An Energy-Efficient Adaptive Group Clustering in Wireless Sensor Networks for Mobile Groups

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Mochammad Zen Samsono Hadi

(モハマド　ゼン　サムソノ　ハディ)

Toyohashi University of Technology

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Department ELECTRICAL AND ELECTRONIC INFORMATION ENGINEERING	Student ID Number	D 149202	Supervisors	Hideyuki UEHARA Takashi OHIRA Shuichi ICHIKAWA
Applicant's name	MOCHAMMAD ZEN SAMSONO HADI			

Abstract（Doctor）

Title of Thesis	An Energy-Efficient Adaptive Group Clustering in Wireless Sensor Networks for Mobile Groups

A large number of sensor nodes create a wireless sensor network. It has components such as sensing, wireless communication, and data processing. Wireless sensor networks (WSNs) have many applications, for example exploration, wildlife protection, and health care application. Other applications that consider group mobility are search and rescue activity and the evacuation of people in a natural disaster. Regarding these applications, a WSN needs to be designed considering mobile nodes. The main goal of mobile WSNs deployed in a network area is to deliver more data from a mobile sensor node to a base station (BS) with the limitation of energy consumption. Then, the data will be analyzed at the BS. Data collection and energy consumption are important factors in designing and determining mobile WSNs. To effectively perform these tasks, this thesis presents several protocols based on a clustering system to tackle such issues.

Firstly, this thesis proposes a protocol which supports handover procedure with entity mobility, i.e., Mobile Node Low-Energy Adaptive Protocol (MN-LEACH). The protocol reduces the distance between cluster head and cluster member when the cluster member moves out from the current cluster head. MN-LEACH outperforms LEACH in terms of number of alive nodes and the energy dissipation per round. Then, to support the group movement and to achieve an energy-efficient protocol, it proposes another protocol, namely a Group mobility based Clustering (GC) scheme. GC schemes apply a group as a cluster which consists of group leader and group member. This protocol reduces the control overhead in the setup phase of a clustering system by introducing a concept of group leader and group member. In this scheme, the communication with cluster-head is only done by the group leader to save the energy consumption. Based on the simulation results, GC Single increases the lifetime of the networks and the number of packets received at a base station, compared with LEACH and MN-LEACH. From this viewpoint, we study the characteristic of sensor nodes in mobile environment with entity mobility (MN-LEACH) and group mobility (GC Scheme).

We then tackle some problems of the existing protocols on the design of mobile group WSNs such as high control packet and energy consumption as well as more frequent topology changes that reduce network lifetime and the number of data items received at the base station. To address these problems and to respond to the challenge of group mobility based scheme, this thesis proposes a new protocol considering group mobility together with assigning an appropriate role to nodes, i.e. an Energy-efficient Mobile Group Clustering (EMGC) protocol for mobile WSNs. It makes a fixed group formation of all sensor nodes to evaluate clearly the effectiveness of the scheme. The sensor nodes are divided into three categories, i.e., a cluster head, a group leader and a group member node. In our cluster formation and group handover scheme, group leaders and cluster heads do most of the communications to save on energy consumption during which group members are placed in the sleep condition. This scheme will reduce the number of control packets and frequent topology changes in the networks. n addition, EMGC provides a group handover procedure when the group of sensor nodes moves out from the current cluster and gets closer to another cluster. EMGC protocol outperforms MN-LEACH, GMAC, MBC protocols in terms of energy dissipation and the number of data items received at a base station.

In mobile group environments, there is a possible event occurring in a mobile group environment where some mobile nodes in the same mobile group move to other mobile groups. This becomes a challenging problem in EMGC protocol because EMGC uses a fixed group formation which causes a longer distance between GL and GM and requires more transmission power. Furthermore, this protocol fails to maintain the number of data delivery and network lifetime as increasing the number of groups also increases the number of control packets and collisions between GL and GM. To address these problems, this thesis proposes a novel group formation scheme which is integrated with an EMGC protocol, i.e. an Adaptive group formation with EMGC (AgEMGC) for mobile group WSNs. It uses a link expiration time and residual energy to form a stable link in a group. It also has a group merging procedure to decrease the number of groups. Furthermore, it develops two additional functions for the protocol, i.e., GL rotation and a stay connection procedure to diminish energy consumption in the network. AgEMGC protocol outperforms MBC, EMGCwoh, and EMGC protocols in terms of data delivery, network lifetime, and energy dissipation per round with various group change probabilities and percentages of groups.

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"Indeed, with hardship comes ease."

(QS. Alam Nasyroh: 6)

I dedicate this doctoral thesis book to:

My late mother who endless supported me

My late mother who endless loved me

My late mother who always prayed me in her do'a

My late father who always inspired me all the time

May Alloh meet us in Jannah

And to my beloved family for their endless love, sacrifice, do'a, support, and patience . . .

Chapter 1

Introduction

1.1 Research Background

A large number of sensor nodes will create a wireless sensor network. It has components such as sensing, wireless communication, and data processing. WSNs have many applications, such as exploration, wildlife protection, search and rescue activity, and natural disaster scene where mobile sensor nodes will be deployed in a network area.

Mobile wireless sensor networks enable to monitor variable environments for many applications in the above-mentioned especially in natural disasters. It will have some benefits when deploying large numbers of mobile sensor nodes in the network area compared with static sensor nodes such as:

- **Extended coverage area**. In the static sensor nodes, it may not guarantee to cover all areas in the sensing network and to connect all nodes. By using mobile WSN, it can cover blank spots and resolve frequent topology changes.
- **Battery-powered**. If some nodes die due to the exhaustion of energy in the mobile nodes, it can cover holes in the WSN's coverage.
- **Multiple mission**. By using mobile WSNs, it can support multiple mission under various conditions. For instance, an object tracking application, and

monitor health condition to evacuate people in disaster area.

Designing a mobile sensor node has some research challenges in order to meet some requirements such as:

1. Energy Efficiency

   In WSNs, the nodes will be equipped with battery and it cannot be replaced. This condition drives researches how to extend the lifetime of WSNs with two primarily considerations i.e. a low duty cycle and energy harvesting. In our research, it will focus how to make the mobile sensor nodes in a low duty cycle to get energy efficiency.

2. System Lifetime

   In relation with energy efficiency, the networks should function as long as possible. System lifetime can be measured using generic parameters, such as the time until the nodes die.

3. Latency

   Data from mobile sensor networks are typically time-sensitive, so it is important to receive the data in a timely manner.

4. Reliability

   There are some problems when deploying WSN nodes such as attenuation, shadowing, interference, packet lost and etc. These problems become challenge to design a WSN protocol especially in large area networks.

5. Scalability

   In large area networks, scalability of WSN is challenged. The protocol should address the problem such as contentions or collisions. To reduce contentions, it could use a scheduling protocol; divide nodes into some groups or clusters so that only a head of cluster or group will participate in routing traffic.

6. Adaptability

   Mobile WSNs has challenge for adaptability, for instance when a mobile nodes move from one location to another location, it will make frequent topology changes. Another problem for group mobility is an adaptive group where group formation is changed time by time.

1.2 Wireless Sensor Networks Applications

WSNs are currently receiving huge attention as a basic tool to monitor physical parameters of interest or detect emergency events, such as pollution, temperatures, pressures, and so on. Static sensors are used as traditional WSN application, for example, environmental monitoring to collect data from large or remote geographical areas to a base station. Recently, WSN applictions have shifted a paradigm from static condition to dynamic environments where nodes are mobile. The nodes could be attached to people, animals and moving objects by non-group or group mobility. We focus on the applications with group mobility in our research, for example:

1.2.1 Animal Tracking

WSNs can be applied to monitor cattle not only in the farms building or on the pastures but also when they are transported between farms. In the monitoring system, the animals form groups and move around a field. Outfitting a sensor and tracking device to a cow's collar, ear, leg, tail, or via an ingestible microchip gives farmers the ability to track a cattle's activity levels, health, and other key behaviors like reproduction activity to increase output and overall herd wellness.

1.2.2 Search-and-Rescue Teams

Robots can be integrated with search-and-rescue teams to find live victims in the damaged building or disaster scenario where there is a possibility of the presence of toxic gases. Therefore, the rescue team can take the necessary precautions before entering the scene. Whenever the victims are detected, the robot provides the rescue team with the location of the victim relative to their position and also the surrounding air quality details, so that the rescue team can reach the victim quickly with the necessary arrangements. During search-and-rescue operations, searchers are organized and moving into groups, with intra and inter-group communication.

1.2.3 Healthcare Monitoring

Healthcare monitoring of patients in health facilities by using body sensor networks is one of the most important applications of sensor networks. Wireless body sensor networks can be used to detect abnormal physiological parameters values or uncommon body positions by putting some sensors in the patient's body. Then it generates and transmits an alarm message to medical staff. The body sensors move together in a group.

1.2.4 Evacuation Systems

Early disaster warning and evacuation system is very common disaster management approach in disaster-prone areas of the world. Lack of preparedness of people causes the major damage during disaster. Therefore, adequate prior disaster warning and effective evacuation system can save significant number of lives in the country prone to frequent disasters. WSN can be applied into this scenario where the people will wear sensor nodes to monitor their vital information, for example, a pulse rate, temperature, blood pressure, step counts, location, direction, and so on. Various sensors can be used to measure the above people conditions, such as (1) pulse oximeter, to measure the amount of oxygen in blood, (2) BPMote, to detect and report the blood pressure, (3) EKG sensor, to detect heart rate. In the evacuation system, people move in groups to go to safe areas (shelters).

Regarding the natural disasters, Japan has the Disaster Management System to respond and mitigate vulnerabilities of the disasters. Because of geographical, topographical and meteorological conditions, Japan is subject to frequent natural disaster such as typhoons, torrential rains and heavy snowfalls, wind and flood, as well as earthquakes and tsunami [1].

On March 11, 2011, a gigantic earthquake of magnitude 9.0 struck off the Pacific coast of Tohoku, Japan and generated a huge tsunami that left 15,868 fatalities and 2,848 missing (The National Police Agency, August 22, 2012). Of the fatalities, over 90% of the dead drowned due to the earthquake-induced tsunami: Of the 13,135 fatalities recovered by April 11, 2011, 12,143 (92.5%) died by drowning, 578 (4.4%) were caused by crushing, 148 (1.1%) by fire, and 266 (2%) were unknown [2].

Concerning to the earthquakes, Japan Meteorological Agency (JMA) constantly monitors seismic activity. Surrounded by water on all sides with long and complex coastlines, Japan is highly vulnerable to earthquake-generated tsunamis. When a tsunami is expected to caused coastal damage, JMA issues a big tsunami warning, tsunami warning or advisory within 2-3 minutes after earthquakes and then follows up with announcements about the estimated height and arrival time of the tsunami. The information is transmitted immediately to disaster management organizations and media outlets, and further forwarded to residents and maritime vessels. This is to maximize time for evacuation and to reduce casualties as Fig. 1.1. An initial step in protecting human lives from tsunami is evacuating to a higher place swiftly and autonomously, without hesitation, as soon as strong or an extended shaking is felt. It is also critical for evacuees to go to a safe place.

In the study's results [2] show that earlier evacuation was positively associated with higher survival rate. There are three factors of the survival rate which are analyzed in the study, i.e., (1) safety of evacuation places, (2) preparedness before disasters, and (3) evacuation time. Persons who started evacuation within 30 minutes reported

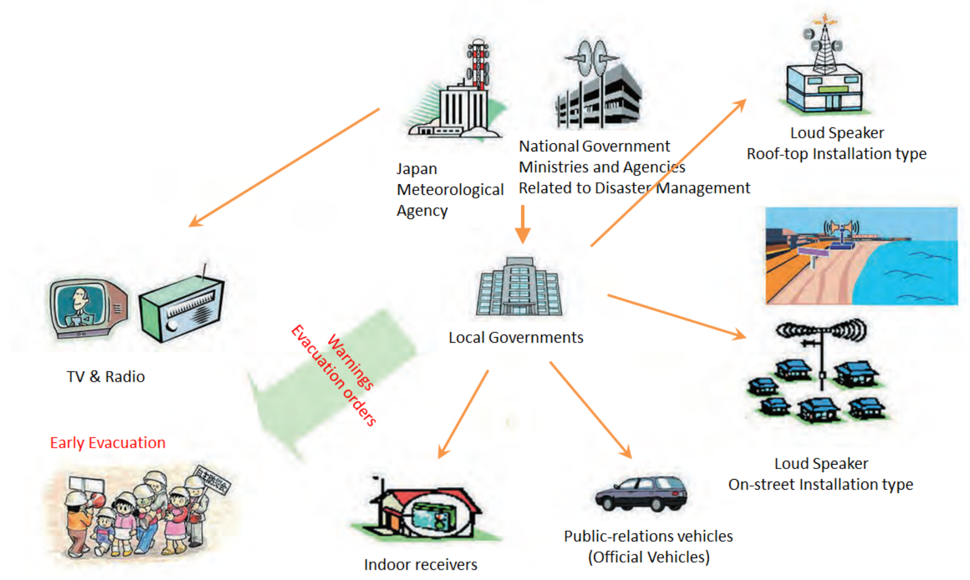


FIGURE 1.1: Early Warning Systems [1].

TABLE 1.1: Evacuation Time Result

Evacuation Time	**Survivors**	**Death/Missing**
Immediately	14% (71)	10% (36)
1-5 minutes	17% (84)	7% (23)
6-10 minutes	19% (94)	11% (38)
11-20 minutes	17% (87)	8% (28)
21-30 minutes	11% (56)	9% (32)
31-60 minutes	8% (42)	6% (20)
61-120 minutes	2% (9)	1% (2)
More than 120 minutes	1% (4)	1% (2)
No evacuation	11% (58)	48% (170)
Total	100% (505)	100% (351)

greater survival rates as Tables 1.1 and 1.2. Safer evacuation place and better preparedness before the disaster, however, had no positive effect on survival.

Regarding the walking speed of people in the evacuation system of natural disaster, there are two types of evacuees were established: fast walkers and slow walkers [3] and it can be seen on Table 1.3.

In another research [4], the average pedestrian speed of 1.10 m/s agrees with the maximum value of 1.33 m/s and the average car speed of 5.03 m/s with the maximum value of 8.33 m/s.

TABLE 1.2: Evacuation Time Scale

Evacuation Time	Scale
Immediately	9
Within 5 minutes	8
Within 10 minutes	7
Within 20 minutes	6
Within 30 minutes	5
Within 60 minutes	4
Within 120 minutes	3
More than 120 minutes	2
No evacuation	1

TABLE 1.3: Walking Speed of Evacuees

Density	Fast walkers	Slow Walkers
Less than 2 people/m2	2.0m/sec	0.5 m/sec
2-3 people/m2	1.5m/sec	0.375 m/sec
3-4 people/m2	1.0m/sec	0.25 m/sec
More than 4 people/m2	0.75m/sec	0.189 m/sec

1.3 Problem Definition and Solution

Based on the above applications, it needs to design good protocol for mobile WSNs with group movement. In some cases, there is a possible event where some mobile nodes in the same group move to other groups. We call it a dynamic group change. There are some interesting issues and challenges to address the problem, such as:

1. How to handle group mobility well in the networks
2. How to make group formation and group transition
3. How to reduce frequent topology changes which causes the depletion of energy consumption
4. How to reduce control packets
5. How to reduce energy consumption to prolong network lifetime
6. How to deliver more data to a base station

Regarding these requirements, we have designed an adaptive group formation integrated with clustering scheme for mobile group that is a protocol architecture for mobile WSNs which achieves low energy dissipation and latency. This protocol uses a clustering architecture where the mobile nodes in the cluster send their data to a local cluster head. Then the cluster head send the aggregated data set to the end-user (base station).

The objectives why we choose the clustering scheme are:

1. Maximal network lifetime with reducing energy transmission because the mobile nodes are close each other to share data.

2. Fault tolerance with rotating cluster head. A cluster head node is much more energy consumption than non cluster head node because it receives data from all the nodes in the cluster and transmit the data to a base station. By rotating cluster head, it will evenly distribute the energy load among all the nodes in the network and to avoid fault network when the cluster head node is dead.

3. Reduce collisions of data within cluster, saving energy and time because it uses a time division multiple access (TDMA) approach in the steady-state phase.

The previous works related to topics that is essential for this thesis are summarized as Table 1.4.

LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol is as basic clustering reference. It proposes two schemes, i.e., (1) LEACH with decentralized clustering where cluster formation by nodes itself, (2) LEACH-C with centralized clustering where cluster formatin by base station. It uses homogeneous energy that is the same initial energy for all the nodes.

As we can see on Table 1.4, there is lack protocol to support group handoff and mobility both with homogeneous and heterogeneous energy. Our designed protocol fill in this lack.

TABLE 1.4: Previous works on clustering scheme

Protocol	Cluster Distribution	Individual Handoff	Mobility Model	Distribution Energy	Problem
LEACH/ LEACH-C [5]	Decentralized/ Centralized	x	x	Homogeneous	do not consider mobility
M-LEACH (Mobile-LEACH) [6]	Centralized	v	Non-group based	Homogeneous	Link quality deterioration
Leach-Mobile [7]	Decentralized	v	Non-group based	Homogeneous	Increase control overhead, high energy consumption
Cluster Based Routing (CBR) [8]	Decentralized	v	Non-group based	Homogeneous	Increase control overhead due to frequent topology change
Mobility-based Clustering (MBC) [9]	Decentralized	v	Non-group based	Homogeneous	Fails to address the critical node occurrence problem
Group Mobility MAC (GMAC) [10]	Decentralized	x	Group based	Homogeneous	No handover scheme to address frequent topology changes

1.4 Contributions

We build a protocol of mobile sensor nodes with adaptive group mobility scheme integrated with clustering protocol for mobile group WSNs that has contributions as follows:

1. To provide a protocol for mobile WSN which is applied in group movement scenario, such as the evacuation system of natural disaster.
2. To address some problems in designing mobile WSN such as frequent topology changes, the number of data items received at the base station, energy consumption per round, adaptive group formation and etc.
3. To provide a protocol with features such as energy-efficient, reliability, scalability, and adaptability.

1.5 Outline of Thesis

The outline of this thesis is as follows.

- **Chapter 1** describes our motivation for doing research in the field of mobile group WSNs. This chapter also explain WSNs application using group movement, problem definition and solutin, as well as our contributions.
- **Chapter 2** presents the state of the art and the research challenges.
- **Chapter 3** presents fundamentals of mobile WSNs.
- **Chapter 4** presents a protocol to handle non-group mobility based clustering scheme for mobile WSNs.
- **Chapter 5** presents a protocol to handle group mobility based clustering scheme for mobile WSNs.
- **Chapter 6** presents a novel protocol with adaptive group formation scheme for mobile group WSNs.
- **Chapter 7** concludes the thesis with a summary, followed by the future work.

Chapter 2

State of the Art and Research Challenges

Wireless sensor networks are one of technologies which consist of a large number of sensor nodes. They can sense a variety of physical phenomena and are able to self-organize in order to maintain the network. They also have the small size of nodes where the sensor nodes can be easily installed inaccessible areas or expensive to wired system.

A large number of applications have been proposed for wireless sensor networks (WSNs). Werner et al. [11] deploy WSNs to monitor active volcano that employ seismic and infrasonic sensors. Camilli et al. [12] use temperature, humidity, and pH sensors from the environment using WSNs for precision agriculture. Stoianov et al. [13] deploy WSNs to monitor large diameter, bulk-water transmission pipelines using hydraulic and acoustic/vibration sensors.

Nowadays, Mobile wireless sensor networks (MWSNs) has already spread out in many applications such as healthcare and assited living environments using wireless body area network (WBAN) [14][15][16][17], pilgrims tracking using a geographical information system (GPS) to send its user identification (UID), latitude, longitude, and time stamp to server [18], and natural disasters [19][20] where nodes are attached to people and vehicles to monitor their activities [21] as well as integration WSNs with IoT systems [22][23].

WSNs have wireless channel which presents several networking challenges, such as limited channel bandwidth and node energy, electromagnetic wave propagation, error prone channel, time-varying conditions, and mobile nodes [24]. Some of the above networks may change their topology due to some reasons, for example, when the sensor nodes have hardware failure or exhaust their batteries and when new nodes join the network [25]. To address the above limitations, it can use a schedule-based MAC protocol with clustering scheme [25].

2.1 Media Access Protocol (MAC) Protocol

MAC protocols are used multiple users to share the channel. Almost all of the MAC protocols in WSNs can adapt with slow change in a network's topology [26]. For example, nodes in SMAC [27] update their neighborhood knowledge by exchanging synchronization packets with a contention-based protocol. MS-MAC [28] is a contention-based protocol extends SMAC where a mobile node can connect with a new virtual cluster by running synchronization frequently. There are two advantages with this protocols, i.e., (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.

TRAMA [29] is a schedule-based MAC protocol which adjust the frame size and the proportion within a frame. LMAC [30] is an extended TRAMA protocol where the protocol uses TDMA to give nodes the opportunity to communicate collision-free. The network is self-organizing in terms of time slot assignment and synchronization with main goal of the MAC layer is to minimize overhead of the physical layer.

MMAC [31] is a schedule-based MAC protocol which introduces a flexible frame time that enables the protocol to dynamically adapt the mobility. MACA [32] is a mobility adaptive clustering algorithm where clusters are formed by a simple point predictor for combined criterion prediction and stability value.

2.2 Clustering Protocol

Mobility has decreased the quality of communications because of network topology changes often, and the movement of the node will break wireless connections [33]. Clustering techniques in WSN are used to allow sensor nodes send data in a hierarchical manner. This method is to increase the performance of the nodes such as reducing the workload of each sensor and power consumption in the devices as well as allowing scalability [34]. Based on the above conditions, the clustering techniques in MWSNs offer an alternative to wired networks when disaster occur affecting infrastructure collapses.

The implementations of clustering protocols mostly assume that the nodes are static [5][35][36][37][38][39][40][41]. The mobility of the sensor nodes affects the performance of the clustering methods become drop because it does not consider such as handover mechanism. Some protocols are designed to take the consideration of mobile nodes [6][42][7][43][44][45][46][47][48], however the protocols use randomized movement model which have independently velocity and direction. In some real applications such as evacuation of the victims in the natural disaster, search-and-rescue operation, they will move together in a group. This condition needs a group mobility movement model to simulate the coordination and to save the energy consumption in the network.

How to get the efficient way to send data from the node to a base station is one of the important research topics in mobile sensor networks. It has the goal such as how to get the maximum of the data delivered to the base station and to minimize the energy consumption during communication [10]. In the mobile environment, the node will move from one location to another location, which causes the change of the network topology and effects on the network performance, especially in energy efficiency [49][50][51][52]. A variety of protocols which support mobility of the nodes have been proposed to overcome the energy efficiency problem and prolong the lifetime of the networks as well as increase the successful packet delivered to the base station [6][42][7][10][9]. To reach the goal, cluster based topology gives a vast improvement in mobile wireless sensor networks by reducing the overhead when all nodes send their data to the base station [53]. In the clustering scheme as in Fig. 2.1, the sensor nodes will send their data in the scheduled time manner, and the medium access is scheduled for the nodes to wake up, sleep, transmit, and receive [25][54], and it makes a highly dynamic, stable network topology [55].

2.2.1 LEACH Protocol

On the clustering protocols, the first hierarchical method for static WSN is Low-Energy Adaptive Clustering Hierarchy (LEACH) [5], and Hybrid Energy-Efficient Distributed clustering (HEED) [35]. The protocols are divided into a number of rounds where each rounds consists of two phases i.e. setup phase and steady phase. In the setup phase, some nodes are selected become cluster-heads by using probabilistic calculation. After that, the cluster-head broadcast ADV message to all nodes, then the nodes will choose the cluster-head based on the received signal strength. The cluster-head make TDMA schedule and transmit the schedule to all cluster members. In steady state phase, each cluster member sends its data to cluster head based on the scheduled time in TDMA slot. After one frame, all data from cluster members will be forwarded to sink node by cluster head. In the Fig. 2.1, it is the process to create cluster and timeline showing LEACH operation.

Another variant of LEACH protocol that supports mobility is M-LEACH [6]. In

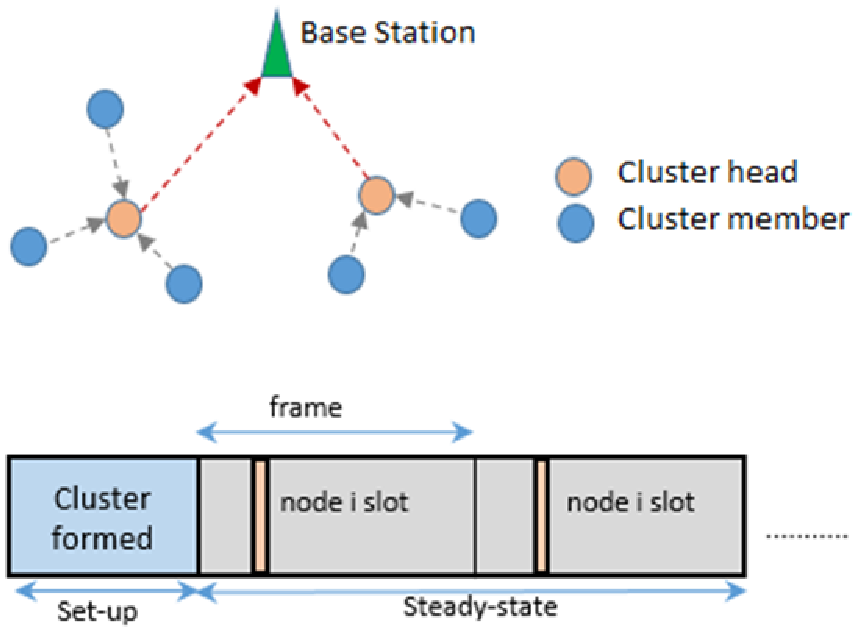


FIGURE 2.1: LEACH protocol and the timeline.

M-LEACH protocol, if a node in one cluster wants to move closer to another cluster-head, it will spend more energy to keep still in touch with the previous cluster head. To improve the performance of the protocol, M-LEACH supports a hand-off mechanism which permits the nodes to change its cluster head. In the set-up phase, all nodes send the information containing locations, velocity and energy level to Base Station (BS). Then BS will compute the cluster-head by adding parameter i.e. mobility. The node with less mobility will be chosen as a cluster-head. M-LEACH used zone area to create a cluster. In the steady state phase, each cluster member sends its data to CH, after that the aggregated data will be transferred to the BS by the CH. During invitation in transmission phase, CH will let other nodes join in their cluster by calculating the willingness (the cost to join). The node will choose the smallest value to decide the new CH. It will send a DIS-JOIN message to the previous CH and JOIN to the new CH. After that, CH adds or removes its transmission schedule based on the JOIN and DIS-JOIN message and broadcast the schedule to nodes in the same cluster.

Awwad et al. [8] proposed cluster-based routing (CBR) protocol with an adaptive

Time Division Multiple Access (TDMA) scheduling and round-free cluster-head to reduce the packet loss in the LEACH-mobile. However, it increases the control overhead used in the networks which causes more energy consumption.

2.2.2 MBC Protocol

The mobility-based clustering (MBC) protocol [9] makes a stable cluster and supports an adaptive TDMA. In the MBC protocol, a node elects itself as cluster head based not only its residual energy but also on its mobility. During clustering, a non cluster head node takes into account its connection time with a cluster head to make link stability. A cluster head creates a TDMA schedule based on the estimated connection time of each node in its cluster. Then, the non cluster head nodes send data packets according to the time schedule. When a sensor node has lost or is going to lose connection with its cluster head, it will broadcast a joint request message in order to join a new cluster and avoid more packet loss.

This scheme increases the successful packet delivered to the base station and achieves balanced energy consumption of all nodes to prolong the lifetime of the networks.

MBC protocol is suitable for the applications with non-group mobility, such as sea exploration, wildlife protection, and traffic congestion control.

2.2.3 GMAC Protocol

Group Mobility Adaptive Clustering (GMAC) protocol [10] is a clustering protocol that considers group mobility. The protocol calculates a mobility group metric, i.e. historical group and prediction group to form clusters. GMAC makes a fixed number of cluster by dividing the networks in equal zones as Fig. 2.2 in which only one cluster head will be elected. During the cluster head election phase, nodes use the mobility group metric and zone definition to get steady clusters. Then, each cluster

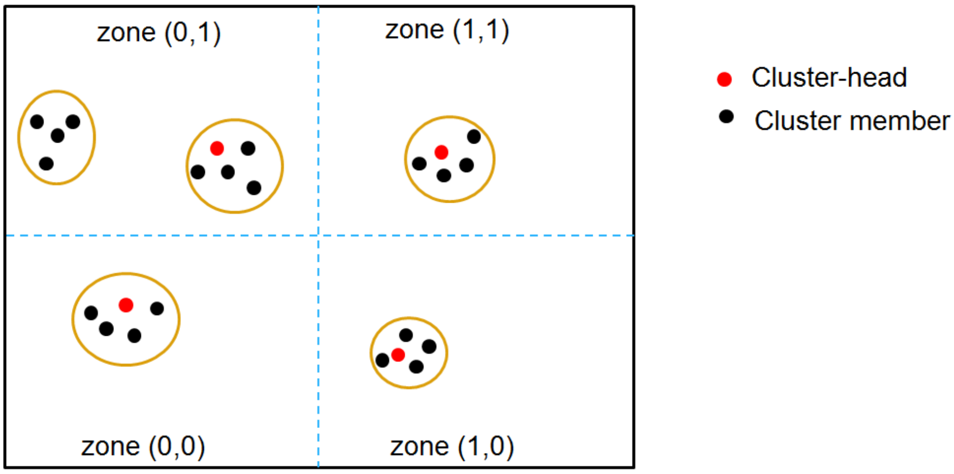


FIGURE 2.2: Zoning area in GMAC protocol.

head broadcast an advertisement (ADV) message to all nodes in the network. After the expiration of the waiting delay to receive all ADV messages, each sensor node selects the cluster head based on the strongest received signal strength. After that, each sensor node sends a request join message to the chosen cluster head. Finally, each cluster head creates a time schedule (TDMA) in which time slots are allocated for intra-cluster communications.

Applications which is supported by GMAC protocol are military network where mobility coherence among the nodes and search-and-rescue operations where searchers are organized and moving in groups.

Chapter 3

System Models of Mobile WSNs

Wireless sensor networks are one of technologies which consist of a large number of sensor nodes. They can sense a variety of physical phenomena and are able to self-organize in order to maintain the network. They also have the small size of nodes where the sensor nodes can be easily installed inaccessible areas or expensive to wired system.

A large number of applications have been proposed for wireless sensor networks (WSNs). Werner et al. [11] deploy WSNs to monitor active volcano that employ seismic and infrasonic sensors. Camilli et al. [12] use temperature, humidity, and pH sensors from the environment using WSNs for precision agriculture. Stoianov et al. [13] deploy WSNs to monitor large diameter, bulk-water transmission pipelines using hydraulic and acoustic/vibration sensors.

Nowadays, Mobile wireless sensor networks (MWSNs) has already spread out in many applications such as healthcare and assited living environments using wireless body area network (WBAN) [14][15][16][17], pilgrims tracking using a geographical information system (GPS) to send its user identification (UID), latitude, longitude, and time stamp to server [18], and natural disasters [19][20] where nodes are attached to people and vehicles to monitor their activities [21] as well as integration WSNs with IoT systems [22][23].

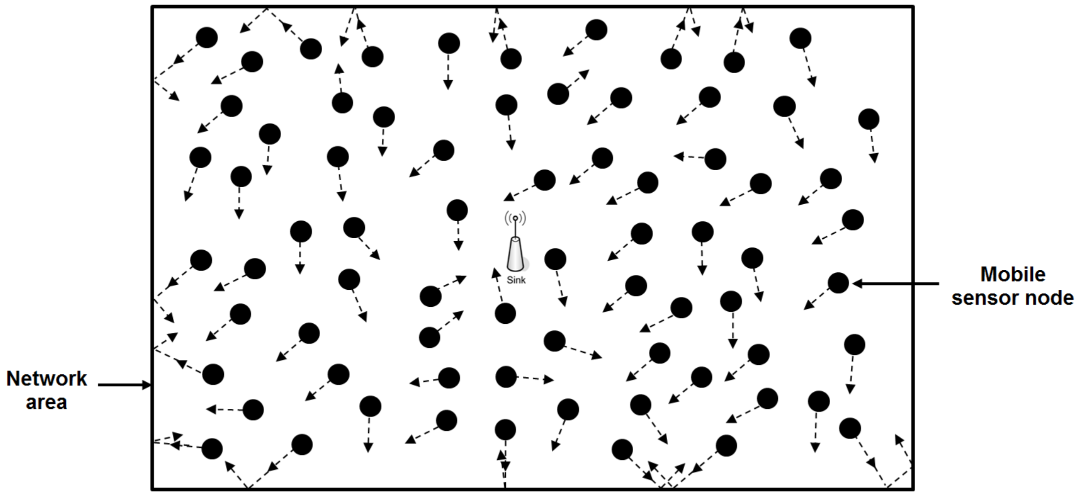


FIGURE 3.1: Network model.

WSNs have wireless channel which presents several networking challenges, such as limited channel bandwidth and node energy, electromagnetic wave propagation, error prone channel, time-varying conditions, and mobile nodes [24]. Some of the above networks may change their topology due to some reasons, for example, when the sensor nodes have hardware failure or exhaust their batteries and when new nodes join the network [25]. To address the above limitations, it can use adaptive routing and MAC layer protocols [24][25].

3.1 Network Model

We consider a mobile sensor network show in Fig. 3.1. The sensor nodes are deployed in network area for monitoring. The sensor nodes move in groups into some direction randomly inside network area. If the movement of nodes reach the edge of network area, the nodes will turn back their direction into inside the area again. The sink (base station) node is located inside or outside the network area.

The communication radius R of a sensor node is static and same for all the nodes in the network. If the distance between any two nodes is less than R, then the nodes are able to directly communicate with one another.

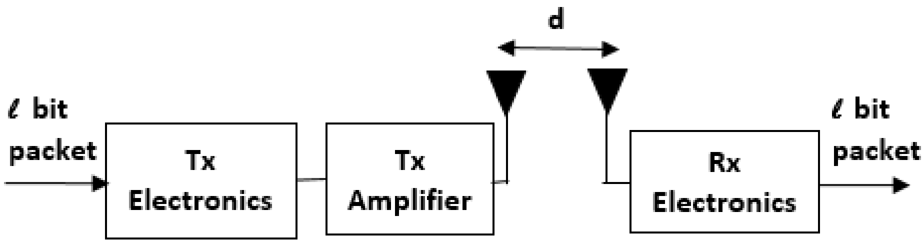


FIGURE 3.2: Radio energy dissipation model.

We have some general assumptions about the sensor nodes in the network area:

- Nodes in the network are mobile after deployment
- Node death is due to energy depletion only
- The homogeneous sensor network is considered, i.e., all the nodes are having equal initial energy. Meanwhile, the heterogeneous sensor network is that some nodes or all the nodes are having unequal initial energy.
- All mobile nodes are location-aware. The sensor nodes can apply location schemes such as GPS to know their location in the networks.
- A base station (sink) is a high powered node without any energy constraint.

3.2 Radio Energy Dissipation Model

Figure 3.2 shows the radio energy dissipation model where energy consumption for the transmitter is to run the power amplifier and the radio electronics [56][57]. Meanwhile, energy consumption for the receiver is to run the radio electronics [5]. Radio electronic energy (E_{elec}) is 50 nJ/bit, meanwhile radio amplifier energy for free-space (ε_{fs}) is 10 pJ/bit/m^2, and radio amplifier energy for multipath (ε_{mp}) is 0.0013 pJ/bit/m^4. The power can be controlled to reduce energy consumption. To transmit a data with l bit and distance d, the transmitter expends:

$$E_{Transmitter} = E_{Tx-electronics} + E_{Tx-amplifier} \tag{3.1}$$

$$E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) \tag{3.2}$$

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, & d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, & d \geq d_0 \end{cases} \tag{3.3}$$

And to receive the data, the receiver expends:

$$E_{Receiver} = E_{Rx-electronics} \tag{3.4}$$

$$E_{Rx}(l) = E_{Rx-elec}(l) = lE_{elec} \tag{3.5}$$

where E_{T_x} is the transmitting cost and E_{R_x} is the receiving cost. E_{elec} is the electronics energy to run the transmitter or receiver circuitry. Meanwhile, ε_{fs} is for the free space propagation and ε_{mp} is for the multi-path fading channel, and the threshold distance is d_0.

3.3 Mobility Model

In the mobile environment of wireless sensor networks, it has to consider what kind of the mobility model will be used. Due to the mobility models have the important role regarding the accuracy of simulations, and it depends on the application. By the mobility scenario, it is possible to determine whether the proposed protocol will be useful or not when implemented. There are two types of mobility models for ad hoc networks [58], i.e., non-group mobility model and group mobility model. We will explain more detail in the next SubSection.

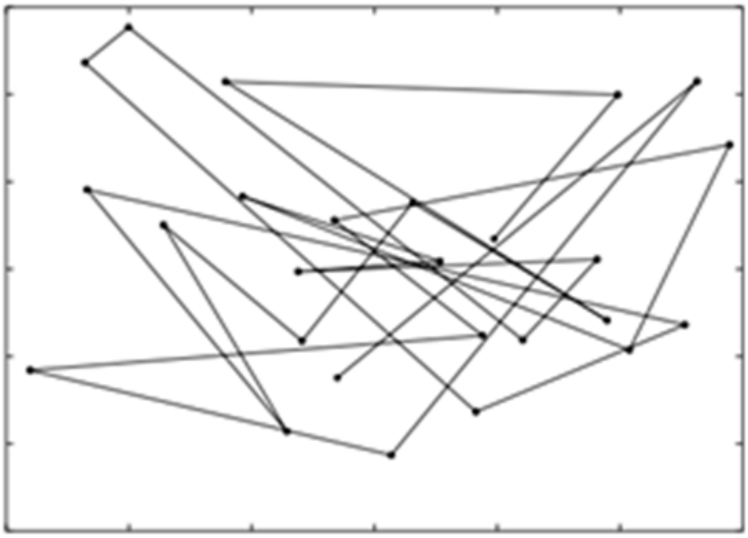


FIGURE 3.3: Random Waypoint Mobility (RWM).

3.3.1 Non-group Mobility Model

Some application such as exploration and wildlife protection [9], animal tracking [6], and environmental monitoring [59], a mobile sensor node will randomly, individually move from one location to others. Random Waypoint Mobility (RWM) model [58] is appropriate for such applications. In RWP model, a mobile node begins by staying in one location for a certain period of time. After this time expires, the node will choos a random destination in the simulation area with uniformly distibuted speed between *minspeed* and *maxspeed*. Then, the node travels towards the new chosen destination at the selected speed. Upon arrival, the node pauses for a specified time period before starting the process again as in Fig. 3.3.

3.3.2 Group Mobility Model

In the application, such as body area network to monitor health condition of patients [60], mobile group target tracking [61], and an evacuation system of the disaster area, the victims will wear the sensor node to go to a safe zone, and the movement of the people mostly use grouping. Reference Point Group Mobility (RPGM) model [62] is suitable for the application wherein the model, every group of nodes moves together

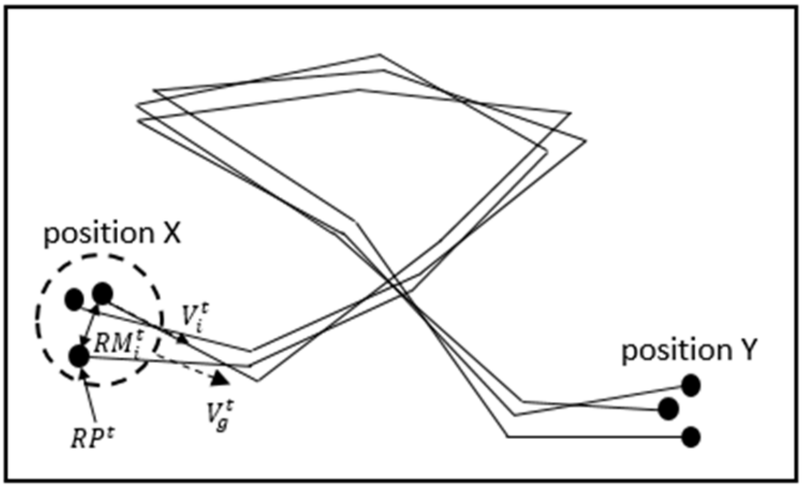


FIGURE 3.4: Reference Point Group Mobility (RPGM).

[63]. In RPGM model, each node that belongs to a group follows a logical center that determines the flow of the entire group. The nodes will be randomly distributed around the reference point. At each instant, the logical center moves from its current location to a new location by randomly choosing a speed and direction. Then every node has a direction and speed which is derived by randomly deviating from that of a logical center. Each group and each member of the group use random waypoint (RWM) model for their moving.

The movement of a logical center (V_g) at time t, is represented by group motion vector V_g^t, and each node in the group deviates from V_g^t by some degree as in Fig. 3.4. The motion vector of the node i, in the group g at time t, V_i^t, can be described as follows.

$$V_i^t = V_g^t + RM_i^t \tag{3.6}$$

where RM_i^t is a random vector of the mobile node i, which is deviated from its own reference point (RP^t) at time t. The length of the vector RM_i^t is uniformly distributed in the interval [0, r_{max}] where r_{max} is maximum allowed distance deviation centered at the reference point. In Eq. (3.6), each node will pick up the current speed of the motion vector.

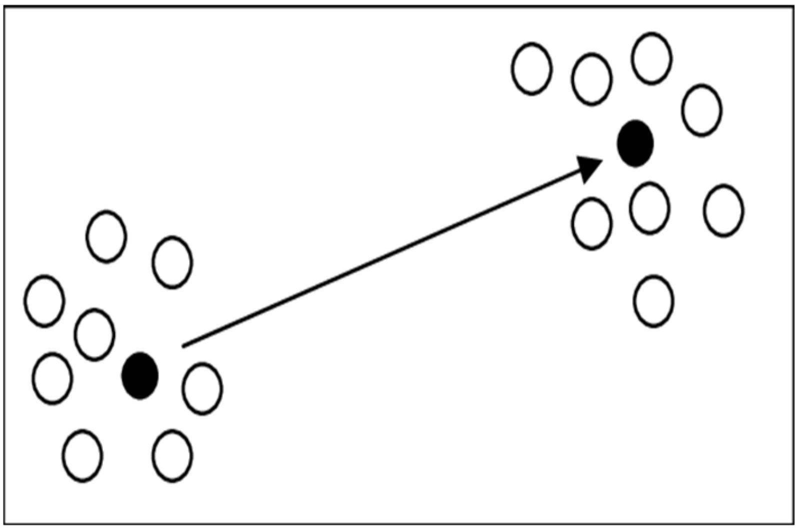


FIGURE 3.5: Nomadic Community Mobility (NCM).

Another group mobility model is Nomadic community mobility (NCM) model [58] as Fig. 3.5. Nomadic model looks like RPGM model which represents group of nodes move from one location to another location. However, some nodes in the group will roam around a particular area individually. In NCM model, each mobile node uses a non-group mobility model (e.g., RWP model) to roam around a given reference point. When the reference point changes, all mobile nodes in the group travel to the new area defined by the reference point and then roaming around the new reference point. The parameters for the non-group mobility model define how far the node may roam from the reference point. For example, consider a class of students touring an museum. The class will move from one location to another together. However, the students within the class would roam around a particular location individually.

Some protocols take into account group mobility in their applications [64][65][66][67]. Some clustering protocols which consider group mobility were also proposed in [10][60][68][69][70]. In [10], the protocol calculates the mobility group metric i.e. historical group and prediction group. During the cluster head election, nodes use a mobility group metric and a zone definition to get steady clusters. Unfortunately, the protocol does not support a handover procedure for group mobility models, and it is hard to implement a zone definition in the natural disasters.

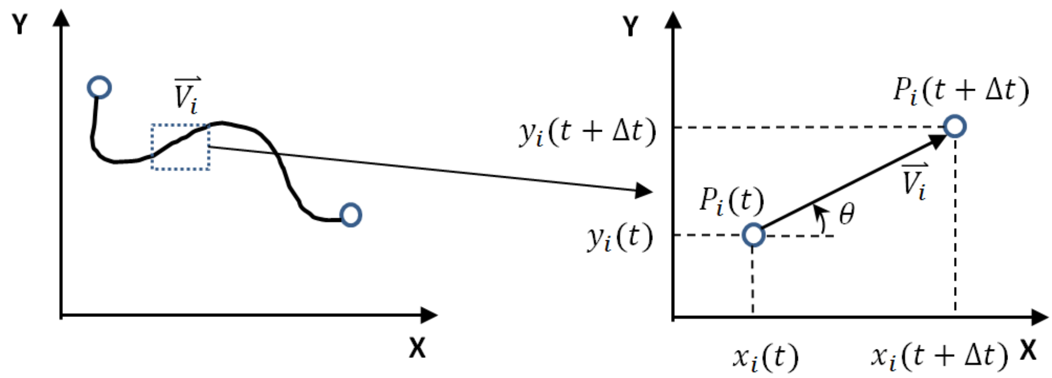


FIGURE 3.6: Position Estimation.

Based on the current issues in designing of mobile WSNs especially with clustering scheme and group mobile nodes, there are some research challenges, i.e., (1) how to design a mobile WSN protocol for natural disaster applications which addresses problems, such as, frequent topology changes, energy efficiency, and adaptability, (2) how to address an adaptive group formation problem in a mobile group environment.

3.4 Position Estimation

To estimate nodes position in the next step, it takes into account node velocity and direction in the estimator [71][72][73][74][75][76]. EECMPR [75] predicts the position of nodes to minimize the overhead and improve accuracy the prediction to maximize network lifetime. Su et al. [76] proposed a protocol which predict future state of network topology and thus provide a transparent network access during the period of topology changes.

As in Fig. 3.6, the trajectory is supposed a rectilinear with a fixed velocity during periods of time. The position of the node i at the instant t_{pred} is given according to its actual velocity and position by:

$$P_i(t_{pred}) = V_i \times \Delta t + P_i(t) \tag{3.7}$$

$$x_i = v_i \times \cos(\theta) \times \Delta t + x_i(t) \tag{3.8}$$

$$y_i = v_i \times \sin(\theta) \times \Delta t + y_i(t) \tag{3.9}$$

t_{pred} can take many values in the time period from time to time. In this thesis, it will be evaluated the time period to take the data [77][78].

In the group movement by using reference point group movement (RPGM) mobility model, it needs to estimate the position for the next movement of the group. In application such as search-and-rescue operation, some people will move together. There are two types of the nodes i.e. group leader, and group member. In the setup phase of a clustering protocol, it will make a group formation. To create a group formation as Fig. 3.7, there are parameters such as cosine similarity, the current distance between a group leader and group member, and the predicted distance between a group leader and group member.

3.4.1 Cosine Similarity

Cosine similarity as Fig. 3.8, is a measure of similarity between two non-zero vectors of an inner product space that measures the cosine of the angle between them. Cosine similarity is particularly used in positive space, where the outcome is neatly bounded in [0,1]. The name derives from the term “direction cosine”: in this case, note that unit vectors are maximally “similar” if they’re parallel and maximally “dissimilar” if they’re orthogonal (perpendicular). This is analogous to the cosine, which is unity (maximum value) when the segments subtend a zero angle and zero (uncorrelated) when the segments are perpendicular.

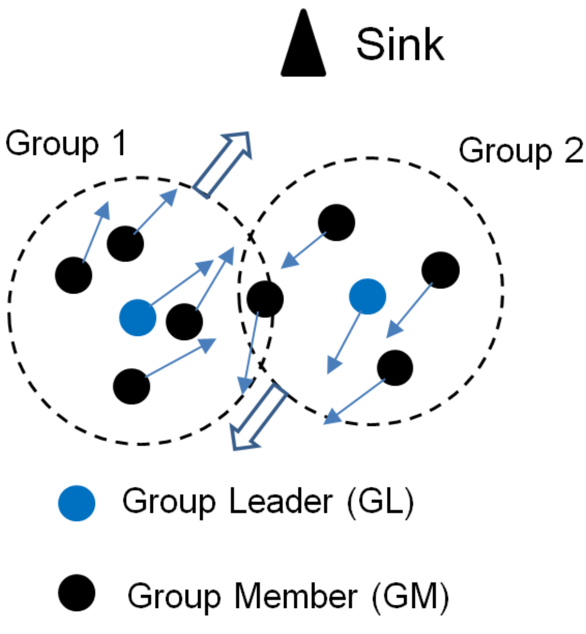


FIGURE 3.7: Group Formation in clustering protocol.

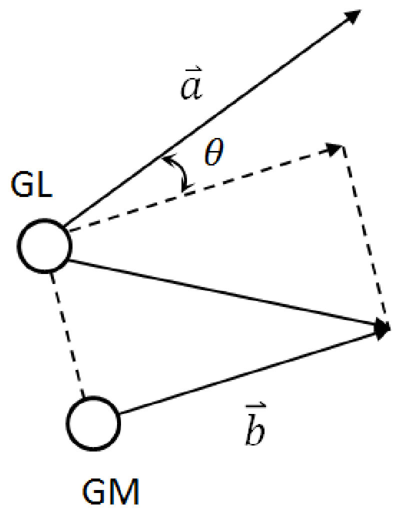


FIGURE 3.8: Vector for node similarity.

If the vector of a group leader (GL) is $\vec{a}$, and the vector of a group member is $\vec{b}$, the cosine similarity, $\cos(\theta)$, is represented using a dot product and magnitude as

$$\theta = \arccos\left[\frac{\vec{a}.\vec{b}}{|\vec{a}|\,|\vec{b}|}\right] \tag{3.10}$$

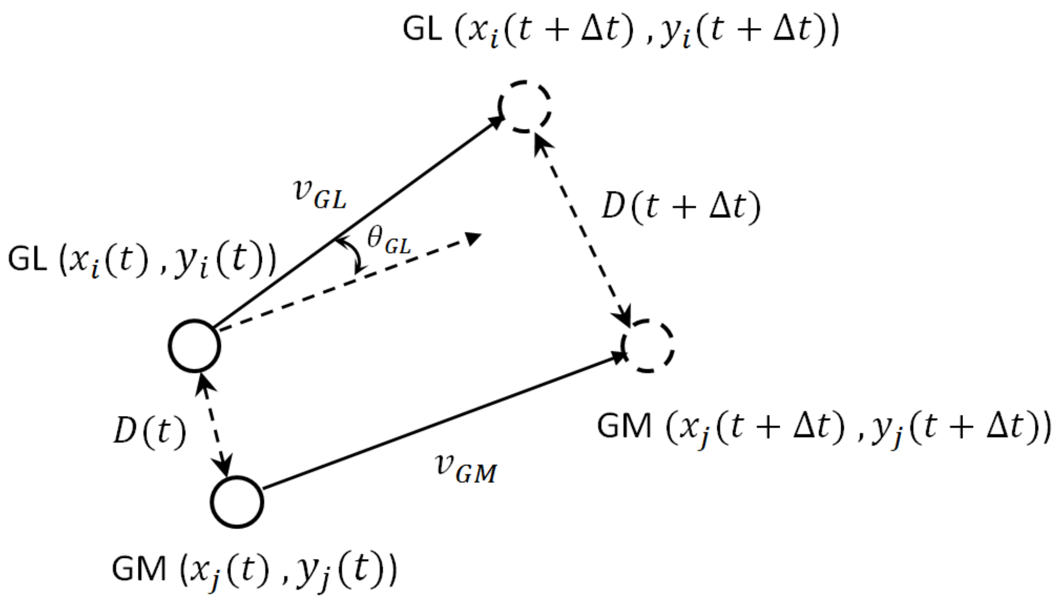


FIGURE 3.9: Current and estimated position.

$$\theta = \arccos\left[\frac{\sum_{i=1}^{n} a_i.b_i}{\sqrt{\sum_{i=1}^{n} a_i^2}\sqrt{\sum_{i=1}^{n} b_i^2}}\right] \tag{3.11}$$

where $0 < \theta < \pi/2$ for a vector similarity.

3.4.2 The current position of the nodes

In the group formation, all group leaders will broadcast a message, and the group member which hears the message calculates the current distance between its position to the group leaders as Fig. 3.9.

The formula to calculate the distance is:

$$D(t) = \sqrt{(GL(x_i(t)) - GM(x_i(t))^2 + (GL(y_i(t)) - GM(y_i(t))^2} \tag{3.12}$$

3.4.3 The estimated position of the nodes

All group leaders and group members will predict of their position in the next steps as Fig. 3.9. The formulation to calculate the predicted position of a group leader is:

$$GL(x_i(t+\Delta t)) = v_{GL}\cos\theta_{GL}\Delta t + GL(x_i) \tag{3.13}$$

$$GL(y_i(t+\Delta t)) = v_{GL}\sin\theta_{GL}\Delta t + GL(y_i) \tag{3.14}$$

And the formulation to calculate the estimated position of a group member is:

$$GM(x_i(t+\Delta t)) = v_{GM}\cos\theta_{GM}\Delta t + GM(x_i) \tag{3.15}$$

$$GM(y_i(t+\Delta t)) = v_{GM}\sin\theta_{GM}\Delta t + GM(y_i) \tag{3.16}$$

Based on the above equations, we can derive the predicted distance between a group leader and a group member i.e.:

$$D(t+\Delta t) = \sqrt{\{GL(x_i(t+\Delta t)) - GM(x_i(t+\Delta t))\}^2 + \{GL(y_i(t+\Delta t)) - GM(y_i(t+\Delta t))\}^2} \tag{3.17}$$

The metric value for a group formation depends on the below condition:

- Angle between GL and GM with requirement: $0 < \theta < \pi/2$
- The distance between GL and GM in the predicted position to address the worst condition
- The distance between GL and GM in the current position to filter data in the nearest GL

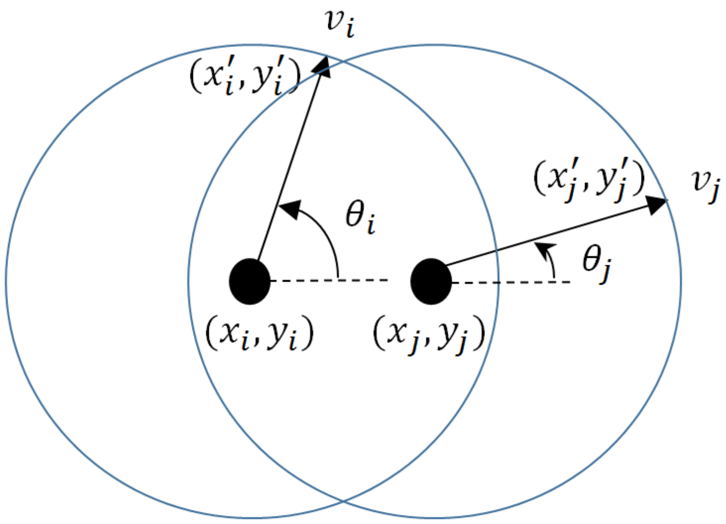


FIGURE 3.10: Calculation of LET.

There are two state of the worst condition i.e. (1) θ and $D(t+\Delta t)$ nearly high, (2) θ nearly zero and $D(t+\Delta t)$ nearly high.

3.4.4 Link Expiration Time

Based on the above parameters, we can also determine the duration of time that two neighbors remain connected if the speed, direction, and radio propagation range are known. It is called Link Expiration Time (LET) as in Fig. 3.10. This is to estimate the amount of time two mobile nodes will stay connected each other [79][80][81][82][83]. Let GM i and GL j be within the transmission range R of each other. We previously present the distance between two nodes in the next position

$$D_{LET} = \sqrt{(x_j{}' - x_i{}')^2 + (y_j{}' - y_i{}')^2} \tag{3.18}$$

$$x_j{}' = x_j + v_j \cos\theta_j t \tag{3.19}$$

$$x_i{}' = x_i + v_i \cos\theta_i t \tag{3.20}$$

$$y_j{}' = y_j + v_j \cos\theta_j t \tag{3.21}$$

$$y_i{}' = y_i + v_i \cos\theta_i t \tag{3.22}$$

Then, we can calculate the value of LET between GM i and GL j as

$$LET_{ij} = \frac{-(ab+cd) + \left[(a^2+c^2)R^2 - (ad-bc)^2\right]^{1/2}}{a^2+c^2} \tag{3.23}$$

where

$$a = v_i \cos\theta_i - v_j \cos\theta_j \quad b = x_i - x_j \tag{3.24}$$

$$c = v_i \sin\theta_i - v_j \sin\theta_j \quad d = y_i - y_j \tag{3.25}$$

Note that when $v_i = v_j$ and $\theta_i = \theta_j$, LET becomes ∞. At least two samples, for each neighbor, are needed to compute the remaining connectivity time between them.

In this research, we only consider LET in two-dimensional (2-D) with positional coordinates as (x,y). Meanwhile, each node in three-dimensional (3-D) has coordinates as (x,y,z) with application such as underwater sensor networks. We put this consideration in our future works to implement mobile group nodes in 3-D environment.

Chapter 4

Non-group Mobility Based Clustering Protocol for Mobile WSNs

4.1 Introduction

A large number of sensor nodes will create a wireless sensor network. It has components such as sensing, wireless communication, and data processing. WSNs have many applications, such as fire detection, tracking target, monitoring of water quality, traffic management exploration [84][85], wildlife protection, search and rescue activity, and natural disaster scene where mobile sensor nodes will be deployed in a network area, and it causes frequent topology changes. Regarding this issue, it needs to design a WSN considering mobile nodes [86].

How to get the efficient way to send data from the node to a base station is one of the important research topics in mobile sensor networks. It has the goal such as how to get the maximum of the data delivered to the base station and to minimize the energy consumption during communication [10][87]. In the mobile environment, the node will move from one location to another location, which causes the change of the network topology and effects on the network performance, especially in energy efficiency [88][89][90][91]. A variety of protocols which support mobility of the nodes have been proposed to overcome the energy efficiency problem and prolong the lifetime of the networks as well as increase the successful packet delivered to the base station [7][6]. To reach the goal, cluster-based topology gives a vast improvement in mobile wireless sensor networks by reducing the overhead when all nodes send their data to the base station where network structure in WSN is divided into 3 sections i.e. flat-based, hierarchical-based and location-based [5][92]. In the clustering scheme, the sensor nodes will send their data in the scheduled time manner, and the medium access is scheduled for the nodes to wake up, sleep, transmit, and receive [25][93][94][95], and it makes a highly dynamic, stable network topology.

The most widely used hierarchical clustering algorithm is LEACH (Low-energy Adaptive Clustering Hierarchy) with a distributed method to determine the cluster head and LEACH-C using a centralized method to determine the cluster head [5]. Nevertheless, these protocols do not consider mobility in the network environment.

In other research, Mobile-LEACH (M-LEACH) [6] proposed the scheme to address the problem of reducing the control overhead by making a handover mechanism when the mobile node gets the deteriorated link quality. The mobile node will save more energy because the distance to the coordinator closer than before. However, M-LEACH is centralized clustering protocol where the cluster formation is created by base station.

In this chapter, we propose a protocol to overcome issues, such as decentralized clustering to handle mobility, prolonging network lifetime. We called Mobile Node LEACH (MN-LEACH) to handle non-group mobility model. The protocols have a goal to provide the minimum energy consumption when the nodes move and to increase the successful packet delivered to the base station. MN-LEACH protocol supports mobility of nodes by using a hand-off mechanism to permit the nodes changing their cluster head.

4.2 Related Works

As a cluster-based protocol, Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol [5][96] concerns about energy efficiency, where number of generated cluster head become important parameters to achieve the best performance. There are two phases in LEACH/LEACH-C protocol, namely setup phase and steady phase. During setup phase, LEACH choose a node in one cluster as cluster head and to determine cluster head, it can be used a distributed or centralized method. LEACH randomly selects a few number of nodes as cluster head, then the information will be broadcast by the cluster head to all nodes. Cluster heads invite all nodes to join with them based on the strongest signal (RSSI) between nodes and cluster head. In this way, the cluster is formed, after that cluster head create scheduling for data transmission of cluster member based Time Division Multiple Access (TDMA). Based on the TDMA schedule, all nodes in the cluster will know time to send their data and the setup phase is complete. Then the steady state operation (data transmision) can begin.

In the steady phase, all cluster members send the data to the cluster head according to the slots provided. The duration of each slot in data transmission is constant and the number of nodes in the cluster will effect the data transmission time. In this condition, cluster head must be alive to receive the data so that in next round, it must be changed to other nodes to save their energy. The cluster formation and time-line of LEACH protocol for one round, where adaptive clusters are formed, can be seen in Fig. 2.1.

Determining cluster heads in the setup phase uses the following formula:

$$T(n) = \begin{cases} \frac{p}{1-p\times(r \bmod \frac{1}{p})}, & n \in C \\ 0, & \text{otherwise} \end{cases} \tag{4.1}$$

$$\frac{1}{p} = \left\lceil \frac{N}{k} \right\rceil \tag{4.2}$$

where p is the percentage of cluster heads to indicate the rate between the expected number of CHs and the total number of mobile nodes, $1/p$ is the expected number of mobile nodes in one cluster and it is set of positive integer values, $\mathbb{Z} = \{1, 2, 3, ...\}$ with round up value or ceiling of (N/k). Meanwhile, k is the expected number of cluster heads for this round and N is the total number of mobile nodes. And r is the round number of cluster formation as well as C is the set of nodes that are not yet as cluster head in the previous *1/p* round. Here, *1/p* was defined as integer by Eq. (4.2).

LEACH-C [5] is centralized method in cluster formation where base station will determine cluster head. In the setup phase, all nodes will send information about their remaining energy levels and current locations to base stations then it chooses the cluster head node based on remaining energy level. By using simulated annealing algorithm, base station selects cluster. The algorithm minimize total energy of non-cluster head nodes by using euclidean distance between nodes and their cluster head. After choosing cluster head nodes, base station will broadcast the information to all nodes. The contains of information are cluster head nodes, cluster member nodes and transmission schedule for each cluster. Then the nodes determine its TDMA slot for their data transmission based on the above information.

M-LEACH protocol [6] is development of LEACH-C protocol to support mobility. In a round time of LEACH-C, if a node moves away from its cluster head, it will consume more energy to maintain connection with the current cluster head. It will not cause energy utilization. The protocol supports hand-off mechanism to permit the nodes changing their cluster head to get energy efficiency.

In M-LEACH protocol, setup is the inital stage of formation of the cluster head. Transmission 1 is initial stage of cluster head to communicate with nearby nodes. Cluster head nodes broadcast information about its condition to the nearby nodes so that each node make communication to closer cluster head. If a node moves away from the current cluster head, the node will send DISJOIN message to the current cluster head so that time slot of TDMA schedule in old cluster head will be deleted.

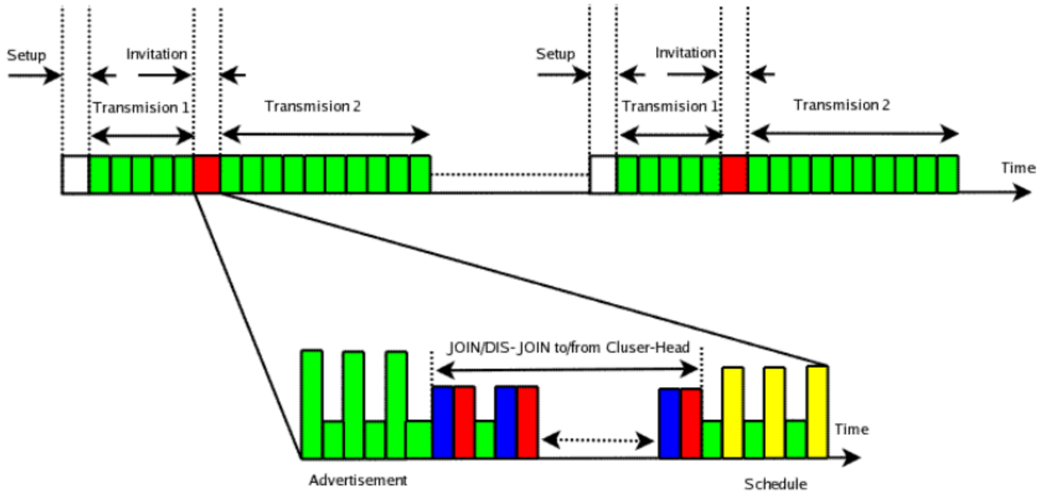


FIGURE 4.1: M-LEACH process.

If the node get closer to another cluster head, the node will send JOIN message to new cluster head. Then the new cluster head creates time slot to that node in order to send its data to the new cluster head.

4.3 Mobile Node - LEACH (MN-LEACH) Protocol

MN-LEACH (Mobile Node – LEACH) protocol is based on LEACH protocol. In LEACH protocol is divided into rounds, where each round is started with setup phase to create clusters, followed by steady phase, where cluster members send data to base station.

In [7] assumed that the protocol is based on LEACH but it supports mobility without GPS based location information and centralized routing protocol. Different with [7], in the proposed protocol have some assumptions to support the clustering mechanism:

Assumption 1: All nodes are location-aware by using GPS or localization algorithms.

Assumption 2: All nodes are homogeneous in physical characteristics.

Assumption 3: The base station and cluster head are stationary. In the protocol, it only considers the mobility of cluster member.

In the proposed protocol, cluster setup is the same process with LEACH protocol. During setup phase, all cluster member will save position of all cluster head in the list by using GPS or etc. Cluster head node create TDMA schedule to receive the sensed data from cluster member, while non cluster head node send data based on its time slot in the frame of TDMA, then the node sleep for schedule time interval to save its energy. Due to cluster head node is stationary in a round, the position of cluster head is saved temporary in the node and it is deleted to be replaced with the new position after the next round.

The position list of cluster head in the node is very useful to calculate the best distance to the closest cluster head when the node moves away from current cluster head. To choose the best distance, we use the euclidean distance formulation:

$$D = min\left[\sqrt{(x-x_i^c)^2+(y-y_i^c)^2}\right] \tag{4.3}$$

where:

x, y are cluster member position moving away from current cluster head.

x_i^c, y_i^c are the position of all cluster-heads and it will be choosen the minimal value of the distance D.

Cluster member will compute the distance based on the list of the cluster head position saved in the table list. Because the position of cluster heads are stationary, the table list is no changing in a round. The assumptions looks like in GSM network, where BTS is fixed. This technique supports hand-off mechanism to find the best cluster head to get energy efficiency.

After the cluster member gets the closest cluster head, it sends DIS-JOIN message to the previous cluster head and JOIN message to the new cluster head. The cluster head will be waiting JOIN / DIS-JOIN message from the cluster member and then, the corresponding cluster heads create a new TDMA schedule to the covered cluster member. Cluster member send the sensed data based on its time slot (schedule),

TABLE 4.1: Simulation Parameters for Mobile Clustering Scheme

Parameters	Values
Size of network	100x100 m
Size of packet	500 byte
E_{elec} (Radio electronics energy)	50 nJ/bit
E_{amp} (Radio amplifier energy)	100 pJ/bit/m^2
E_{init} (Initial energy)	0.5 J
Number of nodes	100

and all datas from the covered cluster member are aggregated by cluster head then it is sent to base station. This process is in a round, for the next round, it will start in cluster setup again. Whole process can be seen in Fig. 4.2, and the sequence of flowchart is only for one round.

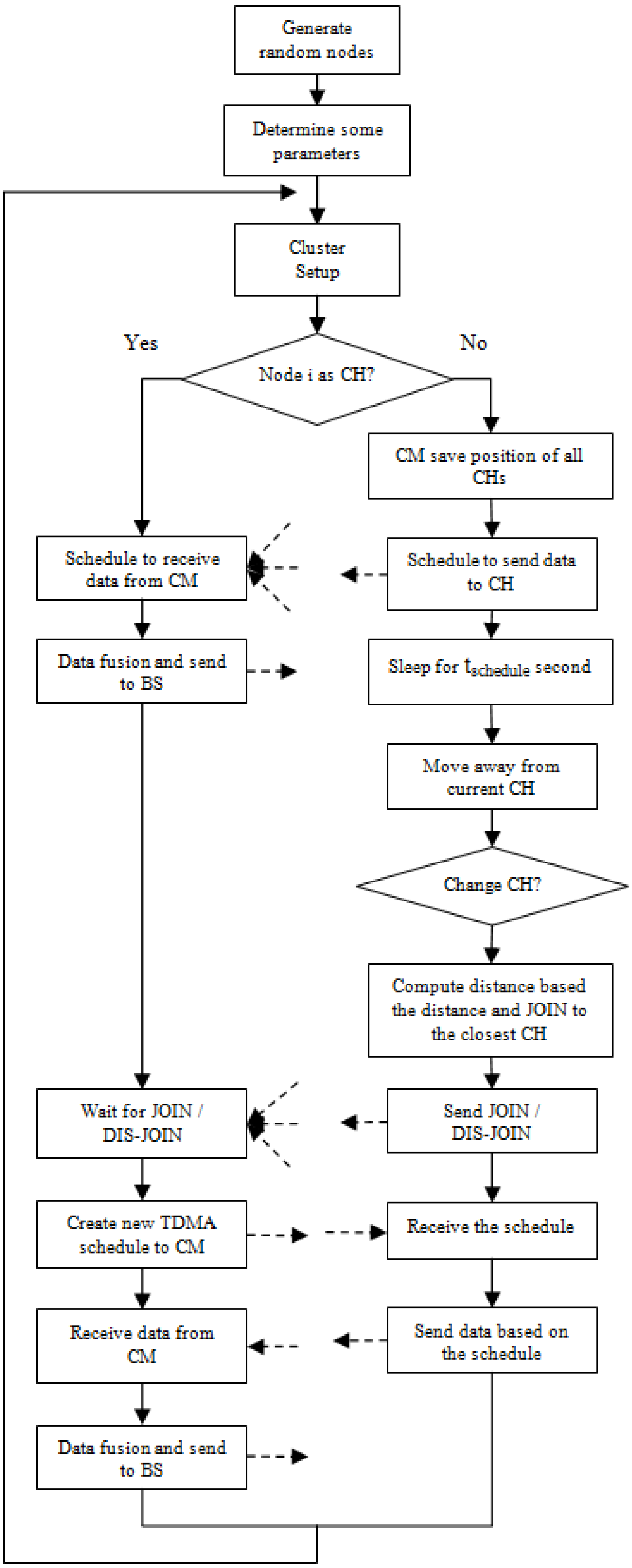
4.4 Experimental Results

We used MATLAB to simulate the protocol with some environment parameters as Table 4.1.

Total number of nodes is 100 where the nodes are distributed randomly in area 100 $\times$ 100 m. The size of packet is 500 bytes and base station is adjustable. The first experiment, base station is at x = 50, y = 50, then it is changed to x = 50, y = 150. Each node begins with 0.5 Joule of energy.

The experiment evaluate performance of LEACH and MN-LEACH protocol by using mobile nodes. We simulated wireless sensor network to get number of alive nodes during increasing number of round and also to get energy efficiency for increasing number of round. In the beginning of LEACH and MN-LEACH, it is a cluster setup as shown in Fig. 4.3.

Figure 4.4 shows number of alive nodes versus round as mobile node increased. Based on the assumption no 3, cluster heads are stationary, so it means the increasing number of mobile nodes referring to the number of cluster member. For example,



CH : Cluster head
CM : Cluster member
BS : Base station

FIGURE 4.2: Flowchart of MN-LEACH.

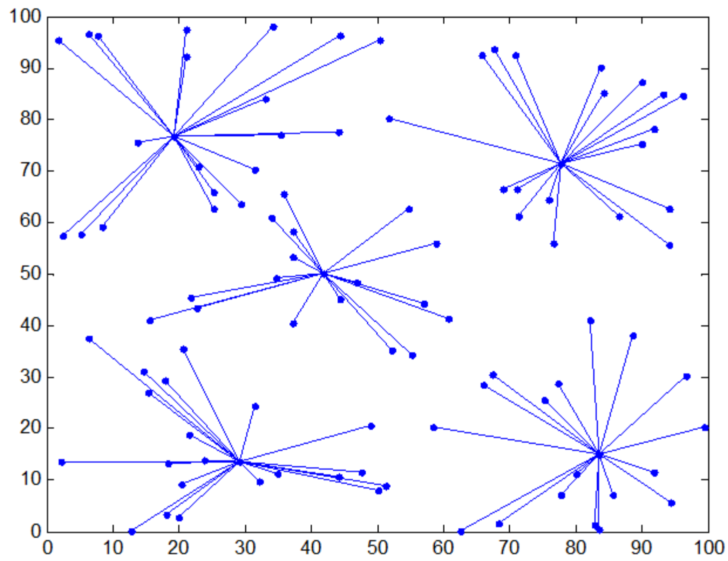
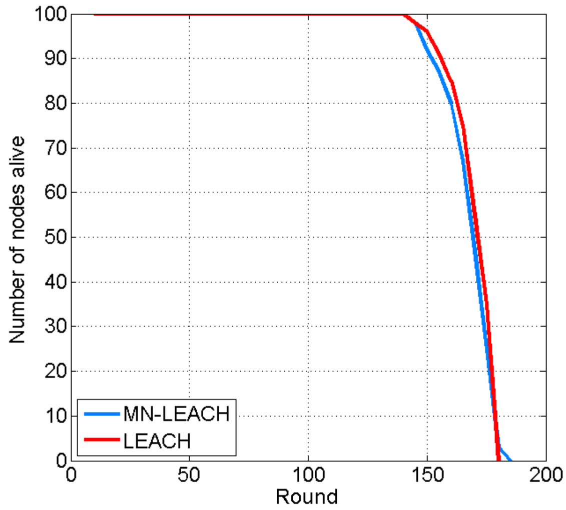


FIGURE 4.3: Cluster setup.

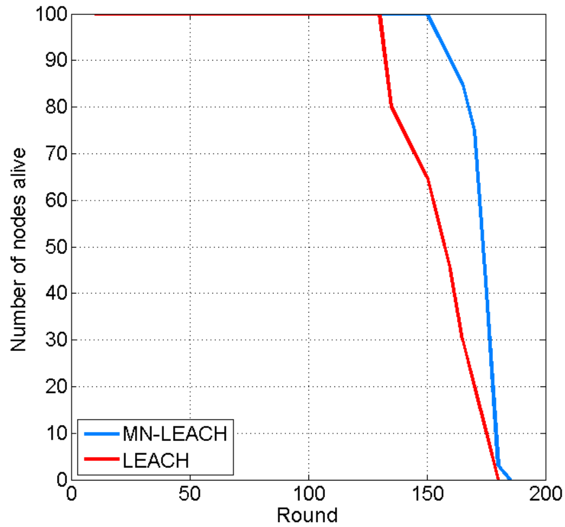
number of mobile nodes = 100, if number of cluster heads are 5, the number of mobile nodes become 95 nodes. It also shows that LEACH is not as efficient as MN-LEACH where number of mobile nodes increase, performance of LEACH become degrade drastically because LEACH does not support hand-off mechanism during changing base station, node become dead fast.

In the Fig. 4.5, it shows that performance of LEACH and MN-LEACH is the same when number of mobile nodes is none, but if number of mobile nodes increase until 100% of number of cluster member, LEACH protocol will need more energy than MN-LEACH. The results of Figs. 4.4 and 4.5 have strong relation where the more energy is needed, the more node become dead fast. In this experiment shows that all energy of the nodes become run out.

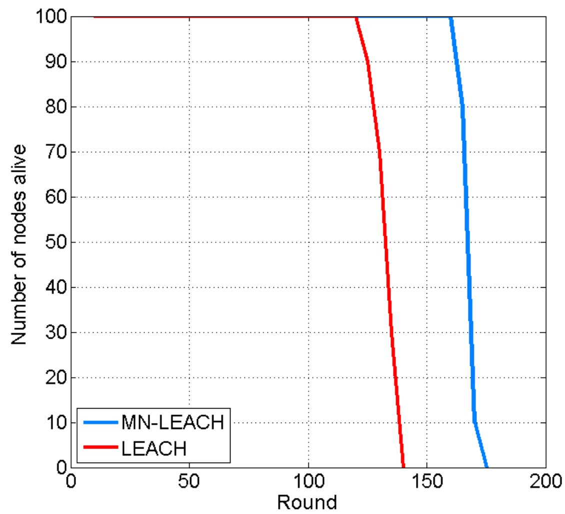
Figure 4.6 is to evaluate the energy dissipation when base station is far away from the nodes. The location of base station is at x=50, y=150. It shows that MN-LEACH perform better for the safe energy than LEACH protocol.



(a) Number of mobile nodes = 0.

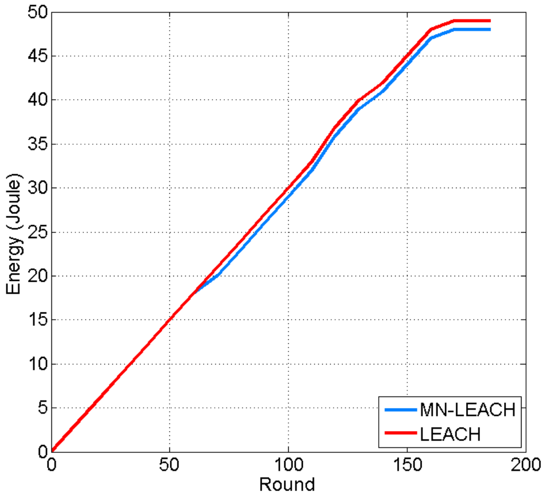


(b) Number of mobile nodes = 20 .

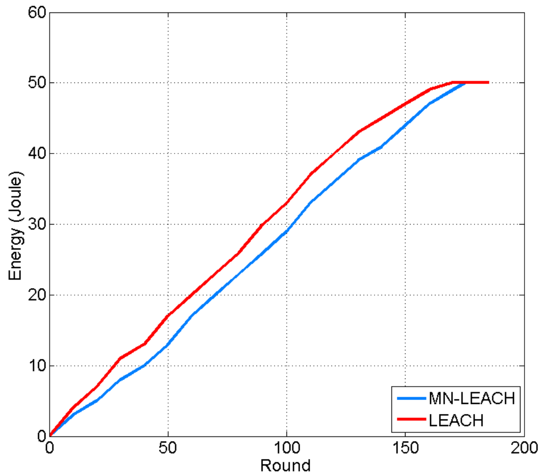


(c) Number of mobile nodes = 100.

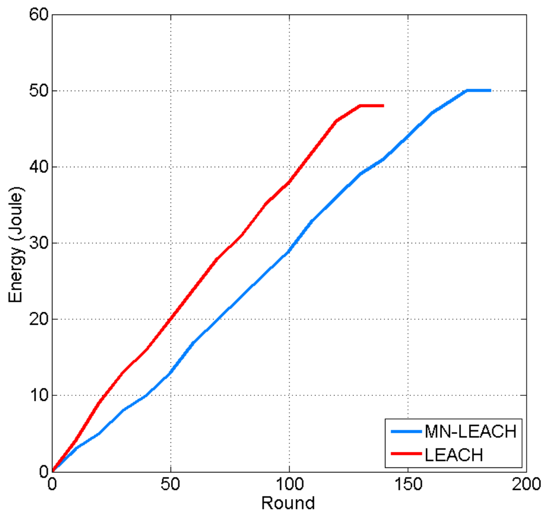
FIGURE 4.4: Simulation with limited energy to evaluate number of alive nodes.



(a) Number of mobile nodes = 0.



(b) Number of mobile nodes = 20 .



(c) Number of mobile nodes = 100.

FIGURE 4.5: Simulation with limited energy to evaluate energy dissipation versus round.

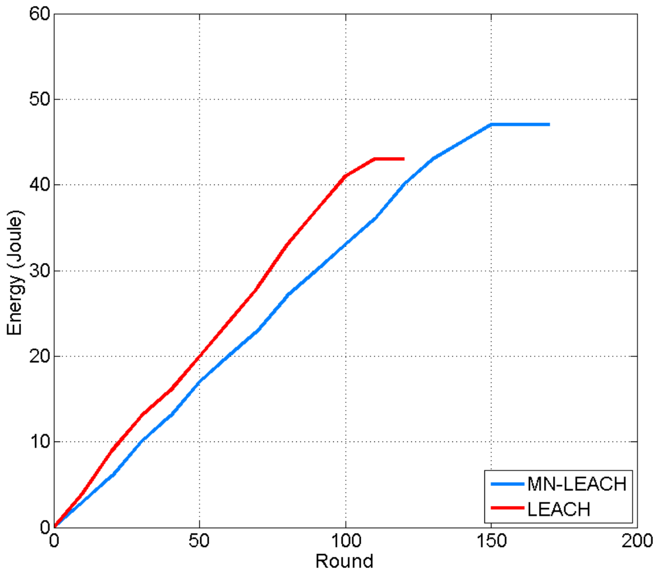


FIGURE 4.6: Energy dissipation with location of base station at x=50, y=150.

4.5 Conclusion

In this chapter, we present MN-LEACH protocol to support mobile nodes. In this research, we focus on the energy consumption of the clustering protocol and then we evaluate it in mobile environment. We use the reference of protocol, i.e. LEACH to evaluate our protocol. The proposed protocol add feature of LEACH to support mobile nodes as well as to get energy efficiency in each round of the network resource. The performance of MN-LEACH outperforms LEACH because it supports hand-off mechanism when cluster member move out from current cluster head.

In this research, we study the characteristic of nodes in the mobile environments by using non-group mobility clustering scheme. After that, we investigate further the characteristic of nodes in the mobile group environments in the next chapter.

Chapter 5

Group Mobility Based Clustering Protocol for Mobile WSNs

5.1 Introduction

Wireless sensor networks (WSNs) consist of a large number of sensor nodes deployed in an area of interest to sense physical phenomena. For many applications, such as health monitoring, wild animal control, and evacuation systems in natural disasters, mobile sensor nodes will be deployed in the network to monitor their activities [25]. Mobile WSNs also offer an alternative to wired networks when a disaster occurs affecting infrastructure collapse [97]. Sensor nodes have an energy limitation which has offered challenges on the design of WSNs, especially for mobile nodes where frequent topology changes would occur [9]. Clustering techniques in WSNs are used to allow sensor nodes to send data in a hierarchical manner. This method can effectively increase the performance of sensor nodes by reducing energy consumption and network contention [98], and has been widely used [5][35].

The protocols which support mobility-based environment are Mobile-LEACH (M-LEACH) [6] and Mobile Node-LEACH (MN-LEACH) [99]. M-LEACH protocol is a centralized scheme in cluster formation where a base station uses an optimization algorithm to determine cluster heads. Meanwhile, MN-LEACH is a decentralized system where mobile sensor nodes elect cluster heads independently. Both protocols support a handover procedure where if a node gets closer to another cluster, it has a chance to change its cluster to reduce energy consumption. During invitation in the steady-state phase, a cluster head will let other nodes join by calculating willingness (the cost to join). The protocols have already considered node mobility and a handover scheme which increases the number of data items received at a base station and prolongs the lifetime of the network at the cost of increased control packet. Cluster Based Routing (CBR) protocol [8] proposed an adaptive TDMA schedule according to mobility and traffic characteristics to cover the handover procedure. Mobility-based clustering (MBC) protocol [9] improved the performance of CBR by making a stable cluster with a new metric to select cluster heads based on the threshold value, i.e. mobility and residual energy. In the steady-state phase, MBC creates a new adaptive TDMA scheduling when a mobile node moves far away from the current cluster by considering the current energy of the cluster head, the distance between sensor nodes and the cluster head, and the estimated connection time.

However, all of the above protocols do not support group mobility. Meanwhile, in some real applications such as in the evacuation of people during natural disasters and search-and-rescue operations, they move together in a group. For example, people in a family will make a group movement for the evacuation system to go to safe areas.

A clustering protocol that considers group mobility, namely GMAC was proposed in [10] where the protocol calculates a mobility group metric, i.e. historical group and prediction group. During the cluster head election, nodes use the mobility group metric and zone definition to get steady clusters. Unfortunately, the protocol does not support handover in the group mobility models, and it is hard to implement a zone definition for natural disasters. In addition, Yong Li *et al.* [100] proposed a group-based handover scheme for correlated mobile nodes (MNs) to enhance the performance of PMIPv6 (Proxy Mobile IPv6). The goals of the research were to reduce handoff delay and signaling cost. The system proposed in [60] enhances the protocol performance of PMIPv6 to be suitable for a wireless body area network (WBAN) environment. The protocol was implemented in the centralized system to support a group movement of the mobile nodes. However, a centralized scheme is not reliable in large scale networks.

Based on the above condition, there are the existing problems on the design of mobile group WSNs such as high control packet and energy consumption as well as more frequent topology changes that reduce network lifetime and the number of data items received at the base station [9]. To address these problems and to respond to the challenge of group mobility based scheme, we propose a new protocol considering group mobility together with assigning an appropriate role to nodes. This is the first challenge to them, so we make a fixed group formation of all sensor nodes to evaluate clearly the effectiveness of our scheme.

We define two group mobility based clustering protocols, i.e., (1) Group Clustering Protocol and (2) an Energy-efficient Mobile Group Clustering (EMGC) protocol.

In the Group Clustering Protocol, it divides the nodes in the group into a group leader and group members where the group leader has a function which looks like a cluster-head in a clustering scheme. There are two scenarios of the group mobility based clustering scheme i.e. single- and multi-scheme.

In the single-scheme (*GC Single*), the group members make a sensing activity and then send their data to the group leader. After that, the group leader will send the aggregated data from the group members to the base station. The position of the group leader is changed every round. This mechanism provides the energy efficiency due to the communication only occur between the group members and the group leader with the minimum distance. In the multi-scheme (*GC Multi*), the aggregated data from the group leader will be sent to the cluster-head as a relay node then it is transferred to the base station.

Meanwhile, EMGC protocol divides the sensor nodes into three categories, i.e. (1)

a cluster head node which has a major role in a cluster formation and to send the aggregated data to the base station in the steady-state phase, (2) a group leader node which is used to make a communication with a cluster head in the set-up and steady-state phases, (3) a group member node as a normal node. Most communications, such as the process of a cluster head advertisement and a cluster join request, only occurs between cluster heads and group leaders in the set-up phase. Otherwise, all group members are in a sleep condition to save on their energy consumption. This mechanism in the set-up phase will affect to decrease the energy consumption in the steady-state phase. In addition, EMGC provides a group handover procedure when the group of sensor nodes moves out from the current cluster and gets closer to another cluster.

5.2 Group Clustering Protocol

In the application scenarios, such as evacuation system in natural disaster, animal tracking, and search-and-rescue, it considers group mobility model. In this research, we first study the effect of group movement in the mobile environment by using fixed group formation.

5.2.1 Protocol Description

We make assumptions for the proposed protocol:

1. All sensors are mobile in the network with the same physical characteristics such as energy, antenna gain, etc.
2. All sensors are location-aware.
3. The base station is stationary.
4. It has an initial group in the beginning time.

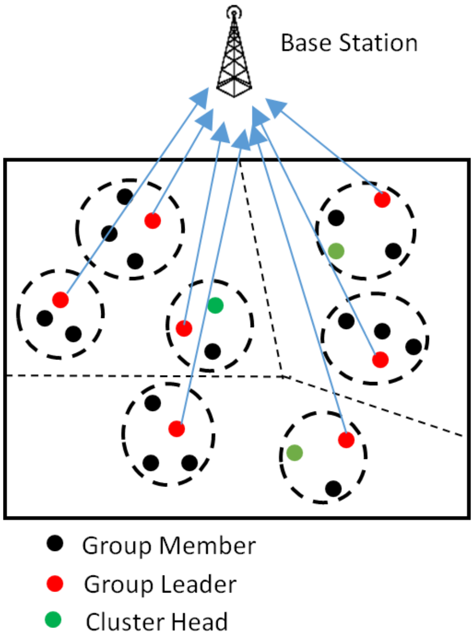


FIGURE 5.1: Network model for GC Single.

Similar with LEACH protocol, in our proposed protocol, there are two phases i.e. setup phase to create cluster formation and steady phase to transfer data from group members to the base station. There are two types of the proposed protocol which have the same setup phase, but different steady phase:

1. Group Mobility based Clustering Single-scheme (GC Single)

   It creates a cluster which consist of several groups; then the group leader will send the aggregated data from its group members to the base station directly.

2. Group Mobility based Clustering Multi-scheme (GC Multi)

   In this scheme, the aggregated data from group members will be sent to the group leader and then the group leader sends the data to the base station through cluster-head.

5.2.1.1 Group Clustering Single-scheme (GC Single)

The GC Single protocol can be seen in Fig. 5.1. The cluster is created in the group where there are the group members and one group leader. The group member sends

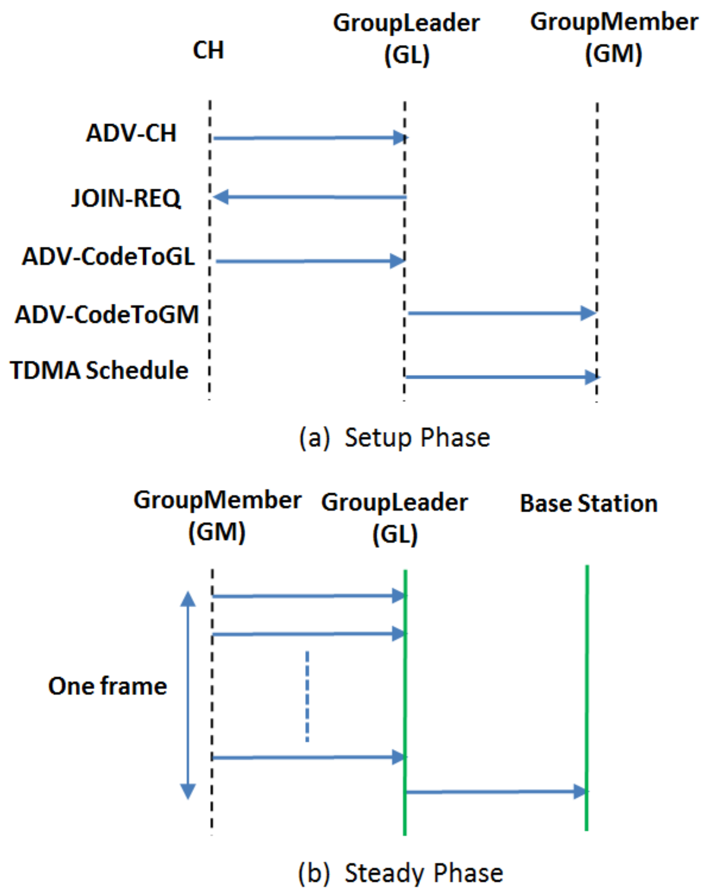


FIGURE 5.2: GC Single process.

the data based on the schedule (TDMA) to the group leader, and then the group leader transfer the aggregated data directly to the base station.

In the setup phase for *GC Single* scheme, there are some steps to make coordination between group members, group leaders, and cluster heads. At the beginning time as in Fig. 5.2(a), all nodes will wake up to select cluster-heads, and then the selected node as the cluster-head broadcast an advertisement message (ADV-CH) to only group leaders because the group members are in sleep condition to save the energy. The communication only occurs between cluster-heads and group leaders. After receiving all broadcast messages from the cluster-heads, then the group leader determines its cluster-head based on the strongest RSSI value. In the group of nodes, the list of the group member information is already saved in the group leader. The group leader sends a join request message to the cluster-head with the list of its group member. After that, cluster-head specify the code for each group which participates in the cluster. The cluster-head will differentiate the code to prevent collision each group [101][102][103]. In the scheme, if there is only one group in the networks, the elected cluster-head only communicate with one group leader. This is a multi-channels communication where two kinds of codes are used i.e. between cluster-head and group leader (*CHcode*) and between the group leader and the group member (*GroupCode*). *CHcode* is based on the sequence the broadcast information from the cluster-heads received by the group leader, and for the *GroupCode* will be determined by using below algorithm.

Require: List of the group leaders join in the cluster-head

1: $m \leftarrow 0$
2: $n \leftarrow constantvalue$
3: **while** (list of the group leader exists) **do**
4: increase m
5: $GroupCode \leftarrow CHcode * n + m$
6: Make list of *GroupCode*
7: **end while**
8: $message \leftarrow listofthegroupleader + listofGroupCode$

If more than one group leader are joining in the cluster-head, it will determine the special code for each group based on the *CHcode* multiply by the constant value. Then the value is added by m variable to become a unique number, the unique number is the unique code for each group. In the next process, the cluster-head send the message (*ADV-CodeToGL*) containing list of group leader and group code to the group leader. The group leader determines the *GroupCode* based on the sequence in the list. Afterward, the group leader transmits a message containing the *GroupCode* and *GroupID* to the group members. Now, the communication between group leader and group members will use the same *GroupCode*. Finally, the group leader makes a TDMA schedule to all group members.

Fig. 5.2(b) describes a process in the steady phase where the group member will wake up and transmits the data based on the schedule for one frame, then it will be sleep again. After all group members send their data to the group leader, then the group

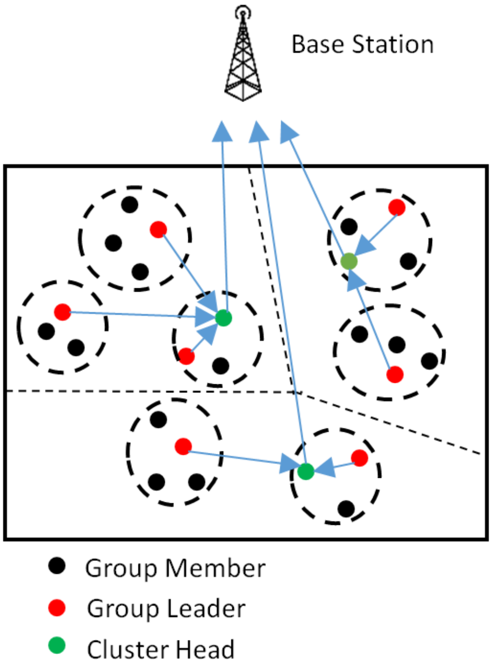


FIGURE 5.3: Network model for GC Multi.

leader make a data aggregation. Finally, it transmits the aggregated data to the base station. Group leader is always wake up in the round. In this phase, the cluster-head will change the function become group member.

5.2.1.2 Group Clustering Multi-scheme (GC Multi)

For *GC Multi* protocol with the network model is in Fig.5.3, the process is the same with *GC Single* in the setup phase where cluster formation is made to distribute the unique code from the cluster-head to the group leaders. The different one is in the steady phase where the cluster head become a relay node to transfer the aggregated data from the group leader to the base station. The group members will start sensing data and send the data based on the scheduled time to its group leader. After the group leader receives all data from its group members, then it will send the aggregated data to cluster-head. Finally, the cluster-head as a relay node transmit the aggregated data to the base station.

The main different with *GC Single* is that the cluster-head will be wake up condition

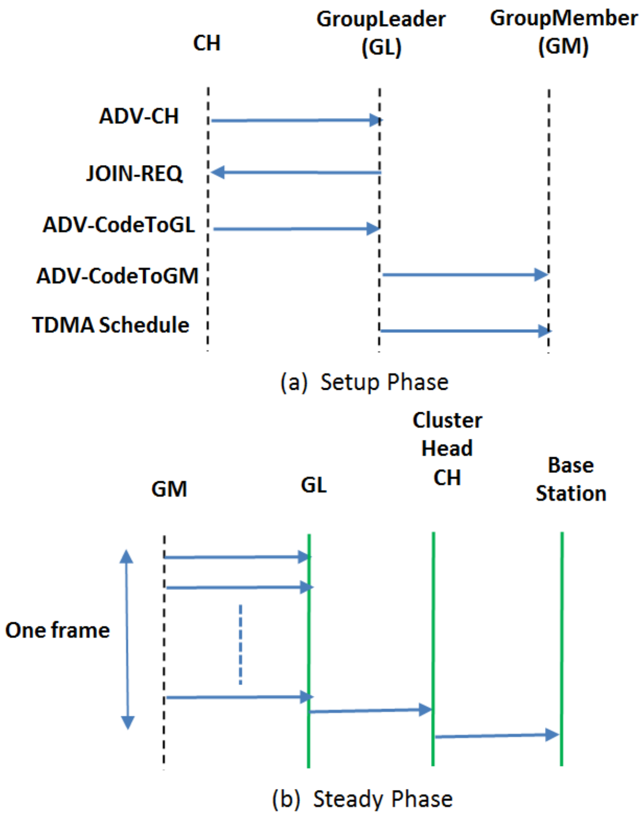


FIGURE 5.4: GC Multi process.

in one round to receive the data from the group leader. It makes the energy depletion fast because not only the group leaders will always wake up but also the cluster-heads. In the *GC Single*, the group leader will send the aggregated data directly to the base station, meanwhile in the *GC Multi*, it makes a multi-hop system from the group leader to the cluster-head. This scenario is to reduce the energy transmission by the group leader to not send data directly to the base station. For the simple scenario, we make a mechanism to let the cluster-head always wake up in the steady phase to receive the aggregated data from the group leader, but it sacrifices the energy of the networks due to there are two nodes which always wake up to make multi-hop system. The detailed process can be seen in Fig. 5.4.

TABLE 5.1: Simulation Parameters for Group Clustering Scheme

Parameters	Values
Size of network	100x100 m
Size of packet	500 byte
E_{init} (Initial Energy)	2 J
Number of nodes	100
Number of clusters	4 and 5
Location BS	(50,125)
Max velocity of mobile nodes	2 m/s
Movement model	RPGM with 5 groups

5.2.2 Performance Evaluation

For the simulation, this thesis uses network simulator 2 [104] with energy model is the same conditions in [5]. Network area is 100x100m with the number of mobile nodes is 100. We apply RPGM for the movement model of the mobile nodes with five groups in the network and maximum velocity is 2 m/s. The position of a base station is located outside of the network i.e. (50,125). The initial energy for all nodes is 2 joule. The length of the messages is 500 bytes with the packet header is 25 bytes. The round time for all groups is set to 20 seconds. The detailed parameters can be seen in Table 5.1.

In this research, we study the characteristic of group mobility with the number of clusters mostly used in the existing protocols, i.e., 4 and 5 clusters. For example, LEACH and MBC use 5 clusters for 100 nodes to evaluate their performance. Meanwhile, GMAC uses 4 clusters in its simulation.

We consider max velocity of mobile nodes as the speed of people in the evacuation system as in Chapter 1. It compares the performance of *GC Single* and *GC Multi* with the basis clustering protocol i.e. LEACH and the protocol which support handover mechanism i.e. MN-LEACH. The two protocols are decentralized scheme which is suitable to compare with our proposed protocol. The simulation results are categorized into two sections i.e. the number of nodes alive and the number of data received at the base station.

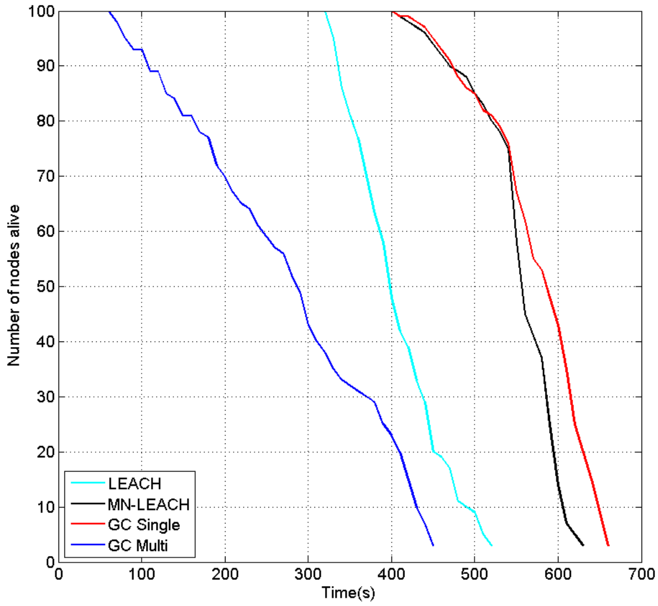


FIGURE 5.5: Number of nodes alive at 4 clusters.

5.2.2.1 Number of nodes alive

In this subsection, it evaluates the performance of protocol with four and five clusters. Figure 5.5 shows that the performance of the *GC Single* protocol is slightly the same with MN-LEACH in 4 clusters but it outperforms LEACH and *GC Multi* in terms of the energy consumption. Meanwhile, in the 5 clusters as Fig. 5.6, the *GC Single* outperforms the others. This is because *GC Single* creates the cluster in the group so that it will make a stable cluster and less energy consumption. Besides that *GC Single* reduces the control overhead in the setup phase when determining cluster formation. *GC Multi* is the worst protocol because the group leaders and cluster-heads have to be awake in the steady phase.

5.2.2.2 The number of data received at the base station

Figure 5.7 and 5.8 show that *GC Single* receives more data at the base station than the others both in 4 clusters and 5 clusters. The reason is that *GC Single* rotates the function of group leader in the group so that all group members have a chance to

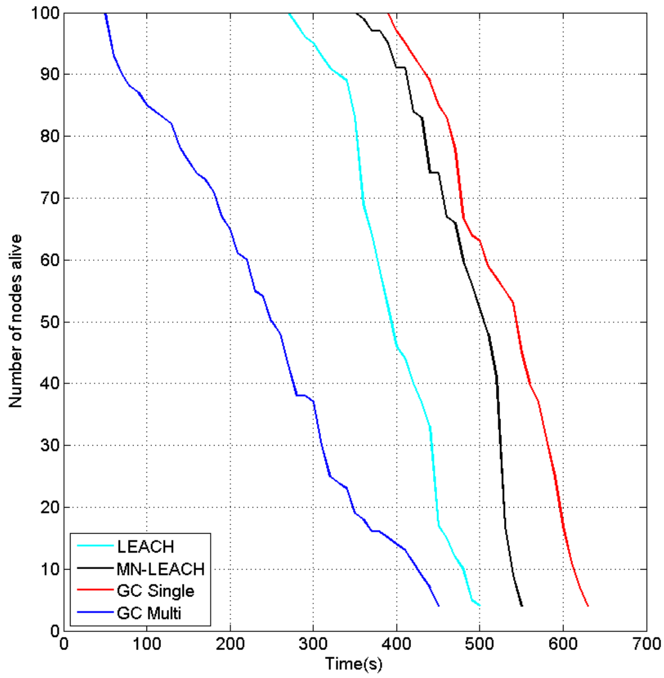


FIGURE 5.6: Number of nodes alive at 5 clusters.

become a group leader. This condition causes the energy evenly distributed to all nodes and dead simultaneously. Finally this scheme prolongs the lifetime and the number of data received at the base station increases.

The worst protocol is *GC Multi* where the nodes are died quickly affecting the number of data items received by the base station. For the best cluster in the group mobility is 4 clusters due to it has fewer control overheads than 5 clusters. The results can be seen in Fig. 5.9.

5.2.2.3 The average number of control overhead each round

In Fig. 5.10, *GC Single* reduces the control overhead of LEACH and MN-LEACH because the communication in the setup phase is only between cluster-heads and group leaders. The fewest control overheads of *GC Single* is 4 clusters because the number of clusters is reduced so that the communication between the cluster-heads and group leaders become decreases. It prolongs the lifetime of *GC Single* and

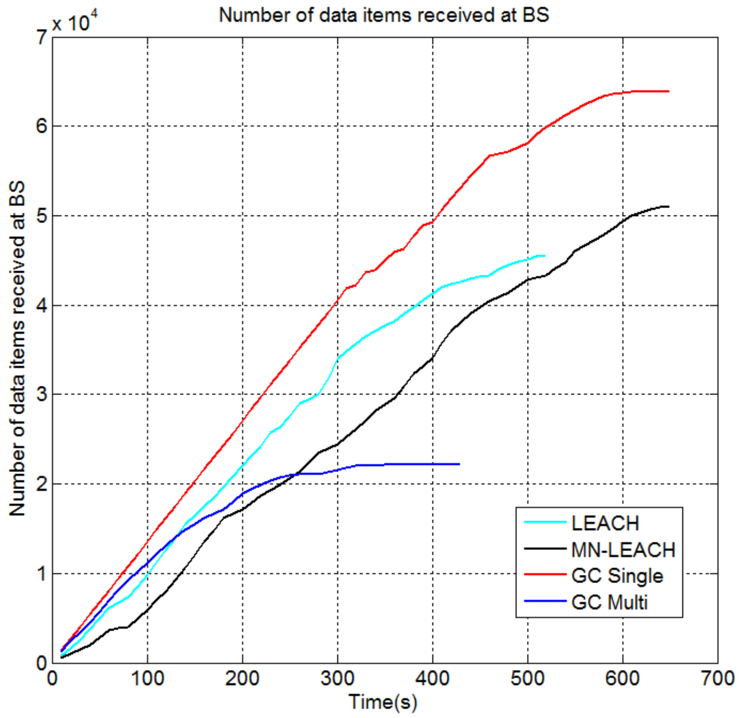


FIGURE 5.7: Number of data received at base station at 4 clusters.

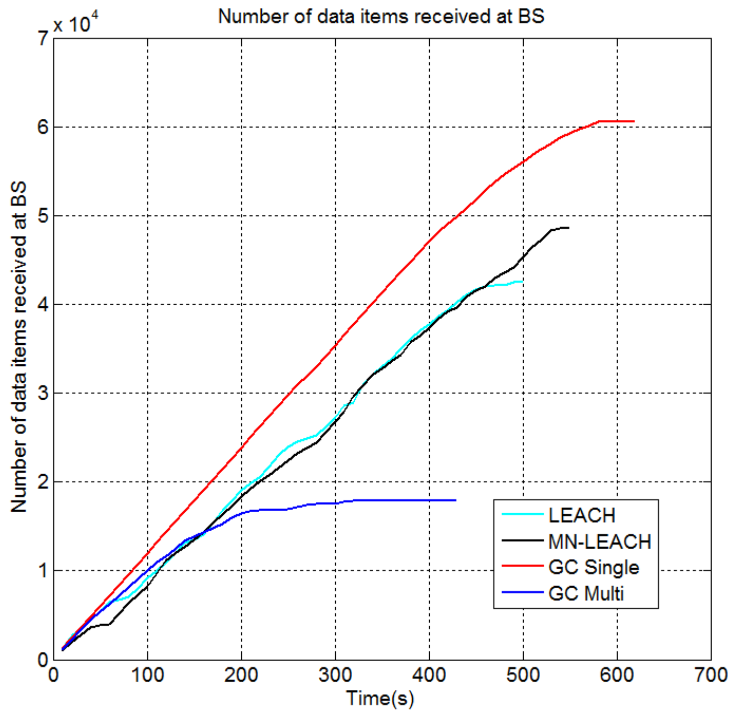


FIGURE 5.8: Number of data received at base station at 5 clusters.

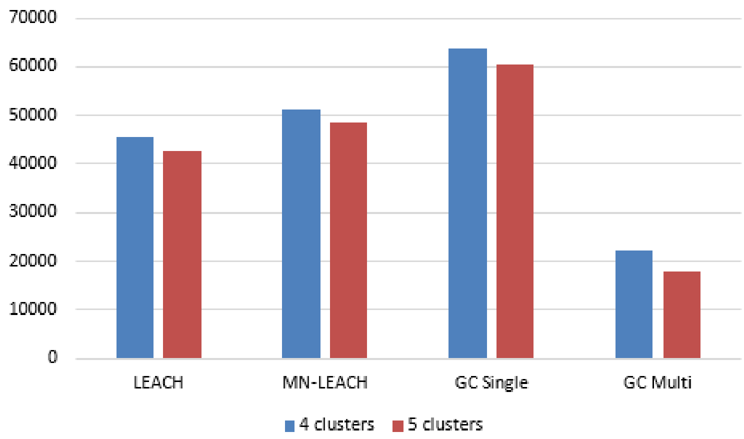


FIGURE 5.9: Number of data received at base station for 4 and 5 clusters.

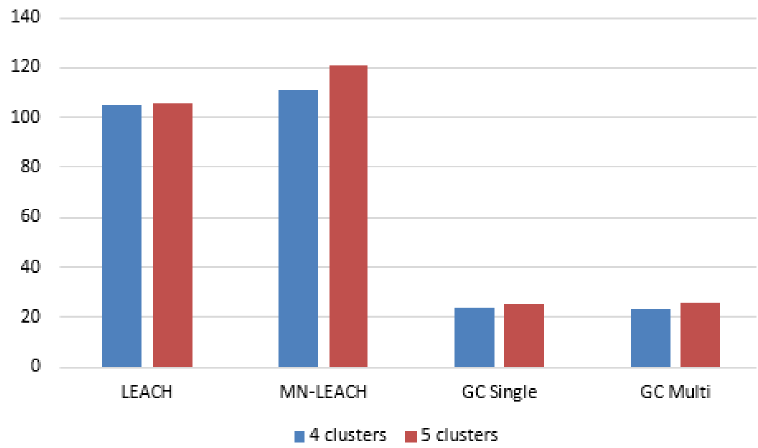


FIGURE 5.10: Average number of control overhead each round.

increases the number of data items received at the base station.

5.2.3 Conclusion

In designing protocol for mobile wireless sensor networks with the group movement, the mobility consideration is one of the factors to increase the successful packet delivered to the base station, and to reduce the control overhead as well as to prolong the lifetime of networks. The Group mobility based Clustering Single-scheme (*GC Single*) presents a protocol which supports the group mobility by using RPGM model and single-hop communications. From the simulation results, the *GC Single* outperforms LEACH, as a reference for clustering scheme which does not consider mobility, and MN-LEACH in terms of the number of nodes alive and the number of data received at the base station. The best cluster for *GC Single* with five mobile groups is 4 clusters where it decreases the control overhead in the networks.

5.3 Energy-efficient Mobile Group Clustering (EMGC) Protocol

In this section, we describe EMGC protocol for mobile WSN which supports group mobility. We will first present a term of a group of mobile nodes and a cluster in our network structure, and then describe a slot structure which consists of the set-up and steady-state phases. Finally, we discuss how a group of mobile nodes does a handover. Our preliminary work [105] employed not only three types of node such as cluster head (CH), group leader (GL), and group member (GM), but also two types of data delivery path to a base station (BS) such as two-hop and three-hop. Based on this result, EMGC employs the revised version of two-hop scheme. Moreover, EMGC has a group handover process to save more energy consumption.

In designing EMGC protocol, we make the following assumptions:

Assumption 1: All mobile sensor nodes are in homogeneous networks where the nodes have the same physical characteristics such as antenna gain, initial energy, memory capacity, etc.

Assumption 2: Group formations of all sensor nodes have been determined initially and there is no change in the roles of the group leader and group members.

Assumption 3: All mobile sensor nodes are location-aware. The sensors can apply location schemes or GPS to know their location in the networks [106][107].

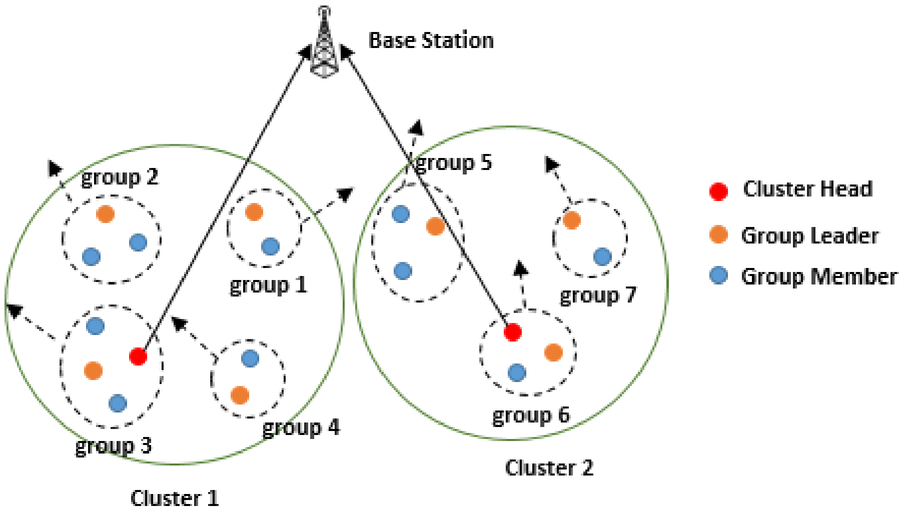


FIGURE 5.11: Group movement in the clustering system.

5.3.1 Group of Mobile Nodes and Clustering

We present a network structure as shown in Fig. 5.11, where mobile nodes will move together in a group from one location to other locations. Some groups will be handled by one cluster. We divide the mobile nodes into three categories, i.e. CHs, GLs, and GMs. One group contains one group leader and some group members, and one cluster consists of one cluster head and some groups (cluster members).

In Fig. 5.11, there are four groups in Cluster 1, and three groups in Cluster 2. Group 1 has a possibility to get closer to Cluster 2 in the next movement, and therefore, it performs a group handover procedure. In the cluster formation and a group handover procedure, most communications are between GLs and CHs. This scheme gives more time for GMs in the sleep condition to save on their energy consumption and to reduce control packet in the networks.

Assuming an application such as an evacuation system for a disaster area, there will be many groups of people moving to safe zones. People wearing a sensor node will move together in the same direction and at the same velocity. A mobile group of people could be one family or one block-neighborhood in the disaster area with a fixed group formation. We are thinking that it is very natural to suppose a fixed

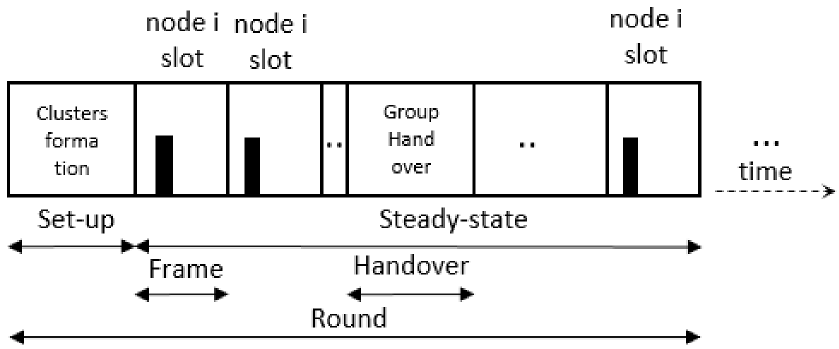


FIGURE 5.12: EMGC slot structure.

group formation and group mobility when considering some applications such as evacuations in a disaster area. In the family, for example there are two roles, i.e. (1) a leader, it might be a father, and (2) the members, they might be his wife, kids, and other family members. In EMGC protocol, we also divide a mobile group into two roles, i.e. a GL and its GMs as in the above family's condition.

5.3.2 EMGC Slot Structure

The operation of EMGC protocol is divided into rounds. Each round consists of two phases as Fig. 5.12, i.e. (1) set-up phase, for cluster formation, and (2) steady-state phase, to deliver data from sensor nodes to a base station. A clusters formation is created in the set-up phase where a CH and GLs perform most communications to form a cluster.

In the steady-state phase, a mobile node will transfer data to its CH at the allocated time slot every frame in Time Division Multiple Access (TDMA) manner. A frame contains time slots for all mobile nodes in the same cluster. Then the CH will transfer the aggregated data to the base station. There is a group handover procedure in the steady-state phase and it performs only one time.

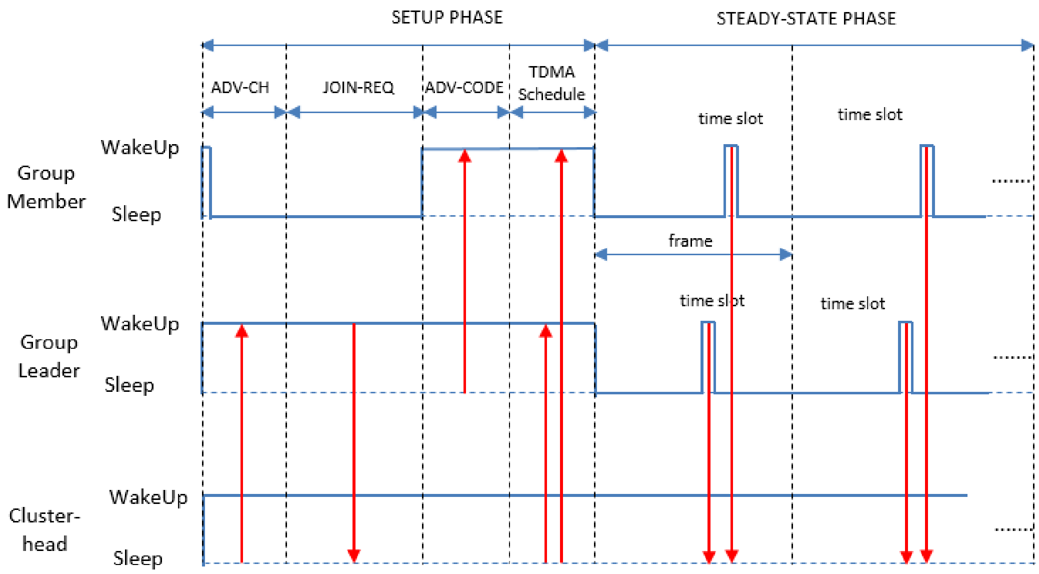


FIGURE 5.13: Process of the EMGC protocol.

5.3.3 Set-up Phase

Figure 5.13 shows the communication procedure of EMGC protocol and Fig. 5.14 shows a state transition diagram of EMGC protocol to clearly differentiate role of each node. We assume that all nodes have a fixed group formation as in Assumption 2. Then, at the beginning of the set-up phase, all nodes will wake up, and CHs are elected only from GMs based on the threshold value [5] as in Eq. (5.1).

$$T_n(r+1) = \begin{cases} \frac{p}{1-p\times(r \bmod \frac{1}{p})} \\ \times\left(\frac{E_n(r+1)}{E_{\max}}\frac{v_{\max}-v_n(r+1)}{v_{\max}}\right), & n \in G \\ 0, & \text{otherwise} \end{cases} \tag{5.1}$$

where p is the percentage of cluster heads to indicate the rate between the expected number of CHs and the total number of mobile nodes, $1/p$ is the expected number of mobile nodes in one cluster and it is set of positive integer values, $\mathbb{Z}$ = {1, 2, 3, ...} with round up value or ceiling of (N/k) as Eq. (4.2). Meanwhile, k is the expected number of cluster heads for this round and N is the total number of mobile nodes. And r is the number of rounds that have passed as well as G is the set of nodes

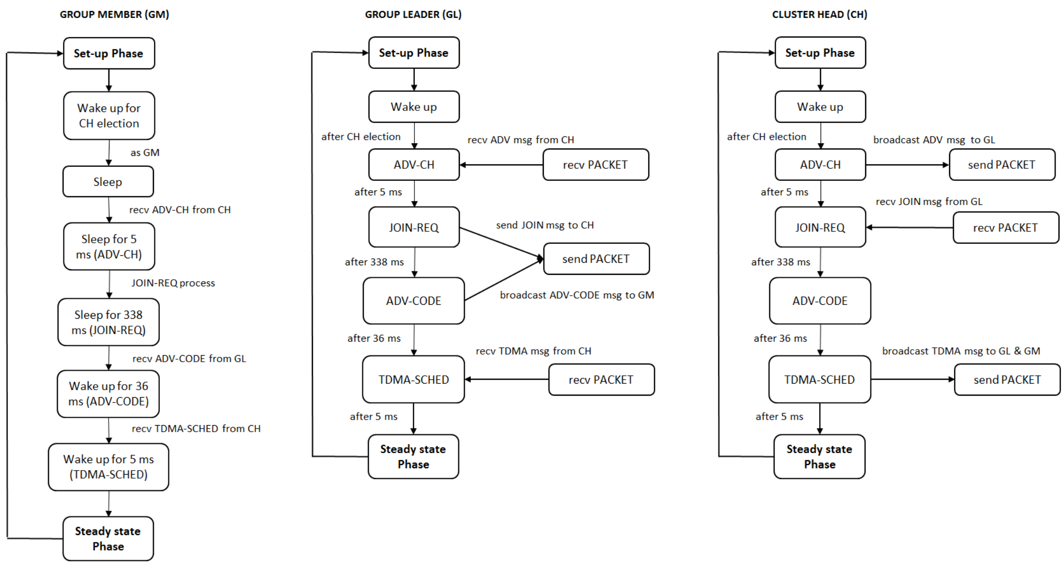


FIGURE 5.14: State Transition Diagram of the EMGC protocol.

that have not been elected as CHs in the last $1/p$ rounds. This parameter p can be programmed into the mobile nodes *a priori*. Meanwhile, $E_n(r+1)$ and $v_n(r+1)$are the current residual energy and the current speed of the node n, $E_{\max}$ and $v_{\max}$ are the initial energy and the maximum speed of the node. Using this threshold, the nodes with lower speed and more residual energy will have more chance to be elected as CHs. In the proposed protocol, each node calculates a threshold by Eq. (5.1). After that, the node creates a random value of [0 1], and then compares with the threshold. If the value is below the threshold, the node will become a CH. Otherwise, the node remains as a cluster member.

The elected nodes will promote the node's condition from a GM node to a CH node. Meanwhile, a GL node cannot become a CH node because it has a special task, i.e. to communicate with a CH in the cluster formation and the group handover procedure. Afterward, CHs broadcast an advertisement (ADV-CH) message that contains cluster-head's ID and its position to all GLs using non-persistent Carrier Sense Multiple Access (CSMA). The GL sends a join-request (JOIN-REQ) message containing its GMs to the CH with the shortest distance. It will reduce the control packet between CHs and cluster members because only the GLs will join in the cluster while the GMs are in the sleep condition. Thereafter, the GLs broadcast an advertisement code (ADV-CODE) message which contains cluster-code's ID, cluster-head's ID, and group's ID to its GMs. The code is used to make communication among nodes within the same cluster avoid a collision. Finally, the CHs broadcast a TDMA schedule to the cluster members which consist of its GLs and GMs.

5.3.4 Steady-state Phase

After cluster formation completed in the set-up phase, the steady-state phase is started. In the steady-state phase, the CH receives data from its cluster members in allocated time slots, then transmits the aggregated data in one frame to the base station.

The protocol also supports a group handover procedure to reduce signaling cost and frequent topology changes [100]. The detailed procedure is explained in Subsection 5.3.5.

5.3.5 Group Handover Procedure

To address frequent topology changes, we apply a group handover procedure in the steady-state phase. As shown in Fig. 5.15, when a mobile group j moves from position A to position B, that is, it moves away from the current CH1 and gets closer to another CH2, it has a possibility to change its CH and performs a group handover procedure. This scheme uses a mobile controlled handover type where the GL monitors the signals of surrounding cluster heads and starts the handover process when it meets a condition. Since a group of mobile nodes will have possibility to move away from the current cluster head in a half process of steady-state phase before set-up phase in the next round, we have made a handover period in the steady-state phase and allowed a group to handover only one time even in the steady-state phase. This mechanism can reduce the transmission distance of GLs and GMs to its CH and then reduce energy consumption for transmission power. This mechanism can also avoid GLs or GMs to be in wake-up state periodically in the steady-state phase.

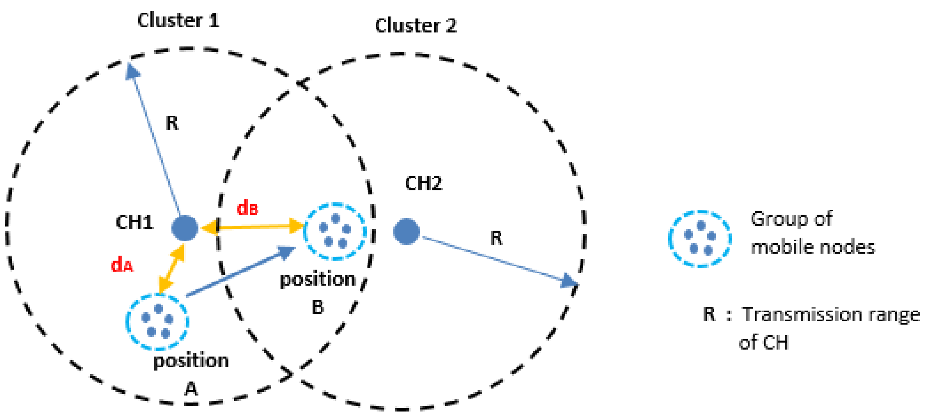


FIGURE 5.15: Group handover.

We employ a two-step decision as to whether a mobile group will make a handover or not. The first step is to decide whether the mobile group remains in the previous cluster or it joins the new cluster. If the mobile group has a willingness to join the new cluster, it performs the second step to elect the minimum communication energy to a new CH.

In the first step, the GL of group j (GL$_j$) uses the following formulation to calculate the willingness, $F_j(r)$, at round r.

$$F_j(r) = d_j(t_{hr}) - d_j(t_{sr}) \tag{5.2}$$

where $d_j(t_{sr})$ is the distance between GL$_j$ and CH1 when GL$_j$ is at position A at time t_{sr}, i.e., at the beginning of the set-up phase at round r. Similarly $d_j(t_{hr})$ is that when GL$_j$ is at position B at time t_{hr}, i.e., at the beginning of the group handover procedure in the steady-state phase at round r. Note that during the group handover procedure as in Fig. 5.16, a CH broadcasts a message (ADV-CH) that contains a CH's ID and its position to all GLs. Thus, after receiving this message, the GL will calculate the distance to the CHs.

In ADV-GL process, all GMs will be in the wake-up condition to detect an advertisement message from the GL (ADV-GL) which contains a group's ID and a join value. If F is negative, the GL broadcasts an ADV-GL message with the join value

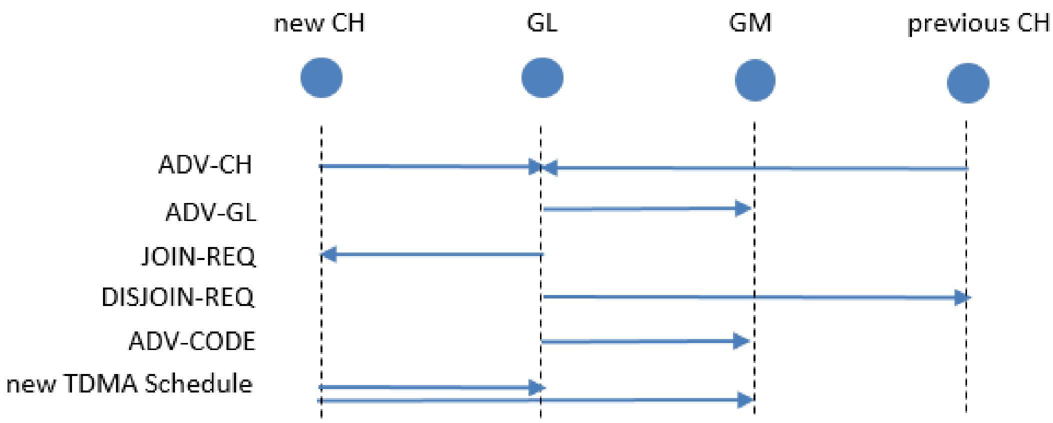


FIGURE 5.16: Group handover procedure in EMGC protocol.

0. Therefore, all nodes of the group use the previous cluster-head and cluster-code information. Then, the GL and GMs are in the sleep condition until the next TDMA scheduled slot.

Meanwhile, if F is positive, it will use the second step, that is, the final decision of the GL at round r to make a handover. It is based on the equation below:

$$H_j(r) = \arg\min_k d_{j,k}(r) \qquad \forall k \in C \tag{5.3}$$

where $d_{j,k}(r)$ is every distance between GL_j and CH_k at round r. C is the set of CHs in the network. Based on the above equation, the GL will choose the smallest value of $d_{j,k}(r)$ to join the new cluster. If the smallest value is that of the previous CH, the GL will broadcast the ADV-GL message with the join value 0 to the GMs to remain in the previous cluster and they will be in the sleep condition until the next TDMA scheduled slot.

When the elected CH has a closer distance value than the previous one, the GL broadcasts the ADV-GL message with the join value 1 to the GMs to give information that the group will change its CH. After that, only the GL is in the wake-up condition to make a communication to the new CH, and the GMs are in the sleep state until the ADV-CODE process. Afterward, the GL sends a join message (JOIN-REQ) to a new CH and a dis-join message (DISJOIN-REQ) to the previous CH. Then, the GLs broadcast an advertisement message to its GMs in the ADV-CODE process. Finally, CHs broadcast a new TDMA schedule to its cluster members.

5.3.6 Performance Evaluation

In this subsection, we evaluated the performance of our proposed protocol. Firstly, we describe group mobility models and radio energy dissipation model which are used in the simulation. Then, we discuss simulation results of EMGC protocol compared with GMAC, MN-LEACH, and MBC protocols.

All mobile nodes are randomly group distributed based on the RPGM and NCM models as explained in Chapter 3 section 3.3. We used BonnMotion [104] to produce the mobility models. The setting parameters for the mobility model used in our simulation are as follows.

We define the percentage of groups (P_g) to indicate the ratio of the number of groups to the number of nodes in the network with formulation as below

$$P_g = \frac{N_g}{N} \quad , \qquad N_g \leq \frac{N}{2} \tag{5.4}$$

where Ng is the number of groups and N is the number of nodes in the network. The maximum number of groups is half of the number of nodes. It means that one group has only one GL and one GM. The setting of P_g is 5%, 10%, 20%, and 30%. The maximum distance to the group center is 8 meters, the maximum pause time is 0 to indicate that all nodes always move, the group change probability is 0 to refer a fixed group formation as in Assumption 2, and the random seed is 0 to initialize a pseudorandom number generator. The maximum speed ($v_{\max}$) is 2 m/s, 5 m/s, or 10 m/s, and the minimum speed is 0.5 m/s.

Regarding the radio energy dissipation model as in Chapter 3 section 3.3, we do not consider the energy dissipation in a wake-up state and sleep state in EMGC protocol.

TABLE 5.2: Simulation Parameters for EMGC Protocol

Parameters	Values
Number of nodes	100
Network size	100×100 m^2
Size of packet	500 bytes
Packet header	25 bytes
Channel bandwidth	1 Mbps

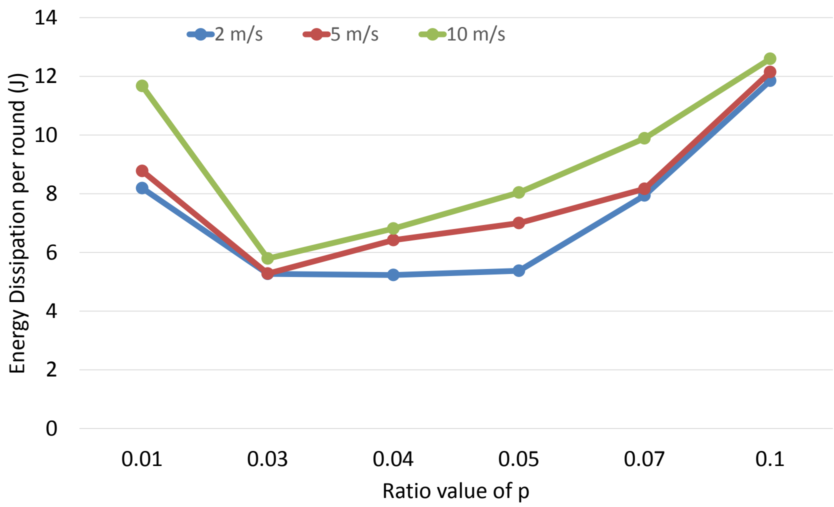
In our simulation, the parameters for the communication energy are set as E_{elec} = 50 nJ/bit, ε_{fs} = 10 pJ/bit/m^2, ε_{mp} = 0.0013 pJ/bit/m^4, d_0 = 87 m, and the initial energy (E_{init}) = 2 J.

To evaluate the performance of our proposed protocol, we simulated by using Network Simulator 2 (NS2) [108]. Table 5.2 shows the parameters used in the simulation. The location of BS is the center of networks.

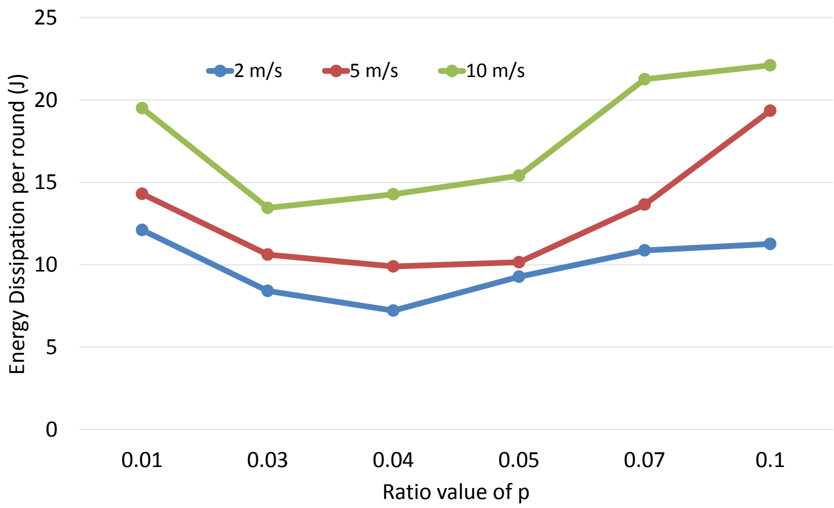
We define another parameter, i.e., the percentage of cluster heads (p) to indicate the rate between the expected number of CHs (k) and the total number of mobile nodes (N). Regarding this parameter, we evaluated the energy dissipation per round as a function of p (0.01-0.1) for different maximum speeds (2 m/s, 5 m/s, 10 m/s), and different network areas (100×100 m^2, 400×400 m^2) as in Fig. 5.17. It can be seen that the optimum value of p falls between 0.03 - 0.05 in every case. Therefore, we have set the value of p in Eq. (5.1) to 0.04 this time.

Regarding the time duration, we set total time of the set-up phase is 384 ms with ADV-CH is 5 ms, JOIN-REQ is 338 ms, ADV-CODE is 36 ms, and TDMA Schedule is 5 ms. The time length of one round is 20 s. EMGC reduces JOIN-REQ time because the communication is only between CH and GL. Meanwhile, in the handover process, there is an additional event, that is, ADV-GL when the time duration is 32 ms. Therefore, the total time of handover is 416 ms.

In the simulation, we compare our proposed protocol with MN-LEACH, GMAC, and MBC protocols in terms of the number of nodes alive, energy dissipation per round, the number of data items at base station, and the number of control packets per round.



(a) Network area 100m×100m with 100 nodes.



(b) Network area 400m×400m with 100 nodes.

FIGURE 5.17: Energy dissipation per round as a function of p.

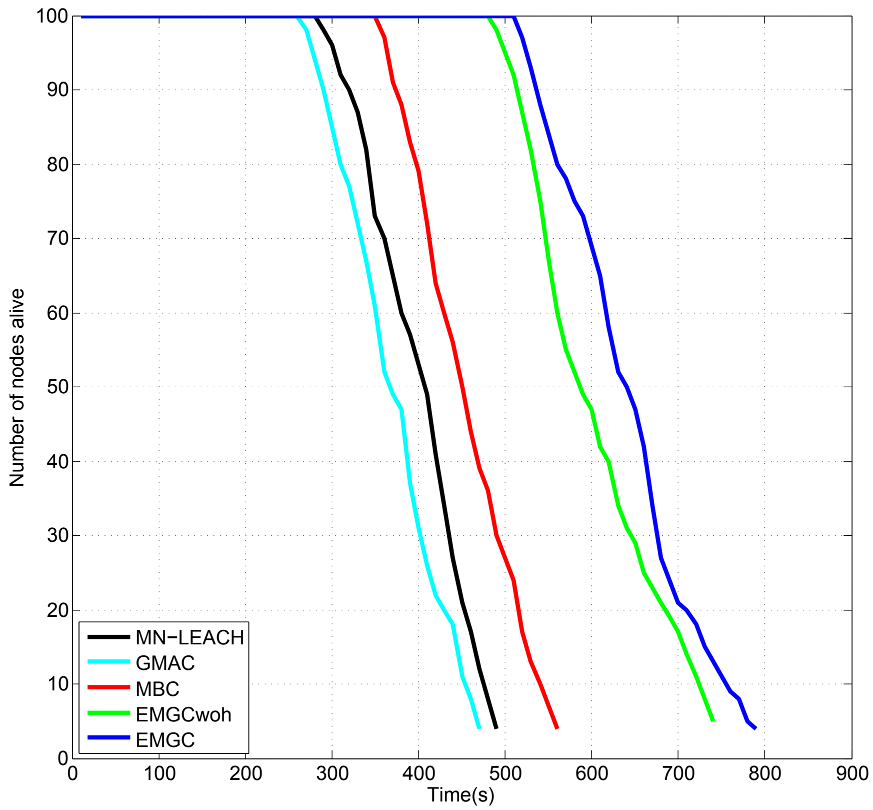


FIGURE 5.18: Number of nodes alive over time when P_g = 10% and $v_{\max}$ = 2 m/s.

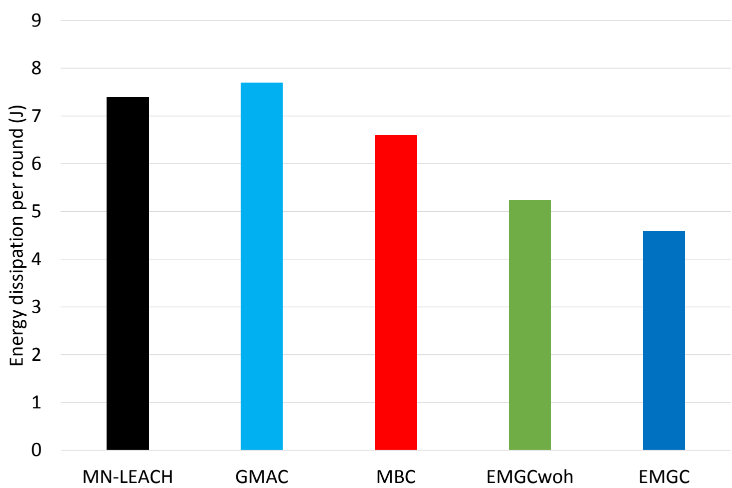


FIGURE 5.19: Energy dissipation per round when P_g = 10% and $v_{\max}$ = 2 m/s.

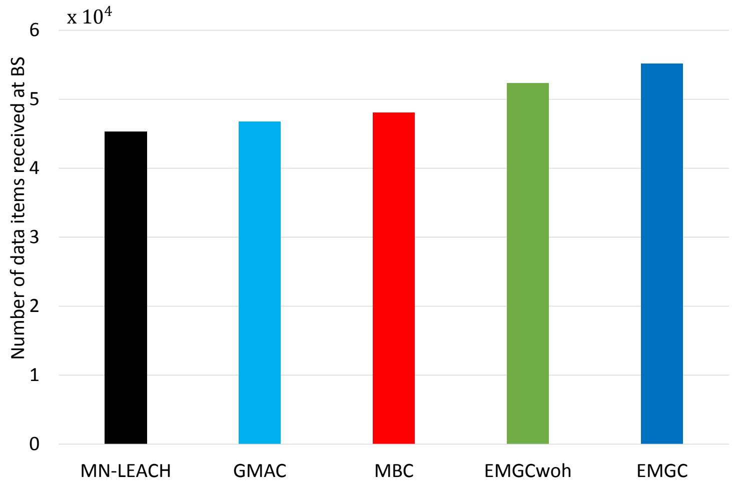


FIGURE 5.20: Number of data items received at BS when P_g = 10% and $v_{\max}$ = 2 m/s.

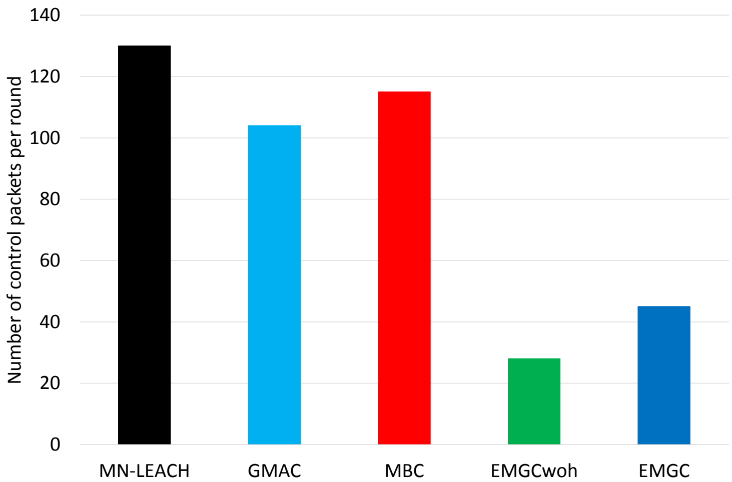


FIGURE 5.21: Number of control packets per round when P_g = 10% and $v_{\max}$ = 2 m/s.

Furthermore, to evaluate the effect of handover in steady-state phase, we also adopt EMGC without a group handover procedure (EMGCwoh) for comparison.

We assume that each node always has data to transmit in its time slot of TDMA manner in all protocols. The protocols also use CSMA/CA in the set-up phase, the steady-state phase (when a CH sends an aggregated data to a BS and a normal node sends data directly to a BS), and the handover process. Therefore, there is a possibility to produce packet losses if the number of transmissions excesses its limit (it is four times in our simulation) due to collision.

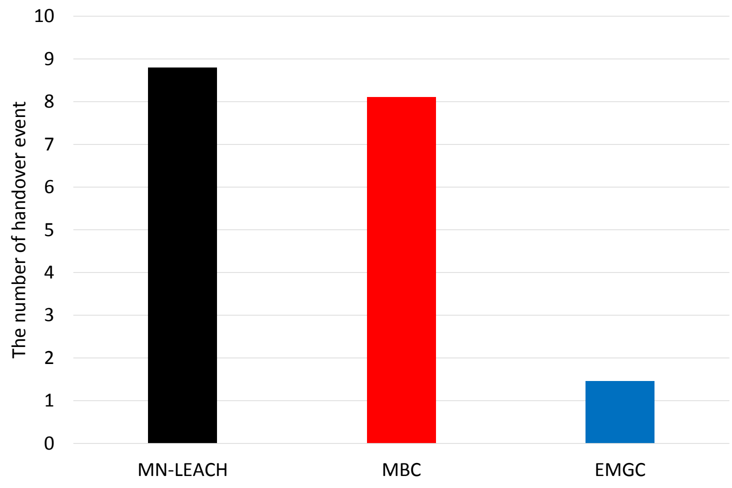


FIGURE 5.22: Frequency of topology changes in the handover procedure per round when P_g = 10% and $v_{\max}$ = 2 m/s.

5.3.6.1 Fixed Percentage of Groups and Maximum Speed

We evaluated our proposed protocol by using the RPGM model and set the maximum speed 2 m/s, the percentage of groups 10%. Figures 5.18, 5.19, and 5.20 show that EMGC protocols outperform GMAC, MN-LEACH, and MBC protocols in terms of the nodes alive over time and energy dissipation per round, and the number of data items received at the base station. This is because the protocols are specialized in the group mobility where most communications are only between CHs and GLs in the set-up phase for a cluster formation. Therefore, GMs as dominant nodes could be on the sleep condition and reduce the energy dissipation per round, which yielded prolonging the lifetime of the networks and increasing in the number of data items received at the base station. This observation can be supported by Fig. 5.23 as explained in the next subsection. Besides, EMGC shows the better performance than EMGCwoh, because EMGC supports a group handover to reduce energy consumption when the distance to a new CH is closer.

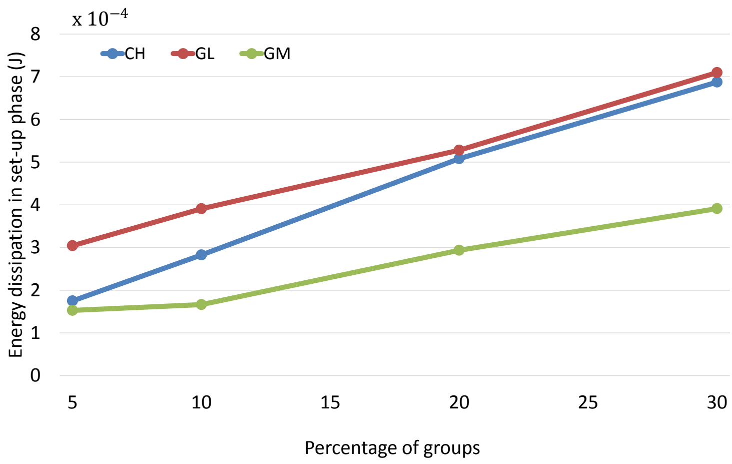
Such a good performance is also supported by the following two figures. Figure 5.21 shows the evaluation of the number of control packets on each round for successfully received data packet. The control packets is used for transferring any packets in the set-up phase and handover process. From this figure, it can be easily seen that EMGC protocols have significantly cut down on control packets. Here EMGCwoh has less control packets than EMGC, because of no group handover procedure.

On the frequent topology changes, we only evaluated protocols which support handover scheme as shown in Fig. 5.22. In the topology changes of MBC and MN-LEACH protocols, a sensor node will join individually in a new cluster when the node moves away from the current cluster to reduce the energy consumption. The joining process for a single node is one handover event. For a group handover, the event will be undertaken by a GL to join a new cluster and dis-join the previous cluster. From this viewpoint, a group handover will reduce the number of handover events. Therefore, EMGC protocol has fewer handover events compared to MBC and MN-LEACH protocols.

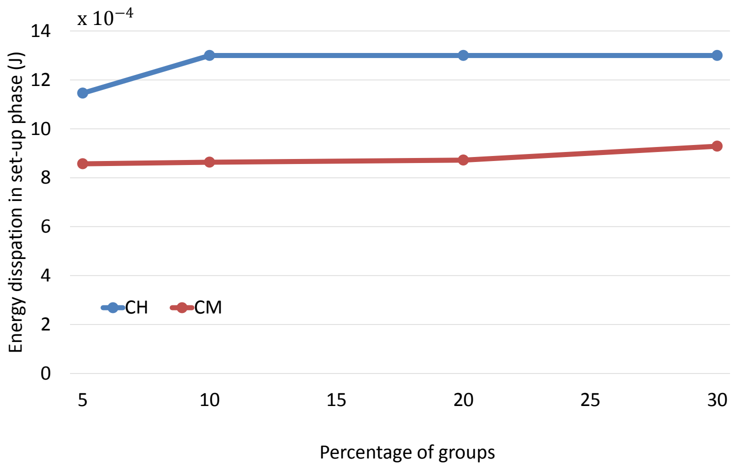
5.3.6.2 Various Percentage of Groups and Maximum Speeds

In this evaluation, we used RPGM as mobility model with various percentage of groups, i.e. 5%, 10%, 20% and 30%, and various maximum speeds, i.e. 2 m/s, 5 m/s and 10 m/s. The previous simulation results have revealed that the frequent topology changes and large amounts of control packet will affect the energy dissipation and the number of data items received at the base station. Therefore, we will hereafter focus on evaluating of two performance indices, i.e. the energy dissipation and the number of data items.

In Fig. 5.23, we evaluated the concentrated energy on all categories of mobile nodes, i.e. CHs, GLs, and GMs. In the set-up phase of EMGC protocol, a GL dissipates more energy because most communications are between GLs and CHs. Meanwhile, the GMs are in the sleep condition. As the percentage of groups increases, the energy of all categories of nodes also increases because there is a significant increment in the



(a) EMGC Protocol.

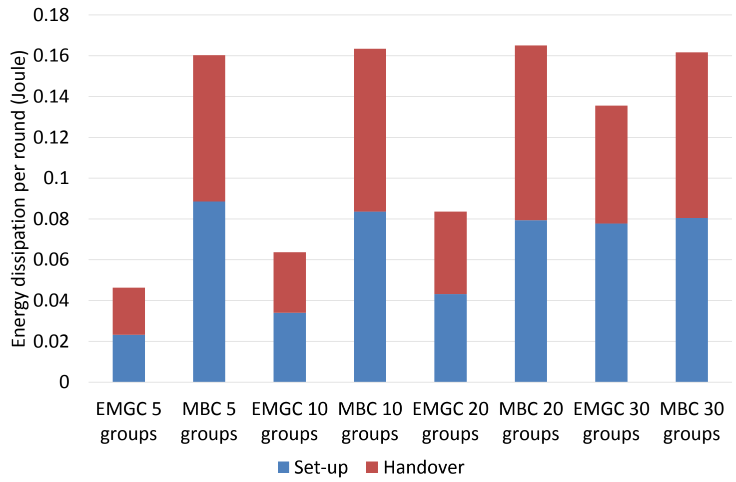


(b) MBC Protocol.

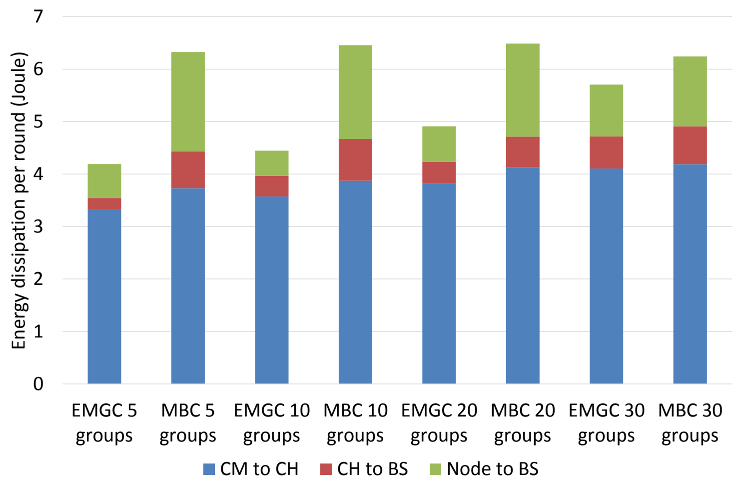
FIGURE 5.23: Energy dissipation per node in the set-up phase for all categories of nodes with various percentage of groups when v_{max} = 2 m/s.

number of join-request and ADV-CODE processes. As the results, EMGC protocol outperforms MBC in terms of energy dissipation in the set-up phase and it indicates that our three-categorized node organization and assignment works well.

Figure 5.24(a) shows that EMGC saves more energy than MBC in the set-up and handover phases, because most communications are performed between CHs and GLs due to using three categorization of nodes. However, its improvement is not so large overall. Using three categorization also affects to decrease the energy dissipation in the steady-state phase. From Fig. 5.24(b), most significant improvement can be seen



(a) Set-up and Handover phases



(b) Steady-state phase

FIGURE 5.24: Energy dissipation per round in the set-up, handover, and steady-state phases with various percentage of groups when v_{max} = 2 m/s.

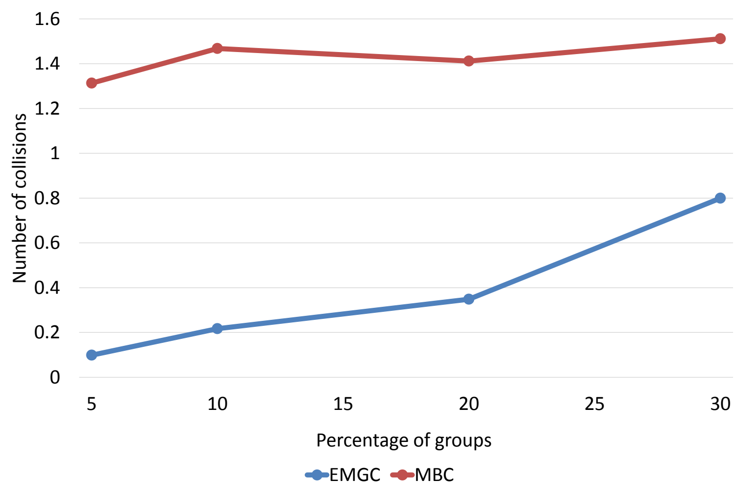


FIGURE 5.25: Number of collisions from CMs (GLs) to CHs.

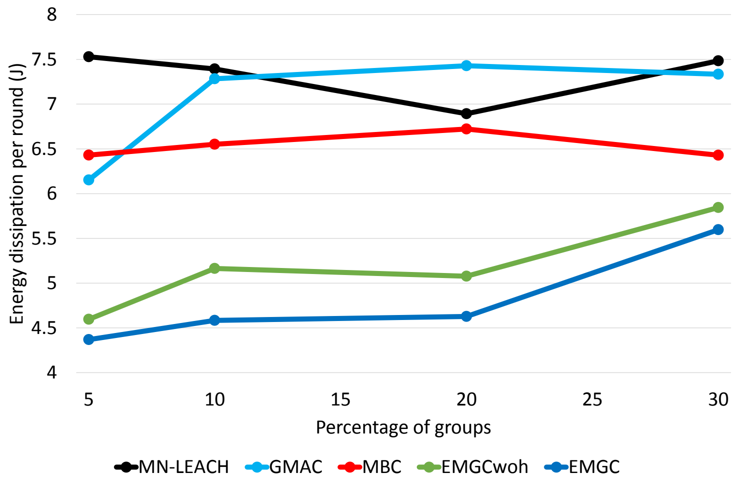


FIGURE 5.26: Energy dissipation with various percentage of groups when v_{max} = 2 m/s.

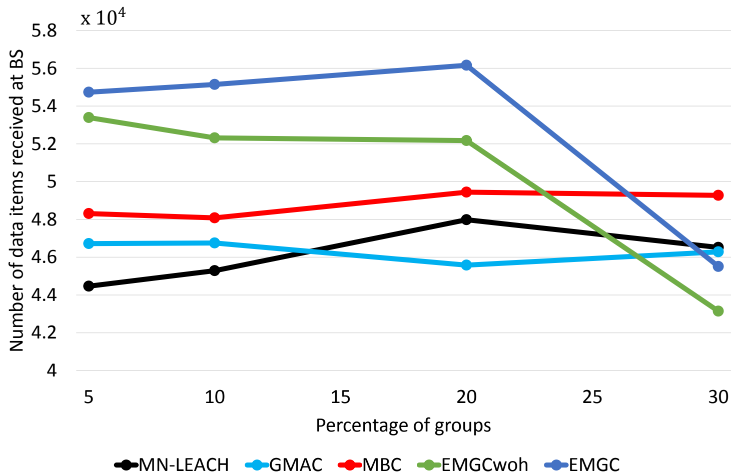


FIGURE 5.27: Number of data items received at BS with various percentage of groups when v_{max} = 2 m/s.

in the communication of "Node to BS". When a node cannot belong to any CHs, it sends data directly to BS. We call it "Node to BS" communication. Such an isolated node is likely to be generated when JOIN request message from a node cannot be received at CH due to packet collision. In EMGC, only GLs send JOIN message so that the number of collisions can be reduced compared to MBC as shown in Fig. 5.25.

Figures 5.26 and 5.27 show that if the percentage of groups is less than 20%, EMGC protocol achieves the best performance. However, if the percentage of groups is more than 30%, EMGC protocol is the worst in term of the number of data item received at the base station. The reason is that an increase in the percentage of groups causes more control packets in the cluster formation and handover procedure such as the join-request process from GLs to CHs, and also the ADV-CODE process from GLs to GMs. On the other hand, GMAC also supports group mobility and its performance is relatively stable against the percentage of groups compared with EMGC. This is because GMAC divides the network area into zones to form steady clusters, and GMAC has less energy dissipation in the low percentage of groups where the group will be close enough to its CH. However, due to no handover procedure, GMAC expenses more energy than EMGC when a group of mobile nodes moves from one zone to another zone. Meanwhile, MBC and MN-LEACH are almost independent of the percentage of groups because they do not support group mobility, and thus each cluster member will make the communication directly to its CH and take a handover procedure by each node.

We also evaluated the performance of our protocol with various maximum speeds, i.e. 2 m/s, 5 m/s, and 10 m/s in Figs. 5.28 and 5.29. EMGC protocol outperforms the other protocols in terms of the energy dissipation per round and the number of data items received at the base station. It shows that the protocol can better adapt to a highly mobile environment.

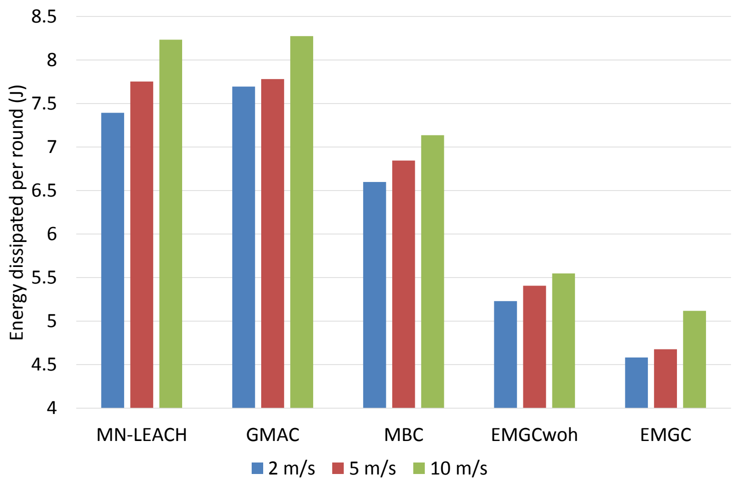


FIGURE 5.28: Energy dissipation per round against speed when P_g = 10%.

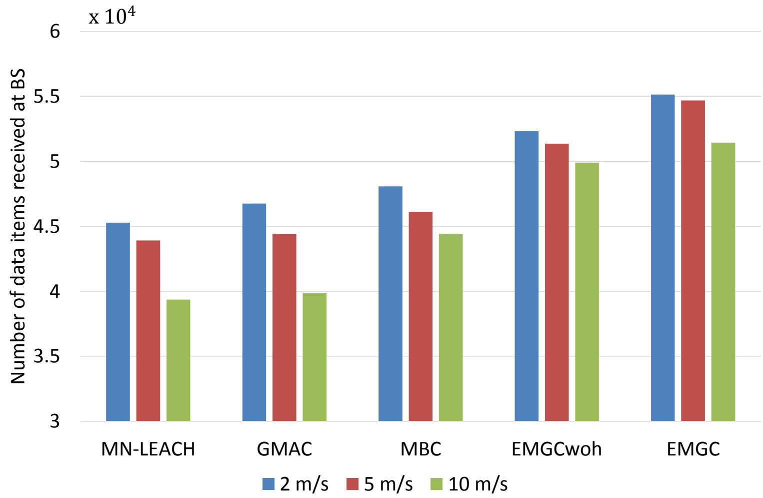


FIGURE 5.29: Number of data items received at BS against speed when P_g = 10%.

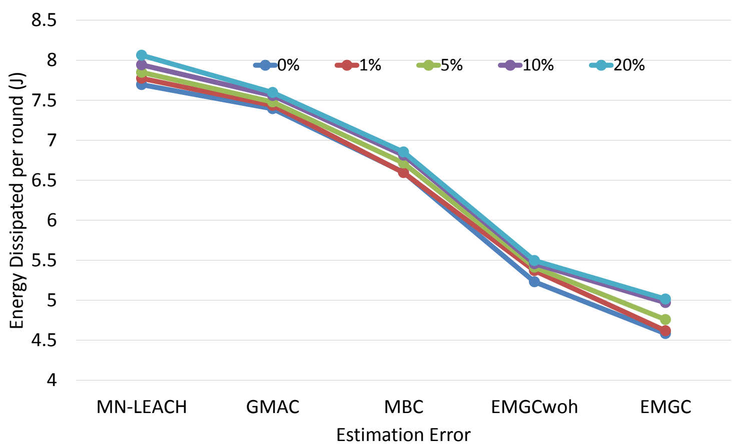


FIGURE 5.30: Energy dissipation per round with the estimation error of distance when P_g = 10% and v_{max} = 2 m/s.

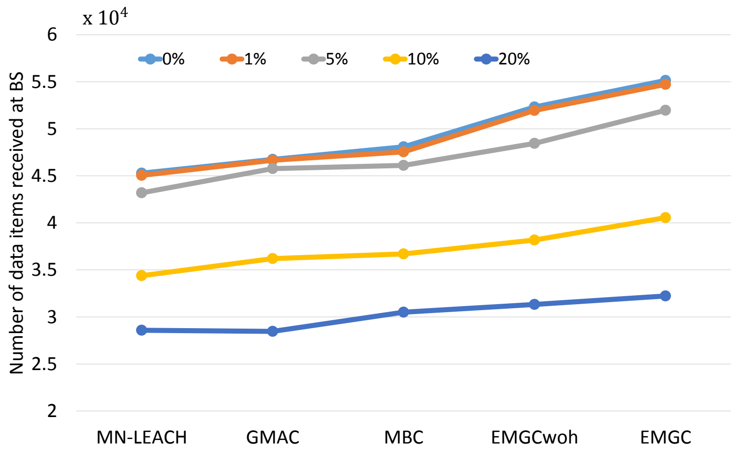


FIGURE 5.31: Number of data items received at BS with the estimation error of distance when P_g = 10% and $v_{\max}$ = 2 m/s.

5.3.6.3 Effects of Error in Distance

In addition, the effect of the estimation error in the distance on the energy dissipation is studied. We applied RPGM as mobility model with the percentage of groups 10% and the maximum speeds 2 m/s. Then, we evaluated the effect of the estimation error in the distance between a GL and a CH while they are moving, in relation between energy dissipation and the number of data items at the base station. Figures 5.30 and 5.31 show that the protocol performance does not degrade significantly if the estimation error in the distance is below 5%, in terms of the number of data received at the base station. The reason is as follows. If the distance is underestimated, that is, the GL gets the distance shorter than the exact value, the signal cannot reach the CH, which causes the decrease in the number of data items received at the base station. While the signal can reach enough the CH when the distance is overestimated, though the excess energy is wasted. However, the energy consumption does not significantly change in spite of the margin of error, because the estimated values are uniformly distributed around the exact value.

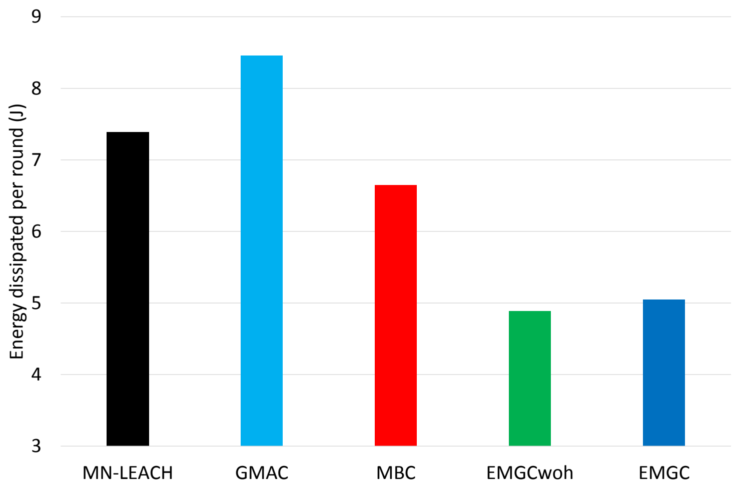


FIGURE 5.32: Energy dissipation per round for Nomadic Community Mobility Model when P_g = 10% and $v_{\max}$ = 2 m/s.

5.3.6.4 Nomadic Community Mobility

Finally, we evaluated by using NCM model with the percentage of groups 10% and the maximum speed 2 m/s. Figures 5.32 and 5.33 show that EMGCwoh outperforms the other protocols in terms of the energy dissipation per round and the number of data items received at the base station in the NCM model. This is because of a characteristic of the mobility model where some nodes in the same group roam around a particular area individually and are separated from the group for a while. Then, they will be in unity again. Therefore, the above condition degrades the performance of a group handover scheme because the separated nodes will use more energy to communicate with their GL and CH. This results suggest that a dynamic grouping to address the above problem is required.

5.3.7 Conclusion

The EMGC protocol proposed herein supports group mobility, and is equipped with a group handover procedure. The scheme is designed for energy efficiency of mobile WSNs with three categories of nodes, namely cluster heads, group leaders and group members. The key factor is how to make the sleep condition for group members as dominant nodes as long as possible and to reduce amounts of control packet in the

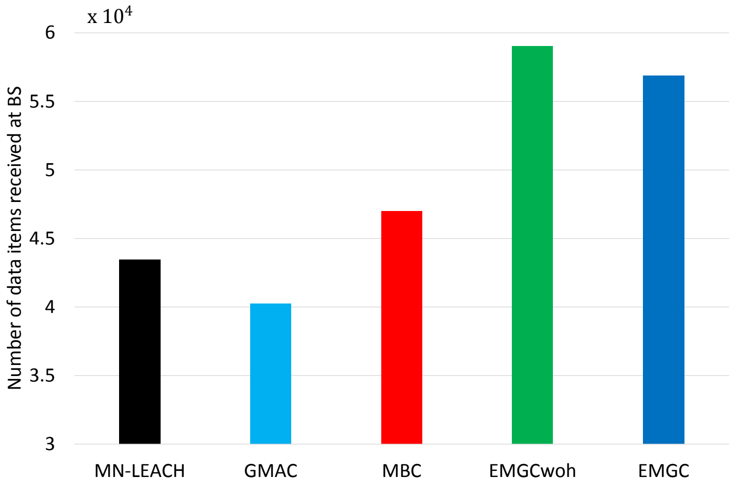


FIGURE 5.33: Number of data items received data at BS for Nomadic Community Mobility Model when P_g = 10% and v_{max} = 2 m/s.

networks. Most communications only occur between group leaders and cluster heads in the set-up phase. The protocol has outperformed MN-LEACH, GMAC, and MBC protocols in terms of the number of nodes alive, the number of data items received at the base station, and the energy dissipation per round as well the number of control packets per round. Our future work is to study dynamic group formation which is highly adaptable to various characteristics of group mobility.

Chapter 6

Adaptive Group Formation Scheme for Mobile Group WSNs

6.1 Introduction

A large number of sensor nodes creates a wireless sensor network. It has components such as sensing, wireless communication, and data processing. Wireless sensor networks (WSNs) have many applications, for example exploration, wildlife protection, and health care application. Other applications that consider group mobility are search and rescue activity and the evacuation of people in a natural disaster [109]. Regarding these applications, a WSN needs to be designed considering mobile nodes [25][86][110][111]. The main goal of mobile WSNs deployed in a network area is to deliver more data from a mobile sensor node to a base station (BS) with the limitation of energy consumption. Then, the data will be analyzed at the BS. Data collection and energy consumpton are important factors in designing and determining mobile WSNs [98][59]. To effectively perform these tasks, several protocols based on a clustering system have been proposed to tackle such issues.

Cluster Based Routing (CBR) protocol [8] supports the mobility of a sensor node by adding an adaptive TDMA schedule based on traffic characteristics to increase the successful packet delivery rate. Thereafter, Mobility-based Clustering (MBC) protocol [9] improves the performance of CBR. MBC considers reliable path using an estimated connection time and the distance when a non cluster head node joins a cluster. However, these protocols assume that sensor nodes move independently according to random models and they do not support group mobility scenarios.

GMAC protocol [10] takes into account the group formation in the set-up phase. It calculates a group mobility metric and partitions the network area into zones to obtain steady clusters. However, the implementation of zones cannot adapt well in group mobility if there are nodes which are located in different zones.

In the previous chapter, we proposed an EMGC protocol [112] to address some existing problems on the design of mobile group WSNs that reduce network lifetime, such as high energy consumption, control packets, and frequent topology changes. The EMGC protocol considers mobile group sensor nodes in scenarios such as an evacuation system. The network structure of the EMGC protocol is shown in Fig. 5.11 and there are three categories of mobile nodes, i.e. (1) a CH node which has a major role in the set-up and steady-state phase, (2) a GL node which has a key role also in cluster formation together with CH node, and (3) a GM node as a normal node. Furthermore, it offers a group handover mechanism in order to increase packet delivery and network lifetime. The simulation results have shown that EMGC outperforms some existing protocols such as MN-LEACH [99], GMAC, MBC in terms of the number of nodes alive, the energy dissipation per round, and the number of data items received at a base station.

Therefore, EMGC is the best grouped mobile protocol which integrates group mobility in the clustering system. However, there is a possible event occurring in a mobile group environment where some mobile nodes in the same mobile group move to other mobile groups. We call it a dynamic group change. This becomes a challenging problem in EMGC protocol because EMGC uses a fixed group formation which causes a longer distance between GL and GM and requires more transmission power. Furthermore, this protocol fails to maintain the number of data delivery and network lifetime as increasing the number of groups also increases the number of control packets and collisions between GL and GM.

After we study the characteristic of nodes in the mobile environment by using non-group and group mobility models in the previous chapter and to address the above problems, we propose a novel group formation scheme which is integrated with an EMGC protocol, i.e. an Adaptive group formation with EMGC (AgEMGC) for mobile group WSNs. The basic function of AgEMGC is to form groups adaptively to a dynamic group change so as to establish a more reliable link between a GL and GMs by considering a link expiration time and the residual energy of each GL. Then, the protocol implements a group merging procedure to address the problem of increasing the number of groups. A group merging will occur if there is no GM in a group, then the GL of each group changes its function as a GM and joins another group. Finally, we add two additional functions, i.e. (1) GL rotation to distribute the energy load of GL, (2) a stay connection procedure to save more energy.

6.2 Adaptive Group Formation with EMGC Protocol

In this section, we provide the detailed mechanism of the AgEMGC protocol for mobile group WSNs. We will first describe an application scenario and slot structure of our proposed protocol. Thereafter, we present an adaptive grouping mechanism which contains the group merging procedure.

In this paper, we make some assumptions as follows.

- All mobile nodes are considered homogeneous with the equal initial energy and heterogeneous with the unequal initial energy.
- All mobile nodes are location-aware [106][107].
- The base station is stationary.

6.2.1 Application Scenario of Dynamic Group Change

Assuming an application scenario such as evacuating people in a disaster area where the disaster will cause some difficulties in communications such as network congestion and infrastructure collapse [110]. A wireless sensor network with a multi-hop manner [25] is one of the promising methods to guarantee communication without an aid of infrastructure.

In evacuation systems, many groups of people will move to safe zones. They wear a sensor node which will report their health condition. Various sensors can be used to measure the above people conditions [113], such as (1) pulse oximeter, to measure the amount of oxygen in blood, (2) BPMote, to detect and report the blood pressure, (3) EKG sensor, to detect heart rate.

One of the people in a group, such as a laboratory member is registered as GL first and we are thinking that this scenario can be applied in the disaster area. In this scenario, all GLs are initially determined based on the distribution of mobile group nodes. Then, the GLs invite other nodes to become their members as GMs. It also allows GMs to change their GLs if they have a better reliable link. There are two possibilities in this scenario, i.e., (1) it is possible that some members in the same group to change their group if they meet their friends in other groups. If this condition happens in family formation, there are some vehicles to evacuate elderly and sick people of the family member. Therefore, the family formation will be changed. (2) a GL will merge to another group if there is no GM in the group.

In the application scenarios of this protocol, family formation in natural disasters is just an example and one of possible scenarios. This study does not cover every case and was not evaluated for all cases.

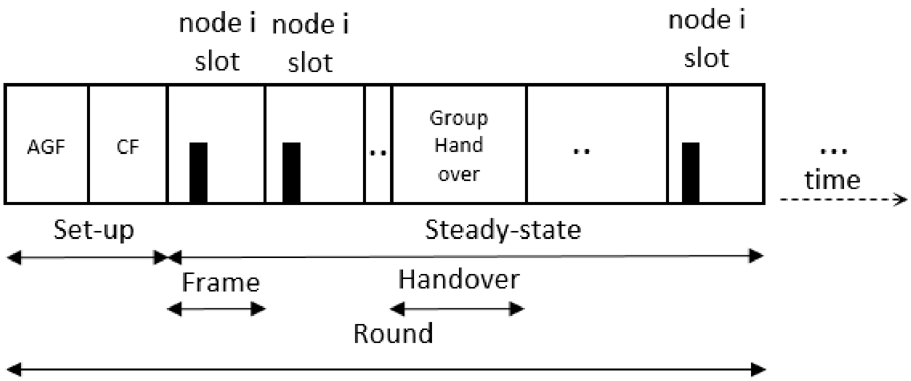


FIGURE 6.1: AgEMGC slot structure.

6.2.2 AgEMGC Slot Structure

The slot structure of the AgEMGC protocol is similar to an EMGC protocol. It is an enhanced version of EMGC that adds an adaptive group formation (AGF) into the protocol in the set-up phase which is periodically repeated in every round. Figure 6.1 shows one round of AgEMGC where it consists of two phases, i.e. (1) set-up phase, for AGF and cluster formation (CF), and (2) steady-state phase, to transfer data from sensor nodes to a BS with the group handover procedure.

In the set-up phase, first of all, all mobile nodes, which consist of GLs and GMs, will form groups. Thereafter, they create clusters where CH and GL perform most communications. After group and cluster formations are completed in the set-up phase, it will start the steady-state phase. All cluster members send data to their CHs in allocated time slots of time division multiple access (TDMA) manner. Thereafter, the CHs transmit the aggregated data for one frame to the BS by carrier sense multiple access (CSMA). To address frequent topology changes and signaling cost, the protocol performs a group handover procedure.

6.2.3 Adaptive Grouping

Adaptive grouping consists of the basic function and two additional functions that is GL rotation and a stay connection procedure.

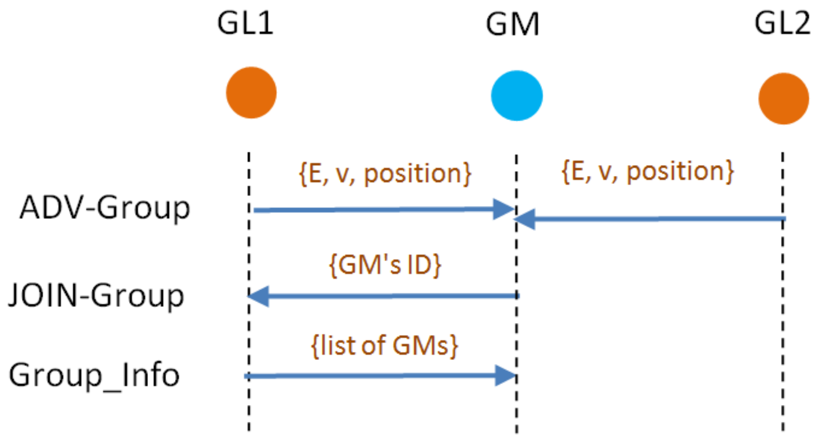


FIGURE 6.2: Basic function of AGF.

6.2.3.1 Basic Function of AGF

Figure 6.2 shows the procedure of the basic function of AGF. All GLs broadcast an advertisement (ADV)-Group message containing energy, velocity, and position using non-persistent CSMA. Each non-GL node receives the message from one or more GLs and calculates G metric which indicates a stable link and the robustness of connection between GL and GM in a group. G metric is composed of a link expiration time (LET) [79] and the residual energy of GL.

LET as in Chapter 3 section 3.4 is to estimate the amount of time two mobile nodes will stay connected each other. Let GM i and GL j be within the transmission range R_{T_x} of each other. We can calculate the value of LET between GM i and GL j at round r as

$$LET_{ij}(r) = \frac{-(ab+cd)+\left[(a^2+c^2)R_{T_x}^2-(ad-bc)^2\right]^{1/2}}{a^2+c^2} \tag{6.1}$$

where

$$a = v_i \cos\theta_i - v_j \cos\theta_j \quad b = x_i - x_j \tag{6.2}$$

$$c = v_i \sin\theta_i - v_j \sin\theta_j \quad d = y_i - y_j \tag{6.3}$$

Finally, we define the value of G metric, $G_{ij}(r)$, which is assigned to GM i and denotes a reliable link with GL j at round r, as follows.

$$G_{ij}(r) = \delta \times \frac{LET_{ij}(r)}{T_r} + \rho \times \frac{E_j(r)}{E_{init}} \tag{6.4}$$

where $\delta + \rho = 1$, T_r is time duration for one round, E_{init} is initial energy, and $E_j(r)$ is the current residual energy of GL j at round r.

Each non-GL node will elect its GL with the largest value of G. Thereafter, a non-GL node sends a JOIN-Group message containing GM's ID to the selected GL. Finally, GLs send a list of GMs to their GMs as an acknowledge (ACK) message. This process will be done in every round, and it gives a chance for GM nodes to choose the best GL with a stable link.

If GL has no GM in its group and it is close to other groups, the GL will initiate a group merging mechanism. The process of group merging is as follows. Let's assume that there are two groups close to each other where GL1 of Group 1 and GL2 of Group 2 are set as GLs at round r. In the group formation process, the GLs broadcast a message to their neighbors. We assume that all neighbors join the GL1 as GMs of Group 1. In the next round r+1, GL2 broadcasts a message again to confirm whether any GMs want to join. If there is no GM, GL2 will change its function from a GL node to a GM node. Finally, GL2 joins the other group as GM at round r+2.

To increase the performance of basic AgEMGC, we define two additional functions as follows.

6.2.3.2 GL Rotation

As in Fig. 6.2, after each GM receives an ADV-Group message from GLs, it elects the best GL based on the highest value of G from Eq.(6.4). Then, GM i calculates the value by replacing $E_{j(r)}$ with $E_{i(r)}$ as the current residual energy of GM i. GM

i transmits a JOIN-Group message which consists of (GM's ID, G) to the chosen GL. Each GL makes a list of GMs in descending order based on the G value. This order means that the highest value of G at index 0 of the list will be the next GL in the next round where the node has the longest connection time with the current GL and the highest energy. Finally, the GL broadcasts the Group_Info to its GMs. GM, which receives the message and at index 0 of the list, is set as the next GL. With this function, it can distribute the energy load of being GL among the nodes.

6.2.3.3 A Stay Connection Procedure

Figure 6.3 shows the changing group event. If GM node 1 of the Group 1 receives an ADV-Group message from GL2 and it has better G value than that of from GL1, there are some conditions to decide whether node 1 needs to join Group 2 or not as in Fig. 6.4.

- "Changing Group"event occurs if and only if G_{i1} is not the best and is below a threshold (S_g). Therefore, GM node 1 sends a JOIN-Group message to the GL2 and a DISJOIN-Group message to the GL1.
- Otherwise, it will be "Stay Connected". GM node 1 stays connected to the GL1 and does not send back a JOIN-Group message.

This evaluation ensures that GM node 1 still has a strong connection or not with the GL1 and reduces the control packet which is used in the network. If "stay connected", GM node 1 also receives the list in which other new GMs may join and the G values are updated.

6.3 Performance Evaluation

In this section, we will first describe the group mobility models and radio energy dissipation model used in this simulation. Then, we evaluate the performance of

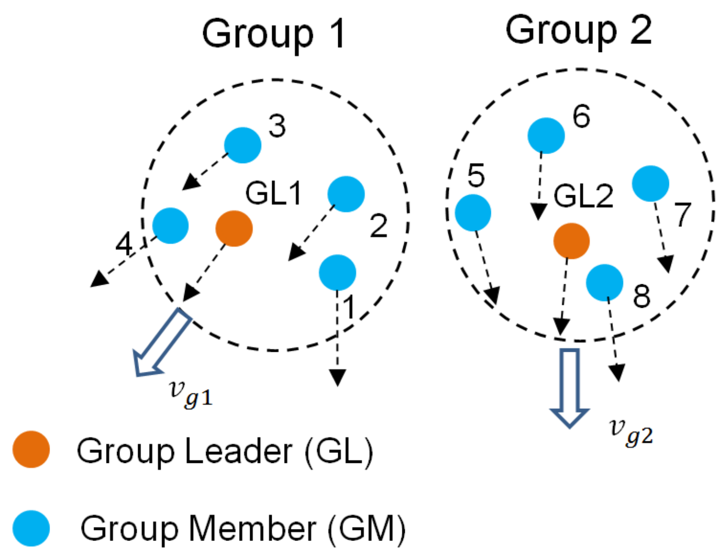


FIGURE 6.3: Changing group event.

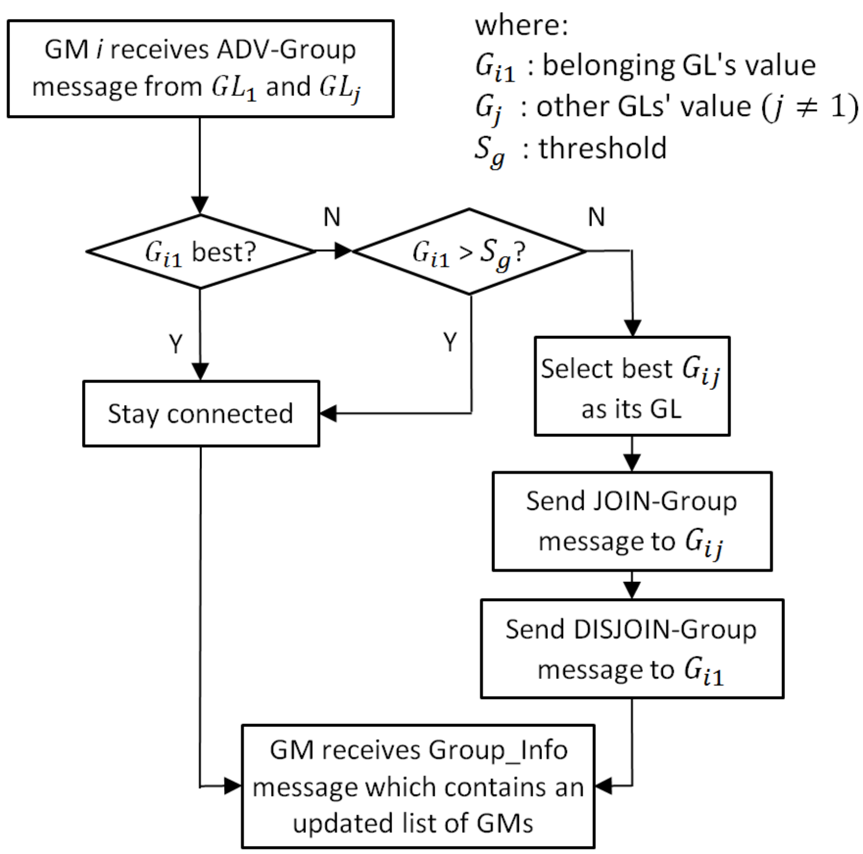


FIGURE 6.4: Stay connection procedure.

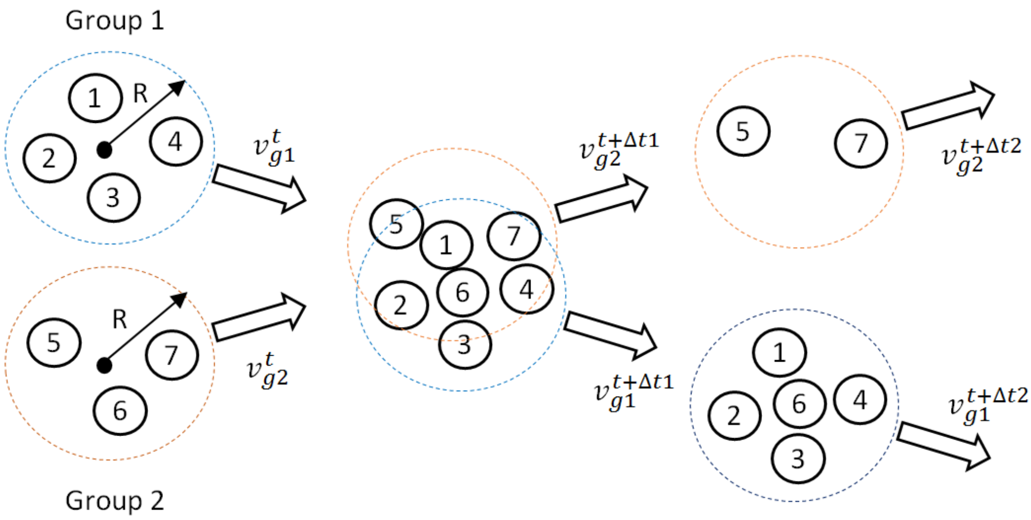


FIGURE 6.5: A dynamic group change in RPGM.

AgEMGC through simulation results. In the simulation, we compare our proposed protocol with MBC, EMGC without a group handover procedure (EMGCwoh), and EMGC protocols in terms of the number of nodes alive, the number of control packets per round, energy dissipation per round, and the number of data items received at a BS. Furthermore, to evaluate the effect of GL rotation and stay connection procedure, we also adopt AgEMGC with some schemes, i.e. (1) AgEMGC as a basic function of AGF, (2) AgEMGCwg, with **G**L rotation, (3) AgEMGCwc, with stay **c**onnection procedure, (4) AgEMGCwgc, with **GL** rotation and stay **c**onnection procedure.

Two group mobility models are used in this paper such as Reference Point Group Mobility (RPGM) model [114] and Nomadic Community Model (NCM) [58] as explained in Chapter 3 section 3.3. These models are used widely in the literature [58][106] for applications such as search-and-rescue operations, evacuation systems, etc. In the RPGM model, each group has a logical center which defines the entire group movement behavior, such as speed, direction, location, etc. The logical center moves at each instance by randomly choosing a direction and speed from its current location to a new location. Fig. 6.5 shows the process of a dynamic group change when there are two mobile groups. Each group has a range of R which is the maximum distance from the logical center of a group. v_{g1}^{t} and v_{g2}^{t} are speed at time t for

Group 1 and 2, respectively. Speed of each node in Group i deviates from v^t_{gi} by some degree. At t+Δt1, Group 1 will come into the range of Group 2 which might cause a certain node of Group 1 to change to Group 2 with a certain probability. Finally, at t+Δt2, it can be seen that node 6 changes to Group 2.

NCM is one of the group mobility types where some nodes in the same group will roam around a certain area separated from its group for a while. Thereafter, they are in one group again.

In our simulation, we use Bonnmotion [104] to generate the mobility models. The simulation parameters are set as follows. The maximum distance R from the logical center is 10 meters, the maximum speed ($v_{\max}$) is 2 m/s, and the minimum speed is 0.5 m/s. Group size standard deviation which indicates the standard deviation of initially created groups is 2. For the RPGM model, the group change probability indicates the probability that nodes will move from their current group to another group and takes the value of 0.05, 0.1, 0.2, 0.3, 0.6. The percentage of groups (P_{g}) which represents the ratio of the number of groups to the number of nodes in the network is 5%, 10%, 20%, 30%, 40%.

Regarding the radion energy dissipation model, we use the radio energy dissipation model as discussed in Chapter 3 section 3.2.

In our simulation, the communication energy parameter are set as E_{elec} = 50 nJ/bit, ε_{fs} = 10 pJ/bit/m^2, ε_{mp} = 0.0013 pJ/bit/m^4, d_0 = 87 m, and the initial energy (E_{init}) = 2 J [9][24].

The simulation of our proposed schemes was implemented based on Network Simulator 2 (NS2) [108]. The parameters used in the simulation are as follows. The number of nodes is 100 which are deployed in a square region 100 × 100 m^2. The size of packet is 500 bytes, packet header is 25 bytes, and channel bandwidth is 1 Mbps. The BS is located in the center of networks. Meanwhile, we set δ = 0.6 and ρ = 0.4 in Eq. (6.4) as well as S_g = 0.65 in Fig. 6.4.

TABLE 6.1: Optimal p in network area 100×100 m^2

N	50				100				200			
Pg	10%	10%	40%	40%	10%	10%	40%	40%	10%	10%	40%	40%
GCP	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6
p	0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.05	0.03	0.03	0.03	0.04

TABLE 6.2: Optimal p in network area 400×400 m^2

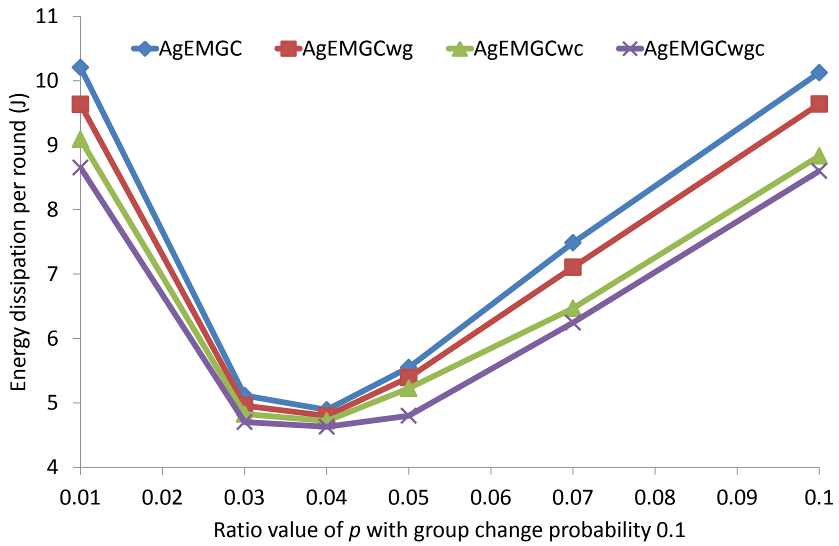
N	50				100				200			
Pg	10%	10%	40%	40%	10%	10%	40%	40%	10%	10%	40%	40%
GCP	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6	0.1	0.6
p	0.04	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

First, we evaluated the energy dissipation per round as a function of the percentage of cluster heads (p) as in Eq. (6.5) [112].

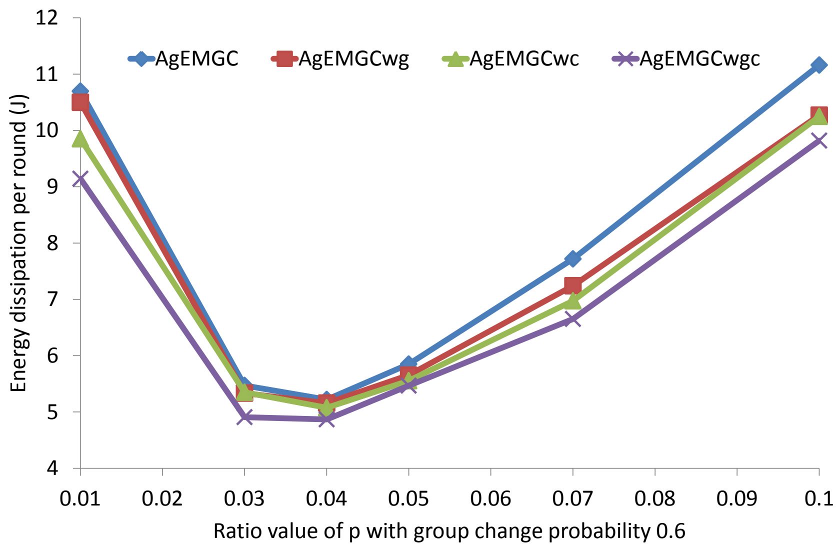
$$T_n(r+1) = \frac{p}{1-p\times(r \bmod \frac{1}{p})} \times \left(\frac{E_n(r+1)}{E_{\text{init}}} \frac{v_{\max}-v_n(r+1)}{v_{\max}} \right) \tag{6.5}$$

where r is the number of rounds that have passed, $E_n(r+1)$ and $v_n(r+1)$ are respectively the current residual energy and the current speed of the node n, whilst E_{init} and $v_{\max}$ are the initial energy and the maximum speed of the node, respectively.

We evaluated the optimal p with different network areas (100×100 m^2 and 400×400 m^2), various number of nodes (N), i.e., N = 50, 100, and 200, low and high percentage of groups, i.e., P_g = 10% and 40%, low and high group change probabilities, i.e., GCP = 0.1 and 0.6., and the range of p value, i.e., 0.01 - 0.1. Figure 6.6 show it is an example of various p values when number of nodes 100 and network area 100×100 m^2. Tables 6.1 and 6.2 show that the average value of p to achieve lower energy dissipation per round is around 0.04. This reason is considered that the clusters are likely to maintain the number of their member nodes as around 25 to save energy with local data aggregation in TDMA manner. Therefore, we set the p value to 0.04, and the area size of 100×100 m^2 is used hereafter.



(a) Ratio value of p with low group change probability.



(b) Ratio value of p with high group change probability.

FIGURE 6.6: Energy dissipation per round as a function of p.

6.3.1 Fixed Group Change Probability

We evaluated our proposed schemes with the RPGM model and set P_g at 10%, and GCP at 0.6. As mentioned in Introduction of this chapter, we addressed two problems with performance degradation; one is when a dynamic group change occurs and the other is when the number of groups increases. Comparing with the EMGC which is the baseline of this paper, we have known that EMGC performance degrades as increasing the number of groups, thus we specially focus on a dynamic group change here. Therefore we have chosen a parameter set of P_g = 10% and GCP = 0.6, in order to highlight the effect of high mobility condition. Then we have shown the effect of dynamic group change in detail in terms of the number of nodes alive, the number of control packets and energy dissipation in the set-up and steady-state. In addition, since P_g = 10% was used in our previous paper [112] to evaluate the same performance of EMGC, we considered that this parameter set was good for easy and fair comparison. This is another reason. After this evaluation we have shown the effect of various P_g and GCP in the following subsections.

As a reference in Figs. 6.7 and 6.8, we show and compare the results of four typical parameter sets, such that (P_g, GCP) = (10%, 0.1), (10%, 0.6), (40%, 0.1) and (40%, 0.6). From these results, the proposed schemes can address well even when Pg = 40% compared with EMGC protocols.

Figures 6.9, 6.10, and 6.11 show total number of nodes alive over time, energy dissipation per round, and number of data items received at BS, respectively when the number of nodes, N = 50, 100 and 200. From these figures, it is found that AgEMGC family outperforms the others. As increasing the number of nodes, the number of groups and the possibility of mobile nodes changing their groups increase. It causes EMGCs to degrade their performance. Meanwhile, AgEMGCs have the dynamic group change function which establishes a stable link in a group. It will reduce the

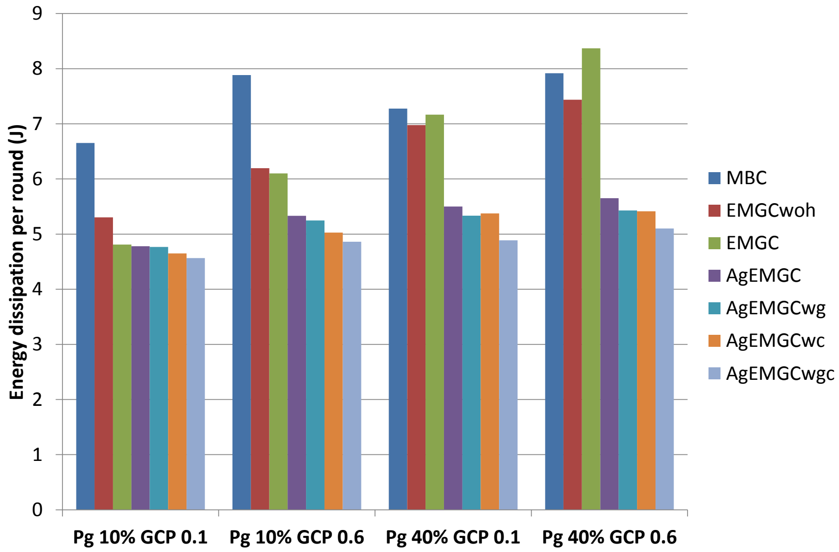


FIGURE 6.7: Energy dissipation per round with various P_g and GCP.

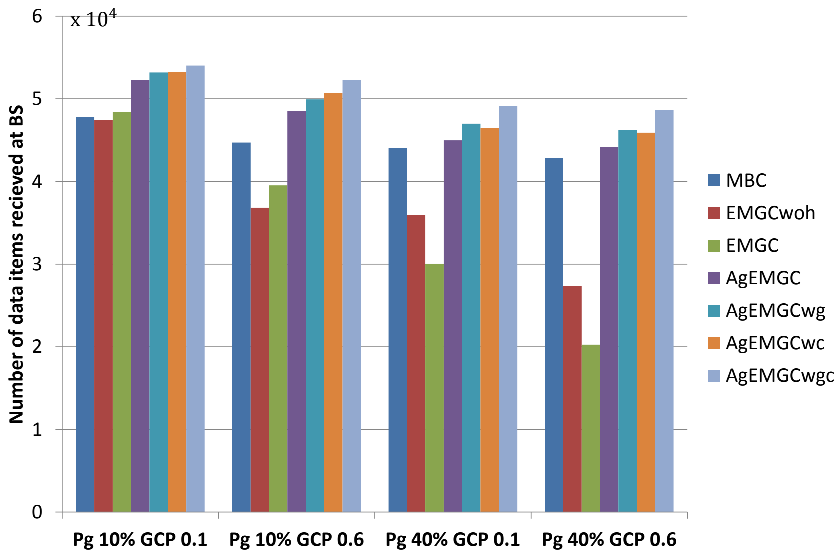
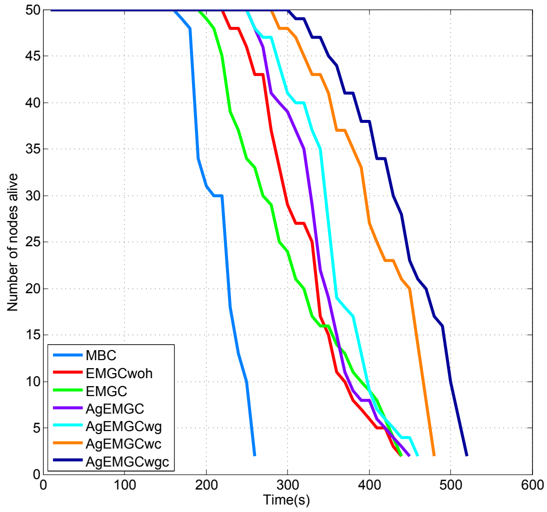
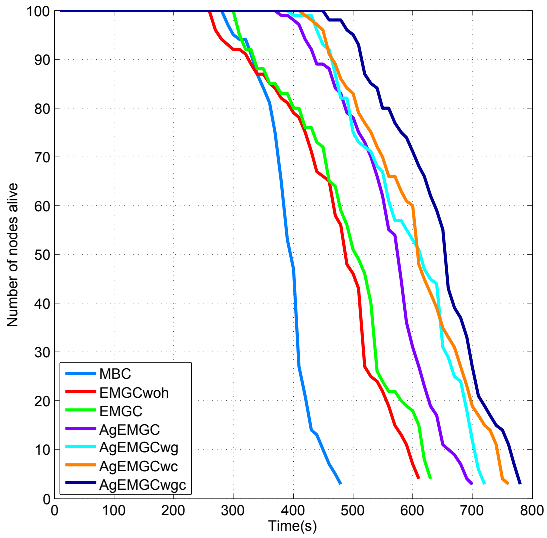


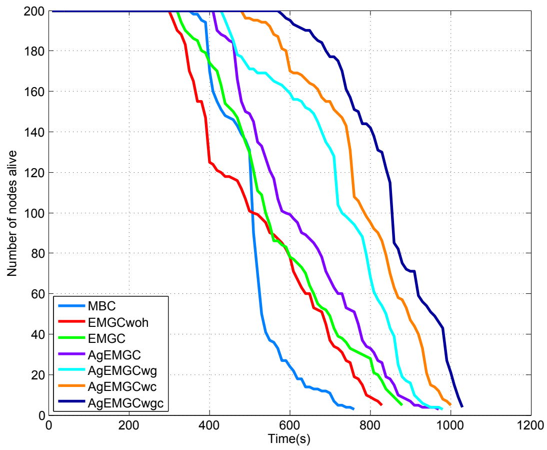
FIGURE 6.8: Number of data items at BS with various P_g and GCP.



(a) Number of nodes 50



(b) Number of nodes 100



(c) Number of nodes 200

FIGURE 6.9: Number of nodes alive over time when GCP = 0.6, P_g = 10% and various number of nodes.

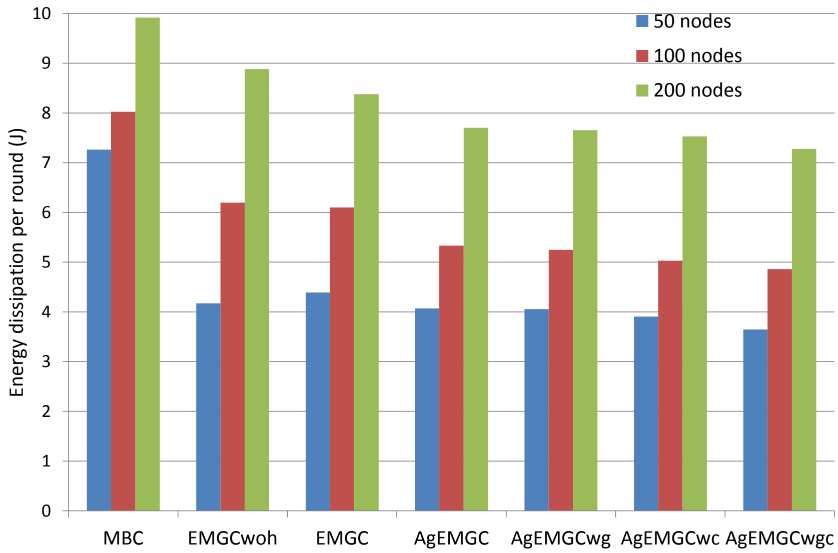


FIGURE 6.10: Energy dissipation per round when GCP = 0.6, P_g = 10% and various number of nodes.

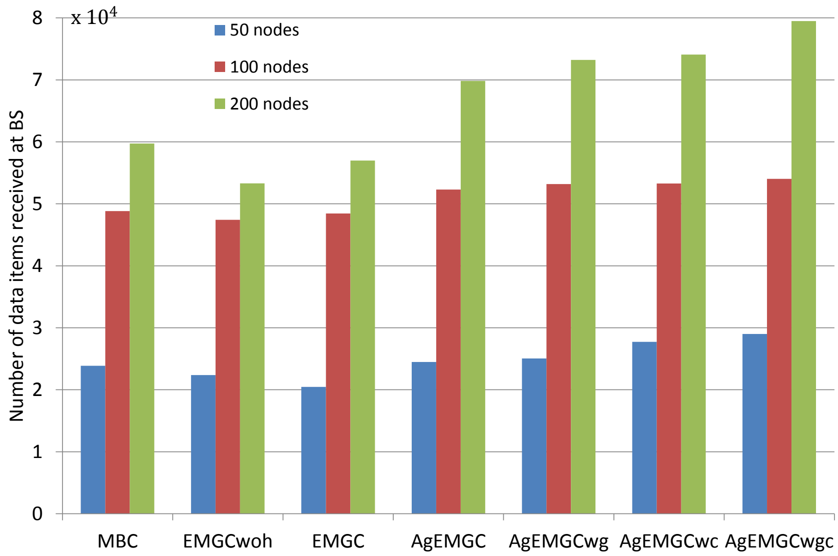


FIGURE 6.11: Number of data items received at BS when GCP = 0.6, P_g = 10% and various number of nodes.

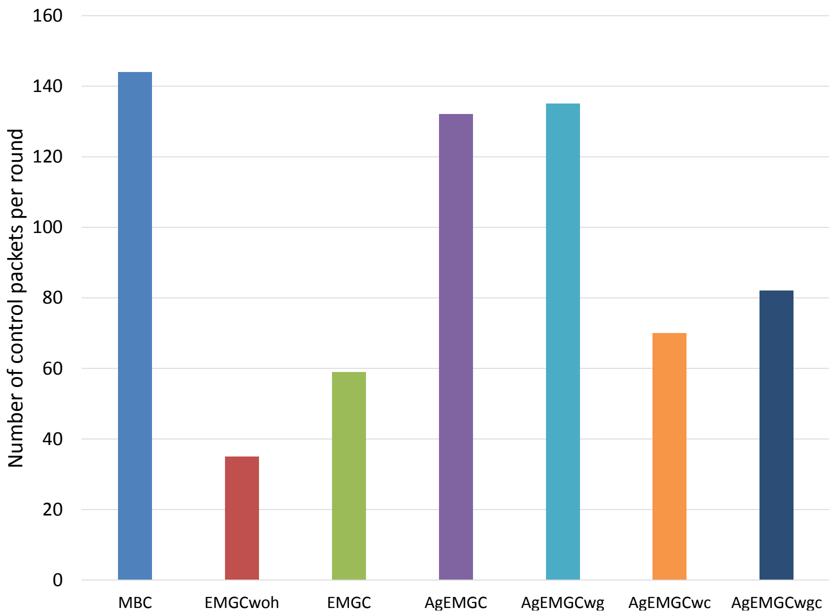
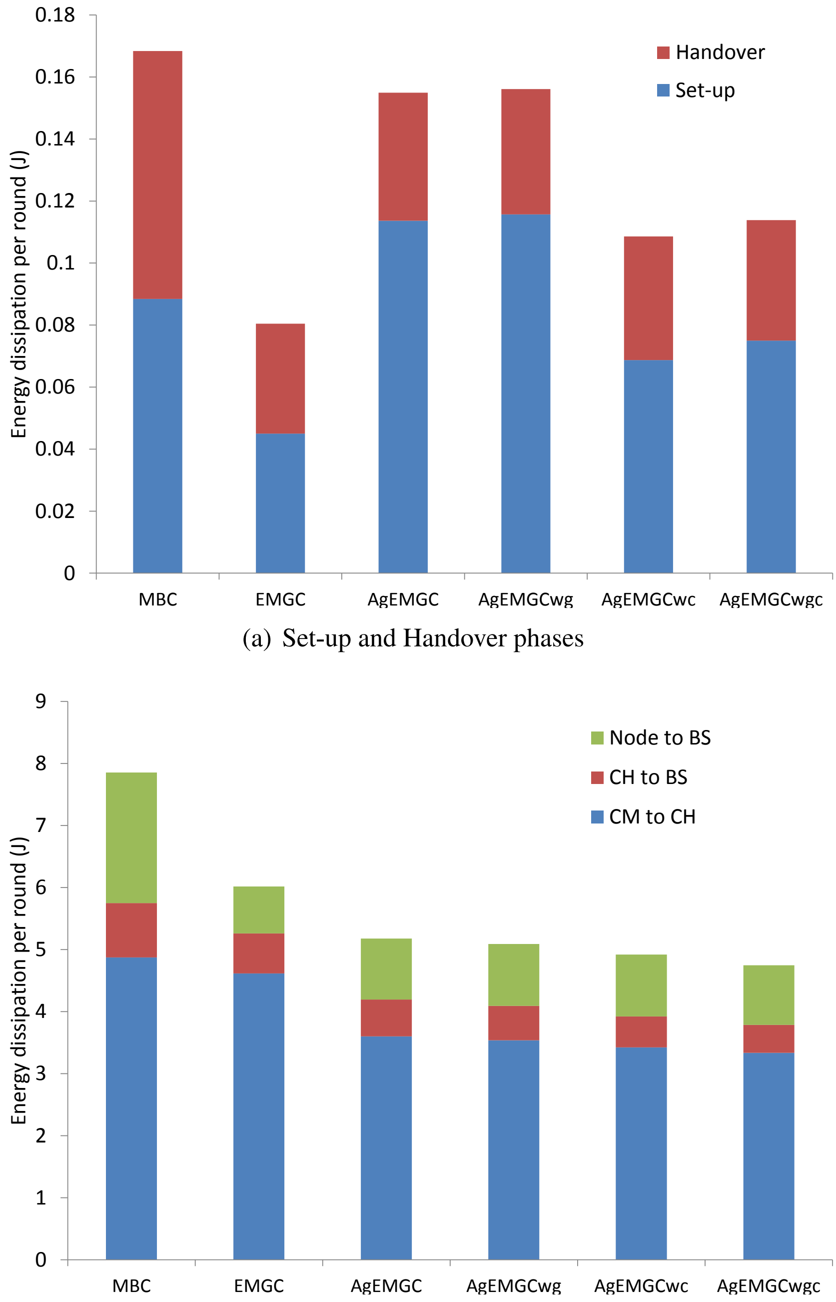


FIGURE 6.12: Number of control packets per round when GCP = 0.6, P_g = 10% and N = 100.

transmission power from GL to GM in the group. In addition, they have two additional functions which are GL rotation and a stay connection procedure. Therefore, they have lower energy dissipation to prolong network lifetime and to deliver more data to BS. Based on these results, the proposed schemes are effective and can adapt well in various number of nodes.

Then, we evaluated more detail when the number of nodes is 100 in terms of the number of control packets and energy dissipation in the set-up and steady-state phases. In Fig. 6.12, it shows that all AgEMGC schemes increase the number of control packets compared to EMGC and EMGCwoh. The reason is that a new procedure of AGF is added. Meanwhile, AgEMGCwc and AgEMGCwgc, with a stay connection procedure, reduce the number of control packets compared to a basic AgEMGC and AgEMGCwg. This is because there is a mechanism to indicate that a GM node will stay connected in the current GL if the GM still has the longest connection time and the highest energy with the GL node. Therefore, this can significantly reduce the JOIN-Group request messages from GM to GL. Additionally, GL rotation does not increase control packets so much, comparing AgEMGCwg with AgEMGC and also AgEMGCwgc with AgEMGCwc.



(a) Set-up and Handover phases

(b) Steady-state phase

FIGURE 6.13: Energy dissipation per round in the set-up and steady-state phases when GCP = 0.6, P_g = 10% and N = 100.

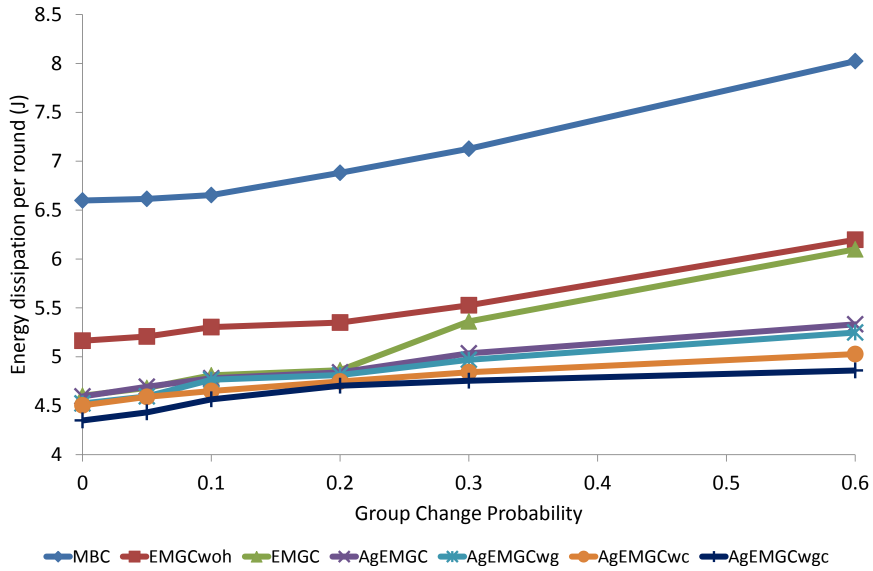


FIGURE 6.14: Energy dissipation per round with various group change probabilities.

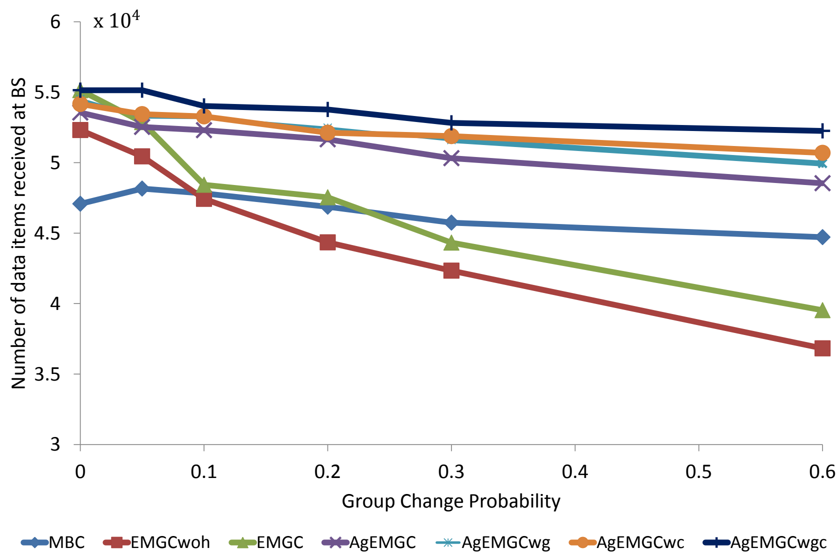


FIGURE 6.15: Number of data items received at BS with various group change probabilities.

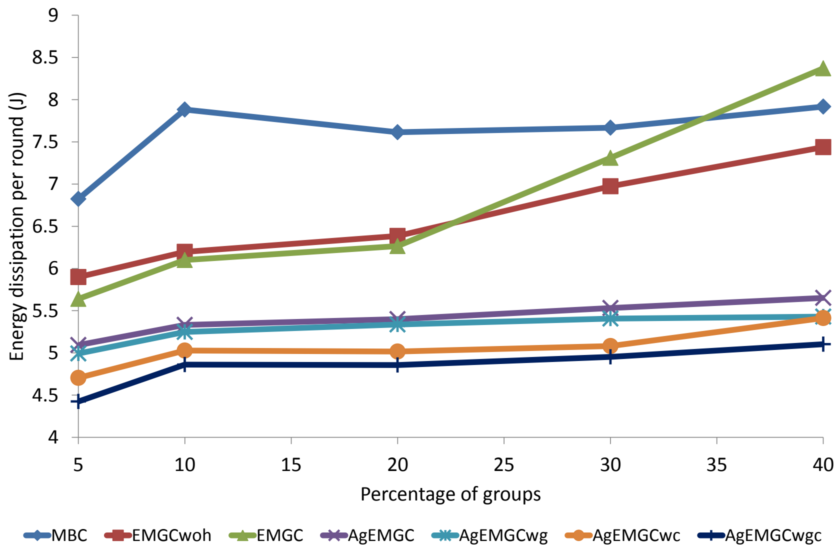


FIGURE 6.16: Energy dissipation per round with various percentages of groups.

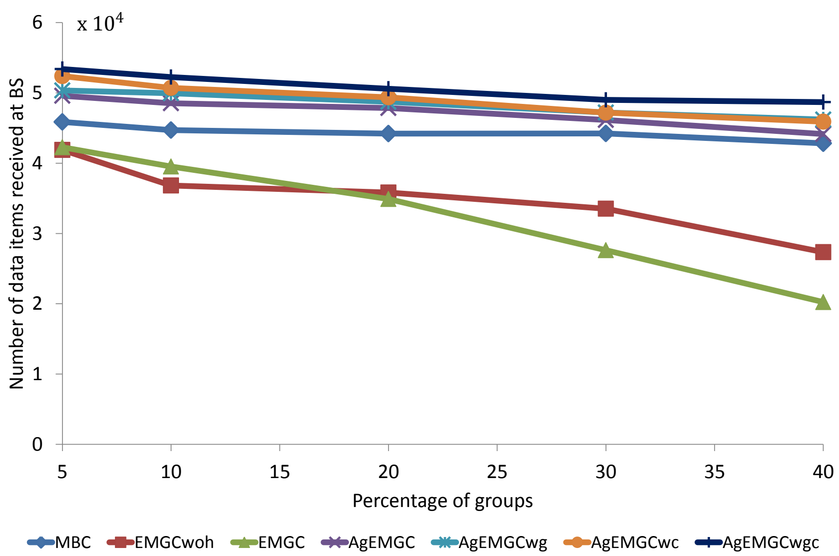


FIGURE 6.17: Number of data items received at BS with various percentages of groups.

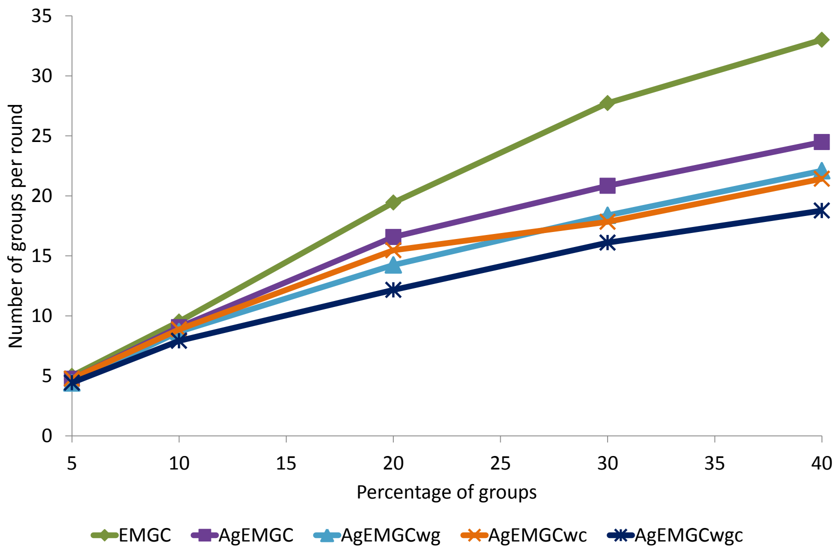


FIGURE 6.18: Number of groups with various percentages of groups.

Figure 6.13(a) shows that AgEMGCwgc and AgEMGCwc, with stay connection procedure, save more energy than AgEMGC and AgEMGCwg. This is because the schemes have fewer membership changes and a lower number of control packets. Although EMGC has the lowest energy dissipation in the set-up and handover phases, it has the highest energy consumption in the steady-state phase as in Fig. 6.13(b) because it does not support a dynamic group change when some GMs in the same group join other groups. Therefore, it increases the energy of "CM to CH", i.e. cluster members (CMs) transmit their data to CH in TDMA manner in the steady-state phase. CMs consist of GLs and GMs where the distance between a GL and some GMs will be distant in a group due to dynamic group change.

6.3.2 Various Group Change Probabilities

In this evaluation, we used RPGM as mobility model with various GCP, i.e. 0.05, 0.1, 0.2, 0.3, 06, and P_g = 10%.

Figure 6.14 shows that the energy dissipation per round with increasing group change probability. The higher the group change probability is, the more GM nodes change the group when their groups are close to other groups. AgEMGCwgc has better performance than other protocols in terms of energy dissipation. The reason is that a GM node of AgEMGCwgc protocol always calculates the longest connection time and the highest energy of the GL in every operation of group formation to maintain a stable link which, in turn, reduces energy consumption. In addition, it has two additional functions to save more energy.

Figure 6.15 shows that AgEMGCwgc outperforms other protocols in terms of the number of data received at the BS. As mentioned in the previous discussion, AgEMGC reduces control packets and rotates the GL operation to further reduce energy consumption which causes more data delivered to a base station.

6.3.3 Various Percentages of Groups

In this evaluation, we used RPGM as mobility model with various P_g, i.e. 5%, 10%, 20%, 30%, and 40%, and GCP = 0.6.

Figures 6.16 and 6.17 show that our proposed schemes outperform MBC and EMGC protocols in terms of energy dissipation per round and the number of data items received at the BS. All proposed schemes can address the problem of an increase of percentage of groups that causes a greater number of control packets in the cluster formation and handover procedure such as a join message from GLs to CHs, and also an advertise code message from GLs to GMs. The reason is that all schemes support a group merging mechanism to reduce the control packets. It can be seen in Fig. 6.18 that our proposed schemes reduce the number of groups per round for each increasing percentage of groups. For example, AgEMGCwgc reduces groups by half in the percentage of groups 40%, which saves more energy than the EMGC protocol. In the EMGC protocol, it dissipates more energy when the percentage of groups and group change probability are high because it uses more control packets and transmission power to communicate between GL and GM.

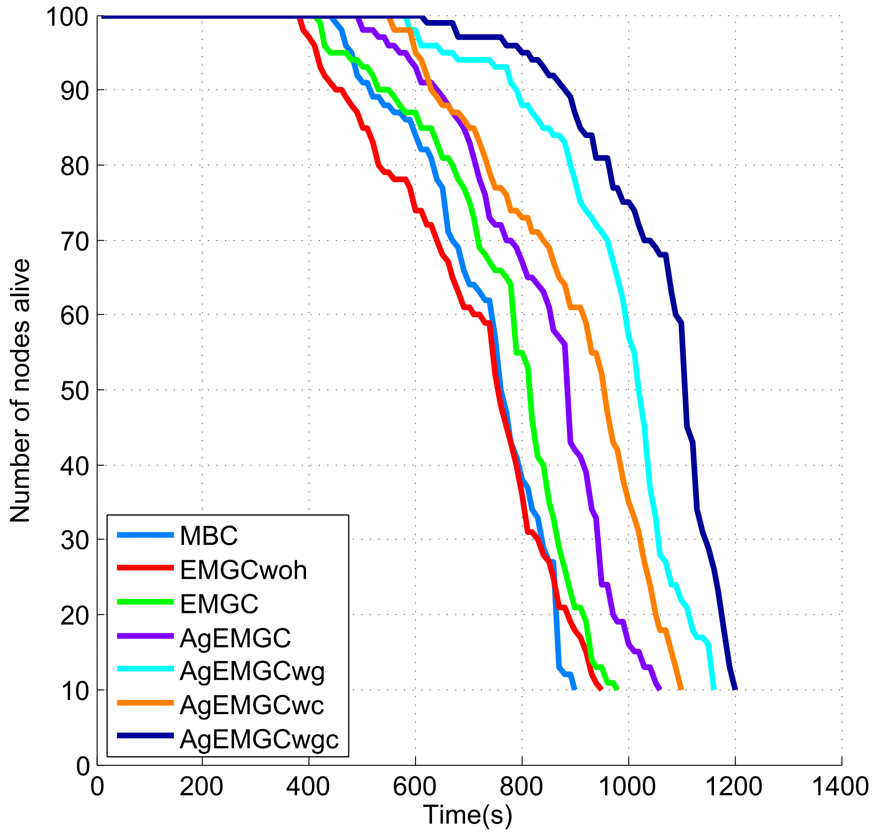


FIGURE 6.19: Number of nodes alive over time with heterogeneous environment.

6.3.4 Heterogeneous Environment

Then, we evaluated with heterogeneous environment which means that there is inequality in initial energy between nodes in a network. To see how well the nodes of the proposed protocol can utilize energy in the network, we put 10 nodes with 200 J of initial energy and the remaining 90 nodes with only 2 J of initial energy in the network [24]. Other parameters are set as P_g = 10%, GCP = 0.6, and p = 0.04.

In the simulation, we took the data until all low-energy nodes are dead, and the high-energy nodes are still alive. Since high-energy nodes have more chances to become CHs that consume more energy in the steady-state phase, based on Eq. (6.5), the proposed schemes can extend their network lifetime as Fig. 6.19. However, Fig. 6.20 shows that AgEMGC and AgEMGCwc are less energy efficient than AgEMGCwg and AgEMGCwgc. The reason is that they use some high-energy nodes as fixed GLs so that the possibility of the nodes becoming CHs is reduced. Therefore, they

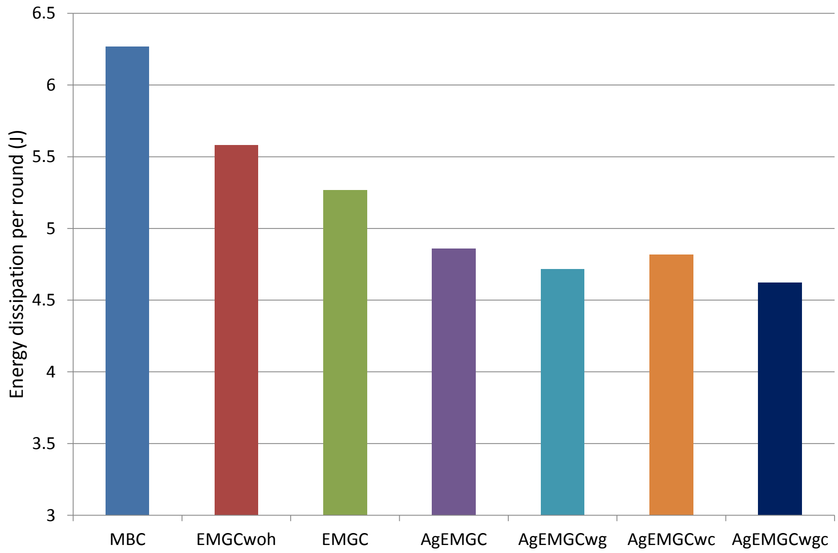


FIGURE 6.20: Energy dissipation per round with heterogeneous environment.

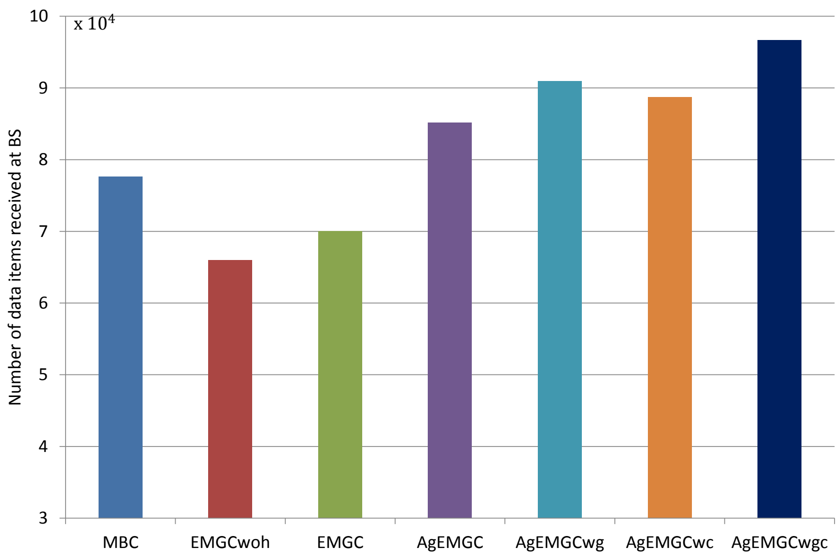


FIGURE 6.21: Number of data items received at BS with heterogeneous environment.

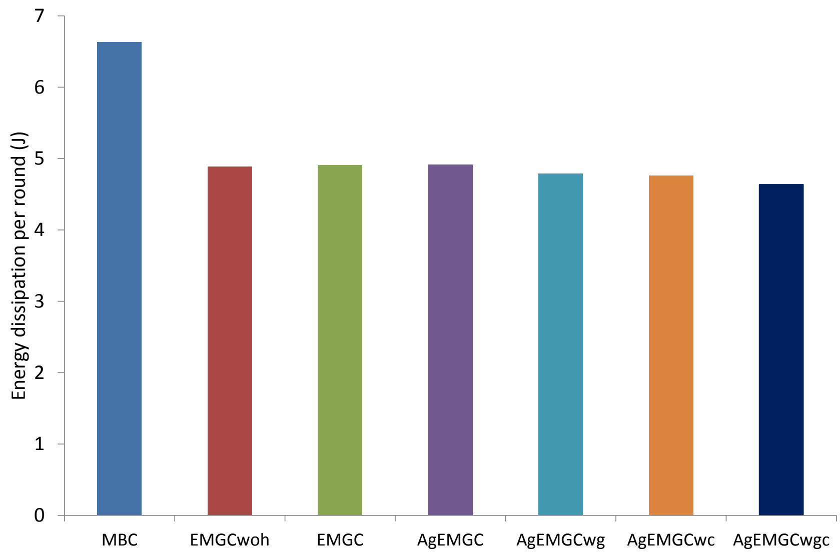


FIGURE 6.22: Energy dissipation per round with Nomadic Community Mobility Model.

also deliver less data items to BS as Fig. 6.21. On the contrary, AgEMGCwg and AgEMGCwgc utilize GL rotation function to distribute the energy among the nodes and to give high-energy nodes more chances becoming CHs.

In addition, homogeneous environment with equal initial energy is little bit faster drain energy because all nodes have equal probability to become CHs where the energy load is evenly distributed throughout the nodes.

6.3.5 Nomadic Community Mobility

Finally, we evaluated by using NCM with P_g = 10%. From Figs. 6.22 and 6.23, we can see AgEMGCwgc does not significantly increase the performance of EMGC-woh. This is because of the characteristic of NCM where some GMs in a group are separated for a while. However, they will be back again in the group. Therefore, the GM nodes may change to another group to obtain a stable link when they are separated. After that, they change again to the previous group if they are back to the group. This will diminish the energy consumption because they have a stable link.

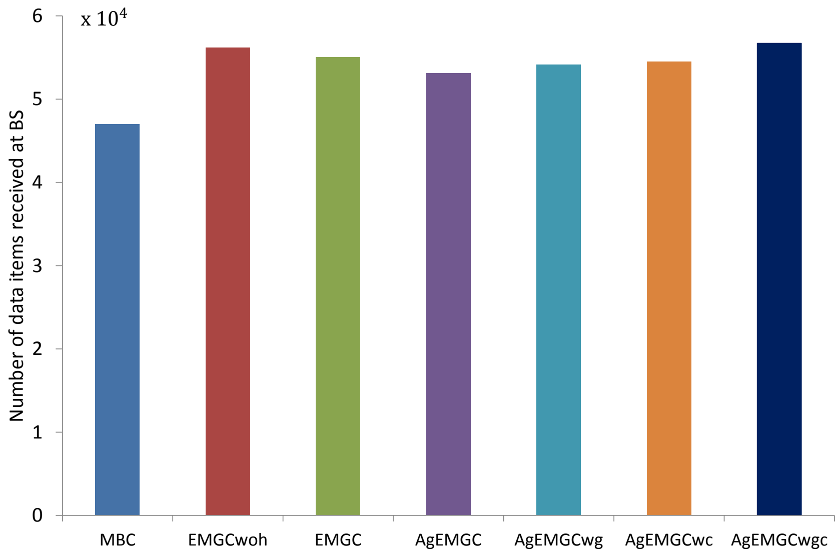


FIGURE 6.23: Number of data items received at BS with Nomadic Community Mobility Model.

6.4 Conclusion

The proposed protocol, AgEMGC, is an efficient way of handling the dynamic group change scenario where some nodes in the same group will move to other groups if they are close each other. For adaptive group formation, it uses a link expiration time and the residual energy to ensure a stable connection in a group. Furthermore, AgEMGCwgc has two additional functions, i.e., GL rotation and a stay connection procedure to save more energy. Simulations showed that AgEMGCwgc outperforms MBC, EMGC, and other schemes in terms of the energy dissipation per round, network lifetime, the number of data items received at BS, and the number of control packets with various group change probabilities and percentages of groups.

Chapter 7

Conclusions and Future Works

7.1 Conclusions

Wireless sensor networks (WSNs) consist of a large number of sensor nodes deployed in an area of interest to sense physical phenomena. For many applications, such as health monitoring, wild animal control, and evacuation systems in natural disasters, mobile sensor nodes will be deployed in the network to monitor their activities. Mobile WSNs also offer an alternative to wired networks when a disaster occurs affecting infrastructure collapse. Sensor nodes have an energy limitation which has offered challenges on the design of WSNs, especially for mobile nodes where frequent topology changes would occur. Clustering techniques in WSNs are used to allow sensor nodes to send data in a hierarchical manner. This method can effectively increase the performance of sensor nodes by reducing energy consumption and network contention, and has been widely used.

We focus on the application with group movement, such as animal tracking, search-and-rescue operations, and evacuation system in natural disasters. Firstly, we propose a Group mobility based Clustering (GC) scheme to support the group movement and to achieve an energy-efficient protocol. This protocol reduces the control overhead in the setup phase of a clustering system by introducing a concept of group leader and group member. In this scheme, the communication with cluster-head is only done by the group leader to save the energy consumption. Based on the simulation results, GC Single increases the lifetime of the networks and the number of packets received at a base station, compared with LEACH, MN-LEACH.

Then, we present an Energy-efficient Mobile Group Clustering (EMGC) protocol that supports group mobility and a group handover scheme. The mobile sensor nodes are divided into three categories, namely cluster heads, group leaders and group members. In our cluster formation and group handover scheme, group leaders and cluster heads do most of the communications to save on energy consumption during which group members are placed in the sleep condition. This scheme will reduce the number of control packets and frequent topology changes in the networks. Simulation results show that the EMGC protocol outperforms MN-LEACH, GMAC, MBC protocols in terms of energy dissipation and the number of data items received at a base station. In terms of total energy exhausted, the EMGC protocol saves up to 46, 38, 40, and 30 percent of energy with respect to GCS, MN-LEACH, GMAC, and MBC respectively.

Finally, we propose a novel group formation scheme which is integrated with an EMGC protocol in order to cope with dynamic group change. It uses a link expiration time and residual energy to form a stable link in a group. It also has a group merging procedure to decrease the number of groups. Furthermore, we develop two additional functions for the protocol, i.e., GL rotation and a stay connection procedure to diminish energy consumption of sensor nodes in the network. Simulation results show that the proposed protocol outperforms MBC, EMGCwoh, and EMGC protocols in terms of data delivery, network lifetime, and energy dissipation per round with various group change probabilities and percentages of groups. In terms of total energy exhausted, the AgEMGC protocol saves up to 39 and 20 percent of energy with respect to MBC and EMGC respectively.

7.2 Future Works

We have presented our protocol relating with mobile nodes especially in group mobility. The proposed protocols are a proficient method to tackle some issues in designing of mobile WSNs, such as frequent topology changes, energy efficiency, and etc. However, the possibility of further development is still open. After I go back to Indonesia, I, with my students, have a plan to implement the proposed protocol in real application and environment to know the reliability and durability of the methods.

The other possible plans are to take into account the group separation to develop mobile group protocol for large area networks where group merging may affect many groups to merge into few groups which will drop the performance of the protocol because a group will have many group members. If this condition happens, it needs group separation.

Then, it will be interesting research how to implement the group mobile design to tackle issues of multi-hop communications in large area network where the proposed protocols can be integrated with tree topology. In our proposed protocols, we still assume that a cluster head sends data directly to a base station. Therefore, it will consume more energy consumption. If there is a special node to deliver data from the cluster head to the sink by using tree topology, it will improve the energy efficiency and the network lifetime.

Thereafter, it will be important to develop multi-sinks WSNs in natural disaster applications where the sinks are put in safe zones which are provided for the evacuated people. In multi-sinks, the energy consumption of every nodes to send the data to the sink will be reduced, as the number of hops is decreased.

Finally, it is possible also to implement mobile group nodes in 3-D environments such as underwater sensor networks.

In addition, we still evaluated the performance of this proposed protocol through simulations. There are some remaining issues if it is implemented into practical use, such as:

- How to synchronize all nodes in order to get the same clock and timing.
- There are many obstacles in the real environment that we do not consider in the simulation.

Bibliography

[1] G. o. J. Cabinet Office, “Http://www.bousai.go.jp/”,

[2] N.Y.Yun and M. Hamada, “A study on evacuation behaviors in the 2011 great japan earthquake”, International Association for Earthquake Engineering (IAEE) 15th World Conference on Earthquake Engineering, LISBOA, 1–10 (2012).

[3] S. Uehara and K. Tomomatsu, “Evacuation simulation system considering evacuee profiles and spatial characteristics”, IAFSS Fire Safety Science - Proceedings of the Seventh International Symposium, 963–974 (1986).

[4] E. Mas, A. Supassari, F. Imamura, and S. Koshimura, “Agent-based simulation of the 2011 great east japan earthquake/tsunami evacuation: an integrated model of tsunami inundation and evacuation”, Journal of Natural Disaster Science **34**, 41–57 (2012).

[5] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks”, IEEE Transactions Wireless Communications **1**, 660–670 (2002).

[6] L. T. Nguyen, X. Defago, R. Beuran, and Y. Shinoda, “An energy efficient routing scheme for mobile wireless sensor networks”, IEEE International Symposium on Wireless Communication Systems (ISWCS), 568–572 (2008).

[7] D.-S. Kim and Y.-J. Chung, “Self-organization routing protocol supporting mobile nodes for wireless sensor network”, First International Multi- Symposiums on Computer and Computational Sciences (IMSCCS), 622–626 (2006).

[8] S. A. B. Awwad, C. K. Ng, N. K. Noordin, and M. F. A. Rasid, “Cluster based routing protocol for mobile nodes in wireless sensor network”, IEEE

International Symposium on Collaborative Technologies and Systems (CTS), 233–241 (2009).

[9] S. Deng, J. Li, and L. Shen, "Mobility-based clustering protocol for wireless sensor networks with mobile nodes", Journal on Wireless Sensor Systems, IET, 39–47 (2011).

[10] T. Benmansour and S. Moussaoui, "Gmac: group mobility adaptive clustering scheme for mobile wireless sensor networks", The International Symposium on Programming and Systems (ISPS), 67–73 (2011).

[11] G. Werner-Allen, K. Lorincz, M. Welsh, O. Marcillo, J. Johnson, M. Ruiz, and J. Lees, "Deploying a wireless sensor network on an active volcano", IEEE Internet Computing **10**, 18–25 (2006).

[12] A. Camilli, C. E. Cugnasca, A. M. Saraiva, A. R. Hirakawa, and P. L. P. Corra, "From wireless sensors to field mapping: Anatomy of an application for precision agriculture", Computers and Electronics in Agriculture **58**, 25–36 (2007).

[13] I. Stoianov, L. Nachman, S. Madden, and T. Tokmouline, "PIPENETa wireless sensor network for pipeline monitoring", Proceedings of the 6th international conference on Information processing in sensor networks - IPSN '07, 264 (2007).

[14] S Dagtas, Y Natchetoi, and H Wu, "An Integrated Wireless Sensing and Mobile Processing Architecture for Assisted Living and Healthcare Applications", Proceedings of the 1st ACM SIGMOBILE international workshop on Systems and networking support for healthcare and assisted living environments, 70–72 (2007).

[15] O. Omeni, A. Chi, W. Wong, A. J. Burdett, and S. Member, "Wireless Medical Body Area Sensor Networks", Review Literature And Arts Of The Americas **2**, 251–259 (2008).

[16] H. Su and X. Zhang, “Battery-dynamics driven tdma mac protocols for wireless body-area monitoring networks in healthcare applications”, IEEE Journal on Selected Areas in Communications **27**, 424–434 (2009).

[17] K. Lorincz, D. J. Malan, T. R. F. Fulford-jones, A. Nawoj, A. Clavel, V. Shanyder, G. Mainland, M. Welsh, and S. Moulton, “Sensor Networks for Emergency Response: Challenges and Opportunities”, Pervasive Computing **3**, 16–23 (2004).

[18] M. Mohandes, M. Haleem, M. Deriche, and K. Balakrishnan, “Wireless sensor networks for pilgrims tracking”, IEEE Embedded Systems Letters **4**, 106–109 (2012).

[19] N. Aschenbruck, E. Gerhards-Padilla, and P. Martini, “Modeling mobility in disaster area scenarios”, Performance Evaluation **66**, 773–790 (2009).

[20] W. Zeng, M. Khalid, and S. Chowdhury, “In-vehicle networks outlook: achievements and challenges”, IEEE Communications Surveys Tutorials **18**, 1552–1571 (2016).

[21] C. Y. Chong and S. P. Kumar, “Sensor networks: evolution, opportunities, and challenges”, Proceedings of the IEEE **91**, 1247–1256 (2003).

[22] P. Bellavista, G. Cardone, A. Corradi, and L. Foschini, “Convergence of MANET and WSN in IoT urban scenarios”, IEEE Sensors Journal **13**, 3558–3567 (2013).

[23] L. Da Xu, W. He, and S. Li, “Internet of things in industries: A survey”, IEEE Transactions on Industrial Informatics **10**, 2233–2243 (2014).

[24] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Application-specific protocol architectures for wireless networks”, Ph.D Thesis Book, Massachu setts Institute of Technology (June 2000).

[25] Q. Dong and W. Dargie, “A survey on mobility and mobility-aware mac protocols in wireless sensor networks”, IEEE Communication Surveys and Tutorials **15**, 88–100 (2013).

[26] O. In, "Mobility-Based Communication in Wireless Sensor Networks", IEEE Communications Magazine **7**, 56–62 (2006).

[27] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient mac protocol for wireless sensor networks", IEEE Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies Proceedings **3**, 1567–1576 (2002).

[28] 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, 558–567 (2004).

[29] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "Energy-efficient collision-free medium access control for wireless sensor networks (TRAMA)", Proceedings of the first international conference on Embedded networked sensor systems SenSys 03 **12**, 181 (2003).

[30] L. F.W. H. Van, P. J. M. Havinga, and L. F.W. V. Hoesel, "A Lightweight Medium Access Protocol (LMAC) for Wireless Sensor Networks: Reducing Preamble Transmissions and Transceiver State Switches", 1st International Workshop on Networked Sensing Systems, INSS 2004, 205–208 (2004).

[31] M. Ali, T. Suleman, and Z. Uzmi, "Mmac: a mobility-adaptive, collision-free mac protocol for wireless sensor networks", IEEE International Performance, Computing, and Communications Conference, 401 –407 (2005).

[32] N. Al-Qadami, I. Laila, A. Koucheryavy, and A. S. Ahmad, "Mobility adaptive clustering algorithm for wireless sensor networks with mobile nodes", International Conference on Advanced Communication Technology (ICACT), 121 –126 (2015).

[33] M. Al-Jemeli and F. Hussin, "An energy efficient cross-layer network operation model for ieee 802.15.4-based mobile wireless sensor networks", IEEE Sensors Journal **15**, 684–692 (2015).

[34] A. Morell, A. Correa, M. Barcelo, and J. Vicario, "Data Aggregation and Principal Component Analysis in WSNs", IEEE Transactions on Wireless Communications **15**, 1–1 (2016).

[35] O. Younes and S. Fahmy, "Heed : a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks", IEEE Transactions on Mobile Computing **3**, 366–379 (2004).

[36] G. Hou, K. W. Tang, and E. Noel, "Implementation and analysis of the LEACH protocol on the TinyOS platform", International Conference on ICT Convergence, 918–923 (2013).

[37] H. Luo, J. Liao, and Y. Sun, "Efficient Sleep Scheduling for Avoiding Inter-Cluster Interference in Wireless Sensor Networks", 2013 IEEE 9th International Conference on Mobile Ad-hoc and Sensor Networks, 414–420 (2013).

[38] C.-t. Cheng, C. K. Tse, F. C. M. Lau, and S. Member, "A Clustering Algorithm for Wireless Sensor Networks Based on Social Insect Colonies", IEEE Sensors Journal **11**, 711–721 (2011).

[39] D. Jia, H. Zhu, S. Zou, and P. Hu, "Dynamic cluster head selection method for wireless sensor network", IEEE Sensors Journal **16**, 2746–2754 (2016).

[40] V. Pal, G. Singh, and R. P. Yadav, "Balanced Cluster Size Solution to Extend Lifetime of Wireless Sensor Networks", IEEE Internet of Things Journal **2**, 399–401 (2015).

[41] S. Sharma and S. Choudhary, "Heterogeneous multi-hop LEACH routing protocol", Proceeding of the IEEE International Conference on Green Computing, Communication and Electrical Engineering, ICGCCEE 2014 (2014).

[42] G. S. Kumar, V. P. M. V, and K. P. Jacob, "Mobility metric based leach-mobile protocol", 16th International Conference on Advanced Computing and Communications, 248–253 (2008).

[43] C. Liu, C. Lee, and L. Wang, "Distributed clustering algorithms for data-gathering in wireless mobile sensor networks", Journal of Parallel and Distributed Computing **67**, 1187–1200 (2007).

[44] I. Souid, H. B. Chikha, M. E. Monser, and R. Attia, “Improved algorithm for mobile large scale sensor networks based on leach protocol”, 22nd International Conference on Software, Telecommunications and Computer Networks (SoftCOM), 139 –143 (2014).

[45] R. U. Anitha and P. Kamalakkannan, “Enhanced cluster based routing protocol for mobile nodes in wireless sensor network”, International Conference on Pattern Recognition, Informatics and Mobile Engineering, 187–193 (2013).

[46] R. Wang, H. Wang, H. E. Roman, Y. Wang, and D. Xu, “A Cooperative Medium Access Control Protocol for Mobile Clusters in Wireless Body Area Networks”, First International Symposium on Future Information and Communication Technologies for Ubiquitous Healthcare (Ubi-Healthtech), 9–12 (2013).

[47] M. Anupama and B. Sathyanarayana, “Survey of Cluster Based Routing Protocols in Mobile Ad hoc Networks”, International Journal of Computer Theory and Engineering **3** (2011).

[48] Y. Liu, N. Xiong, Y. Zhao, a.V. Vasilakos, J. Gao, and Y. Jia, “Multi-layer clustering routing algorithm for wireless vehicular sensor networks”, IET Communications **4**, 810 (2010).

[49] 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), 1–9 (2010).

[50] A. Gonga, O. Landsiedel, and M. Johansson, “Mobisense: power-efficient micro-mobility in wireless sensor networks”, 7th IEEE International Conference on Distributed Computing in Sensor Systems (2011).

[51] 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).

[52] 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, 558–560 (2004).

[53] Y. K. Huang, A. C. Pang, P. C. Hsiu, W. Zhuang, and P. Liu, "Distributed Throughput Optimization for ZigBee Cluster-Tree Networks", IEEE Transactions on Parallel and Distributed Systems **23**, 513–520 (2012).

[54] M. Saedy and B. Kelley, "Foundations of ultra-low power scale free sensor networks for cluster to cluster communications", IEEE Sensors Journal **12**, 3363–3372 (2012).

[55] H. Dang and H. Wu, "Clustering and cluster-based routing protocol for delay-tolerant mobile networks", IEEE Transactions on Wireless Communications **9**, 1874–1881 (2010).

[56] W. Stallings, "Data and computer communications 7th edition", Prentice Hall (2007).

[57] C. S. R. Murthy and B. Manoj, "Ad hoc wireless networks: architectures and protocols", Prentice Hall (2004).

[58] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research", Wireless Communications and Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications **2** (2002).

[59] R. Velmani and B. Kaarthick, "An efficient cluster-tree based data collection scheme for large mobile wireless sensor networks", IEEE Sensors Journal **15** (2015).

[60] Y. Chen, C. Hsu, and H. Lee, "An enhanced group mobility protocol for 6lowpan-based wireless body area networks", IEEE Sensors Journal **14**, 797–807 (March 2014).

[61] T. Das and S. Roy, “Employing cooperative group mobility model for mobile target tracking in mwsn”, Applications and Innovations in Mobile Computing (AIMoC), 55 –61 (2015).

[62] X. Hong, M. Gerla, G. Pei, and C. Chiang, “A group mobility model for ad hoc wireless networks”, Proc. 2nd ACM Intl Conf. on Modeling, analysis and simulation of wireless and mobile system (MSWiM), 53–60 (1999).

[63] R. Marin-Perianu, M. Marin-Perianu, P. Havinga, and H. Scholten, “Movement-based group awareness with wireless sensor networks”, Pervasive Computing, Proceedings **4480**, 298–315 (2007).

[64] K. H. Wang and B. Li, “Group Mobility and Partition Prediction in Wireless Ad-Hoc Networks (CLASSIFICATION BASED ON RPGM)”, IEEE International Conference on Communications, 1017–1021 (2002).

[65] P. Traynor, J. Shin, B. Madan, S. Phoha, and T. L. Porta, “Efficient group mobility for heterogeneous sensor networks”, Vehicular Technology Conference, 1–5 (2006).

[66] J. Lloret, M. Garcia, J. Toms, and F. Boronat, “GBP-WAHSN: A group-based protocol for large wireless ad hoc and sensor networks”, Journal of Computer Science and Technology **23**, 461–480 (2008).

[67] Q. Ren, L. Guo, J. Zhu, M. Ren, and J. Zhu, “Distributed aggregation algorithms for mobile sensor networks with group mobility model”, Tsinghua Science and Technology **17**, 512–520 (2012).

[68] M. Cai, L. Rui, D. Liu, H. Huang, and X. Qiu, “Group mobility based clustering algorithm for mobile ad hoc networks”, 17th Asia-Pacific Network Operations and Management Symposium (APNOMS), 340–343 (2015).

[69] Y. Zhang, J. M. Ng, and C. P. Low, “A distributed group mobility adaptive clustering algorithm for mobile ad hoc networks”, Computer Communications **32**, 189–202 (2009).

[70] M. Haneef, Z. Wenxun, and Z. Deng, "MG-LEACH : Multi Group Based LEACH an Energy Efficient Routing Algorithm for Wireless Sensor Network", International Conference on Advanced Communication Technology (ICACT), 179–183 (2012).

[71] D. Tulone and S. Madden, "Paq: time series forecasting for approximate query answering in sensor networks", European Workshop on Wireless Sensor Networks, 21–37 (2006).

[72] Y.-A. L. Borgne, S. Santini, and G. Bontempi, "Adaptive model selection for time series prediction in wireless sensor networks", Signal Processing Journal **87**, 3010–3020 (2007).

[73] S. Mahfouz, F. Mourad-Chehade, P. Honeine, J. Farah, and H. Snoussi, "Target tracking using machine learning and kalman filter in wireless sensor networks", IEEE Sensors Journal **14**, 3715–3725 (2014).

[74] Y. Huang, W. Yu, C. Osewold, and A. Garcia-Ortiz, "Analysis of pkf: a communication cost reduction scheme for wireless sensor networks", IEEE Transactions on Wireless Communications **15**, 843–856 (2016).

[75] B. S. Mathapati, S. R. Patil, and V. D. Mytri, "Energy efficient cluster based mobility prediction for wireless sensor networks", International Conference on Circuits, Power and Computing Technologies (ICCPCT), 1099 –1104 (2013).

[76] W. Su, S.-J. Lee, and M. Gerla, "Mobility prediction in wireless networks", MILCOM 21st Century Military Communications Conference Proceedings **1**, 491–495 (2000).

[77] M. S. Grewal and A. P. Andrews, "Kalman filtering: theory and practice", Prentice Hall (1993).

[78] A. V. Balakrishnan, "Kalman filtering theory", Optimization Software, Inc. (1987).

[79] M. I. K. Hasan, S. Takahashi, J. Hakoda, H. Uehara, and M. Yokoyama, "Route selection metrics in wireless mobile ad hoc networks", IEICE Trans. Fundamental **E88-A**, 2952–2955 (2005).

[80] A. Rhim and Z. Dziong, “Routing based on link expiration time for manet performance improvement”, IEEE 9th Malaysia International Conference on Communications (MICC), 555–560 (2009).

[81] I. Gruber and H. Li, “Link expiration times in mobile ad hoc networks”, 27th Annual IEEE Conference on Local Computer Networks, 743–750 (2002).

[82] J. Hemmes, M. Fisher, and K. Hopkinson, “Predictive routing in mobile ad-hoc networks”, Fifth International Conference on Next Generation Mobile Applications, Services and Technologies, 117–122 (2011).

[83] M. Ni, Z. Zhong, and D. Zhao, “Mpbc: a mobility prediction-based clustering scheme for ad hoc networks”, IEEE Transactions on Vehicular Technology **60**, 4549–4559 (2011).

[84] H. Taka, H. Uehara, and T. Ohira, “Energy-efficiency of sensor networks in terms of network topology”, IEICE Transactions on Communications **J96-B**, 680–689 (2013).

[85] M. U. H. A, F. A. Saputra, and M. Z. S. Hadi, “Beacon-enabled ieee 802.15.4 wireless sensor network performance”, IEEE International Conference on Communications, Network and Satellite (COMNETSAT), 46–49 (2013).

[86] E. Ekici, Y. Gu, and D. Bozdag, “Mobility-based communication in wireless sensor networks”, IEEE Communications Magazine **44**, 56–62 (2006).

[87] Y. Li, N. Yu, W. Zhang, W. Zhao, X. You, and M. Daneshmand, “Enhancing the performance of leach protocol in wireless sensor networks”, IEEE INFOCOM Workshops (2011).

[88] A. T. Erman, “Multi-sink mobile wireless sensor network: dissemination protocols, design and evaluation”, PhD Thesis, University of Twente, The Netherlands (2011).

[89] C.-L.L.C.-H.H.J.-Y. Pan, “Hand-off evolution with multiple interfaces”, IEEE Journal IT Professional **10**, 22 –28 (2008).

[90] J. Petajajarvi and H. Karvonen, “Soft handover method for mobile wireless sensor networks based on 6lowpan”, International Conference on Distributed Computing in Sensor Systems and Workshops (DCOSS), 1 –6 (2011).

[91] S. Chae, T. Nguyen, and Y. M. Jang, “A novel handover scheme in moving vehicular femtocell networks”, Fifth International Conference on Ubiquitous and Future Networks (ICUFN), 144 –148 (2013).

[92] S. Paul and N. K. Sao, “An energy efficient hybrid node scheduling scheme in cluster based wireless sensor networks”, Proceedings of the World Congress on Engineering (WCE) **II** (2011).

[93] T. Chan, C. Chen, Y. Huang, J. Lin, and T. Chen, “Optimal cluster number selection in ad-hoc wireless sensor networks”, Wseas Transactions on Communications **7**, 837–846 (2008).

[94] H. Taka, H. Uehara, and T. Ohira, “Node scheduling method based on aggregation model for clustering scheme in wireless sensor networks”, The 12th International Symposium on Wireless Personal MultimediaCommunications (WPMC) (2009).

[95] N. T. T. Nguyen, H. Taka, H. Uehara, and T. Ohira, “Attribute change adaptation routing protocol for energy efficiency of wireless sensor networks”, International Conference on Information Technology and Applications (ICITA) (2009).

[96] B. Adamczyk, “Analysis and optimization of leach protocol for wireless sensor networks”, International Conference on Computer Networks, 86–94 (2013).

[97] H. Fotouhi, M. Alves, M. Z. Zamalloa, and A. Koubâa, “Reliable and fast hand-offs in low-power wireless networks”, IEEE Transactions on Mobile Computing **13**, 2620–2633 (2014).

[98] Y. Liao, H. Qi, and W. Li, “Load-balanced clustering algorithm with distributed self-organization for wireless sensor networks”, IEEE Sensors Journal **13**, 1498–1506 (2013).

[99] M. Z. S. Hadi, A. Pratiarso, and H. Uehara, "An energy efficiency mobile clustering sytem for wireless sensor networks", International Conference on Electrical Systems, Technology and Information (ICESTI), 65–69 (2014).

[100] Y. Li, Y. Jiang, H. Su, D. Jin, L. Su, and L. Zeng, "A group-based handoff scheme for correlated mobile nodes in proxy mobile ipv6", IEEE Global Telecommunications Conference (GLOBECOM), 1–6 (Dec. 2009).

[101] L. Hu, "Distributed code assignments for cdma packet radio networks", IEEE / ACM Transactions on Networking **1**, 668–677 (1993).

[102] H. Uehara, "Lecture notes of spread spectrum", Toyohashi University of Technology.

[103] D. Gerakoulis and E. Geraniotis, "Cdma access and switching", John Wiley and Sons (2001).

[104] N. Aschenbruck, R. Ernst, E. Gerhards-Padilla, and M. Schwamborn, "Bonnmotion - a mobility scenario generation and analysis tool", in Proc. of the 3rd International ICST Conference on Simulation Tools and Techniques (SIMUTools '10), Torremolinos, Malaga, Spain (2010).

[105] M. Z. S. Hadi, Y. Miyaji, and H. Uehara, "Group mobility based clustering scheme for mobile wireless sensor networks", IEEE International Electronics Symposium (IES), 81–86 (2016).

[106] Z. Guo, Y. Guo, F. Hong, Z. Jin, Y. He, Y. Feng, and Y. Liu, "Perpendicular intersection: locating wireless sensors with mobile beacon", IEEE Transactions on Vehicular Technology **59**, 3501–3509 (2010).

[107] E.-E.-L. L. and W.-Y. C., "Enhanced rssi-based real-time user location tracking system for indoor and outdoor environments", International Conference on Convergence Information Technology (ICCIT), 1213–1218 (2007).

[108] N. S. NS-2, "Http://www.isi.edu/nsnam/ns/ns-build.html",

[109] S. F. Ochoa and R. Santos, "Human-centric wireless sensor networks to improve information availability during urban search and rescue activities", Journal on Information Fusion **22**, 71–84 (2015).

[110] P. Li, T. Miyazaki, K. Wang, S. Guo, and W. Zhuang, "Vehicle-assist resilient information and network system for disaster management", IEEE Transactions on Emerging Topics in Computing **5**, 438–448 (2017).

[111] B. Sharma and D. Koundal, "Cattle health monitoring system using wireless sensor network: a survey from innovation perspective", IET Wireless Sensor System **8**, 143–151 (2018).

[112] M. Z. S. Hadi, Y. Miyaji, and H. Uehara, "An energy-efficient mobile group clustering protocol for wireless sensor networks", IEICE Transactions on Communications **E101-B, 8**, 1866–1873 (2018).

[113] T. Massey, T. Gao, M. Welsh, and J. Sharp, "Design of a decentralized electronic triage system", Proceeding of the American Medical Informatics Association Annual Conference (AMIA 2006), Washington DC, 544–548 (2006).

[114] G. P. X. Hong M. Gerla and C. Chiang, "A group mobility model for ad hoc wireless networks", Proc. 2nd ACM Intl Conf. on Modeling, analysis and simulation of wireless and mobile system (MSWiM), 53–60 (1999).

Publication Lists

International Journal Papers

- M. Zen Samsono Hadi, Yuichi Miyaji, and Hideyuki Uehara,"An Energy-efficient Mobile Group Clustering Protocol for Wireless Sensor Networks", *IEICE Transactions on Communications*, vol. E101-B, no. 8, pp. 1866 - 1873, Aug. 2018.
- M. Zen Samsono Hadi, Yuichi Miyaji, and Hideyuki Uehara,"Adaptive Group Formation Scheme for Mobile Group Wireless Sensor Networks", *IEICE Transactions on Communications*, vol. E102-B, no. 07, Jul. 2019. (to be published)

International Conference Papers

- M. Zen Samsono Hadi, Aries Pratiarso, and Hideyuki Uehara, "An Energy-efficient Mobile Clustering Scheme for Wireless Sensor Networks", International Conference on Electrical Systems, Technology and Information (ICESTI), pp. 65 - 69, September 10-13, 2014, Bali, Indonesia.
- M. Zen Samsono Hadi, Yuichi Miyaji, and Hideyuki Uehara, "Group Mobility Based Clustering Scheme for Mobile Wireless Sensor Networks", International Electronics Symposium (IES), IEEE, pp. 81 - 86, September 29-30, 2016, Bali, Indonesia.