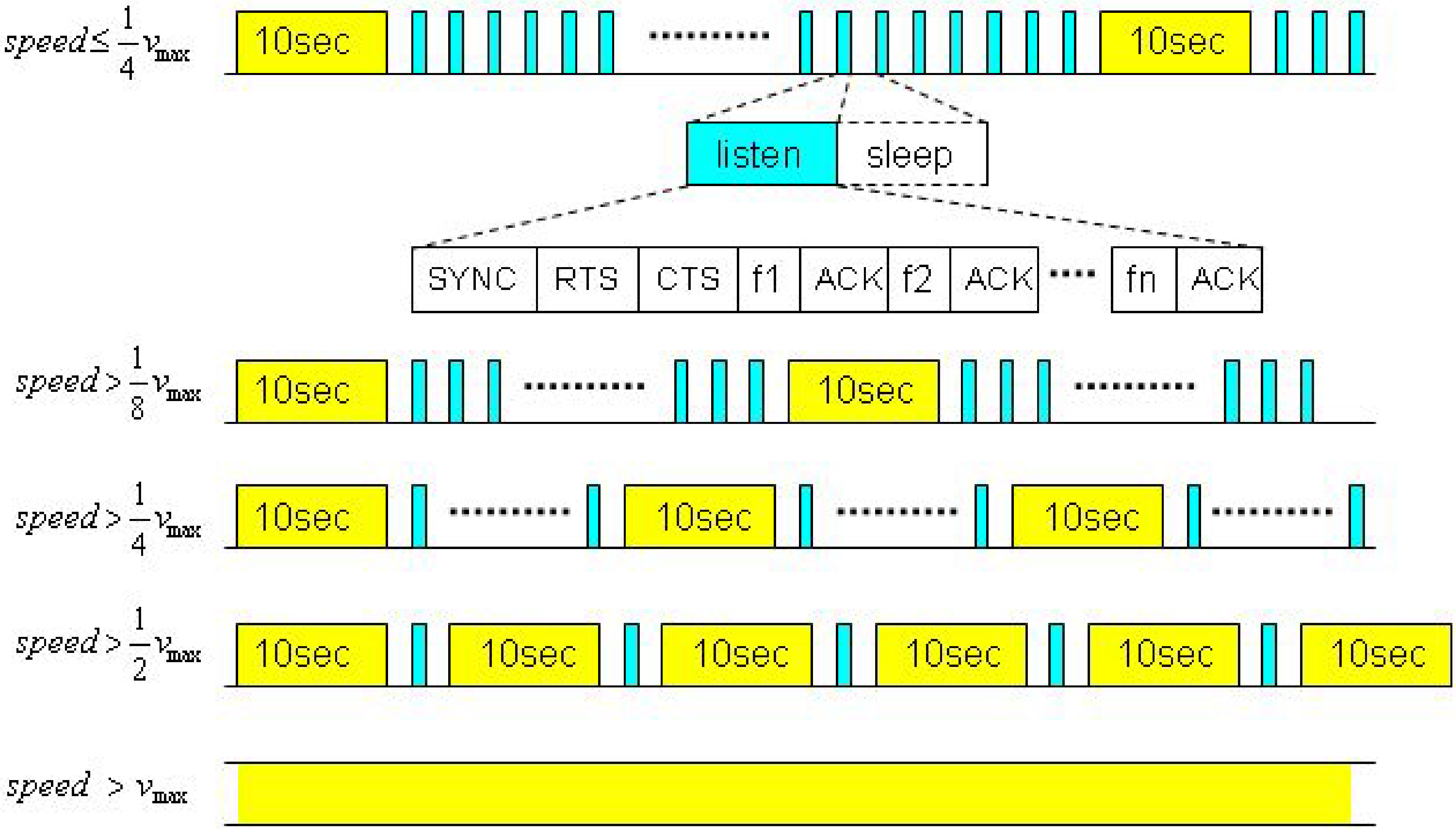
- The mobility-aware MAC protocol for sensor networks (MS-MAC) extends SMAC to support mobility. It introduces coordinated sleep/listen duty cycles and periodically synchronizes the schedule of nodes.
- The synchronization is done by broadcasting a SYNC packet at the beginning of the listen phase every 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.

[61] H. Pham and S. Jha, "An adaptive mobility-aware mac protocol for sensor networks (ms-mac)," *IEEE International Conference on Mobile Ad-hoc and Sensor Systems*, pp. 558 – 560, October 2004.

MS-MAC (Cont.)

- 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.

Synchronization frequency adjustment in MS-MAC

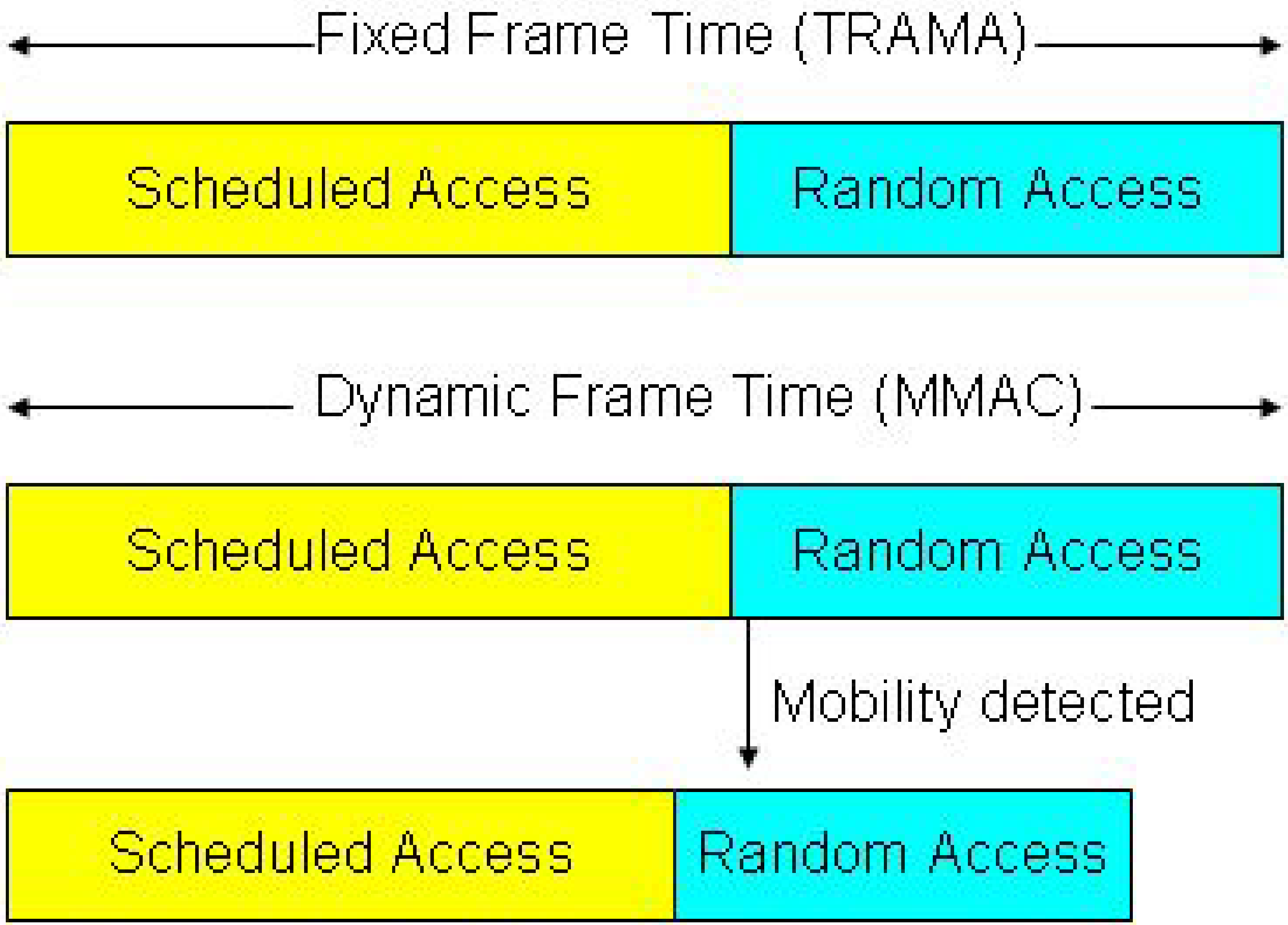


M-MAC [8]

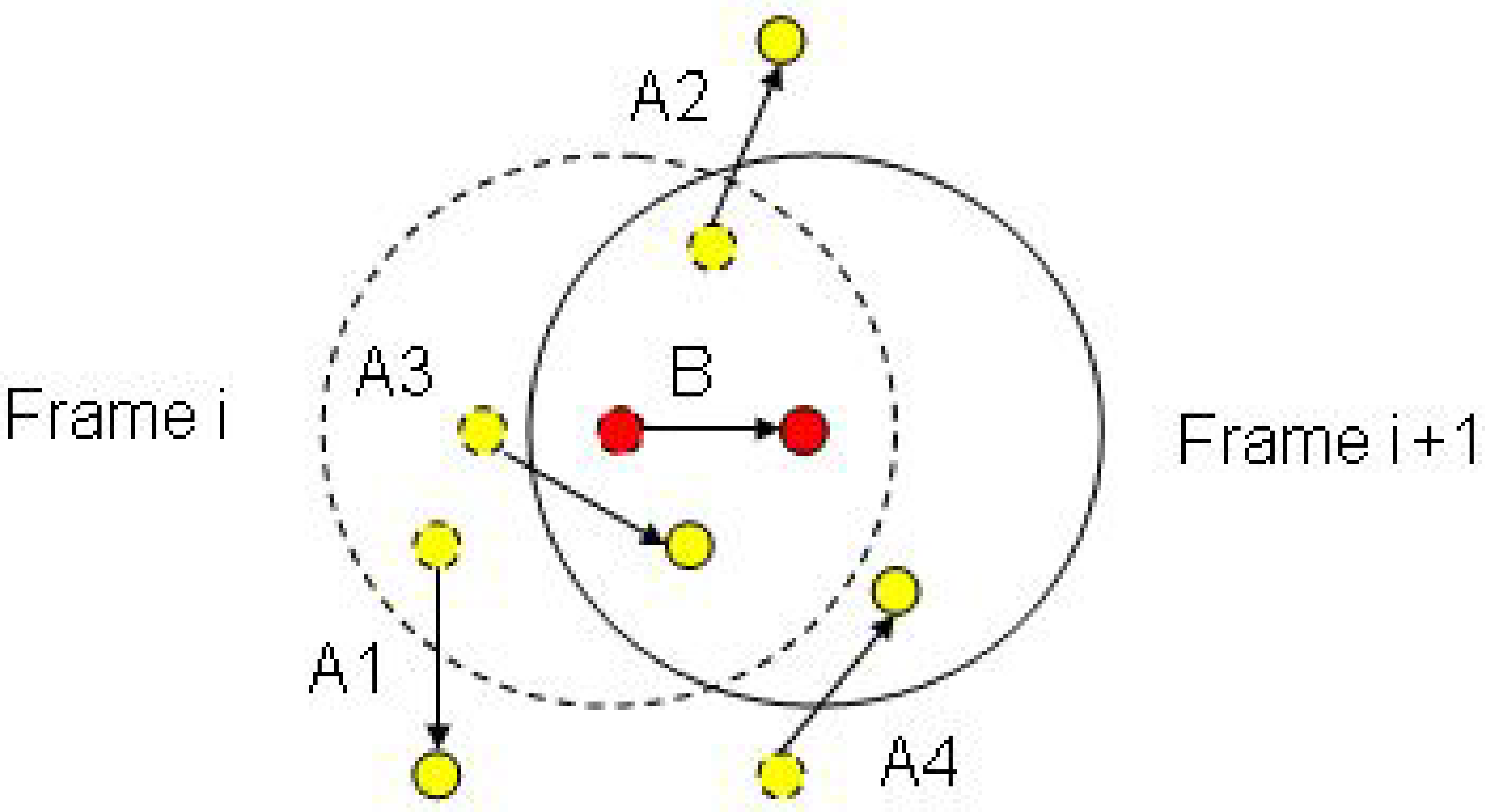
- The mobility-adaptive, collision-free medium access control protocol (MMAC) is a schedule-based MAC protocol following the design principle of TRAMA .
- Instead of the fixed frame length in TRAMA, M-MAC introduces a flexible frame time that enables the protocol to dynamically adapt to mobility, making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

[8] M. Ali, T. Suleman, and Z. A. Uzmi, “MMAC: a mobility-adaptive, collision-free mac protocol for wireless sensor networks,” *24th IEEE International Performance, Computing, and Communications Conference*, pp. 401 – 407, April 2005.

Dynamic frame time in M-MAC



Mobility estimation for the next frame in M-MAC

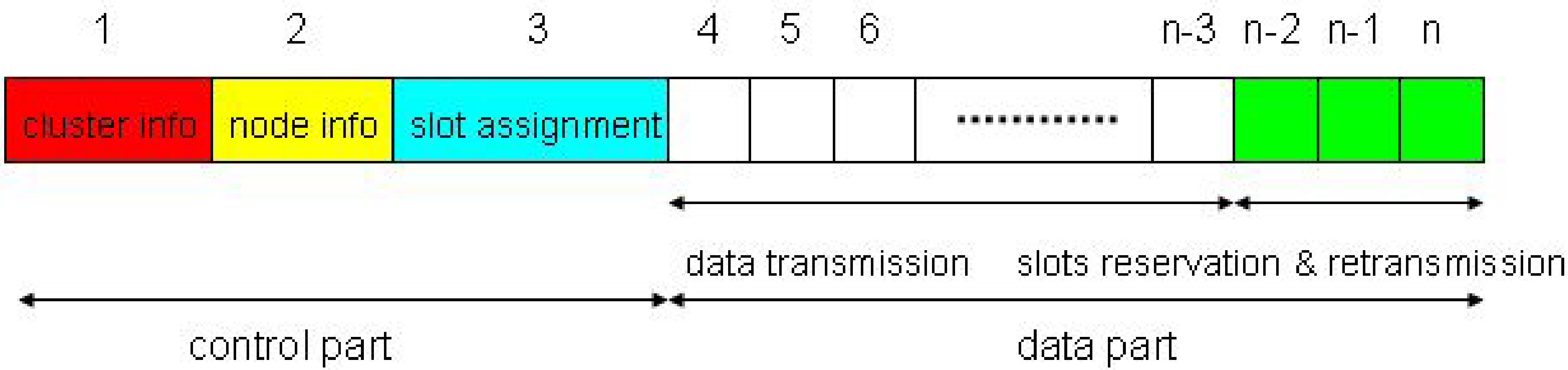


M_TDMA [62]

- The mobility-aware TDMA-based MAC protocol for mobile sensor networks (M_TDMA) 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 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. 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.

[62] A. Jhumka and S. Kulkarni, "On the design of mobility-tolerant tdmabased media access control (mac) protocol for mobile sensor networks," *Proc. 4th international conference on Distributed computing and internet technology*, vol. 4882, pp. 42–53, 2007.

Work principle of M_TDMA

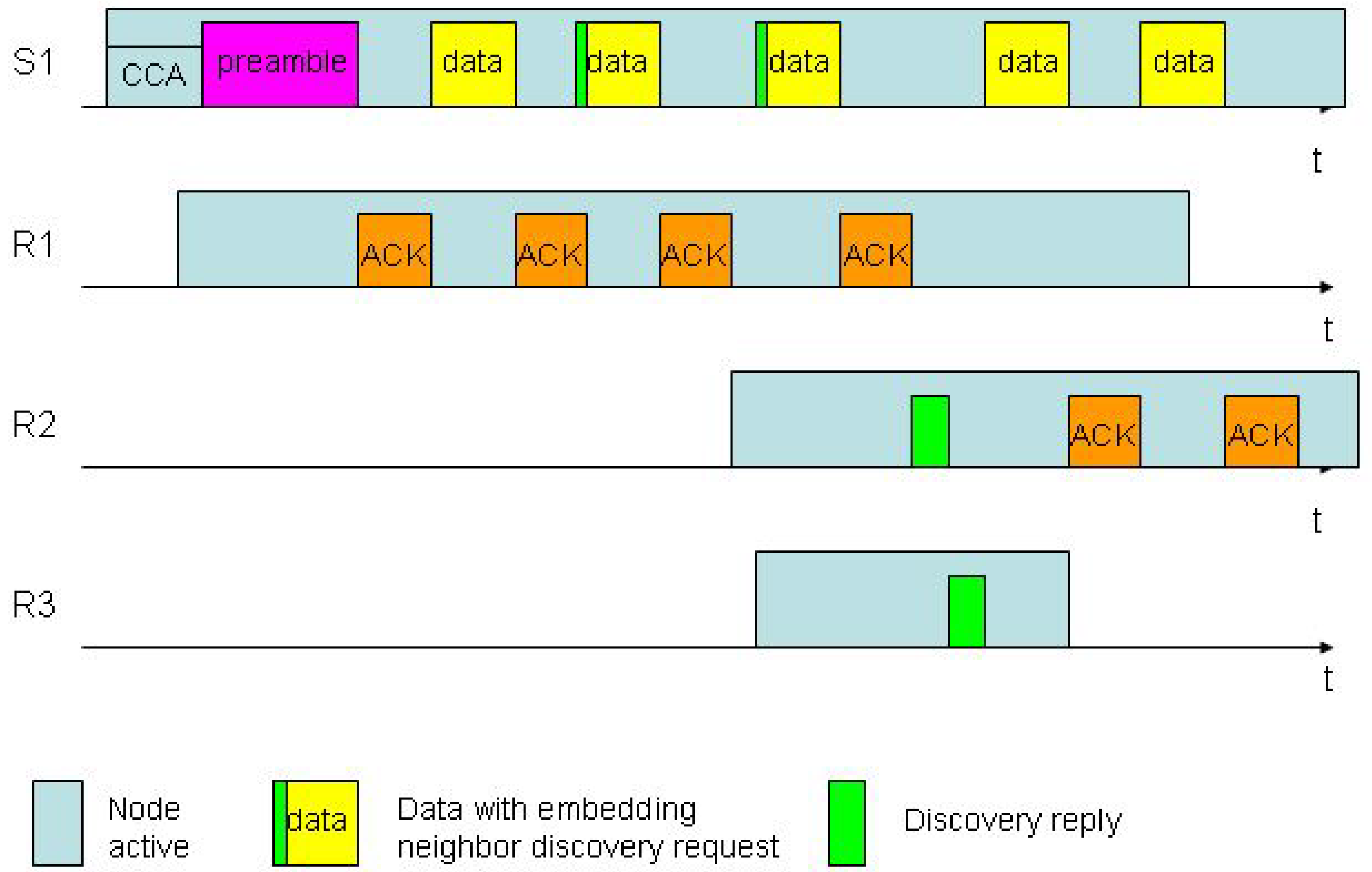


MA-MAC [60]

- The light-weight mobility-aware medium access control protocol (MA-MAC).
- 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.

[60] Z. Tang and W. Dargie, “A mobility-aware medium access control protocol for wireless sensor networks,” *The fifth IEEE international workshop on Heterogeneous, Multi-Hop, Wireless and Mobile Networks (Globecom 2010)*, December 2010.

Handover mechanism in MA-MAC

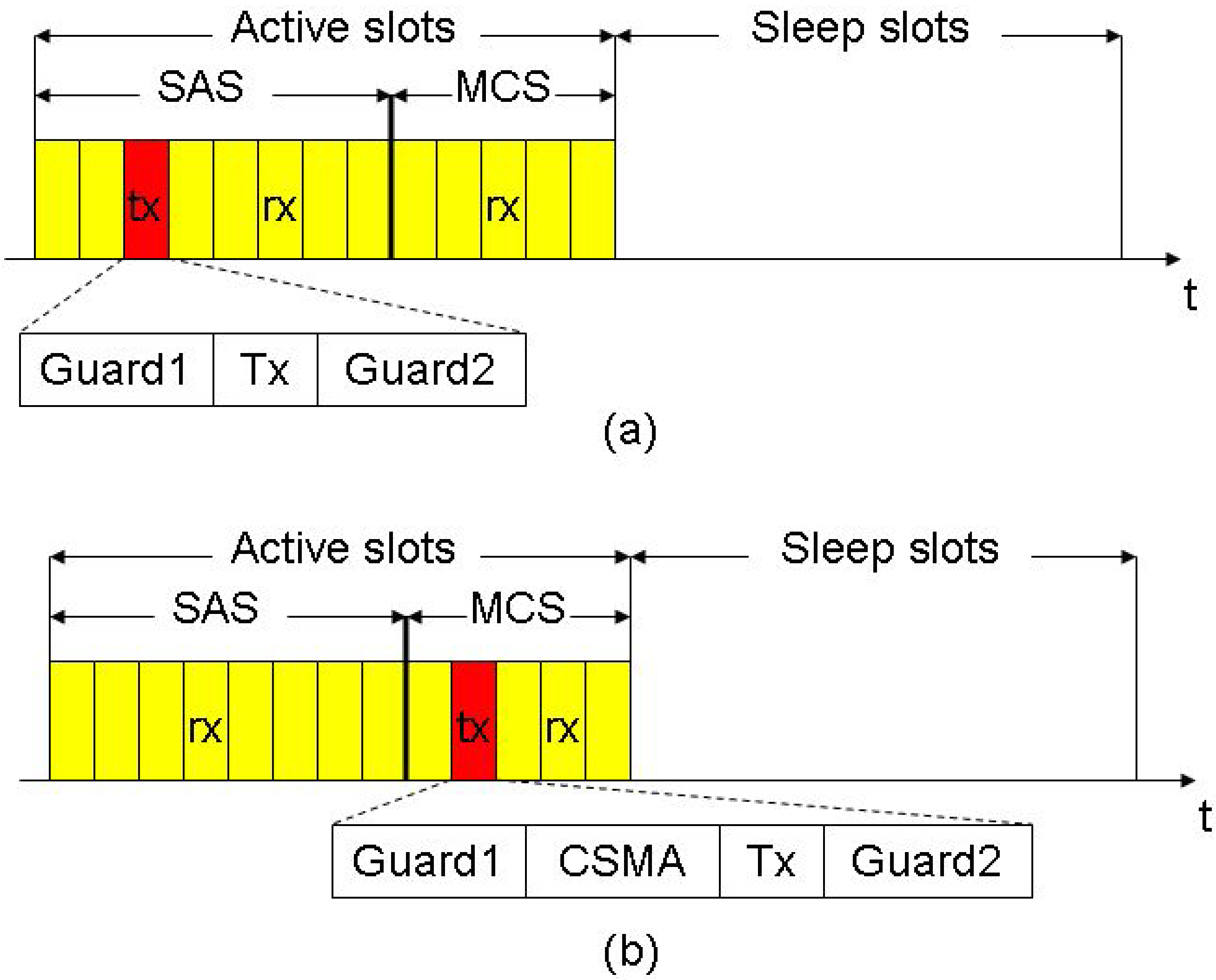


MobiSense [66]

- MobiSense 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.

[66] A. Gonga, O. Landsiedel, and M. Johansson, "MobiSense: Powerefficient micro-mobility in wireless sensor networks," *Proc. 7th IEEE International Conference on Distributed Computing in Sensor Systems*, June 2011.

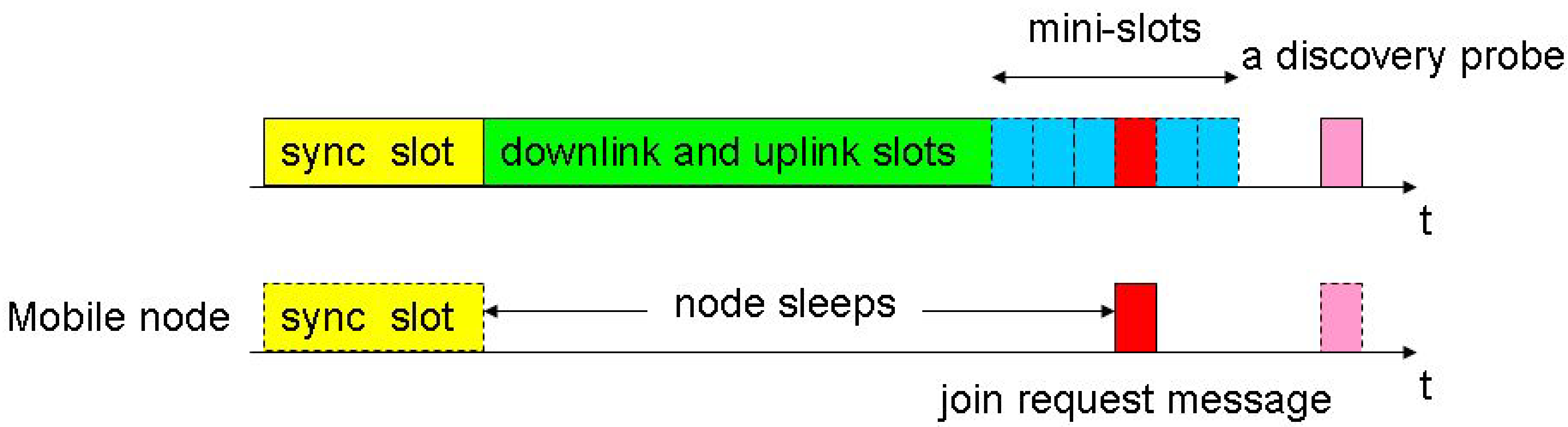
Architecture of MCMAC



tx: transmitting slot

rx: receiving slot

Work mechanism of MobiSense



MCMAC [67]

- The mobile cluster MAC (MCMAC) is a schedule based MAC protocol.
- 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.
- 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).

[67] M. Nabi, M. Blagojevic, M. Geilen, T. Basten, and T. Hendriks, "MCMAC: An optimized medium access control protocol for mobile clusters in wireless sensor networks," *7th Annual IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks (SECON)*, pp. 1–9, June 2010.

Comparison Among The Mobility-Aware MAC Protocols

MAC Protocols	Estimation techniques	Characteristics
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.
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.
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.
MA-MAC	Pattern matching model	1. A contention-based protocol based on XMAC. 2. It defines two thresholds for handling mobility.
MobiSense	Information theoretic model	1. A schedule-based MAC protocol. 2. It uses mini-slots, discovery slots and multi-channel communication for handling mobility.
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.

MAC Protocols	Advantages	Disadvantages
MS-MAC	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	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	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	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	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	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.

Conclusion

- The chapter 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 chapter investigated six mobility-aware MAC protocols and compared their merits and demerits.

Homework #5:

1. Please describe the movement pattern of mobile sinks in this chapter.
2. Please describe three mobility-aware MAC protocols in this chapter.