

Enhancing Wireless Sensor Networks Functionalities

by

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Abstract

WSNs facilitate the detection of numerous real world phenomena such as natural disaster and structural faults. The networks collect information from a particular area and transfer it to a centre for further process. In the data collecting process, there are many considerable issues that might influence quality of service (QoS). Therefore, it is always necessary to be considered about the unpredicted events that might negatively influence QoS in WSNs. The main objective of this research is firstly, to identify the existing gaps in providing a better QoS in the networks. Although many problems can be addressed in this area, only four of them are studied in this thesis. First, a new clustering method for the sensors nodes is proposed to ensure the clusters' formation are maintained during the network lifetime. Next, a concept of quality based data fusion mechanism that deals with collecting and sending only valued data is introduced. In the proposed approach, the nodes play an important role in distinguishing and transferring only valued data. The valued data will then be aggregated and transferred to a base station. In the process of routing the data packets, QoS might also be influenced due to issues such as node failure. Therefore, as a contribution of this thesis we proposed two routing protocols in WSNs that can adjust themselves with changes in nodes' conditions and behaviour. First, the base station is similar to the other deployed sensor nodes is stationary. Each node is responsible to take the current condition of immediate nodes into consideration in a real time to find the most appropriate next hub. Next, we extend the protocol by replacing a mobile sink with the stationary base station. The mobile sink is capable to schedule itself, based on current conditions of the nodes. Therefore, the mobile sink instead of randomly or in an order visits the sensor nodes, can visit the source nodes in a priority manner. Finally, the concept of coverage-hole recovery is introduced to deal with loss of coverage arising from node failure in post deployment scenario. The proposed approach finds the uncovered areas and then, virtually force the nodes to move through the areas.

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Chapter 1

INTRODUCTION

Advances in micro electro mechanical systems (MEMS) technology has provided the opportunity for developing tiny and low-cost sensor nodes containing on-board sensing, signal processing and wireless communication capabilities. These sensor nodes are capable of converting environmental phenomenon into digital signals and send them to other nodes. Each individual node has limited capabilities that might not be able to use in different monitoring systems. However, a combination of hundreds or thousands of them can coordinate by forming wireless sensor networks (WSNs). A WSN is a compact sensing system with a collection of wireless sensor nodes deployed on a region of interest with the purpose of sensing events in a collaborating manner. WSN can be used in many real world applications. Some of these applications require a very high level of performance, reliability and accuracy. Therefore, it is always necessary to consider quality of service (QoS) in WSNs. QoS based on the requirements of WSNs can be used in different meaning and prospective. Nevertheless, QoS in any WSNs is used to enhance the performance of WSNs

for users [1]. In this thesis QoS is analysed based on the consideration of different requirements such as energy consumption, delay, traffic overhead and successful transmission. To enhance them, there are many research questions can be addressed. In this chapter, four research questions with the motivations behind them are introduced.

1.1. Research Motivation

In WSNs QoS can be affected by different reasons. First, the WSN deployment method is one of the most important factors that can influence the data quality. Unreliable or even not suitable model for a WSN can make the sensor nodes waste their limited power and loss data as well as increasing overhead traffic in the network. Another reason that influences QoS is the data fusion mechanism used. Unreliable data fusion mechanisms might increase traffic overhead as well as unsuccessful data transmissions in WSNs. Therefore, as a result of resubmission process, energy consumption would be increased in such networks. Next, a comprehensive routing protocol can play a significant role in transferring higher quality data packets to base station (BS). Each routing protocol needs to be highly capable of adopting itself to different situations. It is also necessary for a source node with important data to make sure that BS can receive the data on time. Failure in receiving data by BS increases the requirement of data packet re-transmissions. Therefore, the QoS requirements such as delay, traffic overhead and energy consumption in the network will be influenced. Finally, coverage of the network is also one of the most significant factors that can help to enhance QoS in a WSN data. To make sure that the entire events in an area of interest are detected and also redundancy in reporting the events is minimised, it is necessary to develop an optimised coverage method for WSNs.

1.2. Research Problem

This thesis deals with QoS requirements such as energy consumption and delay in WSNs. In particular, we address the following four research questions in this thesis.

- *How to cluster a WSN to achieve the optimum QoS in the presence of node failure?*

When the entire deployed nodes are required to forward sensed data packets to the sink, the available energy in each node can be wasted through idle listening and retransmitting due to collision as well as overhearing. To overcome that, sensor nodes are clustered for the purpose of energy minimization. Then, they will be required to communicate with their CHs instead of sending the data packets directly to BS. However, in the case of CHs failure, the clustered structure of the network is ruined and consequently the nodes will be required to be re-clustered again. That causes a lot of missing data as in cluster creation process, the sensor nodes cannot collect data.

There are several research work related to cluster formation in WSN [2-4]. Most of them considered various parameters on different conditions to select the most appropriate CHs in WSN. However, they did not consider CHs failure, as they can simply be destroyed due to hardware or even software failures. To address this problem, we propose a cluster formation with primary and backup CH (BCH). That is to make sure in case of the primary CHs failure, the BCHs are able to take the responsibility on an appropriate time. As a result, the sensor nodes can be sure that, even if their CHs are

failed, their cluster formation is still active without requiring a new clustering creation process. In fact, the nodes can keep collecting and sending their data to BS via their pre-determined backup CHs.

- *How to aggregate WSN data with maximum QoS assurance?*

Data generated from neighbouring sensors is often redundant and consequently influencing QoS in WSNs [5]. In addition, the amount of data generated in large sensor networks is usually enormous for BS to process. Hence, a method to combine data at the sensors or intermediate nodes is certainly required. Such a method combines different data packets from different sources without losing important information, while it eliminates redundant data.

Recently many approaches have been investigated on developing fusion methods with the purpose of enhancing quality of WSN data [6-8]. However, the proposed approaches, did not consider specific limitations for sensors' storages as they can influence QoS in WSN. They simply aggregate the entire received data from sources that include valued and corrupted data. As a result, apart from the created a high traffic overflow, energy consumption in such networks is obviously not efficient.

To address this problem, we propose a data aggregation protocol for WSNs that can distinguish valued and corrupted data from each other. Then, it disregards the corrupted data in the fusion process. The proposed protocol reduces data redundancy as well as enhancing the efficiency of energy consumption in the WSN.

- *How to collect data from the WSN in the present of sensor node failure?*

Node failures that cause loss of connectivity is the most common problem in dynamic WSNs that causes the collected data are not received by BS. To overcome the problem, an efficient quality based routing protocol is required with the capability of adjusting to different unexpected node failure in WSNs.

During the past decade, considerable research efforts have been investigated in developing routing techniques in WSNs with stationary and mobile BS (MBS). Majority of the approaches considered constrains such as energy efficiency and delay as the main objectives to enhance QoS in the networks. However, existed developed protocols have limitations in dynamic environments which contain a variant amount of noise created by interferences. Additionally, MBS is not capable to schedule itself intelligently to visit source nodes in an efficient manner. Moreover, MBS in the existing approaches cannot be called by the source nodes of WSNs. In fact, it needs to visit the entire source nodes even they are not required to be visited.

In this thesis, we develop a dynamic data routing approach for WSNs with the purpose of providing a higher QoS. In that we consider local information includes noisy data. The MBS used in the approach instead of visiting the entire source nodes, is able to smartly schedule itself in the most efficient manner. As a result, we enhance the energy efficiency of the network as well as reducing the traffic overflow in the WSN.

- *How to enhance coverage of WSN to improve QoS in the presence of node failure and coverage redundancy?*

The importance of this problem arises when a WSN needs to be established in inaccessible areas such as forests or chemically polluted regions. In such areas sensors are deployed randomly that is reducing the quality of collected data. That is because of the low possibility of fully covered sensor field, while the node are not overlapped.

There are several research work related to the deployment of wireless sensor nodes [9-11]. Most of them considered a single objective such as coverage ratio. However, the other objectives such as energy consumption minimization, uniformity and data reliability are also practically considered in the choice of deployment process.

This thesis develops a dynamic reconfiguration coverage maintenance scheme for mobile sensor network to meet the specific requirements of the event detection system. When a loss of coverage occurs due to reasons such as dead or noisy sensors, the proposed approach ensures the immediate neighbours to move and replace with the failure node. As a result of locating the sensor nodes uniformly in the area of interest, the energy consumption of the network is consumed more efficiently.

1.3. Methodology

There are many techniques includes statistical and Covariance Intersection (CI) based methods are used to enhance the QoS in WSNs. However, most of them are not capable to cope with the uncertainty of the data produced by WSN's. Moreover, the inflexibility of the methods prevents processing the data realistically [12]. Applying these methods requires very complex and very much computational effort for having optimal

performance [13]. In contrast, flexibility of fuzzy systems provides us with the opportunity to edit and display given information at any point of the structuring. In addition, the 3D display and surface gives us a clearer picture of the output of the system. Therefore, we decided to use fuzzy logic systems as in many previous works the sensors were equipped with the systems [14-16]. Type-1 fuzzy logic systems (T1FLS) use fixed fuzzy memberships that cannot directly address variable conditions. Therefore, uncertain measured parameters in applied systems would be neglected by T1FLS and the performance obviously will be negatively influenced. As a result, Type-2 fuzzy membership functions that use membership degrees which are themselves fuzzy sets were developed. Type-2 fuzzy sets are very useful when there is a difficulty in determining appropriate membership function with ambiguity. Type-2 fuzzy sets allow us to handle linguistic uncertainties. T2FLS technology has been regarded as a way to increase the fuzziness of a relation means increased ability to handle inexact information in a logically correct manner [17]. The fuzzy logic toolbox used in this thesis was built in MATLAB. Therefore, although there are many simulating software such NS3 or OMNET, we used MATLAB to simulate the proposed solutions. To test and validate the proposed approaches in this thesis, we conduct experiments. The inputs of the developed approaches we generate synthetic data. We use a Gaussian distribution with its mean and covariance matrix representing the expected value and its uncertainty (10% of the value). Then, the values are normalized to fit in the $[0, 1]$ as the inputs of the fuzzy system. Then, we extract linguistic variables out of the normalized data. In each experiment, 20% of the data is used for training the fuzzy system to determine the membership functions and also the rules as well as the required threshold values for solutions. Then, we used 80% of the data to test the proposed solutions. In those simulations

and experiments, various parameters were used to examine and demonstrate the viability of the proposed solutions compared to the similar baseline solutions.

We validate our experiments using root-mean-square error (RMSE) as used in previous works [18-20]. RMSE provides a complete picture of the error distribution in an experiment. It provides not only a performance measure, but also a representation of the error distribution. In this thesis RMSE is used to measure of the difference between predicted values and the result of the proposed approaches and also the existing baseline protocols. RMSE gives us a single measure of predictive power to compare the performance of the approaches.

1.4. Research Objectives

The aims of this thesis are:

- To propose a distributed and dynamic self-configurable approach for clustering WSNs, in order to minimize the communication overhead and prolong the network lifetime;
- To develop a cluster based data fusion protocol in order to combine information from various sources to reduce the amount of raw data transmitted over the network.
- To develop two distributed dynamic WSN data routing protocol in WSN with a stationary and a MBS;
- To develop a dynamic distributed coverage strategy in which mobile sensor nodes have the ability of communicating with each other, detect failed nodes or uncovered areas and organize themselves to move and maximize coverage.

1.5. Research Contributions

Figure 1.1 illustrates the overall research contributions made in this thesis. Block i to iv in the “Contribution Overview” window at the bottom correspond to objective i to objective iv , respectively the “Underlying Networks” window at the top reveals the type of underlying network in relation to each contribution. Finally, “Main contribution” window presents the approached thesis objective.

The primary contributions of this thesis are summarised as follows:

- i. Self-configurable clustering protocol in WSN.* The thesis proposes a distributed and dynamic self-configurable type-2 fuzzy based approach for clustering sensor nodes. The algorithm minimizes the communication overhead and prolongs the network lifetime by introducing a backup CHs. Consequently, in case of decreasing the eligibility of the current CHs to a certain threshold level, there is a defined node that takes the responsibility without needing any re-selection process. The proposed approach, compare to the existing approaches, enhances the performance of the system by reducing energy consumption and traffic overflow in WSN.
- ii. Data fusion scheme in WSN.* In this thesis, a data fusion framework protocol that uses type-2 Fuzzy set theory [21] is proposed. The proposed approach is in contrast to the existing developed protocols, distinguishes the valued data to the others. Therefore, instead of transferring and processing the entire data, only valued data are taken into consideration. The main advantages of the proposed technique are firstly, enhancing quality of data as the valued data are not influenced with inaccurate or unsatisfied data.

Next, it enhances the efficiency of energy consumption as the proposed method by eliminating unvalued data make a reduction in transferring data.

iii. *Data routing protocol in WSN.* In this thesis, two routing protocols in a WSN with the purpose of enhancing QoS are proposed. The first proposed approach is basically a routing protocol with stationary sensor nodes and a BS. Each source node needs to consider the current condition of neighbours, in real time, through BS to transfer the data. After that, the proposed protocol is extended by replacing the stationary BS with a MBS. In the extended version of the approach, we develop a unique flexible visiting method for MBS. The direction of MBS can be controlled and changes based on sensors' local information. Additionally, MBS can be called by each node in the sensor field.

iv. *A dynamic WSN coverage scheme.* In this thesis, a dynamic distributed WSN coverage maintenance strategy is proposed. In the proposed approach, the mobile sensor nodes have the ability to communicate with each other, detect failed nodes or uncovered areas and then, organize themselves to move and maximize coverage. This approach, unlike the existing approaches does not need to use global information of the network. QoS is also enhanced as noisy or disordered nodes are detected and then, replaced with immediate neighbours. Moreover, the energy consumption is become more efficient. That is due to firstly, less required message exchanges as well as eliminating the noisy nodes that transfer more bits (noises) in the network. Secondly, the needed energy for random and inaccurate movement of the mobile nodes is reduced.

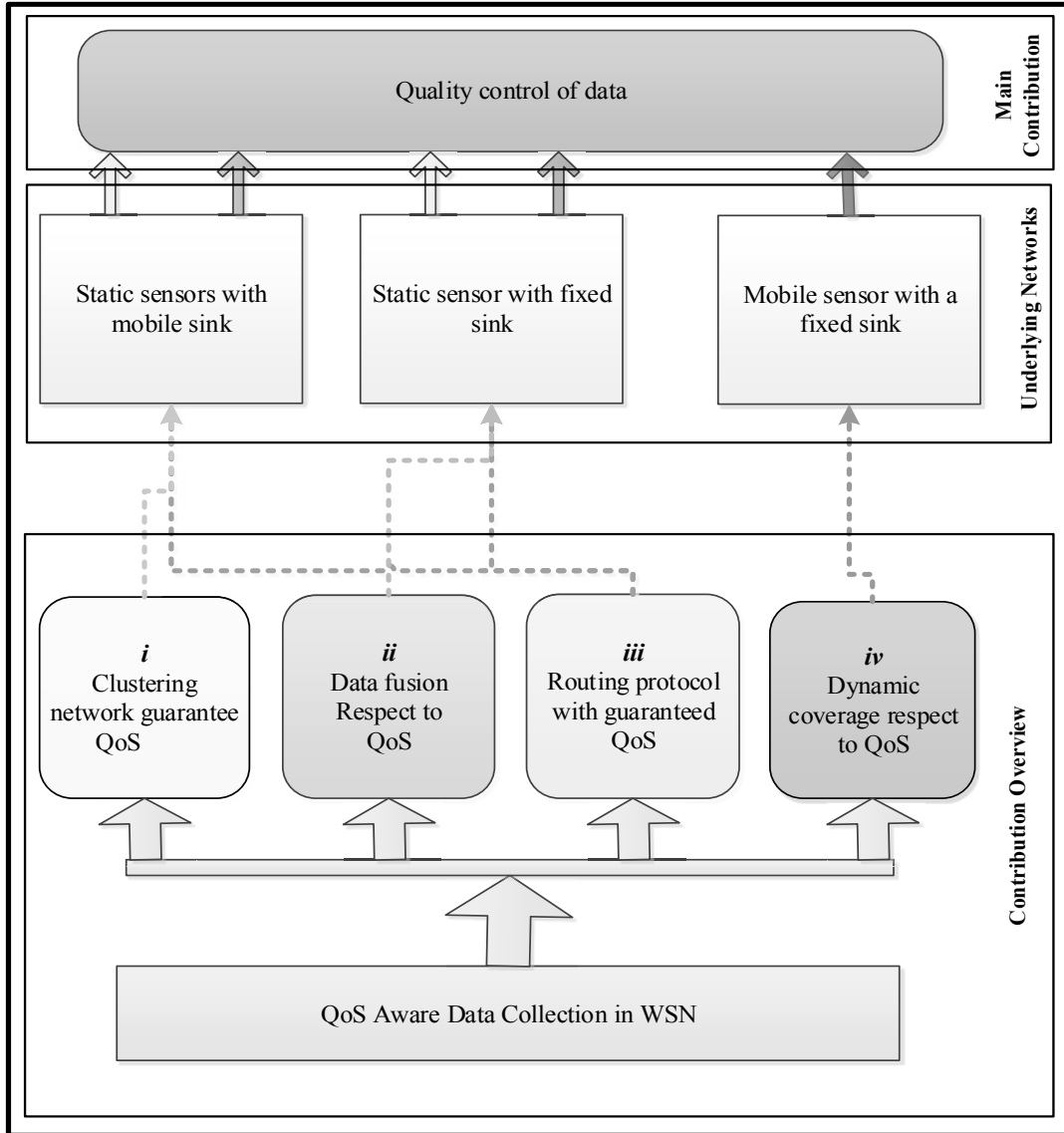


Figure 1.1 Schematic view of the overall research contribution

1.6. Thesis Organization

The remainder of the thesis is organized as the following:

1. Chapter 2: WSN data quality control. This chapter provides an in-depth analysis and overview of existing WSN data quality control approaches, presented within a comprehensive taxonomy.

2. Chapter 3: WSN clustering. This chapter presents an approach to capable WSN of self-configurable cluster head (CH) selection and clustering the entire network.
3. Chapter 4: WSN data fusion. This chapter presents an approach to aggregate WSN data with considering the current storage condition of sensor nodes.
4. Chapter 5: WSN data routing. In this chapter two routing protocols are suggested one with stationary BS and other with MBS. In both scenarios, the network behaviour are analysed separately.
5. Chapter 6. WSN self-configurable coverage scheme. This chapter presents a protocol that is divided into two phases.
6. Chapter 7. Conclusion and future directions. The concluding chapter provides a summary of contributions and a future research challenges

Chapter 2

LITERATURE REVIEW

This chapter provides a comprehensive review of wireless sensor network (WSN) and various quality of service (QoS) issues in such networks. It focuses on four of the major issues which are clustering deployed sensor nodes, data aggregation, proper routing data packets and converge enhancement with mobile sensors in a WSN. In this chapter, an in-depth analysis of the existing approaches is presented to identify the addressed research gaps.

2.1. Introduction

WSN has been an attractive research area and has been used for various applications. WSN integrates low power communication and consists of a large number of sensor nodes that communicate with each other. The sensor nodes can be deployed either randomly or manually depending upon the applications. In addition to the sensor nodes, WSNs need one or more base stations (BS) to be able to make communications and collect data from the sensors deployed in the monitored areas. The role of the BS is to maintain the

communication between sensor network and external source (users). In fact, the communications among sensor nodes and the BS provide users with the accessibility of information from any remote location to allow collecting and analysing the sensor data.

Figure 2. 1. presents a general view of a WSN.

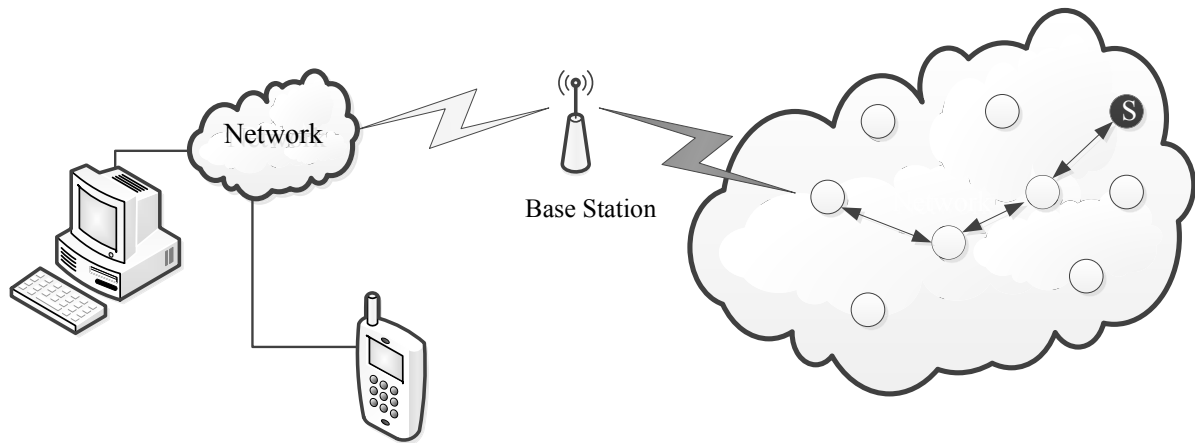


Figure 2.1. A general view of a WSN

A wireless sensor node is a very small transducer that is capable of conveying physical phenomenon such as sound, light and temperature into electrical signals. The technical components are consisted of sensor interfaces, circuit, microcontroller, battery and radio system. Each component and system in the electrical device is required to work properly to achieve the expected outcome of the device. Figure 2.2 shows a general view of a sensor node device.

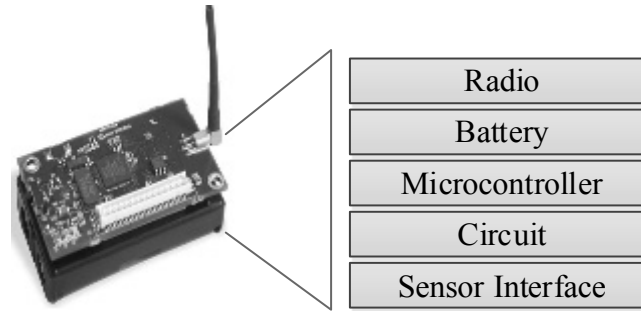


Figure 2.2. Sensor node

In a sensor node the radio subsystem is responsible for data transmission. For this purpose, each sensor node needs to use radio frequencies to be able to communicate with each other. In an operating WSN, there are two types of communications, which are infrastructure and application communication. In infrastructure communication, the sensor nodes are required to build, maintain and optimize the network. This communication is needed to monitor environmental changes or node failures. The application communication is required to forward the collected data to the BS. There are well known technologies such as ZigBee and IEEE802.11 that manage the radio section of the sensor node. The technologies can manage the radio data rate, signal frequency and bandwidth [22].

Power subsystem is another technology consideration of the devices. Each sensor node requires a power unit to function and perform their individual tasks. Power subsystem provides the supply voltage and the requirements of the power are strict due to energy constraints. It also supplies sufficient levels of current during radio transmissions and receptions. In constructing a battery, apart from providing a long life for a WSN, it is necessary to be aware of the weight, cost and the size of batteries as well as the global standards for availability and shipping batteries.

Microcontroller in a sensor node is usually responsible for adapting the applied routing methods, efficiently transmitting sensory signals and processing them [23]. This subsystem also involves data fusion where the different packets arrive from the sensor nodes are gathered to form a single packet thereby reducing the transmission energy in WSNs. Finally, circuits and sensor interfaces are responsible for sensing the environment and are controlled by microcontroller.

After deployment, the sensor nodes are subject to various conditions that have impact on their performance. Some of these factors include:

Environment factors: Each sensor node for a period of time might be subjected to a non-operating environmental limitations without permanently changing its performance under normal operating conditions. Environmental limits are directly related to the storage conditions of the sensor nodes include the highest and the lowest storage temperatures and maximum relative humidity at the temperatures. In such conditions the sensors output signals may increase or decrease which is causing an ultralow frequency noise. Those changes might be occurring in a short term period of time such as a minute or even in a long time of sensors' performance. Therefore, environmental stability, which is a significant requirement of producing sensor nodes, is necessarily needs to be considered by both sensor designer and the application engineers.

The most important factor that influences sensors' performance is their storage temperature. For sensor nodes, the lower and upper extreme temperature (e.g., -5°C to $+80^{\circ}\text{C}$) is usually provided in their data sheets, within which the sensors maintain their specified accuracies. Sometimes the temperature range might be divided into some sections with their specified error in nodes' output. In addition, a relatively fast temperature change may cause the sensor

to generate a false output signals. That is because in the case of a quick change, the temperature, sensors generate an electronic current that might be recognised by their processing units as a valid response and consequently, cause a false detection [24].

Uncertainty: Sensor nodes manufacturers are aiming to produce the most accurate wireless sensor nodes to uniformly and consistently collect and process data. However, the reality is that the produced sensors are never ideal as they carry uncertainty in their measurements. Therefore, users never can be 100% sure about the created measured values [24]. In fact, any individual measurement, x , is expected to be presented a bit different to the true value, x' . That is due to the existed uncertainties that cause errors in the measuring process. The error is calculated by (2.1).

$$\phi = x' - x \quad (2.1)$$

It does not matter how an event (e.g. temperature) is measured by a sensor or how close the measurement is to the true value, never can it be sure that it is accurate. For example the uncertainty in measured temperature of a water bath could be up to $\phi = 0.068$ [24].

2.1.1. WSN Applications

Applications of WSNs in the event detection domain can be categorised into five major categories. In this section some of the applications are going to be explored. First, environment applications in which a large number of sensor nodes are deployed in an area of interest. They are responsible to detect the environmental phenomenon such as biodiversity and ecosystem monitoring [25], air pollution monitoring [26], greenhouse monitoring [27] and food monitoring [28]. Apart from the applications, the use of WSNs in critical environmental hazard detection and disaster warning system attracted more attention

in recent years as it promises safety of human lives and properties. Typical applications in such forest fire detection [29], volcano monitoring [30] and earthquake warning system [31] radiation detection [139, 140], chemical and biological hazard detection [32] or any other meteorological hazard characterised in environments [33]. WSNs can also be applied in industrial fields for monitoring purposes. The main motivation of using WSNs instead of the wired sensor networks in industry is the flexibility and the capability of self-organization. In case of adding or removing a sensor node from the WSN, the networks can reconfigure itself without being worried about cabling. Moreover, sensor nodes can be place in a moving part of machineries and inaccessible areas for remote monitoring, where wired sensors may not be able to apply. WSN are usually used to detect the performance and operational faults and to detect safety issues in large industrial plants [34], building automation [35] and structural integrity monitoring [36]. As a result of monitoring and detecting faults or anomaly in industry possible damages on machineries which could be very costly could be prevented. Moreover from personal safety point of view, WSNs can help the operators who work in the industry. Third, WSNs can also be used in emergency health applications to provide a global and cost effective monitoring system to continuously and independently monitor a person's physiological conditions. Therefore, in case of any emergency the corresponding medical centre can be notified. Some of the emergency health applications include continuous health monitoring and alarm system [37] and fall detection in elderly care [38]. Finally, WSN can be used in our home applications such as vacuum cleaners, stoves, stoves and electricity monitoring systems. WSNs can monitor our everyday life and determine real world phenomena that needs to be taken care of automatically for smart home system [39, 40].

In the all applications, QoS is the main challenging aspect of them that needs to be considered. To enhance QoS in the applications, deployment methods used for developing WSNs for the applications is as much important as collecting and aggregating data from the environments. Transferring data in different environment with different conditions is also an important key in providing a satisfactory QoS.

2.1.2. Event Detection in WSN

Event detection using WSN technology has been a research area over the past decades. That is due to the various applications in the real world. Event in WSNs corresponds to a real world phenomena occurring in environments being monitored. Event detection process generally can be categorized into two main centralized and distributed detection classes. In centralized detection based systems, each sensor is required to send its observations to a centre or a base station without any processing or losing information. Then, the centre would be in charge to process the received data and realize that whether an even occurred. That obviously increases the traffic as well as energy consumption since transferring data consume more energy than processing them. That is clearly become worse in large scale sensor networks in real world applications with the large amount of transmissions from sources to the base station [41-43]. That also incurs a significant delay in event detection process in WSNs. Therefore, decentralized or distributed event detection scheme can perform better as the sensor nodes are constrained by limited power and bandwidth communication. In decentralized detection architecture, sensor nodes instead of sending data packets directly to the base station, they decide on the occurrence of an event, based on the sensed data. Then, only the decisions are sent to the destination. As a result, lower consumption of energy and bandwidth in such networks, make the decentralized

detection to be the most popular technique in event detection process [42, 44-47]. There are many proposed techniques and schemes such as patterned based recognition detection scheme [48-51] and fuzzy logic system [52, 53] that can be used in developing a distributed architecture. In this research, it is decided to use fuzzy logic system detection.

Krasimira et al. [53] identified fuzzy logic suitable for event detection in WSNs. First, the system is capable of tolerating unreliable and imprecise sensor readings. Next, the system work very closely to the natural way of human thinking. Finally, fuzzy logic is much intuitive compared to other probability theory based methods. In fact, fuzzy logic has potential to deal with conflicting situations and imprecision in data using heuristic human reasoning without needing complex mathematical modelling.

There are two types, type 1 and type 2, of fuzzy logic systems. In this thesis only type 2 of the system is used. The interval T2 (IT2) FLS, which is known as interval-valued, is the most popular technique that has been using in type-2 fuzzy systems. The basic concept of IT2-FLS is considering a foot print of uncertainty (FOU), which can be described by two bounding of T1 fuzzy membership functions [17]. Eq. (2.4) calculates the IT2 fuzzy set $\tilde{A}$.

$$\tilde{A} = \iint \frac{1}{(x,u)} J_x \subset [0,1] \quad (2.4)$$

In this equation, x and u are the primary and the secondary variable and J_x is the primary membership function of x . In case of IT2 fuzzy sets, all secondary grade of fuzzy set $\tilde{A}$ are equal to 1. The domain of the primary membership J_x defines the FOU of fuzzy set $\tilde{A}$, which can be described by its upper and lower membership functions. Hence: $\text{FOU}(\tilde{A}) = \bigcup_{x \in X} (\underline{\mu}_{\tilde{A}}(x), \bar{\mu}_{\tilde{A}}(x))$.

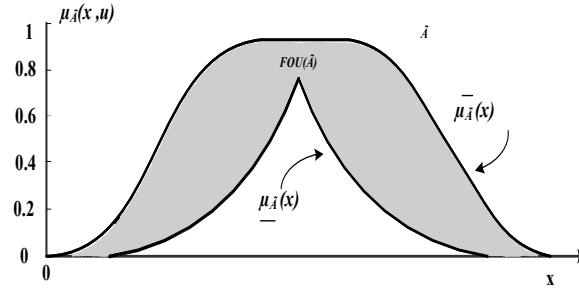


Figure 2.3. Interval Type 2 FLS

Figure 2.3 shows a general view of the IT2 with the upper $\bar{\mu}_{\bar{A}}(x)$ and lower $\underline{\mu}_{\bar{A}}(x)$ membership functions. In order to calculate the final output of T2-FLS, $\widetilde{B}$, there are two main steps, which are reducing the type 2 to type 1 and then defuzzifying the output. The first step, type reduction, which is an important calculation for Type-2 FLSs, is a new and complicated concept. detail of some popular methods in type reduction have been described in [54]. The second step is defuzzification. In order to obtain a crisp (type-0) output from a type-2 FLS, the type-reduced set needs to be defuzzified. For this aim, there are many well-known techniques such as centroid, bisector, mean of maximum, smallest of maximum and largest of maximum. More details of type reduction methods can be found in [17].

2.2. Quality of Service (QoS)

Different techniques in WSNs may recognize QoS in different ways, which can be designed based on applications' requirements. For instance, in a safe control system delay and packet loss may not be allowed, while it might be acceptable in air conditioning systems in an office. Nevertheless, QoS methods in any application are applied to enhance performance of WSNs [55]. There are many considerable challenges that can be categorized into hardware and software aspects of the networks. This research is more focused on

software aspects of the techniques. In this study, the following six parameters are going to be addressed to enhance QoS in the WSN.

- i. Memory Limitation:** Since a sensor node is a small device, the memory used in the device has a strict capacity limitation. Therefore, there is not enough space to run complicated algorithms and also storing much data. Hence, overflow can be a significant issue in providing high QoS [56].
- ii. Delay:** Multi-hop routing, network congestion and data traffics are the reasons behind delay in wireless communications. That can affect synchronization in the network and consequently make issues in data collection processing, especially in critical events. Thus, to ensure data to receive on time to the destination in real time applications, it is necessary to be aware of delay metrics in developing data collection mechanisms. Notice that on-time transmission does not mean fast communication or computation but there is a unique timing requirement for every network that needs to be respected [57].
- iii. Power Consumption:** Energy consumption is the biggest constraint that needs to be considered in developing a WSN. In general, energy consumption in a WSN can be categorized into three main aspects: (i) energy for the sensor transducer, (ii) energy for communication among sensor nodes and (iii) energy for microprocessor computation. It has been shown [58] that the required power for transmitting one bit of data in WSNs is equal to the required energy of processing 800 to 1000 instructions. Consequently, energy constraint necessarily needs to be taken into account precisely in developing a routing protocol for a WSN [59].

- iv. **Accuracy:** Performance accuracy of WSNs is not only depended on physical properties of the environment. Developed algorithms and system protocols also have a significant role in providing an accurate network [60].
- v. **Data Aggregation:** Data aggregation is a combination of data arriving from different sources. The data can be aggregated using some functions to find and eliminate duplicates. That helps to reduce data transmissions in the network. As a result residual energy of the nodes is consumed more efficiency [61].
- vi. **Reliability:** Majority of WSN applications are usually required a high QoS respect to data reliability transmissions. Reliability of a WSN is highly vulnerable as the networks are characterized by resource constraints of the sensor nodes. Moreover, unreliable nature of the wireless links and dynamic changes in the size and density of the network as well as physical attacks to the sensor nodes reduce reliability of the network [62].

2.3. A Taxonomy of QoS-Based Protocols

In this section an in-depth analysis of the existing approaches is presented.

2.3.1. Self-Configurable Clustering WSN

The main purpose of clustering methods in WSNs is to organize the sensor nodes into small disjoint groups where each cluster has a coordinator referred as Cluster Head (CH) and cluster members (CMs). In cluster based approaches, the sensors do not need to communicate directly with BS. Each cluster has a CH with the responsibility of organizing CMs, aggregating the collected data within the cluster and finally sending the data to the BS. CHs reduce a significant amount of transferred data within the network. Consequently,

overheads in communication as well as bandwidth in clustered networks compare to direct communication methods are reduced significantly.

Generally, clustering protocols in WSNs are divided into two main sections. First, cluster formation, in which clusters are organized followed by CH selection process. Then, steady states phase that is for transferring data from sources to the BS. During the steady state phase the energy of sensor nodes dynamically decreases and that leads to disorder the nodes. As a result, the network is faced losing the packets. The problem becomes worse if the failed node is a CH and its failure is not detected. Then, all the transferred data to the CH from CMs will be lost. As a result, the energy consumption and packet overhead in the network followed re-submission of the packets will be increased.

Clustering methods can be classified into centralized and distributed mechanisms. In centralized methods such as [63] and [64], BS finds CHs and constructs clusters according to the gathered local information from all the deployed nodes periodically. In centralized approaches, the entire nodes are required to be in contacted to the BS directly and frequently. That results in substantial energy waste. In contrast, the distributed self-clustering methods that is more effective in large scale WSNs organize the sensor nodes into groups by themselves. Many distributed clustering methods such as LEACH-ERE [65] are developed based on either iterative or probabilistic methods.

From another point of view, clustering protocols can be dynamic or static. A static clustering technique unlike dynamic technique, forms clusters permanently. However, in some circumstances permanent formed clusters cannot perform well as sensor nodes might die and cause disconnections. Thus, a dynamic protocol operation perfumes more reliable although extra overhead is imposed in forming clusters dynamically.

The first well known clustering protocol developed by Heinzelman et al. [66] is Low Energy Adaptive Clustering hierarchy with Deterministic CH Selection (LEACH). LEACH has been developed based on a clustering mechanism to select CHs using optimal probability. The protocol works on periodic randomized rotations of the CH within the cluster range between zero and one. If the random number is less than the pre-determined threshold value, the node becomes a CH for the current round. The authors have succeeded to achieve a reduction in energy dissipation compared to direct communication and transmission protocols. However, since in the protocol the number of clusters is predefined, LEACH cannot guarantee an acceptable CH distribution. Additionally, due to lack of support in deploying network with a large number of sensor nodes, the protocol cannot be used in a large region. Moreover, LEACH suffers from significant energy consumption when there is no CH selected in some rounds.

Applying T1-FLS in distributed protocols improves the performance of the networks significantly. For instance, Gupta et al. [67] introduced a CH election method using fuzzy logic to overcome the drawbacks of LEACH. The achievement of the protocol efficiently increased the network's lifetime. However, this centralized approach is not suitable for networks with a large number of deployed nodes. LEACH-FL [68] is also an improvement of LEACH that employs a similar approach to [67]. In this protocol, the BS selects nodes with higher chance as CHs. Although this method has the same drawback of Gupta's method, it presents a better result than LEACH protocol. To overcome the drawback of centralized algorithms, Jong-Myoung et al. put forward CHEF routing protocol [69]. To a certain extent, CHEF extends the network lifetime. However, it selects the nodes with less neighbour nodes as CHs easily that destroys the balance of energy consumption. Gateway and CH election using fuzzy logic in heterogeneous WSN (GCHE-FL) [3] is a developed

protocol that uses two fuzzy based elections to evaluate the chance of sensors to become a gateway and CH. In the first election (Gateway Election), the qualified nodes are selected based on their energy and distance to the BS. Then, in the second election (CH Election), residual energy of each node and cluster distance are used. Cluster distance is sum of distances among cluster members. Simulation results show that the proposed approach enhances the energy efficiency in the network. Qing et al. [70] proposed a distributed energy efficient clustering (DEEC) algorithm for heterogeneous WSNs. In DEEC, the CHs are selected using probabilistic models based on the residual energy of each node and the average energy of the network. In DEEC the responsibility of CHs is rotated among all the nodes in the network based on their residual energy. To accomplish that, all the deployed nodes need to be informed about the total energy and the network lifetime. That information is broadcasted by the BS. Then, each node compares the received information and its residual energy against a predefined threshold to realise that if it can be a CH on that round. After that, Elbhiri et al. [71] enhanced DEEC by proposing stochastic energy efficient clustering (SDEEC). In this approach, the intra-clusters transmissions are reduced and also increased the energy efficiency by making the CMs into sleep mode. In this protocol, all the CMs are allocated a transmission time to transfer their collected data to their respective CHs. When the CHs start to aggregate the received data the CMs will be deactivated. In this approach, although the authors to some extent reduced the energy consumption in the network, they did not clearly explain about the CH rotating and also the collected data in rotation process. Liaw et al. [72] proposed a steady group clustering hierarchy (SGCH) with the purpose of stabilizing clustered WSNs. In the proposed approach, all the deployed nodes are clustered into different groups based on their initial energy. In this centralized algorithm, BS broadcasts a message, called group head request (GHR) to obtain local information of

all the nodes. Then, the sensor nodes send back an acknowledgement includes ID and initial energy information of the nodes. After that, BS finds and informs group heads for each group. Finally, each group head or CH defines its cluster members. The results in this study show that the stability and energy consumption are increased however, the traffic overhead in the network is quite high as it is a centralized approach. Table 2.1 compares the various existing clustering approaches respect to QoS features.

Table 2.1. The comparison of different clustering protocols with respect of QoS

Clustering Approach	Energy Efficiency	Overhead Rate	Clustering Methodology	CH Failure	Inherent Uncertainty
LEACH [66]	Low	Not Considered	Distributed	Not Considered	Not Considered
Gupta et al. [67]	Low	High	Centralized	Not Considered	Not Considered
LEACH-FL [68]	Low	High	Centralized	Not Considered	Not Considered
CHEF [69]	Low	Not Considered	Distributed	Not Considered	Not Considered
(GCHE-FL) [3]	Moderate	Not Considered	Distributed	Not Considered	Not Considered
DEEC[70]	Moderate	High	Distributed	Not Considered	Not Considered
SDEEC [71]	Moderate	High	Distributed	Not Considered	Not Considered
SGCH [72]	Low	High	Centralized	Not Considered	Not Considered

All the explored approaches to some extent, increased the energy efficiency in WSN. However, in their considerations to select CHs they did not take failure CHs into account. In fact, the main drawback of the existing approaches is the sensor nodes are sending data packets without noticing whether they are received or not. Moreover, they did not fully accommodate the linguistic and numerical uncertainties such as noisy input signals and inaccurate transmitted data packets. To sum up, as it is presented in Table 3, a comprehensive distributed clustering protocol that is capable of providing an acceptable

energy efficiency and overhead rate while considering inherent uncertainties in WSN has not been developed.

2.3.2. Quality Based Data Fusion Mechanism

The main purpose of developing data fusion mechanisms in WSNs is to enhance QoS in the networks. Data generated from sensor nodes is often redundant and highly correlated. In addition, the amount of data generated in large sensor networks is typically massive for the BS to process. Hence, it is necessary to come up with a method to combine data into a high-quality information that cannot be generated by the sensor nodes individually. That is to reduce the number of packets transmitted to the BS resulting in conservation of energy and bandwidth in the WSN [73].

The main process of data fusion in WSN is to provide a greater quality on information and make reliable and accurate decisions about the events of interest based on the collected data from the various sensors. In this section, some common protocols that have been proposed to aggregate data is going to be explained. Then, the advantages and disadvantages of the protocols will be explored. As it can be seen in the figure 2.4, all the aggregating protocols are categorized into two main classes, which are structure and structure free based approaches. The structure based approaches are also further classified.

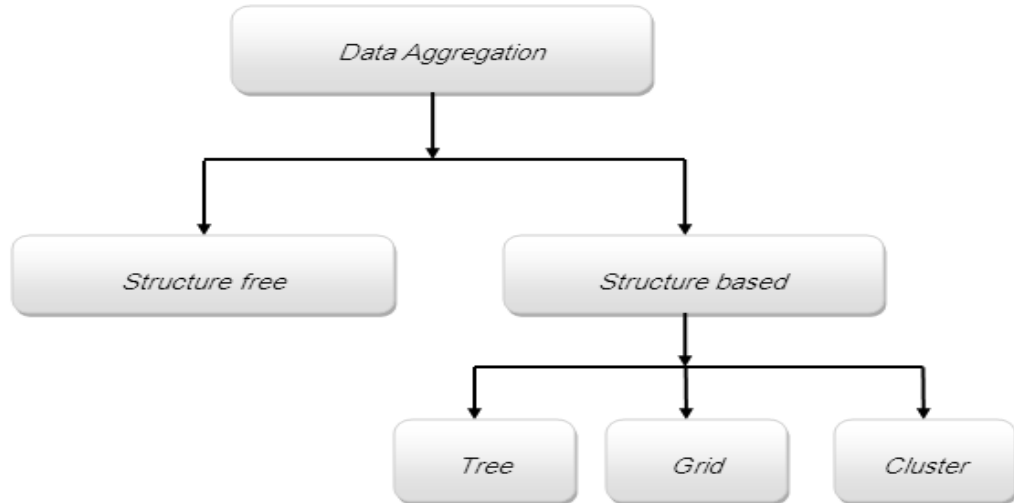


Figure 2.4. Classification of aggregating data protocols in a WSN

2.3.2.1 Structured Based Fusion Method

The structure based methods can be divided into three of the most popular protocols, which are clustering, tree and grid protocols.

2.3.2.1.1 Cluster-Based Data Fusion Method

In cluster-based data fusion methods, usually sensor nodes are clustered into different groups with their own CHs. the CHs are responsible to fuse received data from CMs for the purpose of reducing data transmissions WSNs [74]. Clustered diffusion with dynamic data aggregation (CLUDDA) [75] is a combination of clustering with dynamic diffusion mechanisms. CLUDDA has the ability to fuse data in an unfamiliar environment by using query definitions. Chain Based data aggregation [76] is a clustering based algorithm that is assuming every single sensor in WSNs has the ability to aggregate data

and then, forwards them to the next node. Lindsey et al. [76] proposed a protocol, called power efficient data gathering protocol for sensor information systems (PEGASIS), with the aim of simplifying data fusion process in a WSN. In this protocol, all the deployed nodes need to be located into a stable linear chain and also they need to be aware of each other's locations to choose the closest neighbours. Figure 2.5 shows the general architecture of chain based data aggregation. In the WSN all the sensors need to fuse the collected data, produce the same size of received data and forward it to the closest neighbour. This process continually occurs to reach the closest node to the sink, which is called leader node. Leader nodes that are CHs in this network fuse the entire received data packets again and send to the BS.

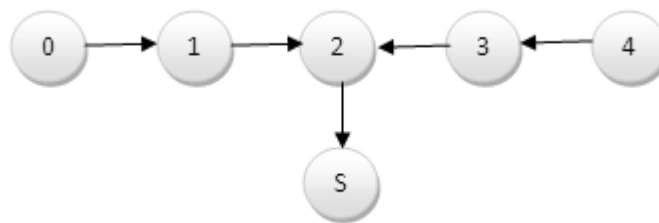


Figure 2.5. Chain based protocol

The authors believed that this technique can be used in a large size of WSN. This technique is more energy saving method than the previous described protocols. However, since all the sensor nodes need to aggregate the collected data the delay, especially in the end nodes cannot be ignored. Furthermore, PEGASIS cannot be a desirable solution for big networks or even for the very far distance sink [77].

2.3.2.1.2 Tree Based Data Fusion Method

Tree based methods arrange the entire sensor nodes into a tree and organize them to be able to aggregate the data by immediate nodes in the network [74]. Then, a brief version of data is transferred to the root node along the tree. Figure 2.6 shows the tree based protocol. To analyse that, there is a query routing based data aggregation algorithms that is designed based on direct diffusion. The main thought behind this method is naming the data using information of the entire network.

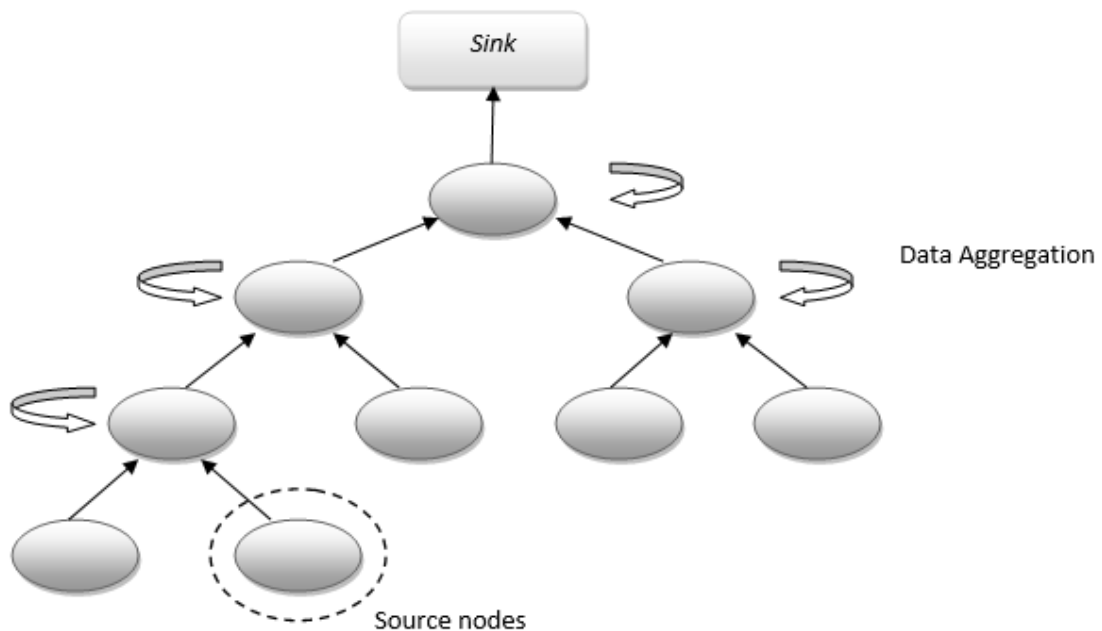


Figure 2.6. Tree-based data fusion protocol

To analyse the method, there are three general phases. Firstly, the BS broadcasts periodically messages to each neighbour and provide them with specific information such as task type and expire time for data. Then, the sink produces control messages with the required gradient to guide the data packet to the destination. Finally, a path reinforcement

method in the network selects the specific neighbours as the next hops to be able to send the packets with a higher rate to the identified nodes.

Although there are some advantages in applying the algorithm such as reducing communication between adjacent nodes and also cutting the additional addressing mechanism, there are some shortages. Firstly, the energy consumption is quite high and also the existed delay of the protocol are not avoidable especially in a large size of network. Suboptimal aggregation tree [78] is another protocol that is more focusing on constructing a possible minimum tree to the BS. To analyse that, there are three main sub-algorithms. Firstly, greedy internal tree (GIT) that is to create the tree in the network gradually and cover the entire network. In this protocol, the closest node to the sink determines a route to the main destination. Then, all other the nodes connect themselves to the created route. Secondly, shortest past tree (SPT) [79] algorithm that is applied in the network to identify the shortest data route to the sink. Overlapping route is a common shortage of SPT. Shinji MIKAMI et al. [79] suggested that aggregation tree could be an acceptable solution in the case of overlapping routes. Finally, the last suboptimal algorithm is CNS (Centre at Nearest Source) [78]. This algorithm gives the aggregating responsibility to the very closest node to the BS. Then, all the other nodes forward their sensed data to the end node to be aggregated. Since the conditions of different networks are changing, the performance of the mentioned sub optimal algorithms are changing. For instance, any changes in the distance of the closest node to the BS influences performance of the network.

2.3.2.1.3 Grid-Based Data fusion Method

Vaidhyathan et al. [80] proposed two data aggregation schemes, which are grid based data aggregation and in-network data aggregation protocols. In grid-based data

aggregation, the deployed sensors are not allowed to communicate with each other. The sensor nodes that are part of virtual particular grid, transmit data packets directly to the pre-determined data aggregator. In-network aggregating method is similar to grid based data aggregation with two major differences. First, any sensor can be an active aggregator and also each sensor within a grid can communicate with its neighbouring sensors [77]. Figure 2.7 shows the general structure of grid based data aggregation.

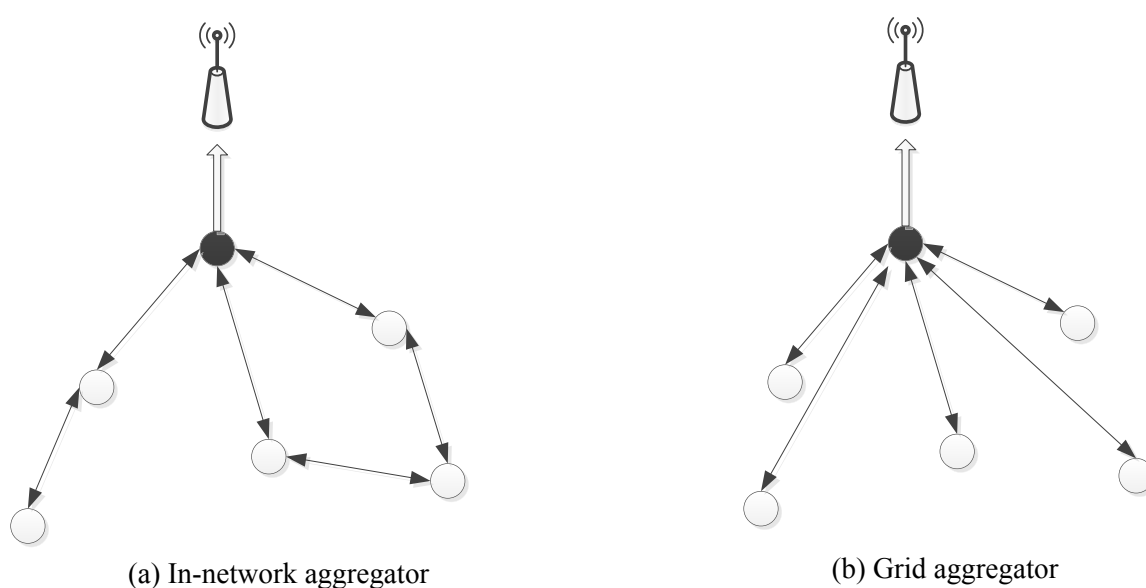


Figure 2.7. Data aggregation methods

Figure 2.7 (a) presents the sensor nodes that are selecting the best node to be the aggregator of the network. Then, the selected node fuses the received packets from the other nodes and forwards them to the sink. On the other hand, figure 2.7 (b), shows that in grid based data aggregation all sensors directly transmit data to a pre-determined grid aggregator.

To enhance the performance of the data aggregation it was suggested to make a hybrid scheme and apply a combination of the in-network and grid-based aggregation schemes [80]. When an event occurs, an aggregator node will be selected while they still maintain

the past events in their table. When a sensor detects an event, it checks its table for the previous event and identifies the nature of it. The in-network scheme will be followed if the sensor identifies the event as a localized event. Therefore, the best aggregator can be chosen depend on current situations. Apart from the authors' claim that increased energy efficiency, complexity of the protocol in a large size of a network is a disadvantage of the scheme. In addition, since all the data from each node is needed to be processed and transferred, the energy cannot be efficiently consumed. Moreover, preventing data redundancy were not taken into account in this approach.

2.3.2.2. Structure Free Based Fusion Method

Structure free based mechanisms in WSN are the attractive techniques that can be used in environments with frequency changes [74]. The technique is more applicable for monitoring systems that are not required any structure. There are two main challenges in accomplishing the techniques. Firstly, as there is no pre-constructed structure, routing decisions for the efficient aggregation of packets need to be made on-the-fly. Secondly, the sensor nodes are not able to wait on data from any particular node before forward their own data. That is because the sensor nodes do not explicitly know their upstream neighbours. Many researchers, as it is surveyed in [81], have been investigated in this area for aggregating data. The most common techniques that is going to be explored in this section are using neural-network and fuzzy logic systems. In [82], Chen et al. proposed a data fusion method. The algorithm uses both neural networks and fuzzy inference. The approach, based on some information such as temperature and smoke density determines whether a fire has been occurred. This technique enhanced the accuracy of detection however, energy consumption and data reduction were not taken into consideration. Doolin and Sitar [83]

proposed a system to monitor forest fires, based on the use of WSNs. The nodes of the system were able to sense temperature, humidity and barometric pressure. In this approach, the energy consumption of the network was not taken into account. Yu et al. [84] proposed a paradigm for forest fires detection. In this approach, they considered temperature, relative humidity, smoke density and wind speed sensors in the environment to detect fire accurately. They reduced the amount of data traffic in the network to prolong the network lifetime. In fact, they used cluster base deployment technique to develop a WSN and lead the CHs to aggregate the data using a neural network. Then, the CHs send the result to a node called manager node. Thus, the node analysis the received results to be able to detect fire in the area of interest. This approach prolonged the network lifetime but still cannot be considered as a comprehensive solution as they used all the received data from the sensor nodes. Thus, they did not consider duplication in the network. As a result, QoS in the network was not fully taken into account. In [85], a variable weight based fuzzy data fusion algorithm for WSN is proposed. The main purpose is to enhance the accuracy and reliability of data fusion in WSN. In this approach, each CH are assigned a different and unfixed fusion weight. The weights are changed using fuzzy logic system, based on some factors such as delay, data amount and trustworthiness of the CHs. The lower fusion weighted CH the lower influence the CH can make. As a result the collected fused data packets are more reliable and accurate. The approach to some extent enhanced the QoS of the network. However, the authors did not take the message overhead and energy consumption into accounts.

2.3.3. Routing Protocols in WSN

A routing protocol in WSN is the process of discovering, selecting and maintaining paths from one node to another and using these paths to deliver flow packets to their

destinations. In the process, determining the next node to which a packet should be forwarded toward its destination is based on given criteria. It is an important aspect of network communication as it affects many other characteristics of network performance. An efficient routing mechanism can become significantly complex due to the fact that it may consider all the current conditions of the nodes in the network [86]. In this section, the routing protocols in WSNs with fixed and mobile BS (MBS) are going to be analysed into different sections.

2.3.3.1. Routing Protocols with Stationary BS

During the past decade, considerable research efforts have been investigated in developing routing techniques for delivering data in WSNs. Majority of the approaches considered QoS constraints such as energy efficiency, delay and reliability as the main objectives. In this section, we present an overview of the most well-known protocols in WSNs.

R. C Shah and J. M Rabaey [87] presented an energy aware routing protocol that maintains a set of paths. The paths will be chosen randomly once the data needs to be transferred from source to the final destination. This approach on the one hand, decreases the risk of losing data and increases energy consumption due to maintain the paths. N Jain et al. [88] proposed an energy-aware multi-path routing approach to spread data traffic over the nodes lying on different possible paths connecting the source nodes to the sink. Sequential Assignment Routing (SAR) [89] for WSNs produces multiple paths from a source node to the BS. The path selection considers both delay and energy resources to prolong the life time. In [90] an energy-aware routing algorithm for cluster-based WSNs have been proposed. The cost function is defined between two sensor nodes in terms of energy conservation, delay

optimization and other performance metrics. Real-time and Energy Aware Routing (REAR) [91] uses metadata to establish multipath routing to increase the energy consumption in the network. In order to evaluate the consumption of bandwidth on the links a cost function is constructed. The best route is then chosen, based on the relationship between the energy and delay. The authors proved that energy consumption is reduced followed by activating image sensors and using metadata of real data in routing setup. However, the idea of metadata cannot be a good option as the metadata for streaming data can itself cause a huge energy and bandwidth consumption. Ant-based Service Aware Routing (ASAR) [92] is a hierarchical protocol that incorporates reinforcement learning to route data. In each round of data collection, three different paths that meet the QoS requirements are chosen. Then, the most optimal route will be maintained in a path table at each CH. The authors enhanced QoS in terms of delay, packet loss rate and energy consumption. However, in hierarchical models, the bottleneck problem and new optimal path setup due to congestion issue, requires extra calculation that might decrease network performance. the issue arises in a large size of WSNs. Zongwu et al. [93] proposed a novel genetic algorithm to satisfy the necessary QoS parameters such as end-to-end delay, minimum cost and maximize network lifetime. A proposed energy efficient routing protocol [94] attempt to manage both energy consumption and delay based on AntNet protocol. This approach uses the concept of ant pheromone to produce two prioritized queues with the purpose of sending differentiated traffic. However, the approach cannot be a comprehensive solution due to the required memory to save both queues. Peng et al. [95] proposed an adaptive QoS and energy-aware routing approach. They developed a biological ant colony algorithm for WSNs with the aim of meeting QoS requirements in an energy-aware fashion to maximize the network lifetime. Their simulation results proved that the proposed algorithm improved the performance of

WSN in different scenarios. M Chen et al. [96] presented a multiple-priorities-based path-scheduling algorithm to guarantee the end-to-end transmission delay while balancing energy and bandwidth usage among all the node-disjoint paths in WSNs. Shu et al. proposed two-phase geographic greedy forwarding (TPGF) [21] with the aim of minimizing the path lengths and end-to-end transmission delay. TPGF firstly explores all the possible paths and then find the shorten distance to forward the data packets. However, the scheme has limitations in adaptability in large-scale, high density and frequent mobility situations. Reference [97] proposed a routing protocol that finds the least-cost and delay-constrained path for real-time packets. They assumed that every node knows the position of all the sensor nodes as well as the cost of links among them in the WSN. The protocol works on finding the path by executing Dijkstra's shortest path algorithm. Mahapatra et al. [98] utilized the geographic location of the sensor nodes as well. They proposed an energy aware dual path routing scheme and aims to balance the consumption of energy in each node in the network. E Felemban et al. [99] proposed multipath multispeed protocol (MMSPEED) to guarantee reliability and timeliness in the WSN. The protocol uses a distributed localized geographic packet forwarding mechanism. It requires the support of IEEE 802.11e at MAC layer with its inherent prioritization mechanism. In this protocol, each node that uses packet loss rate at MAC layer is responsible to calculate the possibility of each neighbour to a destination. According to the gained probability value, each node sends a copy of data packets to a number of neighbours to achieve a desired level of reliability. So, the probability of retransmissions is decreased. MMSPEED improves the network life time however, number of the hops and their available energy are not considered for establishing routes. In Table 2.2, we compare and summarize the above-explained routing protocols for

WSNs based on QoS constrains. The table clearly shows that the existing developed protocols have not sufficiently improved the performance of the WSN.

Table 2.2. Comparison of routing protocols for WSN

Routing Protocol	Architecture		Energy efficiency	Delay	Data Packet loss rate	Inherent uncertainty
	Flat	Hierarchical				
Shah and Rabaey [87]	✓		✗	✓	✓	✗
N Jain et al. [88]	✓		✗	✓	✓	✗
SAR [89]	✓		✓	✓	✗	✗
Younis et al. [90]		✓	✓	✓	✓	✗
REAR [91]	✓		✓	✓	✗	✗
ASAR [92]		✓	✓	✓	✓	✗
Peng et al. [95]	✓		✓	✓	✓	✗
Zongwu et al. [93]	✓		✓	✓	✗	✗
Caro and M. Dorigo [13]	✓		✓	✓	✓	✗
M Chen et al [96]	✓		✓	✓	✓	✗
TPGF [21]	✓		✓	✓	✓	✗
Akkaya and Younis [97]	✓		✓	✓	✓	✗
Mahapatra et al. [98]	✓		✓	✓	✓	✗
MMSPEED [99]	✓		✗	✓	✓	✗

2.3.3.2. Routing Protocols Using MBS

In WSN with stationary sensor nodes and sinks, the probability of significant congestion is highly noticeable. Thereby, an excessive delays and inefficient use of underlying resources can occur. Moreover, due to the excessive use of the sensor nodes close to the BS, the network lifetime is reduced significantly as the nodes become frustrated quickly. In order to provide a longer lifetime in WSNs, many new categories include motion characteristic of WSN has been developed. In the networks, the data collector can be moving in different directions to collect the sensed data from immobile deployed sensor nodes. Then, the source node will communicate with the sink directly or by using fewer hops. Clearly, in this context, there are several advantages and challenging issues that are required

to be addressed. The major advantage of having a data collector or a MBS is to increase the system lifetime. Indeed, the MBS leads the network to use fewer hops to create forwarding routes. Thus, the number of transmitted packets will be reduced and accordingly, the energy consumption will be decreased. In the mechanism, the extra energy spent for the operation and movement of the sink does not influence the overall network lifetime. That is because the MBS is considered as an external to the network. For example, the MBS could be a man, navigated vehicle or an unmanned robot that periodically returns to a fixed point to recharge itself. Another important advantage is the reduction of the probability of transmission errors and collisions in the network. Hence, the throughput and data reliability can be increased. This also further decreases the energy spent at the resource constrained static nodes by cutting the required retransmissions. In spite of the advantages, there are many challenges and issues that need to be discussed. For example, length of physical routes for the MBS. Since the MBS has to pass through the transmission range of the deployed sensor nodes, the following issues can occur. Firstly, long visit latency that is due to the waiting time for each node to be visited by the MBS. The latency also becomes worse if retransmissions will be needed. Besides, the sensor nodes may experience significant buffer overflows until the next contact time.

In order to analyse and improve the performance of WSNs with MBS, there is a huge range of approaches have been developed. For example, Vlajic et al. [100] proposed a routing protocol with a MBS and reduced propagation delay and energy consumption in the network. The deployment strategies of WSN can be generally classified into two main categories which are backbone based and tree based structures.

2.3.3.2.1. Backbone Based Structure with Mobile BS

In backbone or virtual grid structured networks, sensor nodes organize themselves into clusters on the basis of their geographic locations. Therefore, one node per each group may perform data aggregation and communicate with the MBS. Hence, the MBS is not required to visit the entire deployed sensor nodes.

Under the consideration of the explained deployment methods, there are many mobile sink based protocols that have been developed. The protocols are either random or controlled mobility based with their considerable advantages and disadvantages. Ioannis et al. [101] proposed purely random walk as well as a combination of random walk and deterministic walking models. Under the purely random walk model, the following three models have been proposed. Firstly, the MBS moves toward predefined areas with random transitions. Secondly, the sink gives more priority in visiting less frequently visited areas and finally, the MBS gives priority in visiting areas populated with more sensor nodes. In the deterministic walk model, the MBS moves along a predefined trajectory within small areas. The proposed model suffers execute complex movements with a considerable overhead as the sensors are required to constantly update the multicast trees involving the sink. Gandham et al. [102] proposed to dynamically relocate multiple sinks into different time rounds. The authors used an integer linear program to determine the new locations. Results showed that the energy consumption of individual sensors is better balanced and the overall energy consumption of all sensors is minimized. However, this centralized method suffer a high computational complexity of linear programming. Babar Nazir et al. [103] addressed hotspot problem and mobile sink based routing protocol (MSRP) to prolong network lifetime in clustered sensor nodes. The CHs within the vicinity of the sink send the collected

data to the MBS after CH registration processed by the sink. MBS also maintains a CH residual energy table for predicting the next position. Sink looks into this table and moves to the CH with higher residual energy. This ensures that the nodes near the sink have higher energy and thus avoids hotspot problem. However, this approach is not suitable for continuous monitoring application as CHs need to wait for the arrival of mobile sink to deliver data packets. Xu Jianbo et al. [104] studied mobile sink based data gathering protocol (MSDG) for clustered WSN. They adopted a joint strategy of sink mobility and routing to realize high efficient data gathering. In this approach, sensor nodes in WSN are divided into certain number of clusters in the monitoring area with any side length. Then, sink by choosing the closest nodes along the path build a routing tree dynamically. After that, CHs gather the data from the CMs, aggregate and send the aggregated data to the sink reversely using a tree based method. In this method, although the energy consumption has been reduced due to aggregating data, the sensors still need to consume much energy to send data packets by using number of hops to the mobile sink. Jin Wang [105] developed distance-based energy aware routing (DEAR) algorithm for WSNs. DEAR is a routing algorithm that setup and maintain routes in WSNs. In setup phase, the algorithm first calculates the distance among sources and sink nodes. If the distance is less than a predefined threshold, the data will be directly transmitted to the BS. Otherwise a multi-hop routing method will be considered. This algorithm also determines the number relay hops as well as finding the closest relay node to the sink. The author believed that high transmission power will drain a significant amount of energy from the nodes. That is attempting to transmit over long distance, consumes more energy compared to low power multi hop transmission covering the same distance. Apart from the advantages of this algorithm, it increases the traffic at intermediate nodes unnecessarily. Moreover, the closest

node to the sink is in the high risk of losing energy. DEAR does not also measure the available residual energy of selected nodes. This may cause the intermediate node becoming totally drained of their energy during data transmission process.

2.3.3.2.2. Tree Based Structure with Mobile BS

This structure can be classified into source-based and sink-based structures. In source-based structures, source nodes broadcast their information to the entire network and create a tree-rooted for delivering data packets. Then, the MBS uses this tree to retrieve data from the source. On the other hand, in sink-based structures the MBS broadcasts its location to the network and assigns a tree-rooted. Nodes then, use the reverse tree path to deliver data to the sink. Both, source-based and sink-based mechanisms have their benefits and issues. For example, in source-based mechanism, roots creation is usually independent of sink mobility. However, energy consumption as well as congestion are considerably high. That is because each source node is required to be updated about the previous routes periodically to deliver data packets. In contrast, sink-based mechanisms require only one tree for the MBS, irrespective to the number of sources. The MBS is required to periodically update their location for the network. These periodic location updates increase the control traffic overhead and network's energy consumption. To reduce these periodic sink location updates, several solutions have been proposed [106]. Marta et al. [107] developed a method to lead mobile sinks to be relocated once the sink noticed that energy of sensors nearby them is depleted. The mobile sink follows paths that direct it to the node with highest available energy. The authors claimed that an improvement by 4.86 times in network lifetime was achieved compared with static sink case. Their proposed strategy requires that the sensors send additional information to the sink periodically. Hence, the energy consumption as well

as message over head is considerably high. Yun et al. [108] developed an approach with the purpose of maximizing the lifetime of WSNs by using a MBS. They formulated optimization problems that maximize the network lifetime subject to delay, node energy constraints and flow conservation constraints. In this method, each source node is not needed to send the data immediately once it becomes available. Instead, the node can save the data temporarily and transmit it when the mobile sink is at the most favourable location. However, it assumes that the mobile sink needs to visit all the predefined locations in sensor fields even if do not need to be visited. They also did not consider the emergency situations with critical data packets.

Table 2.3 shows a comparison of different routing protocols in WSNs with MBS. The table illustrates that all the approaches that have been explored in this section improved the performance of WSN, but the problem has yet solved properly. That is because of the lack of fully consideration about the local information in WSNs. Moreover, the existed approaches did not take emergency situations with urgent data into account. Additionally, the designed systems have limitations in dynamic environments which contain a variant amount of noise created by some interferences.

Table 2.3. The comparison of different routing protocols using MBS with respect of QoS

Protocols	Methodology	Sink movement	Energy	Traffic overhead	Priority visiting	Urgent of data	Inherent uncertainty
Ioannis et al. [101]	Distributed	Random	✓	✗	✓	✗	✗
Gandham et al. [102]	Centralized	Controlled	✓	✗	✗	✗	✗
MSRP [103]	Centralized	Controlled	✓	✗	✓	✗	✗
MSDG [104]	Distributed	Controlled	✓	✗	✗	✗	✗
DEAR [105]	Distributed	Controlled	✓	✗	✗	✗	✗

Marta et al. [107]	Distributed	Controlled	✓	✗	✓	✗	✗
Yun et al. [108]	Distributed	Controlled	✓	✗	✗	✗	✗

2.3.4. WSN Coverage Method

Solutions to coverage and deployment problems in a mobile WSN investigate how to locate sensor nodes to meet the existing constraints and examine how well a sensing field is monitored. In this regard, recently, there is a considerable number of protocols and algorithms that have been developed to solve the problem. The protocols, in terms of computational organization, can be categorized as centralized and distributed algorithms. In centralized organizations, to process data and also local information on the deployed nodes, a central location is required. The drawback of this method is the very high communication costs and intrinsic delay. This becomes worse when the number of nodes in the network increases. Consequently, the centralized algorithm is not reliable in large networks. On the other hand, in distributed algorithms that distribute the load of computational effort across the network, delay and inter-sensor communications are reduced. In such methods, each sensor determines its location locally by communicating with its neighbours without the requirement of sending and receiving location information to and from the central server. Generally, compared to centralized algorithms, distributed algorithms are more robust and energy efficient [109]. Apart from the computational organization, to address the research problem and make it more understandable, in this section some of the recent developed approaches are analysed.

In WSN, maintaining both coverage and uniformity is vital and there have been many investigations with the aim of improving it. In the networks examined, it has been assumed that deployed sensors have fixed sensing and communication ranges. Huang and Tseng [110] proposed an efficient polynomial time solution by considering the coverage of each sensors' sensing range. In the literature, the coverage problem is formulated as a decision problem with the aim of determining whether the area is sufficiently K -covered. Indeed, every point in the areas of interest needs to be covered by at least K sensors, where k is an integer. However, this approach does not efficiently address the problem as the uniformity and also the number of sensor nodes were not considered. Moreover, this approach is designed for a static environment as it is a deterministic deployment based protocol. PFRL [111] is a probabilistic fuzzy logic based localization algorithm. This algorithm, to some extent, by managing uncertainty associated only with received signal strength (RSS) reduced the localization errors in WSN. In fact, PFRL improved localization accuracy in separating mobile sensor nodes. However, the authors only managed to enhance the node deployment process in a sensor field. They did not consider self-healing, energy consumption and also the uniformity of the WSN deployment. Misra et al. [112] addressed the problem of network coverage and connectivity. They proposed an efficient solution to maintain coverage so as to preserve the connectivity of the network. The main contribution of their research work is to cover the monitoring area by considering the overlap region and connectivity of the deployed sensor nodes. In this process, the authors started with the two nearest nodes in the network which guarantees the connectivity backbone formation and then extended the backbone by activating new nodes in the communication range of those active nodes. That would proceed until the entire area is covered. The main disadvantage of the proposed approach is the lack of consideration of mobile sensor nodes as the approach

is designed for only static networks. In [113] the relationship between deploying density, coverage and connectivity was analysed. The authors raised the sensing-coverage phase transition (SCPT) and the network-connectivity phase transition (NCPT) problems. They proposed a new model of combination for both coverage and connectivity. The connected-coverage problem is approached using the theory of percolation [114], where the goal was to probabilistically calculate the fraction of area covered at the critical density when phase transition occurs. However, the paper does not address how to recover the coverage holes. The main disadvantage of the research work is high energy consumption as it is a probabilistic approach. P. M. Pradhan and G. Panda [115] presented an energy efficient sensor deployment based on a multi objective particle swarm optimization algorithm. In this research work, the main objectives are coverage and network lifetime within the constraint of network connectivity. The disadvantage of the approach is a lack of consideration of uniformity and the distances among deployed nodes. Jiang et al. [116] proposed a cascaded movement solution for the coverage problem. They initially partitioned the area into a number of grids. In each grid, a grid head is selected to execute the intra grid management and inter-grid communication tasks. The grid head that detects a vacant grid will find specific sensors in its grid and then force them to move to the vacant grid. If the coverage-hole healing procedure fails, the grid head will further notify the grid head in its neighbouring grid and then initiate a cascaded movement. In the literature, they enhanced the coverage, however, the energy-balanced degree of mobile sensors and uniformity were not taken into account as they randomly select sensors to heal the vacant grid. Qu et al. [117] developed an efficient method for relocating mobile sensors to achieve optimum sensing coverage. The study introduced an average distance based self-relocation and self-healing algorithm for randomly deployed mobile sensor networks. In this approach, each sensor, by

sending and receiving a message, calculated the distance between each other and made moving decisions. The proposed approach is a random based direction movement that clearly reduces the energy efficiency in the WSN.

Table 2.4. The comparison of different coverage protocols with respect of QoS

Protocols	Node Deployment	Coverage Healing	Methodology	Energy Efficiency	Uniformity	Inherent Uncertainties
K-Coverage [118]	✓	✗	Distributed	✗	✓	✗
PFRL [111]	✓	✗	Centralized	✗	✓	✗
S. Misra et al. [112]	✓	✓	Distributed	✓	✗	✗
M. Amery et al. [113]	✓	✗	Distributed	✗	✗	✗
M.Pradhan [115]	✓	✗	Distributed	✓	✗	✗
Jiang et al. [116]	✓	✓	Centralized	✗	✗	✗
Qu et al. [117]	✓	✓	Distributed	✗	✓	✗

Table 2.4 present a comparison of different developed coverage protocols with respect to QoS in WSN. The table shows that although they enhanced QoS in WSN, they cannot be considered a comprehensive solution. Therefore, in this paper a distributed node deployment and coverage-healing protocol with consideration of energy efficiency, deployment uniformity and inherent uncertainties in WSN is proposed.

2.4. Chapter Summary

In this chapter we deeply analysed number of approaches in WSN respect to QoS requirements. We firstly introduced WSN technologies, sensors and applications in details. After that, the most considerable challenges in WSN were explained and analysed. Then,

we focused more on the existing approaches that have been developed with the purpose of enhancing QoS in the networks. We divided the approaches into four main sections. First, we analysed clustering approaches in the networks with explanation of their advantages and disadvantages. Next, different data fusion methods were analysed and tried to show the existing research gap in the existing approaches. Third, data routing protocols with stationary and mobile sink were addressed. Finally, WSNs coverage were taken into consideration. The approaches showed that they emphasized on enhancing QoS and efficiency of energy consumption.

Chapter 3

A SELF-CONFIGURABLE CLUSTERING SCHEME IN WSN

Despite significant advancements in wireless sensor networks (WSNs), energy conservation in WSN remains one of the most important research challenges. One approach commonly used to prolong network lifetime is through aggregating data at the cluster heads (CHs). However, there is possibility that the CHs are failed in functioning correctly due to number of reasons such power instability. During the failure, the CHs are unable to collect and transfer data correctly that leads to fail the performance of the WSN. Early detection will reduce the data loss and provide possible minimal recovery efforts. Therefore a self-configurable clustering (SCCH) mechanism to detect the disordered CHs and replace them with other nodes is paramount to the WSN.

3.1. Introduction

The most challenging aspect of WSN is they are energy resource-constrained and that energy cannot be replenished. The problem arises when all the sensor nodes are required to

forward the data packets to the sink node. In this process, the available energy in each node can be wasted through idle listening and retransmitting due to collisions as well as overhearing. Cluster-based WSN routing protocols excel network topology management and energy minimization [119]. Clustering methods in WSN lead the sensor nodes to be organized into small disjoint groups, where each cluster has a coordinator referred as CH. In cluster based approaches the sensors do not need to communicate directly with BS. Instead, the CHs are responsible to organize cluster members (CMs) and send the data collected within the cluster to the BS. This process lead to a significant reduction in the amount of transferred data in the network. Consequently, overheads in communication as well as bandwidth in clustering will be reduced significantly [119-122]. Figure 3.1 shows a general view of a clustered WSN. Maintaining the created clusters is the main challenging task in the methods. To choose a node as a CH, it is necessary to define its eligibility. That is calculated based on local information of the nodes' current situations such as its residual energy. The eligibility of the selected CHs however, reduces as they sensor nodes are consuming energy for transferring data. If the eligibility of the CHs reduce to a certain level, they may introduced as failed CHs. In the case, the deployed sensor nodes are required to be re-clustered. As a result, in a period of time the sensor nodes cannot collect data. The problem arises if the failure of the CH is not predicted, which could be a sudden physical damage. Respectively, the CMs keep sending their data to the failed CH and consequently the data will be lost.

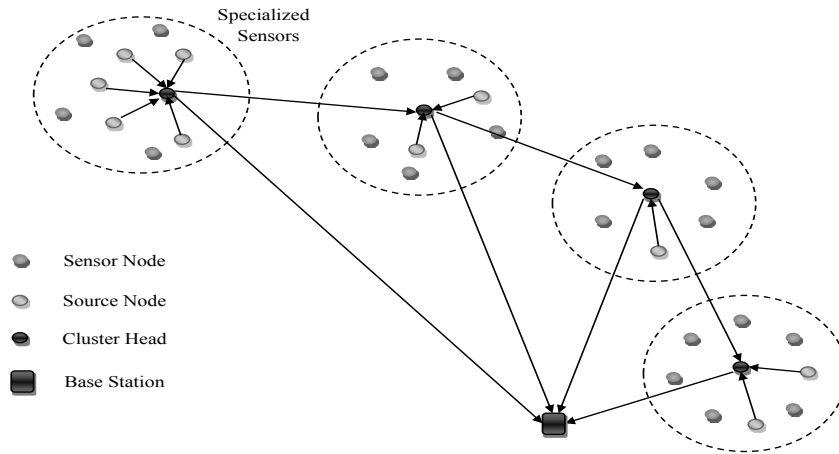


Figure 3.1. A clustered WSN

Many developed approaches investigate the problem and suggested to use backup CHs (BCHs) [123-125]. Figure 3.2 shows a general view of a clustered sensor nodes with BCHs. In those approaches, BCHs take over the responsibility once the defined CHs noticed their eligibilities of being CHs are on a certain level. They proved that BCHs secure more the created clustering formation in the WSN. These approaches however, did not address the problem sufficiently. That is because, they mostly focused on only predicted CH failure. The CMs in the existing approaches cannot define whether their CHs are operating or already failed unless they received an alerting message. Those approaches did not also consider the temporary CH failure. Moreover, they assumed that the determined BCH is always fully functional and always is the most appropriate node to be replaced with the defined CH. Finally, they only considered maximum of two BCH in their protocols. However, their assumptions are not realistic. That is because, in WSN there is no guarantee that the determined BCHs are always fully functional as the sensor nodes do not consume energy equally. In some situations, the BCHs might be used more than the other nodes. Also, considering maximum two BCHs is not ensuring the created cluster formation.

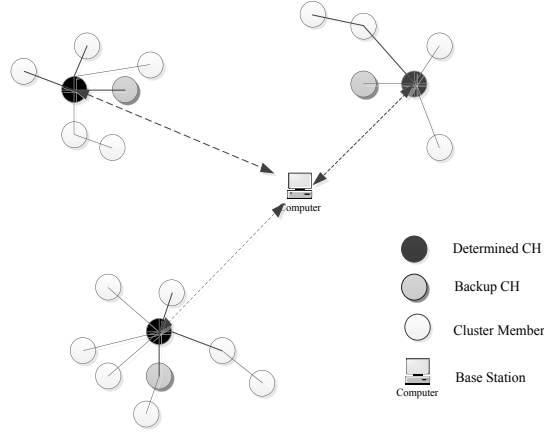


Figure 3.2. Clustering formation of sensor nodes

To overcome the issue, we propose a clustering mechanism for WSNs. In which we use type-2 fuzzy logic system (FLS) [126] and local information of the nodes to calculate the eligibility of the nodes. The node with maximum eligibility is selected as a CH. The other nodes are saved on a list based on their calculated eligibilities as BCHs. Therefore there is always a BCH for a failed CH in each cluster. To replace the BCHs with failed CHs we consider both temporary and permanent failure in the CHs. Moreover, we take unpredictable as well as predictable CH failure into account.

3.2. Problem Overview

Given $\mathcal{L} = \{s_1, \dots, s_n\}$ wireless sensor nodes deployed randomly over a surface area. The sensor nodes and BS are stationary. The clustering problem is to identify and make a collection of CHs and CMs, while they cover the entire deployment area. Generally, clustering protocols in WSN are divided into two main sections. In the first section clusters are organized followed by CHs selection process. In this phase, the sensor nodes cannot collect and transfer data packets among each other. After the clusters were created, the sensor nodes are able to collect and transfer data to each other. They consume energy as

they receive and send the data packets. So, each sensor node is in the risk of being disordered due to its energy depletion. The amount of energy lost in CHs is usually more than CMs as they are responsible to collect data packets from other nodes and transfer them to the BS. Therefore, they are more in the risk of energy depletion. As a result, they cannot monitor their areas of interest. The problem becomes more challenging if the failed CH was not detected. In the case, CMs keep sending their collected data to the CHs without noticing that they cannot be received.

CH failure could be predicted and so, the CMs can be noticed by a message. Then, the CMs are required to replace their defined CHs with the most optimum BCHs. However, finding and replacing BCHs is needed to be considered carefully. In the real world, the deployed sensor nodes are not consuming their energy equally. That means current situations of the nodes are not changing similarly. As a result, the already determined BCHs are not always the most appropriate node to be replaced with failure CHs. In the case, it is a considerable challenge for the CHs to find and introduce the best current BCH to the CMs.

The problem is more challenging if the CHs are failed unpredictably. The CMs then, keep sending their data to the failed CHs without noticing they are not received. Thus, it could make the WSN to lose number of data packets. To prevent of the data lost in the network, it is significantly important to determine the failure CH by the CMs at the earliest moment. The CMs also are required to find and replace a BCH with the CH.

CH failure in WSNs could be permanently or temporarily. Permanent fault means the node is beyond repairs and needed to be replaced to ensure the QoS in the WSN. It can be happened due to reasons such as damaged components. Temporary fault on the other hand, is the one that results from temporary environmental impact or incorrect state of

components. To replace BCHs with the failed CHs it is also necessary to realise that it is not a temporary failure. That is because short-term lower density may not be an issue as long as the network remains connected.

3.3. Self-Configurable Clustering

To develop SCCH, we first need to select an appropriate CH for each cluster. For that purpose, we develop a type-2 fuzzy logic system (FLS) to find the most appropriate CHs for the clusters. FLS is used by the sensor nodes to calculate their eligibilities of being a CH. The input of the system are as followed;

1. **Energy (E):** residual energy in CHs candidates is used in electing CHs with an acceptable energy level. All nodes are aware of their remaining energy.
2. **Node Centrality (NC):** is a value that shows how central the node is among its mobile neighbours within the entire network. The lower value of the centrality, the lower amount of energy required by the other nodes to transmit the data through that node as CHs. NC is defined by Eq. (3.1):

$$NC = \frac{\sqrt{M}}{NZ} \quad (3.1)$$

where $M = \sum_{j \in S(i)} \frac{d^2(i,j)}{|S_i|}$, d is the distance between the CH candidate i and its member nodes, $|S_i|$ is the number of neighbors of node i and NZ is the size of the sensing field area.

3. **Local distance (LD):** This is sum of the distances from a deployed node to its neighbours. Figure 3.3 shows the deployed sensor node and its neighbours within r radius.

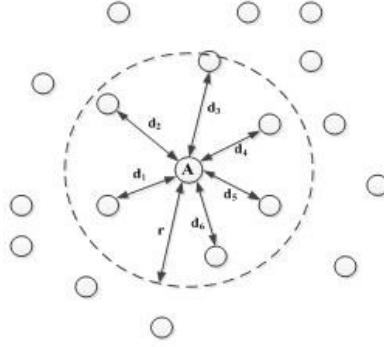


Figure 3.3. A deployed node with neighbours

In order to calculate LD, we first determine the radius (r) value as follows[4]:

$$r = \sqrt{\frac{NZ}{\pi \cdot |\mathcal{L}| \cdot P}} \quad (3.2)$$

Next, we consider only the neighbours within the confine of r radius for each node and then, sum up the distance (d_i) of the node to them, as shown in the Eq. (3.3) [127].

$$LD_{CH} = \sum_{i=1}^n d_i \quad (3.3)$$

Next, the output of the FLS for each sensor node will be sent by a beacon message to neighbours to be informed. Figure 3.4 shows the structure of the beacon message for sending the output of FLS.

Packet Type	Node-ID	FLS-OUT
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Figure 3.4. Eligibility of each node

Where Packet Type presents the purpose of the message, Node-ID is the ID of the node that creates the message and FLS-OUT is the output of the fuzzy system. The nodes that have received the message from the other nodes need to check FLS-OUT. They compare the received FLS-OUTs against its calculated fuzzy output as well as the received other nodes'.

A Sensor node with the highest FLS-OUT introduces itself as a CH. It also lists the other

sensor nodes, based on their FLS-OUT. In the list, they are ordered from the highest to the lowest FLS-OUT of the nodes. In fact, the list prioritises the sensor nodes to be BCHs. Therefore, sensor node with lower FLS-OUT knows that it is a BCH of the node with higher FLS-OUT. That is to ensure there is always a BCH for defined CHs. Figure 3.5 presents structure of the CH joining message.

Packet Type	CH-ID	BCH-IDs
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Figure 3.5. CH joining message

Where Packet Type presents the purpose of the message, CH-ID shows the ID of the elected CH and BCH-IDs is the list of sensors' IDs from highest to the lowest FLS-OUT. Next, each sensor node that received the CH joining message sends an acknowledgement message to join to the CH. Once the clusters are created, the CHs allocate a TDMA (Time Division Multiple Access) for the CMs. Then, the sensor nodes can start transferring data packets in the WSN based on the allocated TDMA schedule. At this stage, the sensor nodes include CHs consume energy. As a result, either CHs or CMs might face to energy depletion. If CHs die, the entire area of their interest will be unmonitored. Thus, replacing the failure CH is necessary. Disordered CMs also influence the eligibility of the elected CHs as NC and LD are affected. Therefore, to maintain the created clusters the CMs are needed to send their residual energy with their sensory data in a single message to their CHs. The CHs also are required to check their own FLS-OUT frequently. In each round of checking the FLS-OUT, the CHs compare it against a determined threshold (β). If the FLS-OUT of each CH is less than the threshold, it will be required to inform the CMs and a BCH about the switching time. So, the sensor nodes can replace their CHs with the introduced BCH.

The available BCH cannot be fixed in the WSN. That is because the BCHs might be physically damaged or in some situations their residual energy might be changed. Therefore,

CHs change the order of the BCHs in the created list based on received their residual energy. The updated list is sent to the CMs periodically to make sure that the most suitable BCH is available.

In the WSN the determined CHs also could be suddenly disordered due to for instance, physical damage. If a CH dies, the CMs are required to be noticed quickly to prevent of data losing in the network. Also if the CMs die, their CHs are required to remove them from their list. To achieve that, we propose to monitor the CHs and CMs using TDMA. Figure 3.6 presents the allocated TDMAs for S_i .

As it can be seen from Figure 3.6 (a), the CMs need to transfer their data packets upon receiving a data request message (Data-Req). If the CH did not receive the requested data at the end of the frame, it will mark an error for the CM. the error mark is to prevent of assuming the temporary dead as a permanent failure. Then the CH sends another request. If the CH did not receive data from the CM by the end of the frame it will check the error mark. If the error mark is existed, the CH realises that it is a permanent failure and it needs to be removed from its CMs' list.

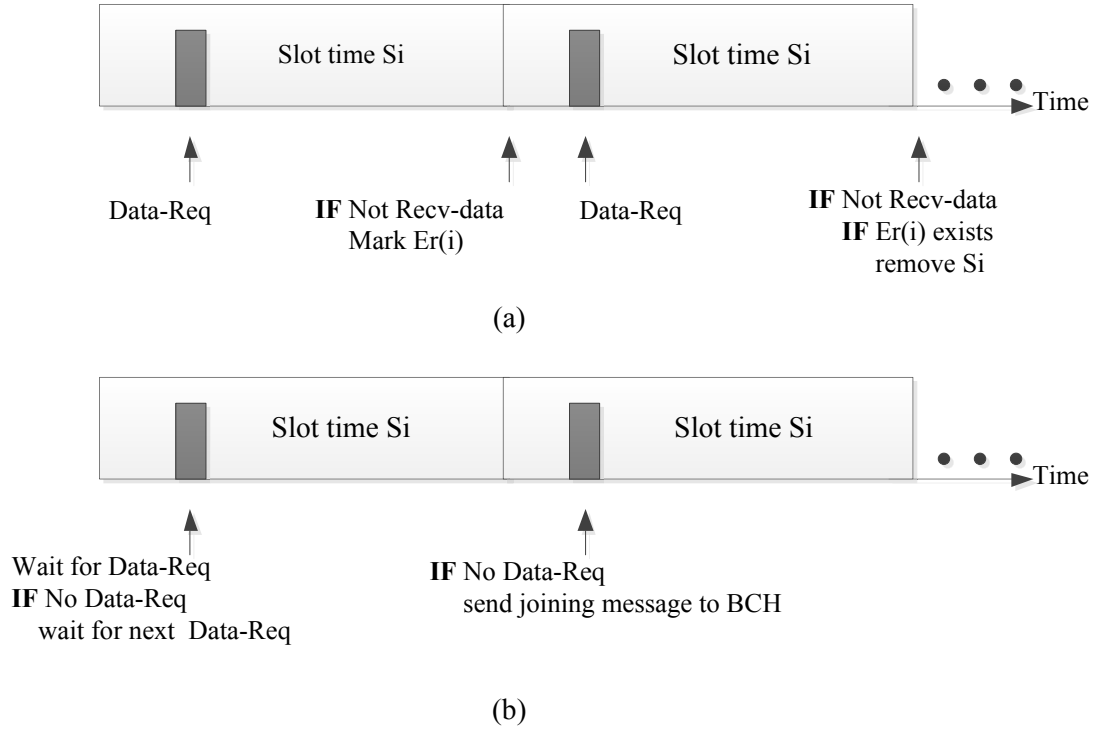


Figure 3.6 Allocated TDMA slots for (a) CH and (b) CM.

Apart from the CM, failed CHs are also needed to be detected. Figure 3.6 (b) presents the TDMA of the CMs. The CMs in the WSN need to wait for a data request (Data-Req) from its determined CH. if it does not receive Data-Req, it will wait for the next frame to receive the request as it might be a temporary failure. In case of not receiving the request in the second frame, it will be required to replace its CH. To replace the CH, the CM needs to check the latest and updated of its BCHs' list. Then it sends a joining message to the first available BCH and waits for acknowledge message. However, there is a possibility that the defined BCH might be disordered. In the case of not receiving the acknowledge message from the BCH, the CM sends another joining message to the second available BCH until it joins to a CH.

3.4. Performance Analysis

In this section we evaluate the performance of the proposed scheme using simulation. As a performance metric, we compare the efficiency of energy consumption of the networks. The communication model for energy consumption used in this evaluation is as explored in [66]. The transmitter dissipates energy to run the power amplifier and radio electronics is shown in Figure 3.7.

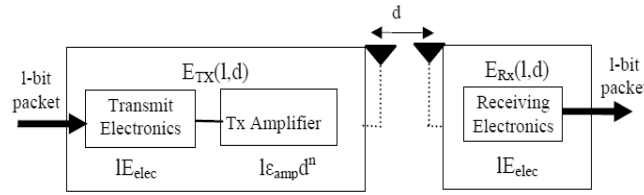


Figure 3.7. Radio energy dissipation model

The required energy for transferring a k -bit message to d distance can be calculated by using (3.4).

$$E_{Tx}(k, d) = E_{elec} * k + E_{amp} * k * d^2 \quad (3.4)$$

Energy consumed in receiving k -bit message can be computed by (3.5). Where based on the referred algorithm $E_{elec} = 50\text{nJ/bit}$ and $E_{amp} = 100\text{pJ/bit/m}^2$.

$$E_{Rx}(k, d) = E_{elec} * k \quad (3.5)$$

Apart from energy consumption, we analyse data loss ratio (DLR) of our proposed approach. DLR is a ratio of the difference of total data sent by the sensor nodes and received by the BS to the total data sent by the sensor nodes as provided below;

$$DLR = \frac{\text{Total data sent} - \text{total data received}}{\text{Total data sent}} \quad (3.6)$$

Finally, we analyse the traffic overhead of our proposed protocol. To evaluate the traffic overhead of the distributed approach in WSN, we tested the average amount of traffic transmitted within the network

3.4.1. Experimental Setup

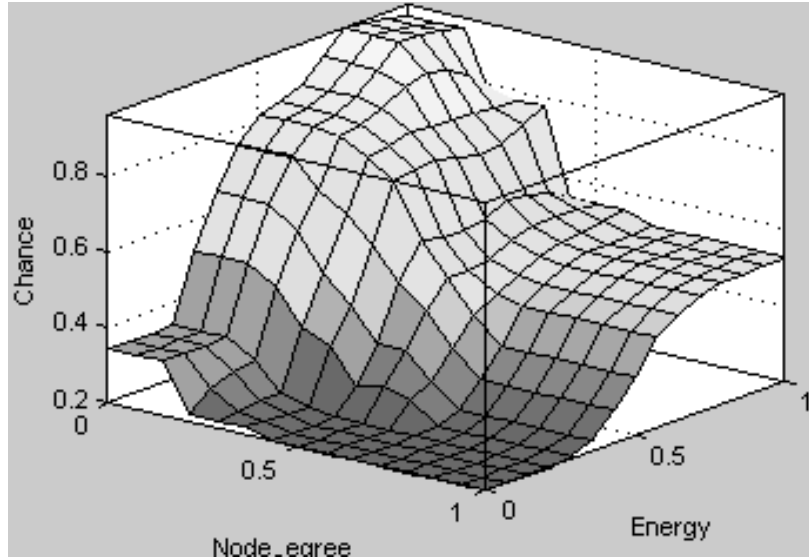
In this section we use MATLAB to compare our proposed approach against PDD (Probability, Distance and the sum of Distances) [128] and Achieving Reliability over Cluster-Based WSN using Backup Cluster Heads (DBCH-LEACH-C) [129]. The reason behind choosing PDD is that it is a fuzzy based approach that increased the network lifetime and DBCH-LEACH-C is also a clustering WSN that proved using BCHs enhances performance of the WSN.

In the simulation, the network consists of a BS and 80 sensor nodes, $\mathcal{L} = \{s_1, \dots, s_{80}\}$, wireless sensor nodes. The sensing range for each sensor is 25m and the communication range is 50m. The sensor nodes are deployed randomly over 200 * 200 meters surface area. The initial energy for each node is 1J equally. In terms of energy, memory and computational power, there is no limitation for BS. BS is located in the middle of the surface. The packet size is 100 bytes and beacon message is 10 bytes.

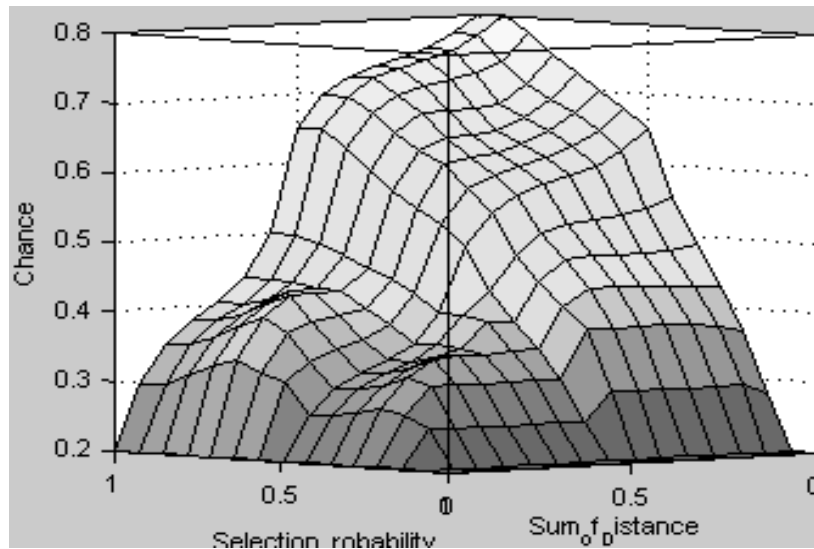
3.4.2. Result and Discussion

Figure 3.8 compares the rule surface of our scheme and PDD. Based on the plotted surfaces, the chance of finding CHs in the network by our system figure 3.8 (a) is higher

than PDD figure 3.8 (b). Moreover, our system introduces a substantially smoother surface. This smooth response will consequently provide a better monitoring performance that can handle the uncertainties although, the complexity of the system with respect to the size of the fuzzy rule based is remained the same (no additional fuzzy rules or fuzzy sets were used).



(a) Our proposed system



(b) PDD

Figure 3.8. Comparison of the response surface generated by the Fuzzy systems

In order to prove that the proposed approach prolongs the network's lifetime, we calculate the required energy for successful transmission of specific number of data packets. As can be seen from figure 3.9, the results show that the proposed approach outperforms both PDD and DBCH-LEACH-C by transferring the same amount of data with less energy dissipation. PDD has the less efficiency in energy consumption. That is due to the lack of consideration of CH and CM failure in the network. In case of CH failure, CMs transfer data packets through the networks without noticing they cannot be received. As a result, the efficiency of energy consumption is negatively influenced. DBCH-LEACH-C enhances PDD as it replaces BCHs with the failed CHs.

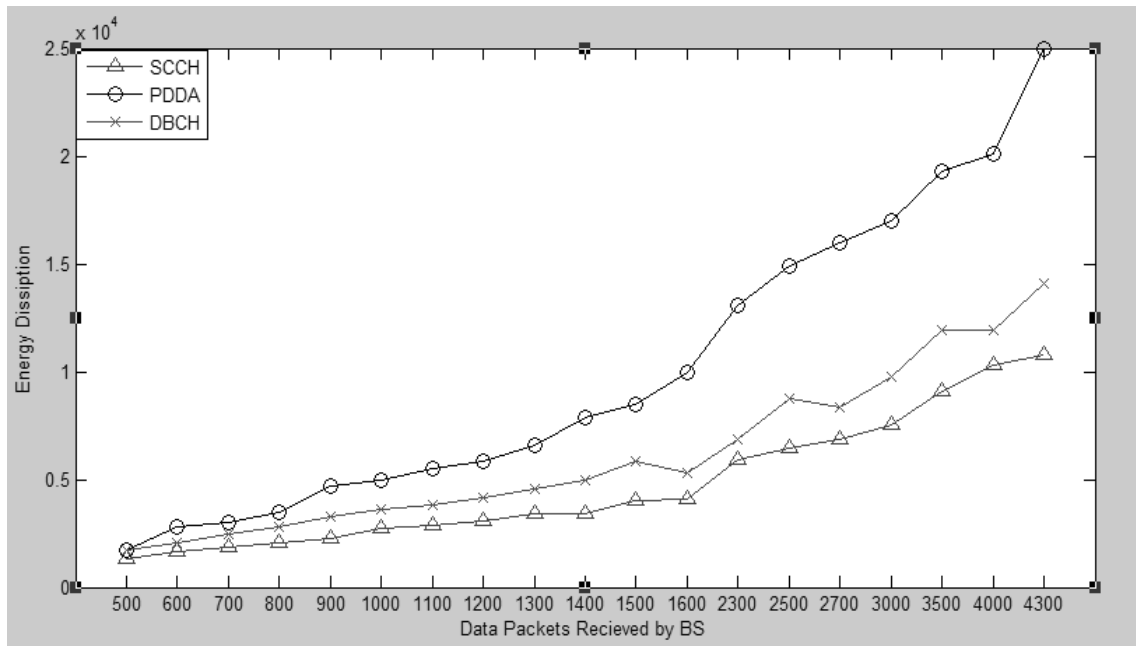


Figure 3.9. Energy consumption

However, as it is a centralized protocol and did not consider the CM failure energy cannot be consumed efficiently. That is because; the network needs to consume energy to make a data request from a CM by a CH without noticing the CM is already disordered. SCCH on the other hand, enhances the energy efficiency in the network. The reason behind it is because SCCH is a distributed protocol, in which the CHs and CMs of a cluster can define whether they are failure or not. In case of CH failure, the CMs are able to replace the most optimum BCH with it. As a result, data request message as well as data packets are not transferring unless the nodes are ensured that the destination node is fully functional. Apart from energy consumption, data loss ratio (DLR) is calculated for the data sent and received at the BS for the whole network. As illustrated in Figure 3.10, SCCH has the lowest DLR.

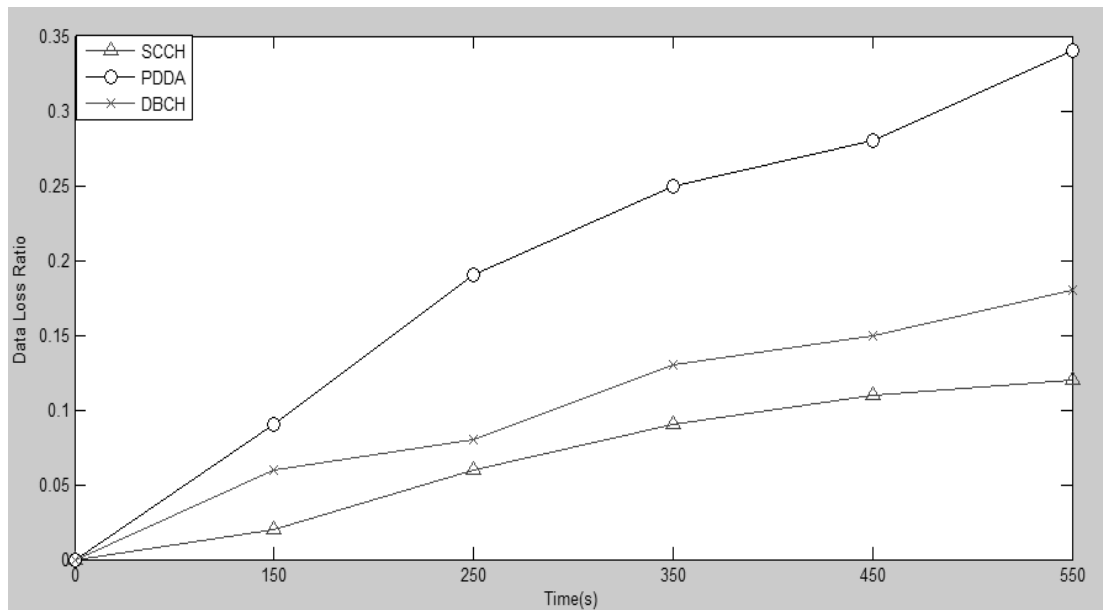
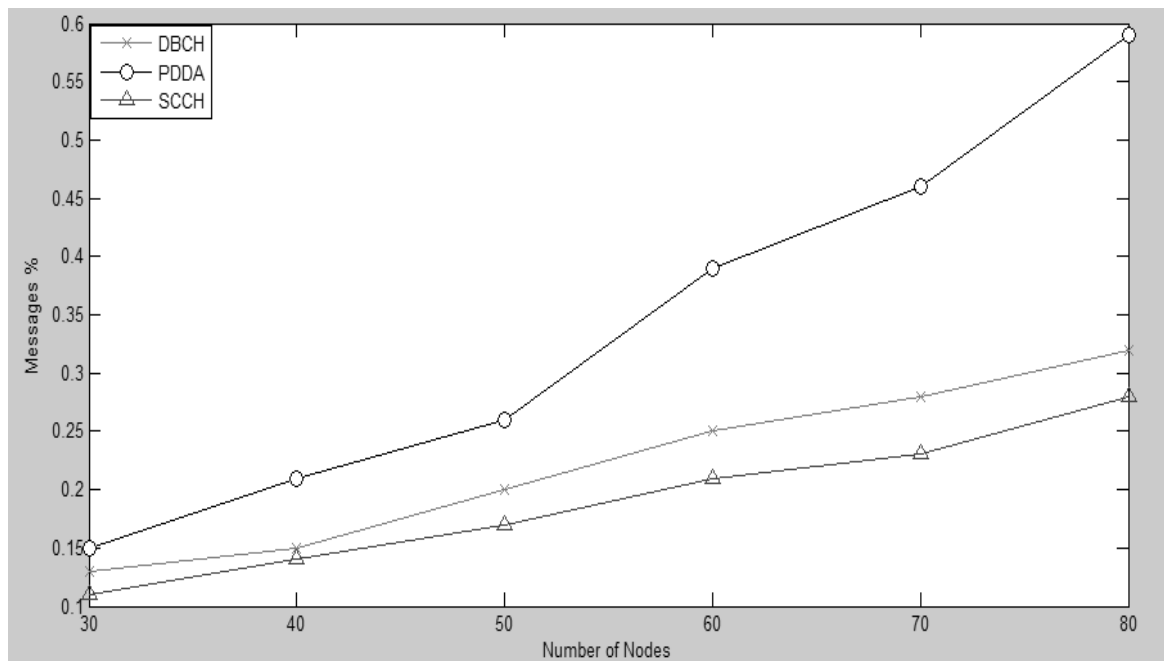


Figure 3.10. Data loss rate

That is due to the following reasons. First, it can determine failure of CHs and CMs. That prevents of transferring data packets to a failure nodes. However, CMs failure is not considered in both PDD and BCH-LEACH-C. In addition, there is always a BCH for a

failed CH. So the CMs do not need to worry about re-clustering process as they can simply replace a BCH with their determined CH. BCH-LEACH-C performs better than PDD as it considers BCH. However, its DLR is lower than SCCH that is due to considering only maximum two BCHs.

Finally, traffic overflow is also used to prove the performance of the proposed approach. In order to evaluate traffic overhead of SCCH, we tested the average amount of traffic transmitted within the network. Figure 3.11 compares the average message for transferring data with different sizes of network. It clearly shows that the traffic in our scheme is lower than PDD and BCH-LEACH-C. The message in PDD is more than BCH-LEACH-C and SCCH because in case of CH failure the nodes are required to be connected to the BS directly.



3.5. Chapter Summary

To prolong WSN lifetime as well as decreasing the created traffic in this chapter, we proposed a new distributed type-2 fuzzy based self-configurable clustering (SCCH) mechanism. SCCH firstly clusters the sensor nodes. That is followed by selecting CH. To define CHs we used a fuzzy system and considered local information of each sensor node. The output of the system is presenting the eligibility of sensor nodes to be CHs. Then, nodes in the network compared their eligibility against others'. A node with the maximum eligibility will introduce itself as a CH and the rest of the nodes as BCHs. As a result, the CMs can ensure that there is always a BCH for their CHs. Therefore, in case of CH failure the CMs can replace the BCH with the permanent CH failure. The claim was proven by comparing the behaviour of the SCCH against a fuzzy and a well-known non-fuzzy approach. It achieves longer lifetime with the ability of reducing overhead in WSNs, compared to existing clustering protocols.

For the future work, we would like to extend the protocol to meet QoS requirements of WSNs, such as coverage preservation, because complete coverage of the monitored area over long period of time is an outstanding issue. Also, since, the amount of uncertainty in different environment is not the same Thus; obviously, a certain fuzzy interval cannot be used in different applications. Therefore, it is necessary to come up with a method to be able to estimate the best fuzzy interval for the membership functions.

Chapter 4

A DATA FUSION METHOD IN WSN

The success of a WSN deployment strongly depends on the QoS it generates about the events of interest. Low data quality is a prevalent problem in WSNs, which is due to a variety of reasons such as sensor failure or data duplication. This is especially challenging in data fusion mechanisms, where a small fraction of low quality data in the fusion input may negatively impact the overall fusion result. To provide a higher quality of fused data a distributed data fusion mechanism is proposed. The proposed algorithm is able to distinguish and aggregate only true value of data instead of processing the entire data. It is generally divided into three main phases. Firstly, to differentiate the true value of data from other data a fuzzy logic controller (FLC) is developed for each sensor. After that, the cluster heads (CHs) fuse the received data. They are also responsible to calculate and then, send the probability of occurring the target events in the monitoring area to the base station (BS). In this process redundant data is simply eliminated and consequently, energy consumption

is reduced. The transferred data are then stored in the BS. To detect the events the BS needs to analyse the history of the received data. If a trend of change in the received data is noticed, the BS can determine whether the events occurred. In such a case, BS reports the detected event to the alerting system.

4.1. Introduction

In WSNs, sensor measurements are referred to as a sensor reading or sensor value. The corresponding correct value of an event in the environment of the data is referred to as the true value. If a sensor reading and the true value disagree, the sensor reading is said to be incorrect. The error that leads to an incorrect sensor reading can occur at a sensor node level. A sensor node itself might in some cases collect incorrect data. Moreover, duplicating data might also decrease the QoS. In order to overcome the problem, a data fusion mechanism is required to be developed to remove the incorrect data as well as duplicated data in the data fusing process.

The main purpose of data fusion mechanism in WSNs is to provide a greater QoS for the purpose of making reliable and accurate decisions about the events of interest. Data fusion mechanisms process the data from multiple sensors and thereby create meaningful new information that cannot be obtained from any single sensor. In fact, fusing data ensures that not only the data quality of the WSN is enhanced but also energy consumption can be lowered as it removes redundant information [73].

There are many data fusion mechanisms with the purpose of reducing the energy consumption in the WSN [130-132]. These mechanisms used different techniques such as probability theory [133], fuzzy set theory [134], possibility theory [135], rough set theory

[136] and Dempster-Shafer evidence theory (DSET) [137, 138]. Most of these approaches are able to eliminate duplicated data in the fusing process. However, these approaches do not consider specific limitations of the sensor devices. In fact, they assume that the entire received data from sensors are the true value, which is an unrealistic assumption. Moreover, all existing schemes transfer include both necessary and unnecessary data to the BS. As a result, energy consumption is quite high.

The goal of the proposed sensor data fusion approach is to improve the performance of a system with respect to the level of QoS generated about the events of interest. Moreover, by transferring only the necessary calculated probability of the events instead of the entire fused data to the BS energy consumption is minimized. Finally, the proposed approach is robust in terms of sensor node failures as it combines all the received data from the sensor nodes to measure the events of interest.

4.2. Research Problem

To avoid heavy traffic and conserve energy in a WSN caused by the transmission of unnecessary data packets to the BS from each sensor node, a data fusion method can be used in such networks. A data fusion method in a node is used to aggregate the received data from the other sensors. A general block diagram of a data fusion mechanism is given in Figure 4.1. The sensor nodes s_1 , s_2 and s_3 collect data D_1 , D_2 and D_3 from the environment. They then send the data to a fusion node. Next, the node will create one single internal representation of the environment from its inputs. The single representation is then consumed by the BS. This means that the BS in general does not have access to the individual sensor measurements.

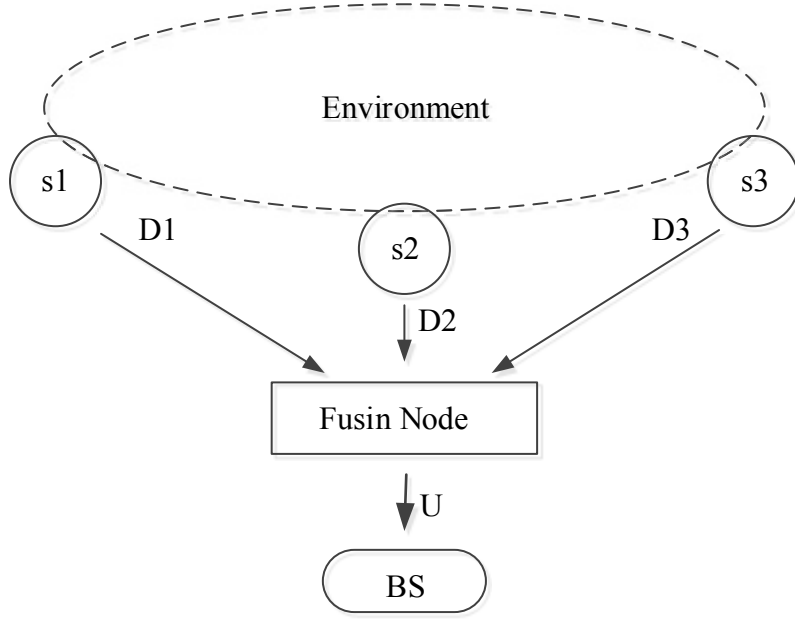


Figure 4.1. Fusion mechanism

In many situations depend on the current conditions of the sensor nodes, D_1 , D_2 and D_3 might not be exactly the true value. There are many useless data packets generated and transferred from each sensor node in each round of data collection. In many situations, a sensor node is not able to recognize the useless data while it generates data packets for further process. The data are transferred to the fusion node and aggregated with the others' true value of data. As a result, they can effect negatively in making accurate decisions as well as efficiency of energy consumption in the WSN. To solve the problem it is necessary to address the unnecessary data in addition to redundant data transferred from sensor nodes. To formulate the problem, we consider a set of sensors in a cluster based WSN deployment. These sensor nodes collect data and then send it to their CHs. CHs are responsible for fusing and transferring the data to the BS. The problem of data fusion can be formulated as follow:

$$\text{Maximise } Z_c \quad (4.1)$$

$$R \geq R_{min} \quad (4.2)$$

$$RD \geq RD_{max} \quad (4.3)$$

The objective (4.1) is to maximise the network life time (Z_c) subject to maintaining or enhancing quality of the produced data. Constraints (4.2) and (4.3) ensure that the percentage of collected true value of data (R) and data redundancy (RD) are satisfied by a user-defined threshold.

4.2.1. Data Quality

In order to enhance QoS in the WSN, it is necessary to make sure that sensor readings and measurements are true values to be used. The main cause that makes a WSNs produce and process incorrect data is the sensor nodes. Different environmental factors such as a sudden change of tempest or humidity influence a sensor node behaviour. These environmental factors decrease or increase the output signal of the sensors, which create an ultralow-frequency noise on the transferred signals [24]. In addition, non-operating environmental limits such as a high or low temperature of air surrounding the sensor nodes usually influence the sensors' performance. The operating temperature range is the length of ambient temperatures given by their upper and lower extremes, within which the sensor nodes maintain their expected accuracy [139].

In different WSN applications, it is impossible to confirm that the collected data are true values of the events without taking samples or analysing data history [24]. Therefore, we suggest to assign a weight for each collected data. The weights are determined based on current storage conditions of the source nodes. If the sensor nodes are not in the expected condition as revealed in their data sheets, the determined weights are changed. The better condition a sensor node is the higher weight is assigned to its collected data. In fact, the

weights show the percentage of correctness of the data. Based on the calculated weights, the correct value of data can be distinguished and separated from others. As a result, a higher QoS can be received by the BS. Eq. (4.4) presents the percentage of the accurate received data packets from an event by BS.

$$R = \frac{v_p}{L} \times 100 \quad (4.4)$$

Where, R is the percentage of the received correct data by BS. L is the total number of events defined by the application and v_p is the number of messages that contain only the received true value of data.

4.2.2. Data Redundancy

Redundancy in WSNs is defined as the use of redundant data, e.g. extra bits to report the events of interest. Obtaining information for a specific event in a location from different sources decreases the quality of collected data. Sensor nodes in a WSN are typically deployed densely and thus they provide a large amount of redundant and duplicate data. That causes serious packet collisions, bandwidth waste and energy consumption. Therefore, removing redundant data enhances the overall quality of the collected data and minimizes the number of transmissions from source nodes to the BS. The key idea is that instead of expecting each sensor node to send messages for each event individually, their data can be combined and transferred with lower traffic. Therefore, we suggest to calculate only the probability of the events to the BS. Next, send only the necessary information out of the entire calculated probabilities to the BS. The necessity of the obtained information is determined based on a trend of changes. If the probability of existing events is more than a pre-determined threshold, the system will send the information to the BS.

4.3. Data Fusion Algorithm

Figure 4.2 shows the proposed data fusion and transferring process. At the first step, the sensor nodes collect data as well as calculating a confidence factor (RF) for each collected data packet in each round. To calculate RF, a fuzzy logic controller (FLC) is programed on each sensor node individually.

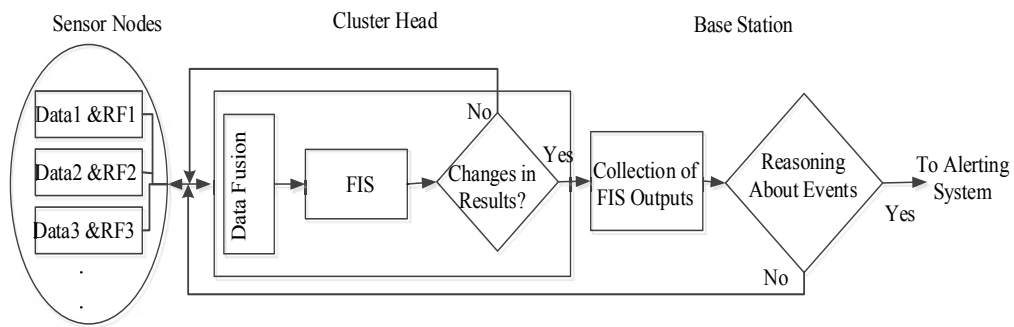


Figure 4.2. Proposed flow chart

FLC is developed based on Sugeno method [140]. The purpose of FLC is to find a confidence level of the collected data considering the current condition of the sensor nodes.

Figure 4.3 shows the proposed FLC in a sensor node.

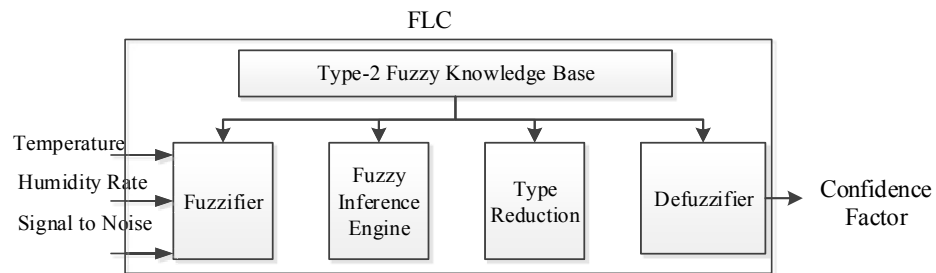


Figure 4.3: Proposed FLC

FLC considers the non-operating temperature (T) and humidity (H) range to create the membership functions. A random membership function is also used for noise to signal ratio

(N) of the sensors. FLC produces a confidence factor ($RF_1, RF_2, \dots, RF_n$) for each sensor data ($D_1, D_2, \dots, D_n$) that is collected in a real time. The FLC in a real time, determines whether the temperature and humidity rates of the sensor nodes and also the signal to noise ratio are in the acceptable range. To accomplish that, FLC compares its input measurements with the desired range for each sensor. The desired range for each sensor can be found on its specified datasheet. The output of FLC for each sensor can be 100% only if the environmental factors are in the desirable range.

In case of being out of the range, FLC produces a confidence factor ($0\% \leq RF_n < 100\%$) for the collected data. Next, each node compares the calculated RFs against a predetermined threshold. If the created factor of each data is less than the threshold value, the data will be disregarded. Otherwise, it will be sent to CHs in a data message. This prevents the occupation of the correct value of data by the other data that does not present the true values, which is shown in Eq. (4.2). For fusion purpose, the message also consists of a Node-ID of each source node.

At the second step, Eq. (4.3), CHs are responsible to aggregate the received data from the cluster members. The data fusion process is started by CHs at the end of each round of data collection. Eq. (4.5) is used to aggregate the entire received data from cluster members in the same kind with different locations.

$$\mathbf{FD} = \frac{(\mathbf{RF}_1 \times \mathbf{D}_1) + (\mathbf{RF}_2 \times \mathbf{D}_2) + (\mathbf{RF}_3 \times \mathbf{D}_3) + \dots + (\mathbf{RF}_n \times \mathbf{D}_n)}{\mathbf{RF}_1 + \mathbf{RF}_2 + \mathbf{RF}_3 + \dots + \mathbf{RF}_n} \quad (4.5)$$

Where D_n is the received data from the same kind of cluster members, RF_n is the calculated confidence factor of the collected data and FD is a combination of the data from the same kind of sensor nodes. In fact, FD is a combination of the data with a higher certainty as it

combines the entire correct received data based on their confidence factors. As a result of considering different sources of one kind of sensor nodes in different locations, FD provides a better view of the environment. FD is also robust as data from multiple sensors with their own confidence factors mitigate the problem of sensor failure. FD is calculated for the three kind of deployed sensor nodes individually. Therefore, that would be a set of FDs. Next, FDs are stored in a matrix with one row and m columns (V_{FD}). Equation (4.6) presents V_{FD} matrix.

$$V_{FD} = \{FD_1, FD_2, \dots, FD_m\} \quad (4.6)$$

As an example, consider three temperature, four light and three smoke density sensors. They are deployed on a cluster-based method. Over a period of time, the temperature sensors sense the environment by 20°C, 15°C and 10°C with the confidence factors of 0.75, 0.65 and 0.41 respectively. As a result, the fused temperature data (FD_T) would be 15.93. Fused light detector (FD_L) and fused smoke density data (FD_S) also are 49.8 and 33.2 respectively. Based on this V_{FD} matrix of the monitoring system is $V_{FD} = \{15.93, 49.8, 32.2\}$

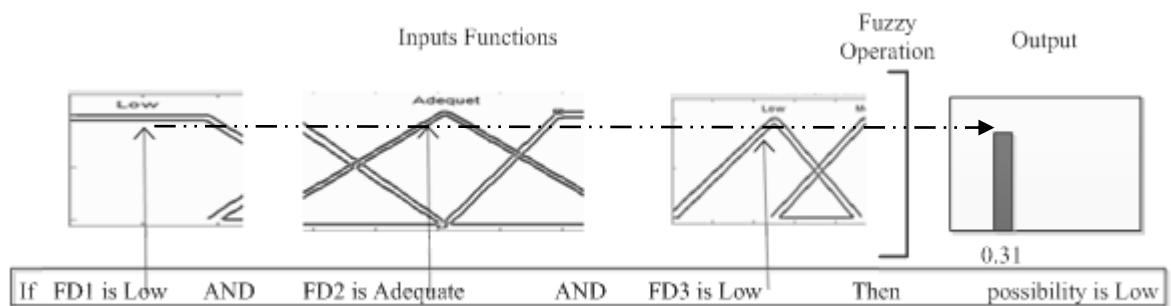


Figure 4.4. Event probability in FIS

Then, the vector V_{FD} will be fed and processed by a type-2 fuzzy inference system (FIS) in CHs. The output of the system is the probability of occurring events in the monitored areas. FIS analyses the V_{FD} vector based on a provided fuzzy rules after data fusion process was accomplished. Figure 4.4 presents an example of calculating the events occurrence by FIS. If the calculated probability in the clustered nodes was not changed, the CHs do not forward the data packet to the BS. Otherwise, the CHs send the probability of the events in their controlled areas. However, the change in the probability does not guarantee a correct detection and it is only considered as a possible event in the monitored area. Therefore, to make sure that the detection is accurate enough, the BS needs to regularly monitor and process the received probabilities that are generated over the time. In fact, all the received probabilities are constantly processed by the BS. If a constant change is noticed, the event will be reported to the alerting subsystem by BS. Otherwise, the algorithm continues collecting data. The following algorithm explains the proposed data fusion process.

Algorithm: Data Fusion Algorithm

1. **INPUT:** (T: Node temperature, H: Humidity ratio, N: Noise to signal)
2. **OUTPUT:** Fused Data
3. **BEGIN**
4. **WHILE (Event NOT Detected)**
5. **FOR** all the cluster members in one kind
6. $RF_n \leftarrow FLC(T, H, N)$
7. **IF** $RF_n \geq \delta$
8. Data and RF_n will be sent CH
9. **ELSE**
10. Collected data will not be considered
11. **END IF**
12. **END FOR**
13. $FD_n \leftarrow$ Received data by CHs from one kind of node will be fused
14. Detection Probability $\leftarrow FIS(FD_1, FD_2, \dots, FD_n)$
15. **IF** the probability was not changed
16. Disregards the received data
17. **ELSE IF**
18. Send the Detection Probability to BS
19. **IF** the event detected by BS

20. Report the event
21. **END IF**
22. **END IF**
23. **END WHILE**

END Algorithm

4.4. Application

The application of the network can be in a forest fire detection system that requires measurements from in-field deployed sensors. In this application, the three different sensors that are responsible for measuring temperature, smoke density and light are clustered in the area. Then, each node, based on their current situation, uses FLC to assign a weight for their data. Next, the data are sent to CHs, which is connected to MBS wirelessly. Figure 4.5 shows an example of forest fire detection.

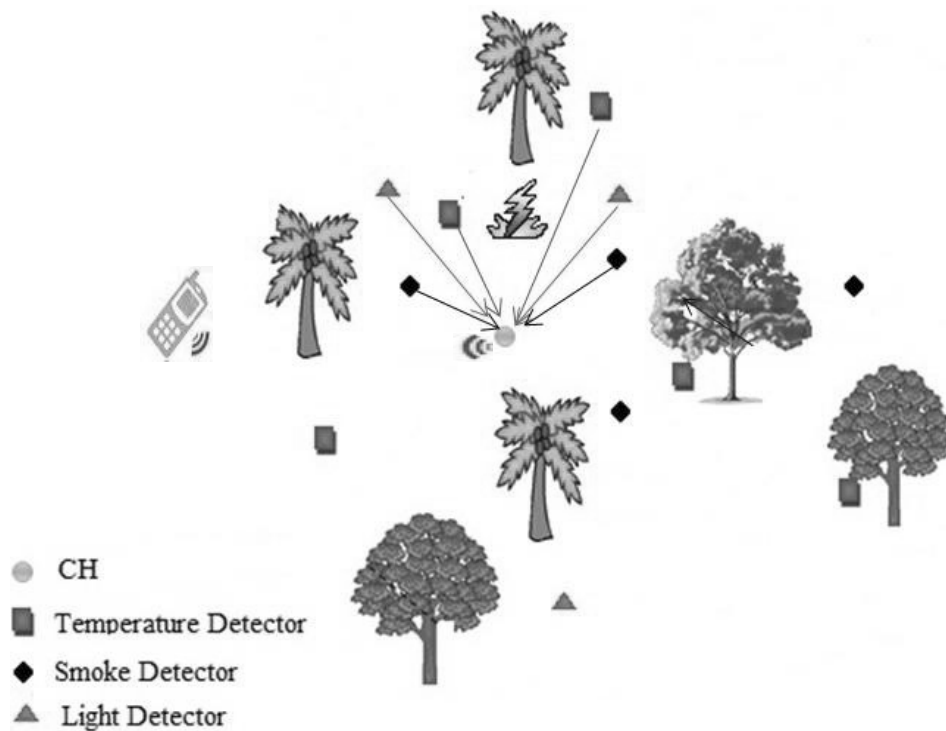


Figure 4.5. Forest fire application

4.5. Performance Analysis

In the simulation, we focus on the expected amount of collecting correct data respect to QoS in WSNs. In each round, many number of data packets are generated but it is not necessary for the entire produced data to be sent.

To evaluate the proposed approach Eq. (4.4) is used. We also estimate the created traffic overflow in the simulated WSN. The traffic overflow is calculated as the following:

$$\text{Traffic overflow} = \frac{\text{transferred data packets}}{\text{generated data packets}} \quad (4.7)$$

Finally, we calculate the energy consumption in each round of data collection using the method proposed in [66].

4.5.1. Experimental Setup

It is assumed to use MTS420/400 sensor board and a BS which could be IRIS with ATmega1281 processor and a mib520 programming base. The sensor board consists of humidity, temperature and light sensor as well as a communication component. By using the obtained information from the device's datasheet, MATLAB was used to implement and analyse the performance of the network. Table 4.1 presents the obtained information of MTS420/400. In order to simulate noise effects in real sensors, a random high-frequency noise signal is added to the sensor signal.

Table 4.1. Parameters of MTS420/400

Parameters	MTS420/400
Temperature Range	-40 to +123.8°C
Humidity Range	0 to 100% RH
Signal to Noise Ratio	0 to 1 db

The results of the experiment are compared against WSNs and fusion information methods for forest fire detection (FIM) [141] and a variable weight based fuzzy data fusion algorithm for WSN (VWFFA) [85]. The reason that we choose FIM is because it is a distributed threshold based algorithm that uses MTS420/400C sensor boards as well as our proposed algorithm. VWFFA is also chosen because it is a distributed fuzzy based data fusing algorithm that enhances the QoS in WSNs.

4.5.2. Result and Discussion

To evaluate the proposed algorithm the percentage of correct data collected is calculated. Figure 4.6 presents a percentage of correct collected data by BS in the proposed approach as well as FIM and VWFFA in each collecting round of data.

As can be seen from Figure 4.6, the proposed approach provides a higher percentage of correct data compared with the other approaches. That is due firstly, to the elimination of the incorrect data to prevent corrupting the true value data in the fusion process. Moreover, in the fusing process data is processed again in CHs assess whether there is any change in the collected data.

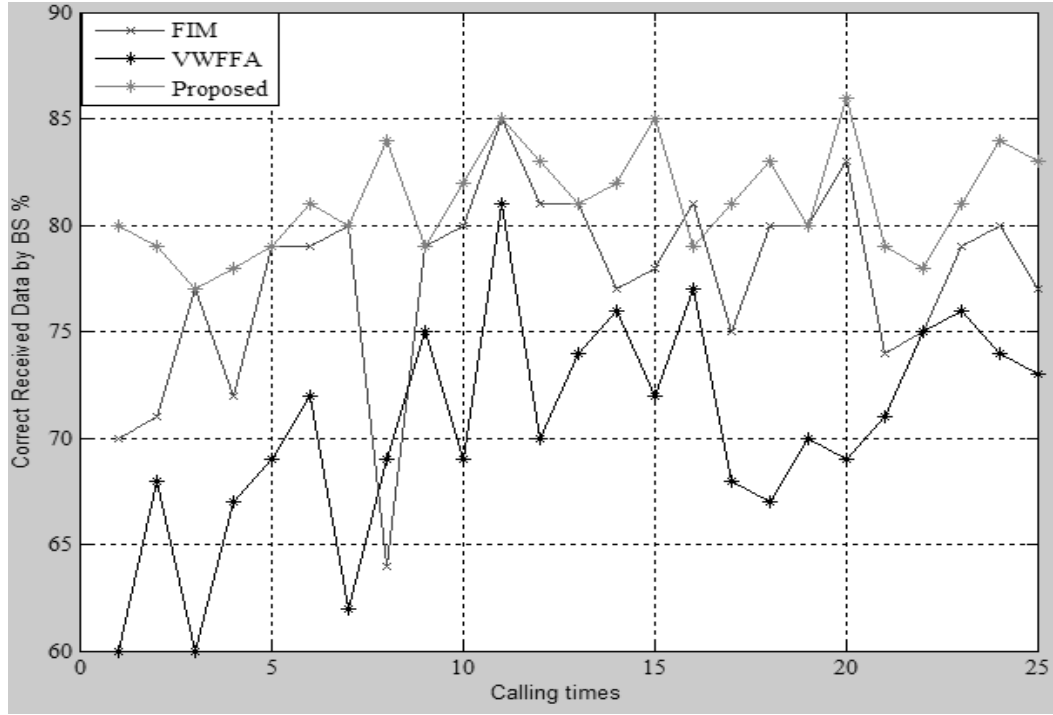


Figure 4.6. Data collection

Finally, the BS by processing the flow of the received data, can determine that the event is correctly detected. After the proposed approach, FIM has a better performance than VWFFA that is due to the consideration of uncertainty in detection process. VWFFA provides worse data quality. In VWFFA the quality of collected data is considered based on their assigned weights. However, the weights are considered on all the data includes true values and incorrect values of data. Therefore in VWFFA, since the entire received data are aggregated by CHs, the true values might be influenced by the incorrect data in the fusion process. In addition to results comparison between the proposed approach vs FIM and VWFFA, root means square error (RMSE) is also calculated. To calculate RMSE, the most optimum result (100%) is considered as the predicted result in each call. RMSE for the proposed approach is less than that for FIM and VWFFA, which are 3.67, 5.13 and 5.9 respectively.

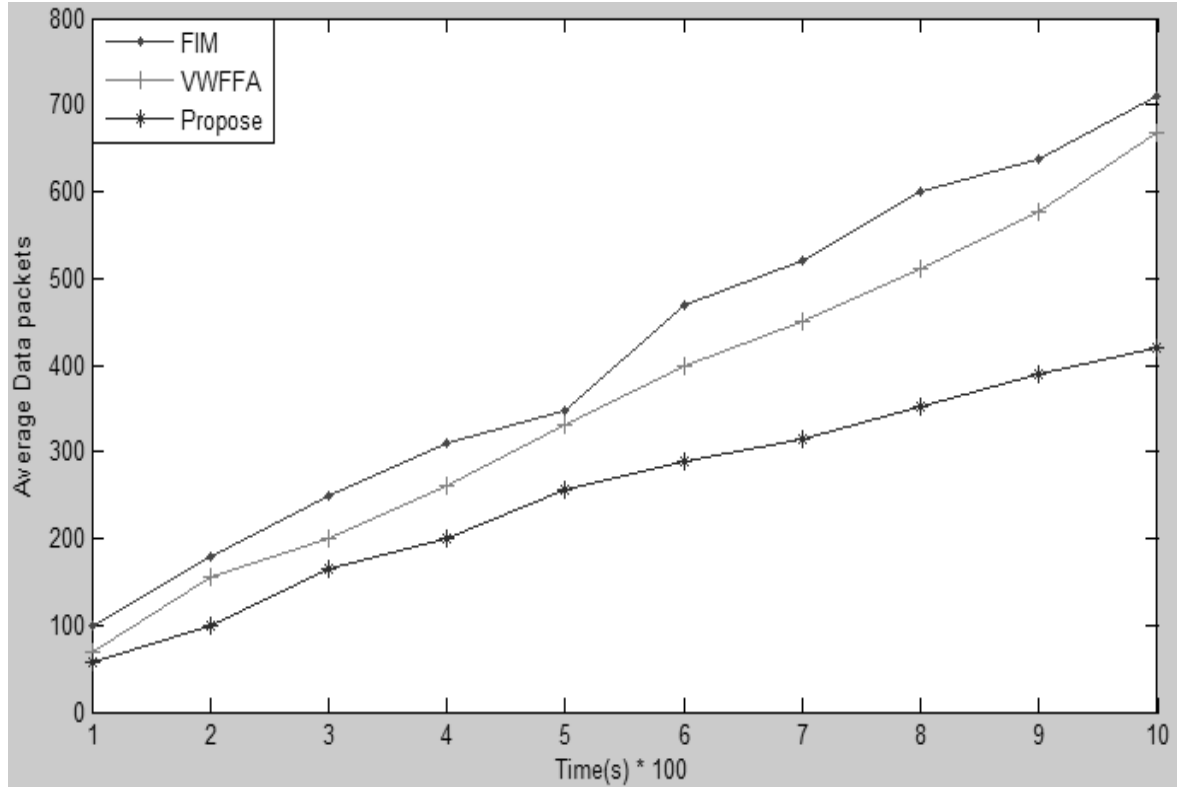


Figure 4.7. Transferred data packets

In addition, the average amount of data packets that are required to be transferred in the network is measured. Figure 4.7 shows the amount of the data packets that are transferred in the proposed scheme is lower than that in the two existing approaches. That is because the entire data do not need to be transferred, as not all of them are true valued data. In fact, in the proposed approach the untrue values are eliminated from transferring as well as data fashioning process. Moreover, CHs are not required to transfer the fused data as they are able to find the probability of occurring the events.

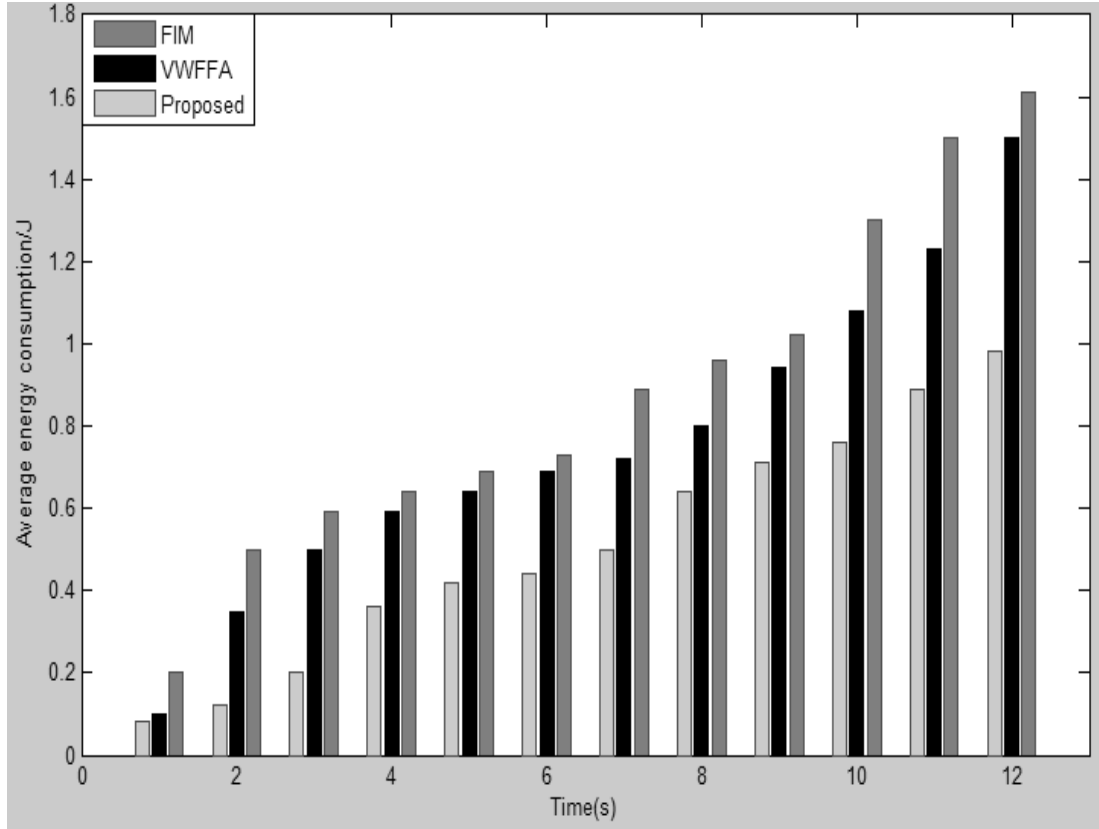


Figure 4.8. Energy consumption

The CHs send the calculated probability only if it shows an abnormality based on the history of data. So, the data that is sent to the BS is going to be only the possibility of the detected fire. In contrast to the proposed approach, FIM has the highest number of data packets that need to be transferred in the network. The reason behind that is the entire incorrect and correct collected data and also redundant data are needed to be transferred. VWFFA has a lower transferred data number in the network than FIM. The reason behind that is the developed network is a cluster based and the data are fused based on the assigned weights on clusters. In VWFFA, the assigned weights reduces the influence of the incorrect data on the true values in the fusion process.

Energy consumption is also a critical feature of a developed WSN. As explained in details, we reduced the transferred data packets in the network. This helps significantly to reduce

the energy consumption. Figure 4.8 illustrates the energy consumption in the networks. As it can be seen, the proposed scheme minimizes the energy consumption in WSN. That is due to firstly, the lower transferred data packets in the network. Moreover, data packets similar to VWFFA are sent to their CHs consequently, lower energy is required compared to FIM.

4.6. Chapter Summary

The main purpose of this chapter is to come up with a quality based method for data fusion to provide a better QoS. In the proposed approach, which was a cluster based network, cluster members were required to collect data from the environment frequently until a target event is detected correctly. Since they needed to make sure that their data are true values, FLC was developed for each of them individually. FLC with the inputs of some information of current conditions of the sensor nodes such as a temperature and humidity ratio, determines a confidence factor for each individual collected data. Based on the factor, each sensor could group their data into true valued and untrue valued data. Next, clearly, the valued data was sent to CHs for further process. Then, the CHs were responsible to aggregate the received valued data. Instead of sending the fused data to the BS, they were required to send the calculated probability of occurring the events in their monitored areas. To calculate the probability, each CH was equipped with a fuzzy inference system with the inputs of the three different fused data and output of the occurrence possibilities. Next, in case of noticing any changes in the calculated possibilities, they sent the fuzzy output to the BS. However, the BS still was needed to process the received data with the aim of realizing whether the detection is accurate enough. Then, the BS was required to record the detection to the alerting subsystem.

Chapter 5

ROUTING WSN DATA

In this chapter, we propose two routing protocols to improve wireless sensor network (WSN) performance and lifetime. The first approach is based on a fixed base station (BS), in which each source node has to find a path to the BS to forward their collected data. The second approach is based on a mobile BS (MBS) with flexible visiting routes to prevent same nodes frequently participate in forwarding data. The direction of the MBS is controlled and changed based on sensors' local information.

5.1. Introduction

A routing algorithm is a process of discovering, selecting and maintaining paths from one node to another and using these paths to deliver flow packets to their destinations. An efficient routing mechanism can become significantly complex due to the fact that it is necessary to consider current condition of each neighbour to be able to find the most optimal path [119].

Routing protocols can be classified into three main classes: proactive, reactive and hybrid routing protocols. Proactive-based routing protocols establish paths and keep them active from all the sensor nodes to the sink during the networks' life time. Then, source nodes forward their collected data packets through the determined paths to the BS periodically. In reactive routing protocols, source nodes need to determine a path for their collected data. For example, Direct Diffusion routing protocol [142] calculates the best route from a source node to the sink once a required message received from the BS. These routing protocols can be used for query-driven applications. Finally, the hybrid routing protocol is a combination of both proactive and reactive routing protocols.

Although there are many routing techniques for WSNs they are based on a set of assumptions that are not realistic. For example, the effect of noise on signals cannot be avoided in processing data by the nodes [143]. Therefore, we extend the T1 fuzzy route management design via incorporating the Interval Type-2 (IT2) fuzzy logic [17].

We develop two routing protocols for WSNs. First, we develop a routing protocol for stationary sensor nodes and a BS subject to enhance efficiency of energy consumption. In this protocol delivery routes for delivering data packets from sources to the BS are established. To define the routes residual energy, buffer capacity and congestion at each node as well as distances among sensors and the BS are considered. Then, we extend the routing protocol with replacing the stationary node with a MBS. We proposed a data collection scheme (IDCS), in which MBS is responsible to visit source nodes to collect data. Thus, the source nodes are not required to worry about establishing routes to transfer data. Visiting time and location are controlled by a fuzzy system. The fuzzy system dynamically prioritises the source nodes that are needed to be visited. The source nodes even have the

ability to call the MBS to be visited. Thus, in case of emergency situation, the source nodes ensures that their collected data can be reached by the MBS quicker.

5.2. Problem Description

The main objective of developing a routing protocol is to enhance efficiency of energy consumption in WSNs. Routing protocols in each data collection round are responsible to find a relay node for transferring data packets. To find a relay node there are many requirements that need to be taken into account. First, residual energy of the next hop. Low residual energy of a node may cause a disconnection in the created route as it is in the risk of failure. Next, buffer capacity is also playing an important role in choosing an immediate node.

Table 5.1. Notations

Symbols	Definitions
E_{s_i}	Current residual energy of each sensor node
z_c	Network lifetime
S	Set of deployed sensor nodes
d	Distance among the sensor nodes and BS
B	Buffer capacity
k_i	$k_i = 1$, if the location of sensor v_i is a sojourn location of the MBS; Otherwise, $k_i = 0$
T_{min} and T_{max}	Minimum and maximum sojourn of the sink at location S_c
D_{max}	Maximum tolerable end-to-end delay

If a buffer capacity of nodes is at the certain level, they might not be able to store the received data packets. As a result, the network faces to data loss. Additionally, delay in transferring data is another challenging point in developing routing protocols. To reduce delay in receiving data from sources, the shortest and the most secured route needs to be

determined. Resubmission of data that could be due to node failure or data collisions increases delay in data transferring. Table 5.1 presents the notations used in this chapter.

5.2.1. Problem Formulation

Distributed routing protocols in immobile WSNs lead the source nodes to find the most suitable neighbour node as a relay node to transfer the data. To establish a route for data, each source node needs to find a relay node subject to decrease the energy consumption. Developing packet routes in an immobile WSN is formulated as follow:

$$\text{Maximize } z_C \quad (5.1)$$

$$E_{s_i} \geq E_{th} \quad \text{for any } s_i \in S \quad (5.2)$$

$$P_{s_i} \geq P_{s_{ith}} \quad (5.3)$$

The objective (5.1) is to maximize the network lifetime. To achieve that, we refer to the residual energy of the relay nodes and their traffic rate. Constrain (5.2) stands that it is essential to make sure that the residual energy of the elected relay nodes is more than a certain level. Constrain (5.3) ensures that transferring rate of the selected relay node is more than a determined threshold.

We then extend the problem by replacing a MBS with the stationary BS subject to reduce energy consumption and transmission delay in the WSN. In this approach we use the cluster method explained in chapter three to create disjoint groups of sensor nodes. The MBS starts from and returns to a location (L_0) to recharge petrol or electricity. The location (L_0) may be outside of the monitored region. During its tour, the MBS sojourns at each chosen location for a certain duration in order to collect the sensing data from source nodes. End to end delay time for a data packet to be delivered from a source node (s_i) to the MBS, is

presented as $D(s_i, \text{MBS})$. End to end delay that is calculated by (5.4) includes the delay among cluster members (CMs) (D_{int}) and the delay between the cluster heads (CHs) along the path to the MBS. It is assumed that D_{int} is the same for all the CMs. The delay between CHs to reach the MBS is basically depends on the propagation delay (d_p), which is the same for all the CHs and number of data packets (k) between the CHs and MBS.

$$D(v_i, \text{MBS}) = D_{\text{int}} + \sum d_p \times k \quad (5.4)$$

We formulate the data collection scheduling (IDCS) as follows:

$$D(v_i, \text{MBS}) < D_{\text{max}} \quad (5.5)$$

$$T_{\text{min}} * k_i \leq t_i \leq T_{\text{max}} * k_i \quad \text{for any } s_i \in S \quad (5.6)$$

Constrain (5.8) stands that it is essential to make sure that sojourn time for MBS is not more than the maximum tolerable end-to-end delay otherwise, it negatively influences the rate of packet drop. Constraint (5.6) ensures that the visiting time for MBS of CHs is limited to ensure the entire data packets are collected, while there is always a maximum time as the other CHs are awaiting to be visited.

5.3. Reactive Routing Algorithm

In this section we first describe the routing protocol for a WSN with stationary BS. The algorithm starts when the BS broadcasts a data request message. All the nodes that are idled and located in the area of interest will wake up to process the message. If the request is not for them, they will go to sleep mode again. Otherwise, they will check their current conditions based on their local information. To calculate that we developed a Type 2 fuzzy logic system (FLS1). The inputs of the system are residual energy, required energy for the

operation and their current queue size or congestion rate. To calculate the existing congestion, arrival and transmission rate of each sensor is calculated. Eq. (5.7) shows the network rate of transferring in a sensor node [144].

$$P_{s_i} = \frac{P_{in}}{P_{out}} \quad (5.7)$$

Where P_{s_i} is congestion rate of the sensor node, P_{in} is the arrival data rate and P_{out} is the transmission rate of the networks. The output of the FLS1 determines one of the three next processes. First, if the output of the FLS1 is more than γ , the requested data will be delivered to the BS directly. Additionally, the energy consumption of the resource nodes and also the neighbours for delivering data and processing the order message will be calculated. The energy consumption is calculated based on Heinzelman's energy model [145] as it is explained in chapter three. Secondly, if output of FLS1 is less than μ the collected data will be lost as the node is not capable to deliver that. Finally, if the output of FLS1 is in between γ and μ , the source will need to find another node to relay the data packets. To find a relay node, there are two main steps that are updating neighbour list and finding the most eligible neighbour for relaying data packets.

Consider a source node (S_s) and its neighbours. To find a relay node, we develop another fuzzy system (FLS2) with three inputs; residual energy, distance to neighbours and the current congestion at the neighbour nodes. To calculate the distances among the sensor node we used received signal strength (RSS). RSS is the measure of voltage by received signal strength indicator (RSSI) circuit of the sensor node. Since there is no additional hardware required to calculate the mentioned parameter, RSS measurement is not a difficult and time consuming task for each node. After measuring the RSS, the theoretical models are usually applied to convert the RSS into a distance estimate [146].

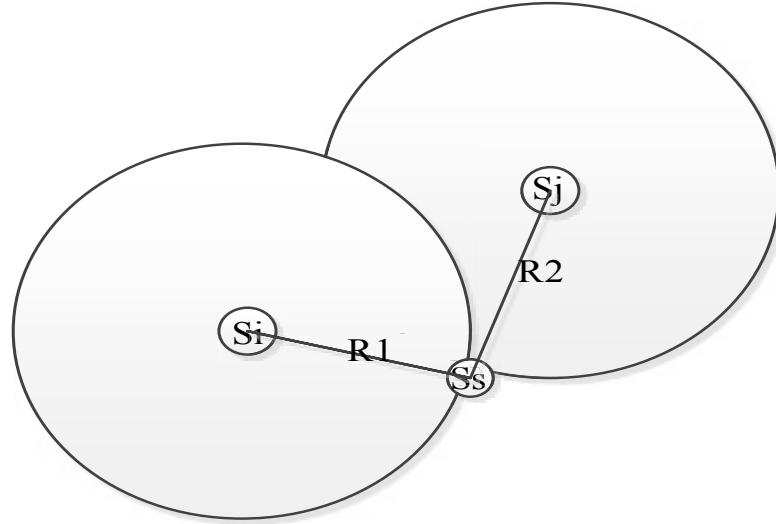


Figure 5.1. T shows and compares the distance from A and B

Figure 5.1 shows how sensor node S_s that is located in different distances from two nodes in WSN. In the first step, RSSI value will be measured by sensor nodes to calculate the distance can be calculated. Eqs. (5.8) and (5.9) can be applied to calculate distances based on RSSI [147].

$$\text{RSSI [dBm]} = - (10 * n * \log(d) + A) \quad (5.8)$$

$$d = 10^{\left\{ \frac{-\text{RSSI [dBm]} - A}{10 * n} \right\}} \quad (5.9)$$

where RSSI is the received signal strength, d is the distance between the nodes and n is the damping coefficient of the signal and A is the absolute value of the signal strength with 1m distance between the transmitter and the receiver.

Then, the neighbours will send the output of the FLS2 to the node “ S_s ” periodically. That helps to update the forwarder table and remove the recent failure nodes from the list. Then, the source node will select the most eligible neighbour. After the selection process, the source node broadcasts a request message (64 bit) and wait for a reply within a certain period

of time. If it did not receive any ACK from the selected neighbour, the source node chooses the second highest qualified neighbour node. When a node from the list of source node is selected and received the data packets, the neighbour will be the new source node. The following algorithm is the presented routing protocol.

Algorithm 1: Data routing algorithm

INPUT: S, D // S – Source node; D – Destination node

OUTPUT: route

BEGIN

```

1:  WHILE (packet not delivered) DO
2:    Check the eligibility (E) of source node
3:    IF ( $E_a > \mu$ ) THEN
4:      Send the packet directly to the sink
5:      Calculate the energy consumption
6:    ELSEIF ( $E_a < \gamma$ ) THEN
7:      Drop = Drop + 1;
8:      Calculate energy consumption
9:    ELSE
10:     Update the neighbour table ' $S_s$ '
11:     Select the most eligible node from the table( $S_s$ );
12:     WHILE (Select a relay node from table ( $S_s$ ) and
        send the packet)
13:       DO
14:         IF ( $E_a$  (selected node)  $> \beta$ ) THEN
15:           Send the request message
16:           Wait for ACK
17:           IF (ACK received) THEN
18:             Send the packet
19:             Calculate the energy consumption
20:           ELSE
21:             Select another eligible node
22:           ENDIF
23:         ENDIF
24:       ENDWHIL
25:       IF the relay node been selected
26:         Go to 2
27:       ELSE
28:         Drop = Drop + 1;
29:       ENDIF
30:     ENDIF
31:   ENDWHIL
END

```

To enhance the proposed algorithm, we replace the stationary BS with the MBS. To develop a routing protocol in a WSN with a MBS, we firstly divide the entire region into equal-sized squares or grids as in [148]. Figure 5.2 presents a small part of our deployed WSN. There are 4 clusters (C1, C2, C3, C4) formed and each cluster has different number of sensors that regularly sense the environment and also can be CHs in each group.

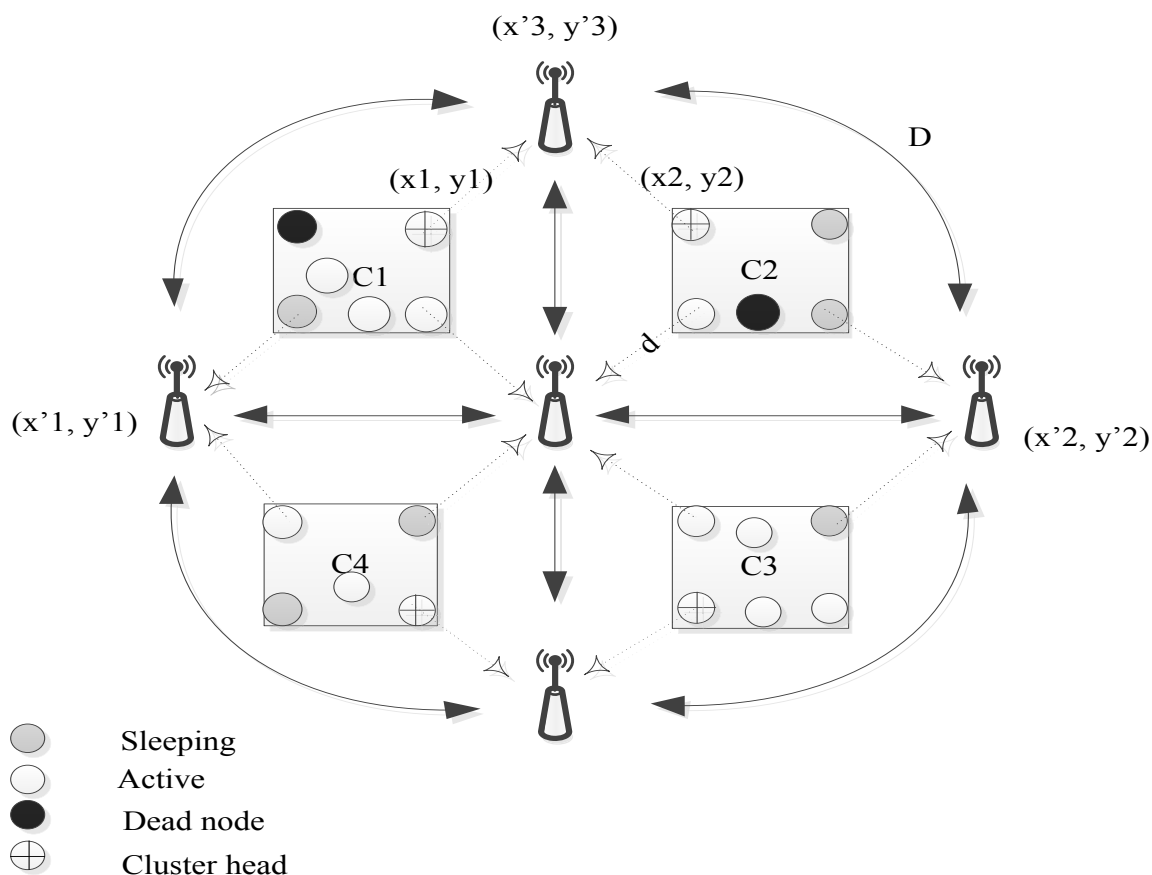


Figure 5.2. Grid cluster formation Network

The CHs are not fixed for the groups as their energy for each cycle of data collection can be depleted quickly. Clusters are formed and CHs are defined based on their residual energy, the direction of the MBS and the communication distance between each cluster and the MBS. In fact, the MBS in the network has the authority to determine a CH for each cluster. For example, the CH for cluster C1 is in $(x1, y1)$ when the MBS is at $(x'3, y'3)$. In the next

data collection cycle CHs, based on the residual energy of the node, can be changed by MBS with the aim of becoming close nodes to the new destination of MBS.

In the initializing phase of the proposed algorithm MBS locates at the starting point, where can be sure that the entire sensor field can receive its signals. Then, it broadcasts a starting beacon message to the whole network. CHs that happen to receive that message are responsible to send *Request to Register* (RTR) message to the MBS and wait for *Agree to Register* (ATR) message from the MBS. This message has dual responsibilities. Firstly, in emergency situations CHs can call MBS to be visited by setting the EMG to 1 in this message. Otherwise, in regular situation EMG is settled to 0. In the situation, MBS will be notified that there is no urgent visiting and need to check the priority of the clusters. To prioritise the clusters to be visited, we developed a fuzzy controller (FLS3) that calculates the priority of clusters based on local information of the nodes. To calculate that, we choose influential parameters from the local information of the CMs as inputs of the system. The output of FLS3 shows the score of each cluster as a new location of the MBS. Finally, the region with the highest score has the most priority to be chosen as the next position of the MBS. Figure 5.3 presents FLS3 that is responsible to place the MBS at the most appropriate location in the real time

The input variables that have been designed based on interval methods, are defined as follows:

1. Energy (E): The average residual energy in each cluster can be calculated by (5.9), where e_j the residual energy of each cluster member and n is the amount of live nodes in the considered cluster.

$$\text{Energy} = \frac{\sum_{j=1}^n e_j}{n} \quad (5.9)$$

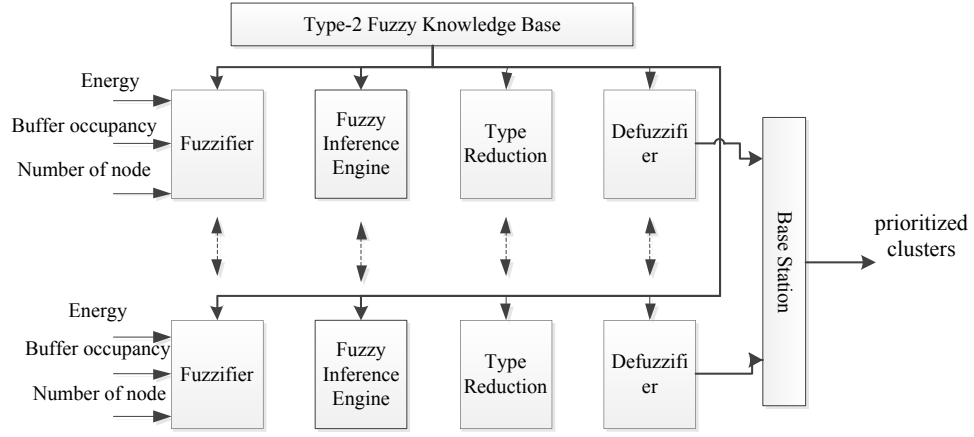


Figure 5.3. FLS3 for controlling MBS

2. Buffer occupancy (B): The average buffer occupancy in each cluster can be calculated by (5.10), where, B_j is the available buffer capacity in each cluster member and n is the number of live nodes in the cluster.

$$\text{Buffer capacity} = \frac{\sum_{j=1}^n B_j}{n} \quad (5.10)$$

3. Number of nodes (n); the more live node in each cluster the more energy consumption. Figure 16 shows the membership function on number of live nodes in the WSN.

Figure 5.4 shows structure of RTR message. Where Packet Type shows the purpose of the message, CH-ID presents the ID of the referred CH. FLS3-OUT is to show the calculated priority of the clusters and EMG-ID is to show the emergency of the cluster to be visited.

Packet Type	CH-ID	FLS3-Output	EMG-ID
-------------	-------	-------------	--------

Figure 5.4. RTR message

Once MBS received RTR message, it needs to prioritise the clusters based on FLS3-OUT. Next, it needs to send ATR message to inform the cluster with the highest FLS3-OUT about its presents. Since the MBS has the authority to change the already defined CH in the RTR message, it needs to define a CH for the targeted cluster in the ATR message. To find the most appropriate CH for the cluster that needs to be visited, the MBS needs to figure out the second prioritised cluster to be visited. If MBS finds a location to collect data from both cluster (e.g. C1 and C2 in Figure 5.2) in one stop (stop point is (x'_3, y'_3)), it chooses the closest node of each cluster to the location. However, this selection of the CH is influenced by the residual energy of the nodes. In fact, the MBS is aimed to choose nodes as CHS with the certain level of their residual energy. Residual energy on each node is received by the MBS with the collected data packets in each data round of data collection. Figure 5.5 presents structure of ART message.

Packet Type	CH-ID	$T = D/v$
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Figure 5.5. ATR message

Where Packet Type shows the purpose of the message, CH-ID presents the ID of the node that is going to be visited by the MBS. Also, MBS calculates T by dividing the distance between its locations to the selected CH (D) to the velocity (V) of movement. As a result, by the time the MBS reached the determined CH in the ATR message the CH collects all the sensed data from the CMs as well as their residual energy. In fact, each cluster has to finish with data collection and save them in the buffer of their CH within the T.

As showing in Figure 5.2, the movement of MBS could be in several ways, for example a mix of clock-wise and anti-clock-wise direction to reach the closest point to CHs. After the

MBS reached to the destination, it would be responsible to send a TDMA (time division multiple access) to the defined CHs. TDMA is an assigned time slot to each CH in a real time to send data to the MBS directly. Figure 5.6 presents the TDMA structure. TDMA consists of two sections, which are the data request and data section. In the data request section, MBS informs its presents and ready to receive the data. The data section in TDMA is reserved for the actual data transfer. Each CH has its own time slot so, data collision is cut off the network.



Figure 5.6. TDMA structure

Next, the MBS stays at the location long enough to collect the data accumulated at the CH, emptying the CH’s buffer. In addition to the sensed data, CHs send residual energy of their CMs, with a 20 bytes table message. At the MBS this residual energy information is maintained in CH Residual Energy Table (CHRET). Moreover, in case of emergency situations, CHs in each cluster will create a message with the cluster ID for emergency visiting.



Figure 5.7. Emergency message

Figure 5.7 shows the emergency message. This message is forwarded to the next neighbour CHs or border nodes down to the MBS. After each movement and data collection process, MBS checks the received data with the aim of defining if there is an emergency collection. If there is no urgent in collecting data requirement, MBS will move toward to the next prioritised cluster. The MBS before moving to the determined cluster sends the ATR

message and informs the CH about the time (T) to reach there. So, other nodes that was not mentioned on the message will be on sleep mode and wait for their ATR message. The further the MBS is the longer a sensor node could afford to spend in sleeping mode. However, in some applications critical sensor nodes are to be sensing and forwarding duties in the entire network lifetime.

Algorithm 2: Data Collection Scheduling

INPUT: (E_{av} , B_{av} , n)

OUTPUT: MBS Destination

BEGIN

1. **IF** it is at the first cycle
 2. Broadcasts starting message to the entire network
 3. **IF** CHs have not been defined for each cluster
 4. Clustering
 5. **END IF**
 6. Received RTR from CHs
 7. **IF** EMG-ID = 0 *//Regular situation*
 8. List the CHs to be visited *//Based on FLS3-output*
 9. Next Destinations $\leftarrow$ Cluster-ID *// Location is the closest point to the defined CH*
 10. **ELSE**
 11. Next Destination $\leftarrow$ EMG-ID *//Urgent cluster needs to be visited*
 12. **END IF**
 13. Sends ART message to the determined CH
 14. Arrange a Time Slot for registered CH
 15. Send TDMA schedule to registered CH when it reaches
 16. Wait *//For collecting data*
 17. Calculate energy consumption *//For transferring data and messages*
 18. **ELSE**
 19. Checks the received sensed data from CHs
 20. **IF** there is an urgent collection
 21. Next Destinations $\leftarrow$ EMG-ID
 22. **ELSE**
 23. Next Destinations $\leftarrow$ Cluster-ID *// Based on FLS3-output*
 24. **END IF**
 25. Find and inform CHs *// Based on CHRET*
 26. Define a destination close to the new CH
 27. Sends ART message *//To inform the CH of moving decision*
 28. Arrange a Time Slot for registered CH
 29. Send TDMA schedule to registered CH when it reaches
 30. Wait *//For collecting data*
 31. Calculate energy consumption *//For transferring data and messages*
 32. **END IF**
 33. **END Algorithm**
-

5.4. Performance Analysis

In this section we evaluate the performance of the proposed scheme using simulations. As a performance metric, we compare the efficiency of energy consumption in the networks. The communication model for energy consumption used in this evaluation is as proposed in [66] and explained in chapter three. Apart from energy consumption, we analyse data loss ratio (DLR) of our proposed approach. DLR is a ratio of the difference of total data sent by the sensor nodes and received by the BS to the total data sent by the sensor nodes as explained in chapter three. Moreover, we analyse the traffic overhead of our proposed protocol. To evaluate the traffic overhead of the distributed approach in WSN, we tested the average amount of traffic transmitted within the network. Finally, in analysing the performance of only the proposed protocol for WSN with MBS, we calculate the end to end traffic delay. The delay is defined as the average time interval between transmission and correct reception instants of a data packet.

5.4.1. Stationary Sensor Nodes and a BS

In this section we analyse the performance of the WSN with a stationary BS.

5.4.1.1. Experiment Setup

In this section, we use MATLAB to evaluate the performance of our proposed protocol and compare it against Fuzzy Based Optimized Routing Protocol for Wireless Sensor Networks that uses T1 fuzzy logic system (Type 1 FLS) [149]. In reference [149] they developed a routing protocol with the aim of improving the performance of WSNs. The main purpose of the research work is to extend the network lifetime applying T1 FLS.

In this approach, they let each source node that are equipped with GPS technology selects the most optimized path individually and forwards the data packets to the BS. They proved that a better energy consumption and reliable path selection can be achieved compare to the existing routing protocols. However, the problem has not been fully solved by the authors. In this section we show that even though they used intelligent system and improved the performance, our protocol outperforms the routing protocol (Type 1 FLS). In this experiment the monitored surface area is $100 * 100$ meters with 50 sensor nodes with randomly assigned initial energy from 0.5J to 5J.

5.4.1.2. Result and Discussion

The behaviour of the proposed approach in establishing data routes can be analysed based on the respective surfaces plot of our proposed protocol and the literature [149]. The surfaces are constructed by calculating the fuzzy confidence value of each node for each combination of the input fuzzy differences. Figure 5.8 presents the surface plot. As the plotted surfaces demonstrate, the proposed approach introduces substantially smother surface. This smooth response will consequently provide a better monitoring performance that can handle the uncertainties. However, the complexity of the system with respect to the size of the fuzzy rule based remained the same (no additional fuzzy rules or fuzzy sets were used).

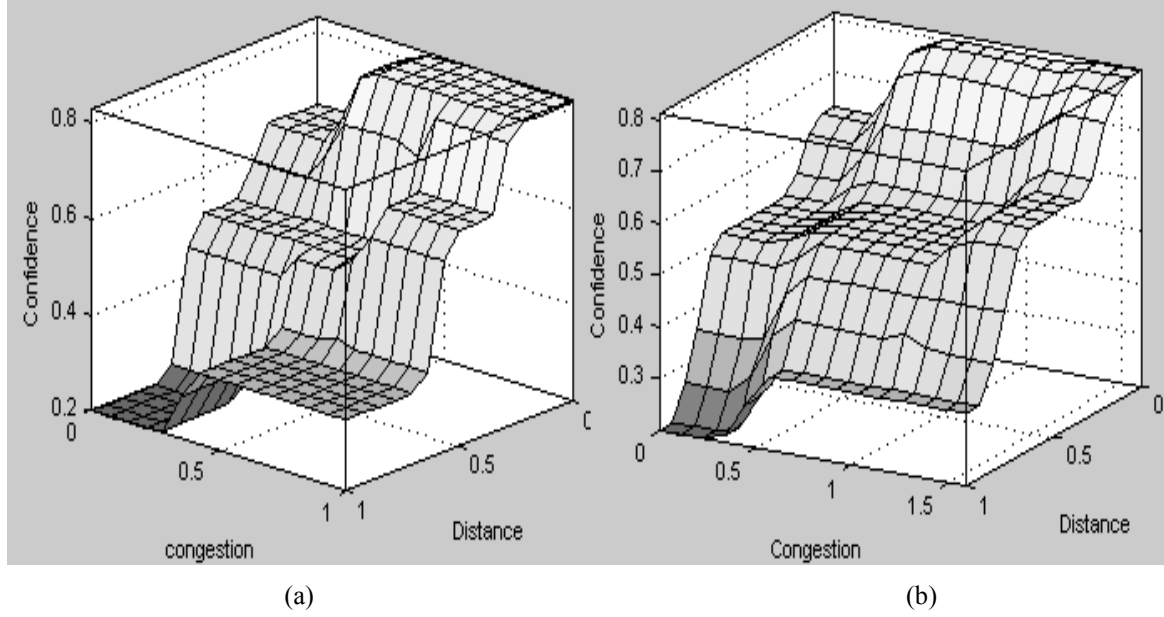


Figure 5.8. Comparison of the surfaces of the type 1 FLS (a) and the proposed approach (b)

Figure 5.9 illustrates a comparison of energy consumption in the networks. As the figure shows, although energy consumption of transferring a data packet in most of the time is the same there are some situations that our proposed approach performs better. For example, the required energy for transferring data from source to the sink in the 41th time of the data collection in our proposed approach (Type 2 FLS) is (1.08×10^{-4} J), which is less than the recent approach [149] (1.17×10^{-4} J).

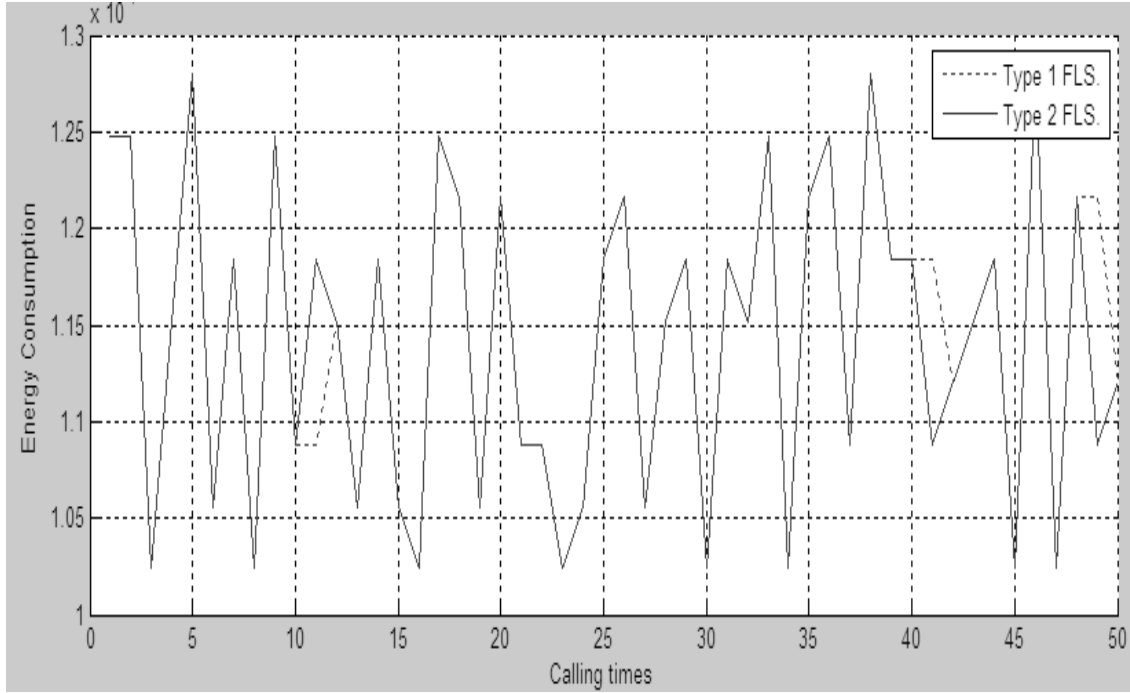


Figure 5.9. Energy Consumption

In addition, we calculate and compare the required energy for transferring data packets in both approaches. The results show that our protocol needs less energy to have a successful transmission. Figure 5.10 presents the relation of the data received and energy dissipation. The total data received by our proposed algorithm is more than that in [149] with the same energy consumption. That is because the proposed mechanism puts an emphasis more on energy balancing. The consideration of balancing energy leads to a scenario that the redundant node might not be chosen as the route node.

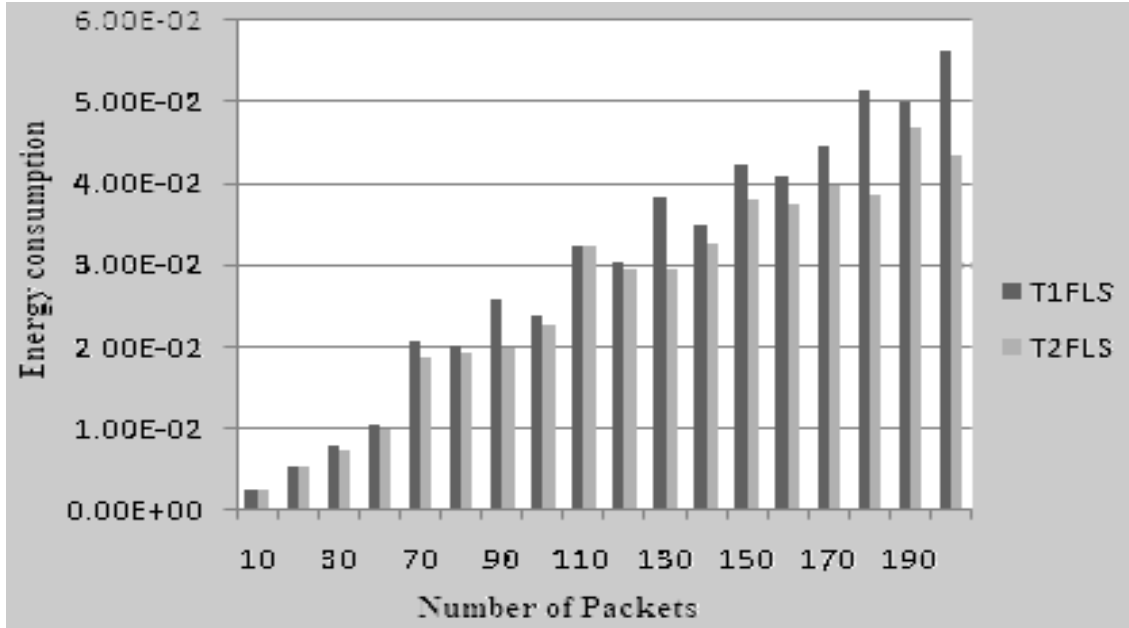


Figure 5.10. Relation of data received and required energy

In addition to the remaining energy in the network, it is worth mentioning that efficiency of buffer usage can be increased by our developed protocol. In order to prove that, remained buffer capacity in the selected node as a next hop for each call was checked. Then, the outcome from our system and the literature (Type 1 FLS) [149] was compared. Figure 5.11 shows the comparison of buffer capacity in the both systems. As can be seen from the figure, both systems are working mostly the same but our approach in some situations can select the next node with fewer available buffers capacity. Type 1 FLS on the other hand, needs more capacity to be satisfied to choose the next hop. For example, in the 3rd times of calling data, the remaining required capacity, in order to be selected as a next hop, for the same amount of data was less in Type 2 FLS than that in Type 1 FLS. Consequently, next hop selection could be more accurate by using our system therefore; routing could not be effected by inaccurate buffer capacity measurement.

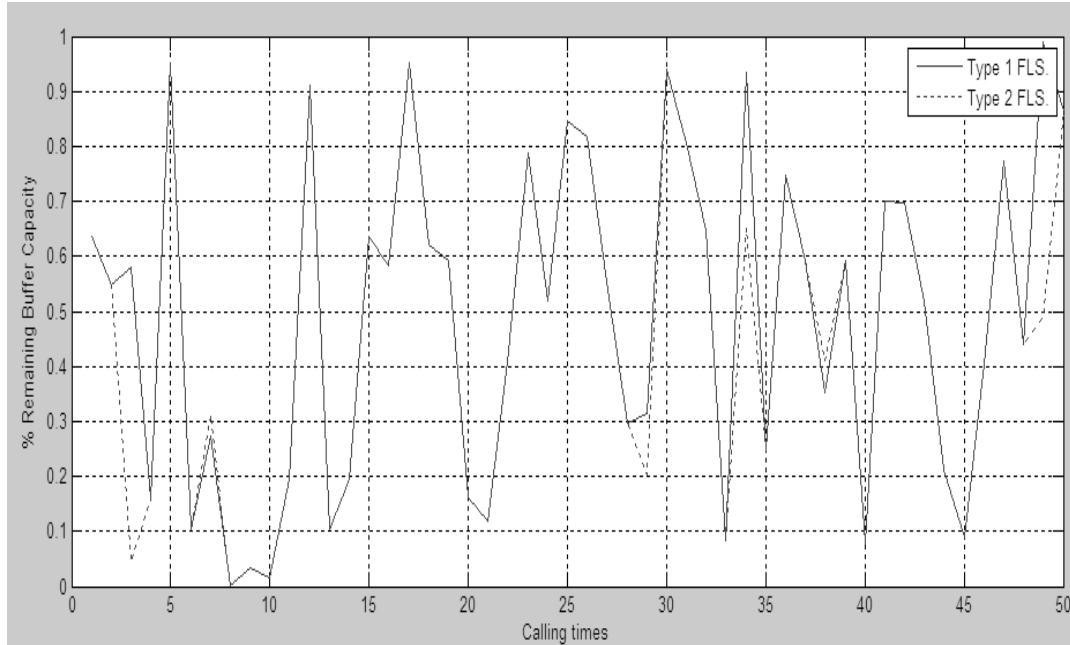


Figure 5.11. A comparison of remaining buffer capacity

The result of the experiment also proves that the amount of dropped packets by our proposed system is less than data packet lost in the literature [149]. Packet drop is undesirable for any protocol that aims at energy conservation and collision control as more packet drop depict collision in the network and increase the energy consumption due to redelivering the data packets to the destination. Packets are dropped either due to insufficient buffer capacity at the receiver or because of the lack of energy needed to transmit the packet. Percentage of packets dropped is significantly lower for our fuzzy approach resulting in greater reliability. Our Proposed protocol by taking the queue size and congestion on candidate nodes into account, selects each particular route based on fuzzy decision making model. For analysing this claim, we detected every dropped packet in each call and added to the previous amount of unsuccessful transmission. Figure 5.12 illustrates and compares the unsuccessful transmission in each designed system. Every dropped packet in each calls added to the

previous amount of unsuccessful transmission. As can be seen in the figure, unsuccessful transmission in our system for the entire 50 times of calling data is less than 10%. However, in the other system the DLR goes up to 50%. Consequently, our system increases the reliability of the system up to more than 40%.

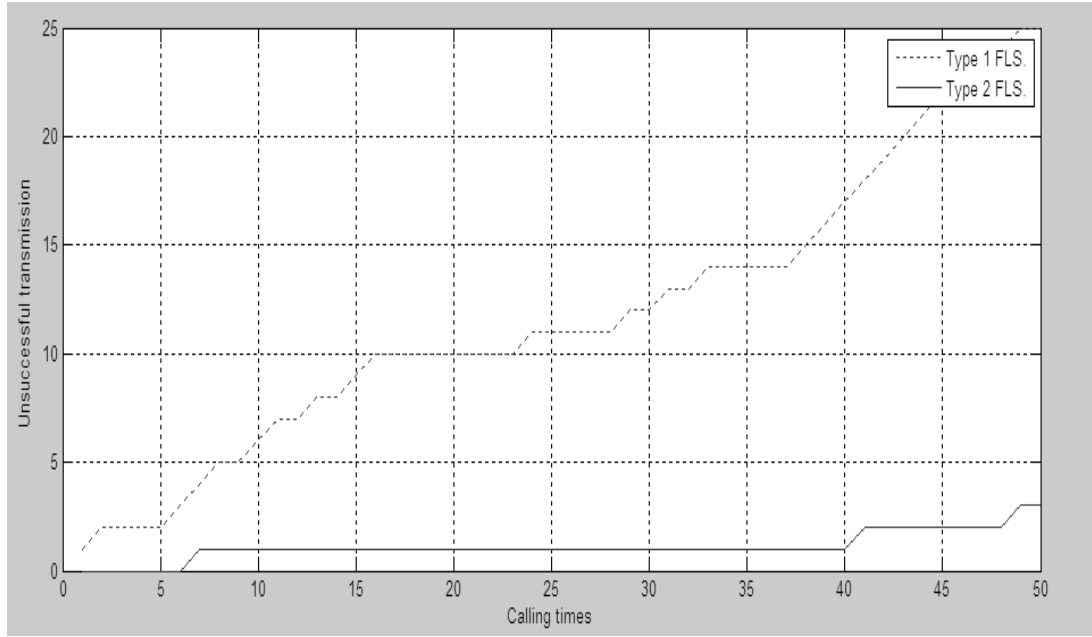


Figure 5.12. A comparison of unsuccessful transmissions

5.4.2. Stationary Sensor Nodes with a MBS

In this section we analyse the performance of the WSN with a MBS.

5.4.2.1. Experiment Setup

The result of our proposed approach are going to be compared against SDD [150] and HCDD [151] via MATLAB. The reasons that we chose the approaches are mainly because of their cluster-based structure and also their focus on energy consumption in WSN. In this implementation there are 100 nodes with the communication range of 50m. In this

implementation, it is assumed that the initial energy for the nodes is chosen randomly between 0.1J to 1J. The beacon message is 10 byte while the packet size is 100 byte. The speed of MBS is randomly from 10m/s to 40m/s. The energy required for data aggregation is set as $5n_j/\text{bit/signal}$ and CHs perform ideal data aggregation (i.e. all the message received from cluster members can be aggregated into a single message)

5.4.2.2. Result and Discussion

To analyse the performance of our designed network with the proposed protocol, we run the system to transfer different number of data packets. The results show that our proposed protocol increases the efficiency of energy consumption significantly. This can be due to the following reasons. Firstly, IDCS unlike the SDD and HCDD does not maintain the discovered path for delivering data. In addition, the proposed policy can make the entire cluster into sleep mode by considering their prioritized order. Moreover, our proposed algorithm unlike the SDD and HCDD reduces the amount of controlling message significantly. Therefore, the network overhead and traffic in the network decreased. So, the risk of collisions and consequently retransmissions the data is reduced. Figure 5.13 presents the required amount of energy for transferring data in different protocols.

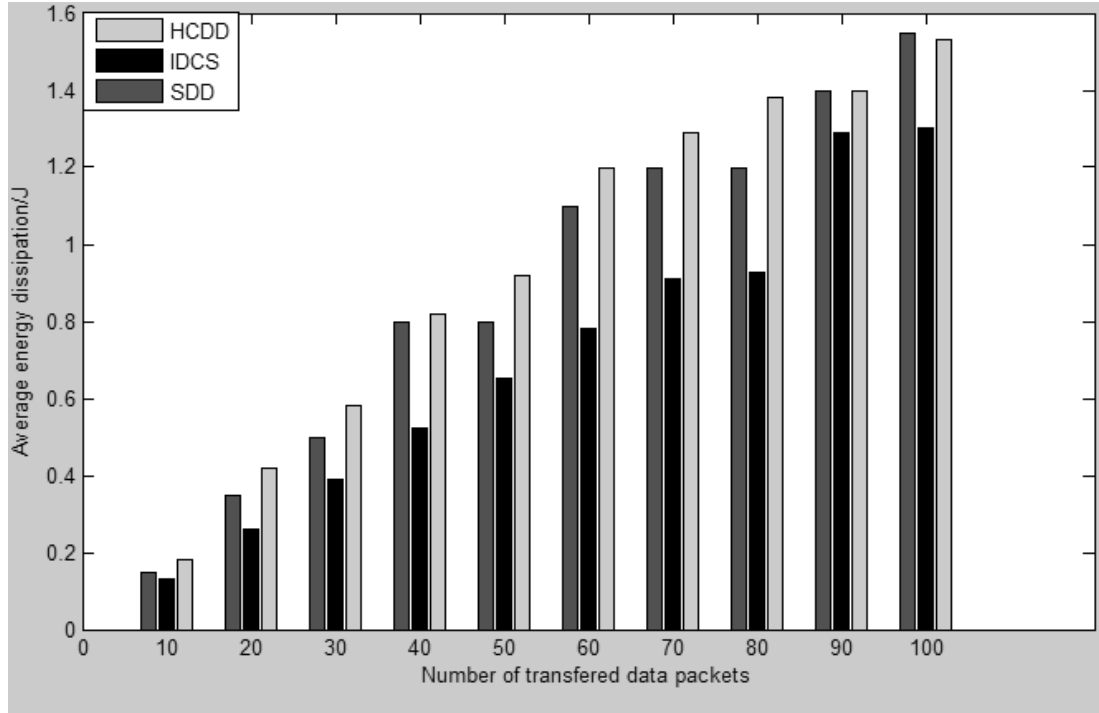


Figure 5.13. Average energy consumption

Apart from the energy consumption in the WSN we analyse specifically energy consumption of the CHs. Network availability depends mostly upon the relaying activity. When the relaying load increases in the routing process, obviously the border nodes (CHs) and also their closest relaying nodes are in the high risk of depletion. To prevent the developed WSN to be fulfilled, it is suggested to investigate on the benefits of dynamically changing the CHs during network lifetime. Using a fixed CH in each cluster in developed protocols e.g. SDD and HCDD, even with a mobile sink the nodes are still in the risk of depletion more than others.

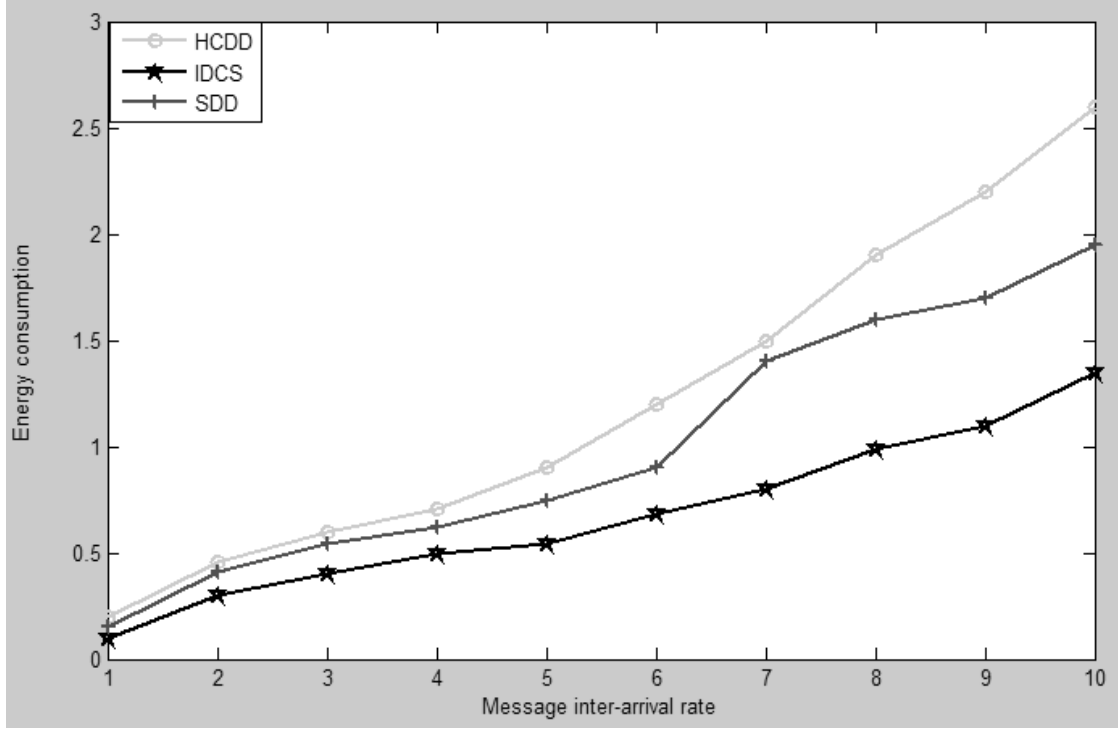


Figure 5.14. Energy consumption of border nodes

Figure 5.14 shows the energy consumption as a function of message inter-arrival period. The figure proves that the amount of consumed energy by the key nodes in IDCS is much less than that in SDD and HCDD. That is due to the reason that in our proposed protocol, MBS dynamically changing CH. So, we could make a better balanced energy consumption among the crucial nodes. As a result, we made the nodes to be more organized to consume their available energy. Also, since the border nodes in SDD are not always the same and in each movement different nodes are used, the total energy consumption of the network can be more balanced than HCDD.

In addition to the energy consumption, delivery delay is also analysed. To route the data source nodes usually select immediate nodes as a next hop. Then, in the optimal status the immediate nodes receive the data packet and forward it through the MBS.

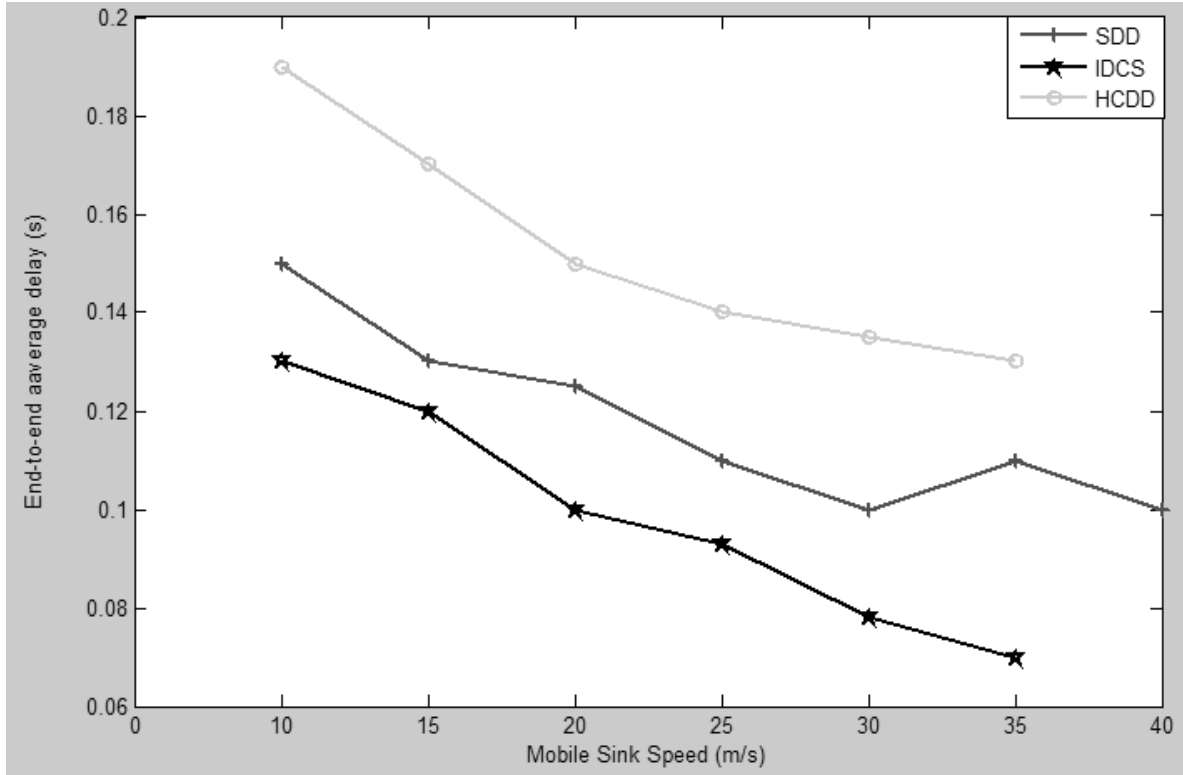


Figure 5.15. End-to-end delay

However, if in this routing process an immediate node forwards the data packets with a bit of delay, the data packets will end up to be received by the previous position of MBS. So, the data either needs to be resubmitted in a proper time again or follow the MBS by finding another next hop. Ultimately, the average delay increases and consequently collision occurs. Figure 5.15 compares the existed end-to-end delay in IDCS with SDD and HCDD. The results proves that our approach works better than the other methods. That is because our protocol unlike SDD and HCDD is not needed to find a path among many sensor nodes in the network. Thus, it obviously cuts a huge number of controlling messages for organizing a path which is changed many times during the network lifetime. In addition, in emergency situations our protocol is capable of calling the MBS to be crossing the network and reach the most urgent cluster. That means, the MBS by skipping and not stopping at the other clusters can decrease the delay in such network. However in SDD and HCDD, MBS does

not care about the emergency situations and urged data as the data packets need to find a path to the MBS.

Finally, we calculate DLR in the proposed approach. It is observed that a major cause for packet loss is link failure between the sink and an immediate relay node. In packet transmission procedure from the representative source to the sink any collision or link failure cause data loss in the network.

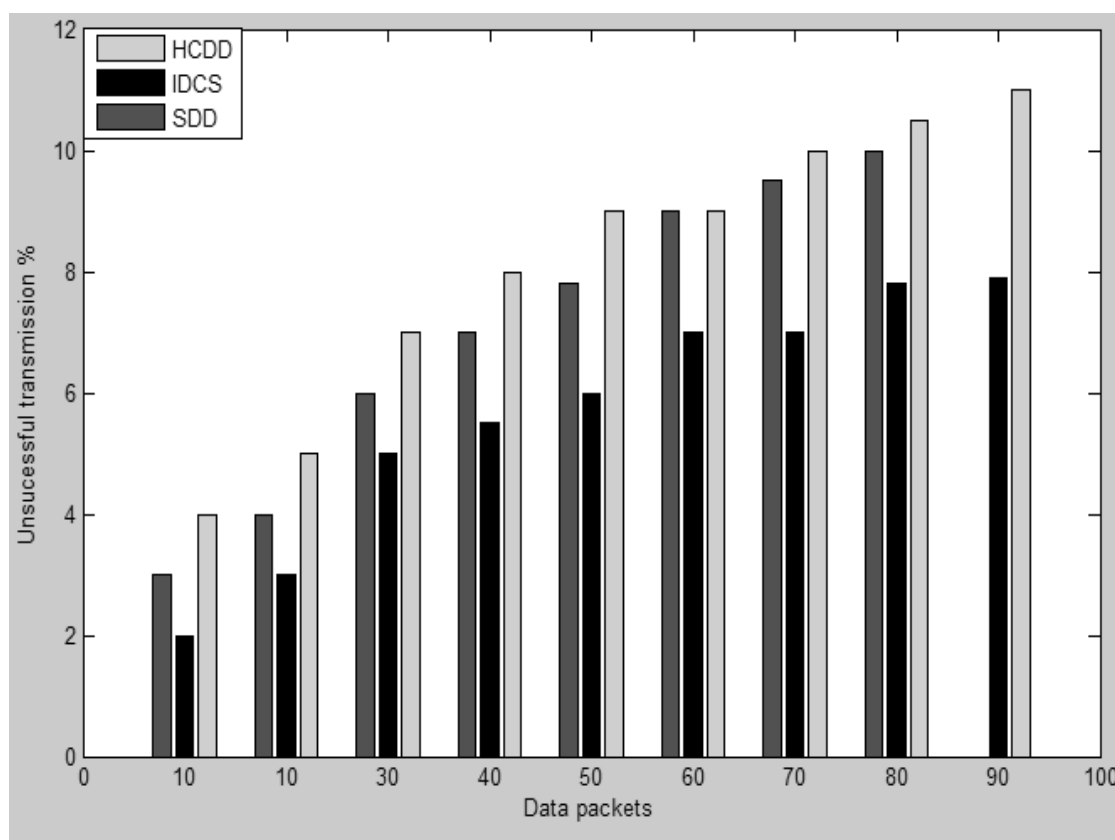


Figure 5.16. Unsuccessful transmission

Thus, the throughput performance can be dominated by the handoff scheme between the old and the new immediate relay node. Figure 5.16 compares the rate of unsuccessful transmission in IDCS, SDD and HCDD. The performance of SDD is better than HCDD due to some reasons include the fewer required hop for delivering data and less signalling for

link detection. However, the amount of control message in IDCS is much less than SDD and also CHs are not required to find another CH to chase the MBS until data delivered. In fact, the MBS finds the best CH and locates itself close to the CH to collect the data packets.

5.5. Chapter Summary

The main goal of this chapter was to develop routing protocols for WSN with stationary and mobile sinks. In the proposed routing protocols the inherent uncertainty was taken into account. In the first section, we proposed a fuzzy logic based reactive routing protocol for a sensor network with stationary sensor nodes and a BS. The main contribution of this was establishing a balance in energy consumption. The obtained results proved that our system increased the efficiency of energy consumption and buffer usage. Then, we extend the proposed approach by replacing the stationary BS with a MBS. We proposed IDCS to control MBS in locating and timing. In our dynamic and expert proposed system MBS determined a location by using local information of deployed sensor node to collect the data. The system has the ability to instead of visiting clusters randomly or in a fixed way of moving, firstly figures out the importance of data in each cluster. Then, it prioritised the CHs to be visited. Next, the MBS defined a closet location to communicate with CH. Simulation results showed our scheme significantly prolonged network lifetime and also reduced the time delay in delivering data packets.

Chapter 6

DYNAMIC WSN COVERAGE

Sensing coverage of a wireless sensor network is an important measure of the quality of service in data. Therefore, it is always desirable to develop a more accurate and energy efficient method to increase coverage ratio. This chapter introduces a fuzzy-based self-healing coverage (FSHC) scheme for randomly deployed mobile sensor networks. The approach determines the uncovered areas that could be due to dead nodes and then select the best mobile nodes and move them to minimize the coverage-hole. Also, it distributes the sensor nodes uniformly considering Euclidean distance and coverage redundancy among the mobile nodes.

6.1. Introduction

In order not to lose data in the networks, positioning of sensor nodes in the region of interest is one of the biggest challenges in designing WSNs. The importance of this problem arises when a WSN needs to be established in inaccessible and sometimes polluted

area. For example, in a uranium polluted area in Japan, which is inaccessible as it is very harmful for human bodies. In those areas, there are many elements such as temperature that needs to be recorded very accurately to prevent an explosion. Each explosion can increase the pollution in the atmosphere, which could be worse in a windy weather. In such areas, sensors are aimed to be deployed randomly. However, there is no guarantee that the nodes are uniformly distributed after random deployment. The possibility of covering the sensing field while they are not overlapped and being within communication range of each other to be fully connected will be decreased. In addition, maintaining coverage is vital as sensor nodes fail due to battery drain or environmental causes or even noise influences. As a result, due to the created redundancy and coverage-hole the quality of collected data is influenced. There are several research works related to the deployment of wireless sensor nodes. Most of them considered a single objective such as coverage ratio or energy consumption [152-154]. However, objectives such as uniformity and data reliability are needed in the deployment. More importantly, existing approaches have limitations in dynamic environments which contain a variant amount of noise created by some defences such as irregular radio propagation in disaster areas.

To develop a coverage optimization scheme in WSNs we enhance a recent developed protocol [155], which is the first approach that introduces mobile node migration. The authors proposed a set of dynamic coverage maintenance (DCM) schemes that can be executed on individual sensor nodes having a knowledge of their local neighbourhood. They claimed that efficiency of energy consumption in maintaining sensor nodes' coverage in WSNs is enhanced. However, energy consumption is still not efficiently consumed by the approach as it is somehow centralized approach and also using GPS technology. Moreover, complexity of using different algorithms particularly in moving more than two sensor nodes

in the network is very high. To enhance DCM schemes, we proposed a distributed self-healing coverage scheme without GPS requirement. We also enhance quality of transferred data in the approach by considering coverage redundancy as well as noisy sensor nodes, which were not taken into account in DCM.

Definition 1 (Neighbour): A neighbour of a sensor node is defined as a node that is located in the communication range of another sensor node in a WSN.

Definition 2 (Sensing area): The sensing area of a node is defined as a point (p) in an area that can be monitored by a node. Generally, a node is assumed to monitor up to a distance of a sensing radius, R_s , (i.e., $|pm_i| < R_s$).

Definition 3 (Noisy sensor): A noisy sensor is a node that adds bits to its produced original signals. The added data, called noise, influences and sometimes destroy the original signal. The more added data the weaker signal is produced. Each produced signal can have a certain signal to noise ratio (SNR) to be detected by receivers. Therefore considering SNR in transferring and receiving high QoS in WSNs is necessarily needs to be considered [156].

For a mobile sensor m_i , transferred signals from the event located at point p is calculated by Eq. (6.1) [157].

$$S(m, P) = \frac{\gamma}{\|m-p\|^k} \quad (6.1)$$

Here the constant γ and k are sensor technology-dependent parameters and $\|s - p\|$ is the Euclidean distance between the sensor m and the target p , $0 \leq p \leq R_s$. For most types of sensors $k=2$ and $\gamma=0.1$. To make sure that transferred signals are detectable $S(m, p)$ needs to be more than a threshold (N_{th}).

Definition 4 (Coverage redundancy): In a densely deployed WSNs, the sensing area of the sensors might be overlapped. The larger the overlap of the sensing area, the more redundant data is produced. As a result, the quality of collected data and efficiency of energy consumption is reduced.

The coverage redundancy for each node can be calculated by considering only its sensing area. Eq. (6.2) calculates the ratio of coverage redundancy for a sensor node.

$$\zeta_{m_i} = \frac{p(A_j, \{m_j\})}{\pi R_{c_i}^2} \quad (6.2)$$

Where, $p(A_j, \{m_j\})$ is the sensing area of m_i that has been covered by m_j , $j = \{1, 2, 3, \dots, n\}$ and $\pi R_{c_i}^2$ is the sensing area of m_i . When $\zeta_{m_i} = 0$, there is no coverage redundancy for the sensor, when $\zeta_{m_i} > 0$ there is a coverage redundant occurred and when $\zeta_{m_i} \geq 1$, sensor m_i has a complete coverage redundancy.

The contributions of this chapter can be summarized as follows:

1. A self-healing coverage maintenance scheme for mobile sensor network is designed to meet the specific requirements of event detection systems. When a loss of coverage occurs due to node death or noisy sensors, the ensuing movements are restricted to the immediate neighbours of the failure node. The neighbours are moved in, using a distributed algorithm. Therefore, the loss of coverage is minimized.
2. A Euclidean distance-based coverage scheme considering coverage redundancy is designed to cover the monitoring area in a very effective manner, especially for randomly deployed WSNs. To maintain the maximum

coverage and to minimize the redundancy of collected data the Euclidean distance of the nodes is fully considered.

3. Reliability of data by detecting noisy or disordered nodes and replacing them with immediate neighbours, is increased.
4. The proposed algorithm consumes more efficient energy than the existing approaches. This is due to first, fewer required message exchanges as well as eliminating the noisy nodes that transfer more bits (noises) in the network. Second, the energy required for random movements and inaccurate movements of the mobile nodes is reduced.
5. Uncertainty, which is an inherent behaviour of WSN, in processing data is considered.
6. This approach, unlike existing approaches, does not need to use the global information of the network.

6.2. Problem Description

In general, the coverage problem can be considered due to two reasons. Firstly, random deployment methods that cannot guarantee the sensor field to be covered uniformly. Figure 6.1 shows a WSN field in which the sensor nodes are randomly distributed. The figure shows that the Euclidean distance among the deployed nodes are not equal. As a result, the WSN experiences uncovered areas as well as coverage redundancy in the network. In addition, coverage maintenance or coverage-hole prevention is another considerable issue that influences the quality of collected data. There are two identified reasons that cause a WSN to experience coverage-hole problem. Firstly, node depletion or physical damage makes the nodes disordered. Secondly, a sensor node may make faulty or

unusual reports, which might be caused by external environmental interferences such as noise.

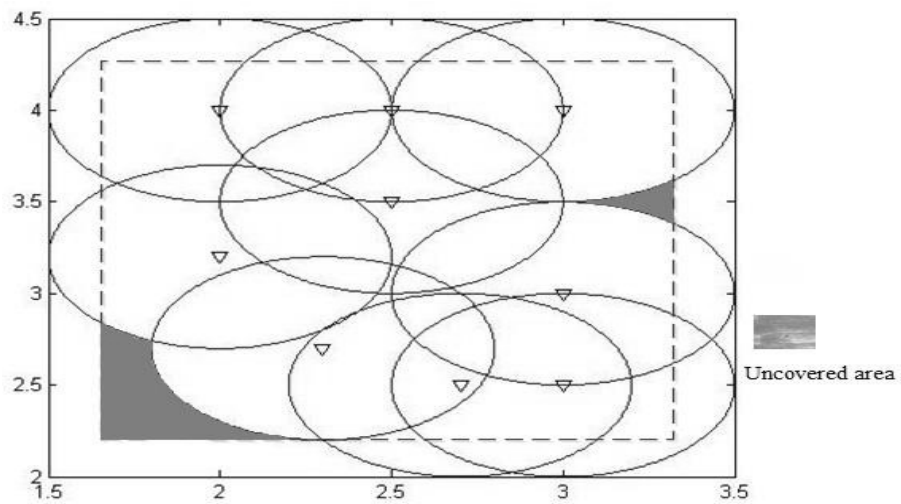


Figure 6.1. Over lapping with uncovered area

In general, there are two main kinds of noise in a WSN; these are white noise and internal thermal noise [158]. Noise can easily add more bits to the original data as well as effecting SNR. The SNR then impacts on the bits error rate (BER) and the BER will become the cause of the fault–estimation factor. In either case, it is assumed that the nodes are disordered. Figure 6.2 shows a sample WSN that faces the coverage-hole problem, in which the node F is the disordered node that cause a coverage-hole in the WSN.

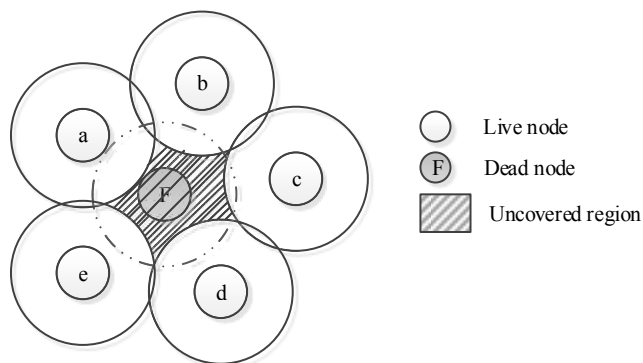


Figure 6.2. Coverage-hole

To overcome the coverage problem we propose an algorithm to detect uncovered areas, move determined sensor nodes towards defined destinations and ultimately achieve maximum coverage with optimum overall energy consumption.

Table 6.1 lists some of notations used in this paper.

Table.6.1 Notations

Symbol	Definition
E	Available energy of a newly deployed mobile node
$\mathbf{m}_i$	Mobile sensor node
$\mathbf{g}_c(\mathbf{m}_i, \mathbf{h}_j)$	Coverage gain if $\mathbf{m}_i$ moves to the hole $\mathbf{h}_j$.
$\mathbf{x}_{i,j}$	$\mathbf{x}_{i,j} = \mathbf{1}$, when a mobile node ($\mathbf{m}_i$) moves to cover a coverage hole ($\mathbf{h}_j$). Otherwise $\mathbf{x}_{i,j} = \mathbf{0}$.
$\mathbf{ED}_{\min} \ \& \ \mathbf{ED}_{\max}$	Minimum and maximum Euclidean distance between two nodes
ζ_{th}	Coverage redundancy threshold
$\mathbf{D}_f = (\mathbf{m}_i, \mathbf{h}_j)$	the Euclidean distance between a mobile sensor node $\mathbf{m}_i$ and a hole $\mathbf{h}_j$
$\mathbf{Cost}(\mathbf{m}_i, \mathbf{h}_j)$	The required energy for each movement of nodes ($\mathbf{m}_i$)

6.2.1 Problem Formulation

We formulate the addressed coverage enhancement problem as follows;

$$\text{Maximize } \mathbf{g}_c(\mathbf{m}_i, \mathbf{h}_j) \quad (6.3)$$

$$\sum_{j \in H} \mathbf{x}_{i,j} \geq 1 \quad , \quad \forall \in \mathbf{h}_j \quad (6.4)$$

$$\mathbf{ED}_{\min} \leq \mathbf{ED} \leq \mathbf{ED}_{\max} \quad (6.5)$$

$$\zeta_{m_i} \leq \zeta_{th} \quad (6.6)$$

$$\sum_{j \in H} \mathbf{x}_{i,j} \times \mathbf{Cost}(\mathbf{m}_i, \mathbf{h}_j) \leq E \quad \text{For each } \mathbf{m}_i \quad (6.7)$$

The objective of Eq. (6.3) is to maximize the coverage ratio of the sensing field subject to deploying the nodes uniformly. The objective of (6.4) is to ensure that the mobile node moves toward the coverage-hole to minimize the uncovered area. Constraint (6.5) ensures that the nodes are located in an equal Euclidean distance from each other. $\mathbf{ED}_{min}$ is half of the maximum communication range and of the sensor nodes and $\mathbf{ED}_{max} = 2 \times \mathbf{ED}_{min}$ [159]. Constraint (6.6) presents that the required coverage redundancy is bounded by a threshold. Constraint (6.7) states that the total required energy by sensor m_i during the optimization is no more than its initial energy.

6.3. Self-Healing Algorithm

In WSN node failures and changes in nodes' behaviour may reduce the overall efficiency or it may change the definition of efficiency itself. In either case, other nodes should move to maintain an effective network layout. To achieve this, each node is doomed to periodically send an identified heartbeat message to their neighbours to ensure that they are fully functional. The sensor nodes that receive the signal can apply RSS [147] method to ensure that there is a functional neighbour located in an expected distance. The sensor nodes also apply Eq. (6.1) to discover whether the neighbour node is a noisy sensor node. If a neighbour is detected as a noisy node or dead or even not located in the expected distance, it will be assumed as a failure node that causes a coverage-hole in the WSN. Figure 6.3 shows a WSN with a failed node (F).

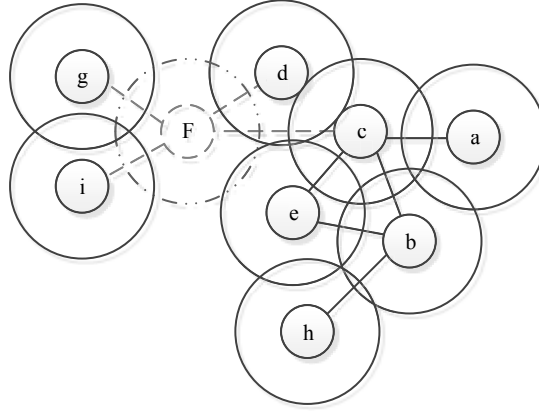


Figure 6.3. A failed node in a WSN

To compensate the coverage lost the neighbours are required to move and minimize the uncovered area. There is a possibility that F has more than one neighbour. Hence, determining a proper neighbour node to be moved to the uncovered area is essential. To choose the most appropriate node, each of the neighbours uses FLS2. FLS2 is a Type-2 fuzzy logic system (FLS) based that is able to handle linguistic and numerical uncertainties in WSNs. FLS2 determines the most suitable neighbour based on available energy (E) of the candidate nodes or neighbours as well as the distance (d) to the detected coverage-hole. In the moving process, FLS2 is required to consider E of the nodes to not expect the mobile nodes with low power take big steps. Moreover, coverage redundancy (ζ) that is calculated by Eq. (6.2) is also taken into account. The more redundant a sensor is the more redundant data is collected and consequently, the lower QoS is produced. To decrease redundancy in a WSN each node needs to determine whether it is a redundant node. Then, the result of the calculation (ζ) determines the redundancy of the sensor node. In fact, FLS2 calculates a ratio of the required maximum distance that sensors can move and their redundant coverage to their residual energy. Then, FLS2 uses the calculated ratio and organizes the neighbours into an order to move and compensate the coverage lost. In the case of a tie, the node with a lower node ID-number moves first to avoid collisions in the movement process. The

defined neighbour nodes are then needed to find a destination to move and uniformly cover the sensor field. To accomplish this we developed FLS1, which is also a type-2 FLS based that is applied by the mobile nodes. The inputs of the system are node density (ND) and average Euclidean distance (ED).

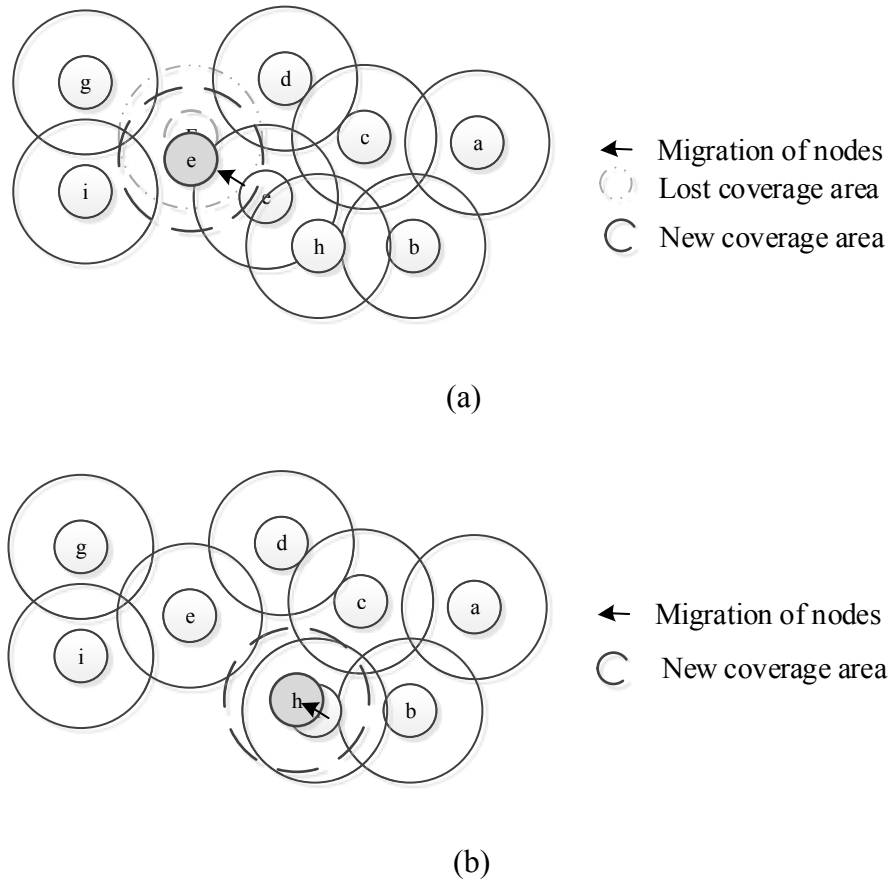


Figure 6.4. Coverage Enhancement

The main mission of the system is to place the entire nodes in the same ED. The nodes are moved to a certain distance to the area with lower node density. In fact, FLS1 is to place the entire nodes at the same distance to each other to reduce coverage redundancy while the area is uniformly covered. Figure 6.4 shows the coverage enhancement process. Figure 6.4 (a) shows that a mobile node (e) move to maintain the coverage from higher density to the lower density. After the movement, it is located at the same average ED from the new

neighbours (I, g and d). Since it is a cascaded algorithm, the moving process is continued by moving h and the other neighbours to be located uniformly from each other. Figure 6.4 (b) shows the relocation process of the second sensor node (h).

Algorithm: Self-Relocation algorithm	
INPUT: E: Available Energy, d: Distance to the detected hole, ND: Node density, ζ : Coverage redundancy, ED: Euclidean distance.	
OUTPUT: Destination position	
BEGIN	
1. WHILE (It detects loss of its neighbour) DO	
2. myFLS2 $\leftarrow$ FLS2 (E, d, ζ)	<i>// Calculate the eligibility</i>
3. Send (myID, myFLS2)	<i>//To neighbours</i>
4. ID $\leftarrow$ max (myFLS2)	<i>//Chose an eligible node</i>
5. IF it is the suitable neighbour	
6. IF received “ self-relocation ON”	<i>//From neighbours</i>
7. Wait until message “Self-relocation OFF” is received	
8. ELSE	
9. New position $\leftarrow$ FLS1 (ND, ED)	
10. Send “self-relocation ON”	<i>//To neighbours</i>
11. Start moving	
12. Calculate the energy consumption	
13. ELSE	
14. Reject the request	
15. END IF	
16. END WHILE	
END Algorithm	

When a neighbour that need to be moved its determined final location, it needs to check whether a “Self-relocation ON” message has been received from other nodes. In such a case, it waits for the nodes to finish with their relocation process and send a “Self-relocation OFF” message. Figure 6.5 shows the structure of a relocation message. Then, it sends a relocation message that includes “Self-relocation ON” and node-ID to its neighbours. Next, the node will be relocated. Once the relocation process is finished, it sends a “Self-relocation OFF” message and finally calculates the energy consumption.

Node-ID	Self-relocation ON/OFF
---------	------------------------

Figure 6.5. Relocation message

Finally, the mobile nodes will be moved to be located within the same ED to the other nodes.

The following algorithm describes the explained relocation process of the nodes.

6.4. Performance Analysis

In the simulation, we focus on enhancing coverage ratio and uniformity of node deployment in the area of interest with considering energy consumption of each mobile node.

To evaluate the coverage ratio of the proposed approach, we used Monte Carlo-based algorithm [160] is used. In this process, coverage measurement was tested and repeated for 200 simulations.

Moreover, to prove that the proposed approach provides a consistent uniformity in deploying the mobile sensor nodes we used the following formulas;

$$U = \frac{1}{N} \sum_{i=1}^N U_i \quad (6.8)$$

$$U_i = \sqrt{\frac{1}{K_i} \sum_{j=1}^K (D_{i,j} - M_i)^2} \quad (6.9)$$

Where N is the total number of nodes, K_i is the number of neighbours of the i^{th} node, $D_{i,j}$ is the distance between i^{th} and j^{th} node and M_i is the mean of intermodal distances between i^{th} sensor node and its neighbours. In the calculation of local uniformity (U), at the i^{th} node, only neighbours within its communication range are considered. A smaller value of U means that nodes are more uniformly distributed in the sensor field.

To analyse the energy consumption of the sensor nodes in the deployment process, we use a developed energy model [161]. According to the approach the required energy for a robot platform to move 1 inch is 0.210 joule.

6.4.1.Experimental Setup

In this section the proposed scheme is implemented and evaluated in MATLAB against Dynamic Coverage Maintenance (DCM) schemes [155], which proposed compensating and maintaining coverage methods for WSNs. We also compare the result of our approach against an energy efficient fuzzy optimization algorithm (EFOA) [162], which proposed a maintenance strategy in the post deployment phase. In this simulation, a 450m by 400m square sensing field is used. The sensing range (R_c) of the sensors used in this experiment is 25m with a communication range of 50m. The sensor nodes have a random initial energy level between 0.1J and 5J and are capable of moving up to 44m with a constant speed. Noise factor (N_{th}) in this implementation is $N_{th} = 0.0001$. Figure 6.6 presents a random deployment that we implement in MATLAB. In this figure 81 nodes are randomly located with a specific (X, Y). They are connected to each other with a link if they are close enough (≤ 50) to neighbours. The number of nodes based on the communication range and sensing area for each node is enough to have the best coverage gain. However, due to applied random deployment method, the nodes are not uniformly located in the area on interest. There are some areas that have not been covered and also some sensor nodes cannot communicate with others. So, it is necessary to relocate the nodes to be uniformly deployed in the area of interest.

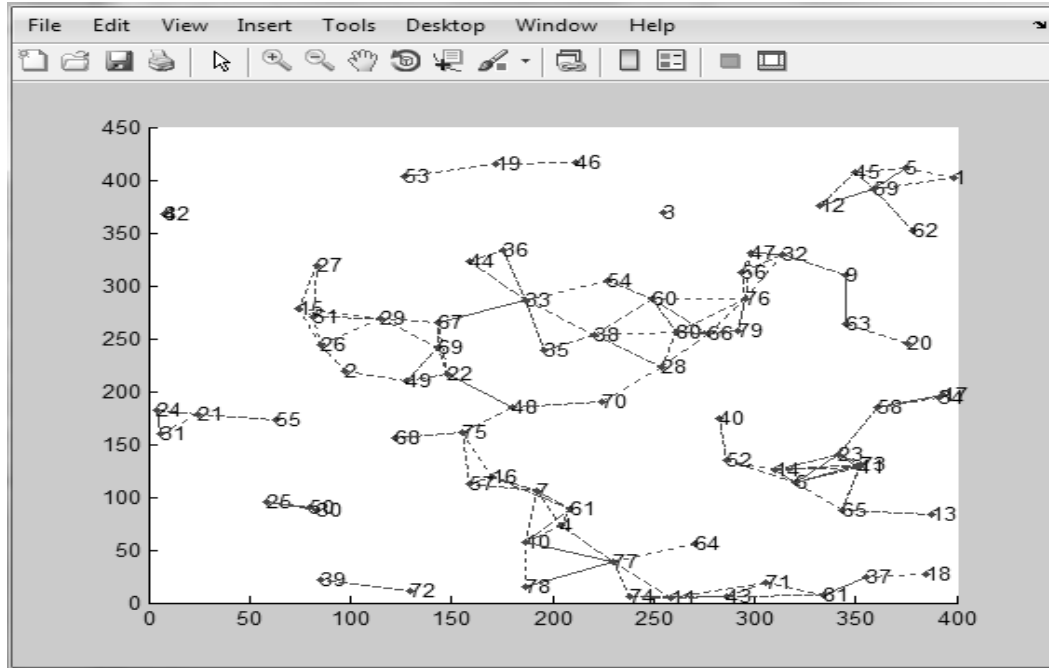


Figure 6.6. Random deployment

6.4.2.Result and Discussion

In this section, the goal is to adjust sensors' positions appropriately with minimum energy dissipation in deployment. To analyse this the consumed energy for each node to travel in FSHC was calculated and compared against that in DCM and EFOA. The sensor nodes were deployed randomly eight times and compared with the required moving distances, while the nodes in each protocol reached the same coverage. Results in figure 6.7 indicate that sensor nodes in the proposed approach consume less energy than in the other approaches. That is due to the accurate positioning of nodes in each movement that is followed the accurately transferred data. More importantly, FSCH unlike EFOA does not move the mobile node randomly.

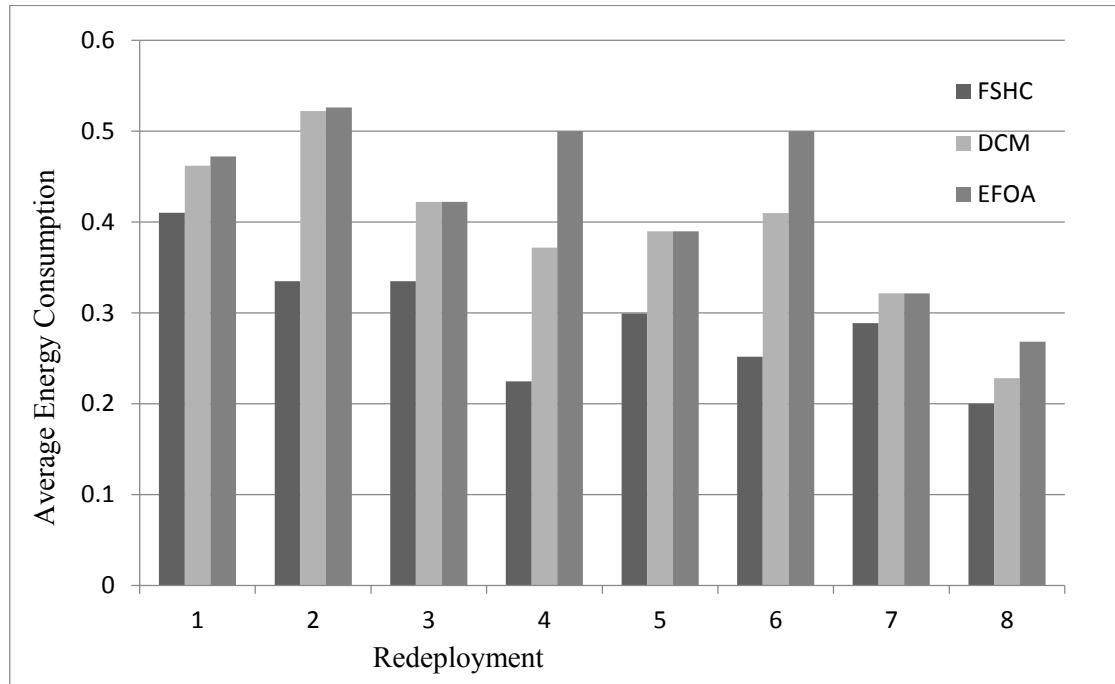


Figure 6.7. Average energy consumption

DCM is also consume less efficient than the proposed approach. That is because it uses GPS technology in each node to find locations. Running GPS system and receiving and processing the signals also consumes an amount of residual energy. Additionally, the mobile nodes in DCM, are directed based on a centralized method by using base station (BS) that is obviously increasing the energy consumption.

In addition to the energy consumption, the coverage ratio is also analysed. Figure 6.8 compares the percentage of archived coverage by the proposed approach against the other two existing schemes. As can be seen, FSHC has a higher coverage ratio for the same number of iterations compared to DCM and EFOA and it almost reaches 99 % for thirty-five iterations.

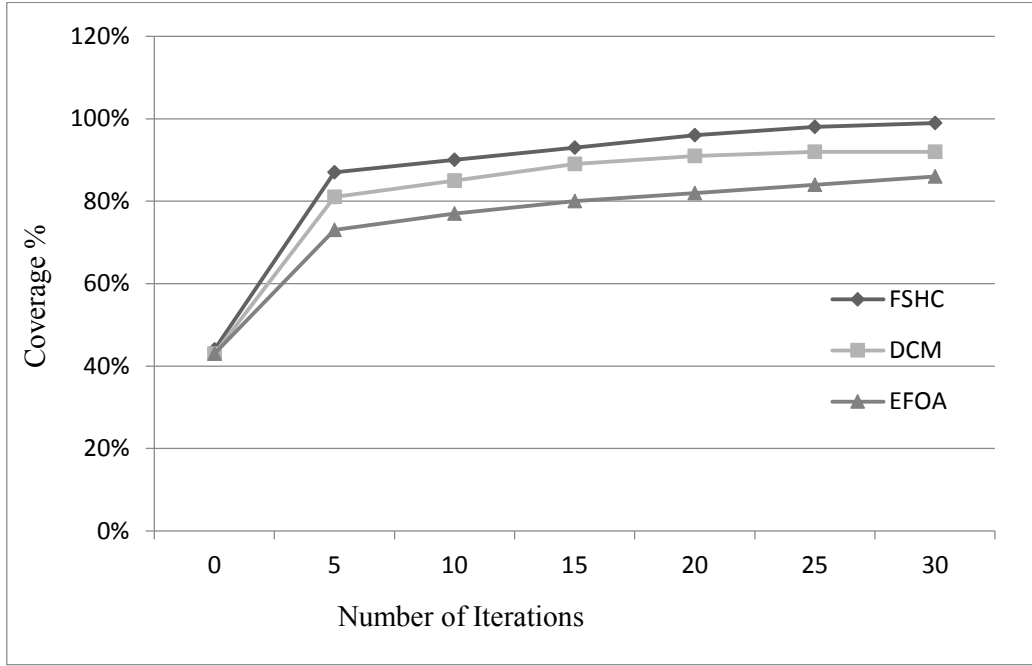


Figure 6.8. Coverage

Coverage ratio of the network was also analysed. Figure 6.9 shows the coverage ratio based on the number of sensor nodes. It can be seen from the figure, that as the number of nodes is increased the coverage ratio is increased in FSHC as well as the other two protocols. Coverage is improved by increasing the number of nodes in the network to 81 nodes, whereas the coverage ratio is approaching 99.5% by the proposed approach, 90% in DCM and just 82% in EFOA. The main reason behind that is in the proposed approach the mobile sensors consider the Euclidean distance among each other as well as coverage redundancy and find moving directions in the network. However, in EFOA, the sensor nodes move randomly. In DCM also due to the high complexity of the approach the coverage ratio is not high. Complexity of the DCM approach for n neighbour of a dead node the complexity of the relocation is increased by n^{2k} [155], where k is the required hops that need to be relocated to compensate the existing coverage-holes.

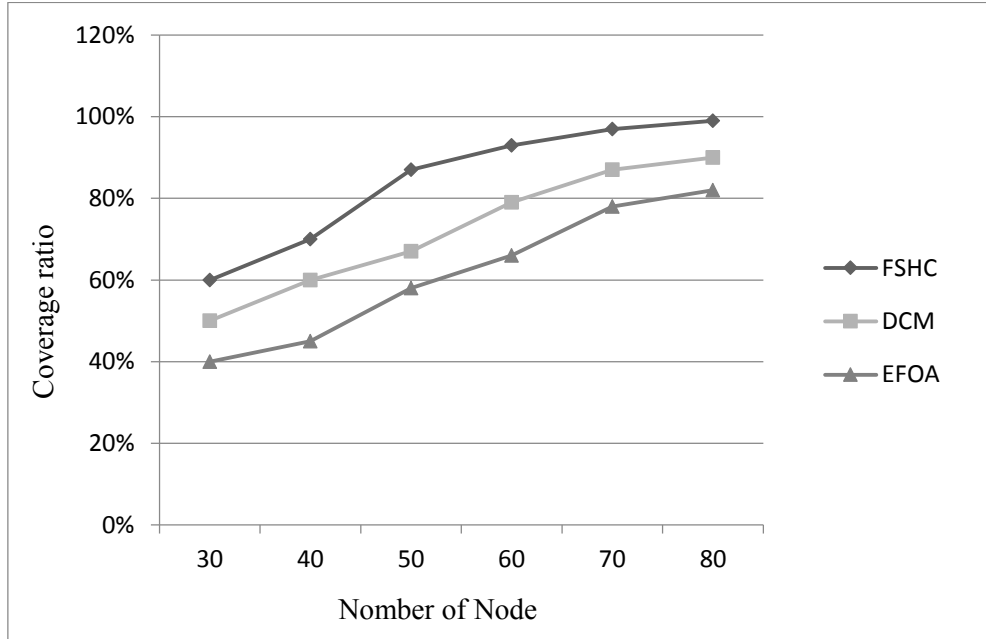


Figure 6.9. Coverage ratio

Uniformly distributed sensor nodes spend energy more evenly through the WSN than sensor nodes with an irregular topology. Uniformity (U) can be defined as the average local standard deviation of the distances between nodes[163, 164]. Figure 6.10 compares uniformity of coverage in FSHC against DCM and EFOA in a WSN. As can be seen by increasing iterations in the network, U becomes smaller in all three networks. From the figure, it can be understood that U in the proposed approach has become at least 15% better than in DCM and EFOA after 55 iterations. The reason behind this is the consideration of the Euclidean distance and node density in the network. U in EFOA is lower than the other algorithms, because the mobile nodes are mainly moved randomly in the network.

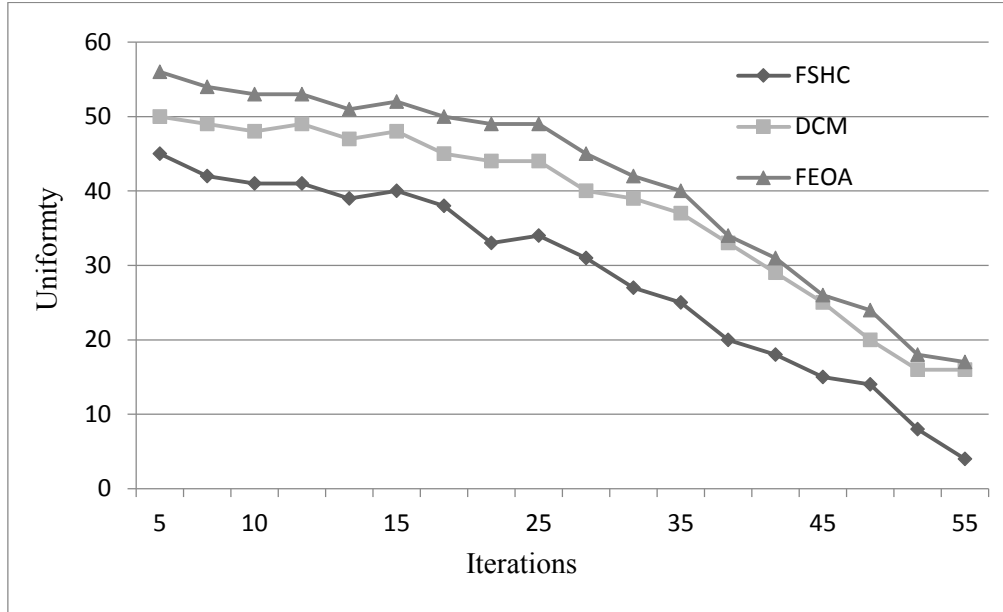


Figure 6.10. Uniformity

6.5. Chapter Summary

The main purpose of this chapter is to provide a better QoS in WSN, particularly, in an inaccessible sensor field. To achieve that, it is necessary to be concerned about dynamic node deployment techniques. In this chapter we firstly, formulated an optimal sensor node deployment problem, in which we used type-2 fuzzy logic systems that has low computation requirements and is robust to incomplete information. Next, we introduced a self-healing algorithm to maintain the coverage rate of the network. The algorithm can be applied after a random deployment. Each node, by applying the algorithm, can be sure that their neighbours are fully functional. If a node noticed that a neighbour node is dead, noisy or not located in an expected distance, it will be assumed as a failed node. Then, the other neighbours will be required to move toward the position of the failed node to be uniformly distributed in an acceptable Euclidean distance from each other. As a result, the network maintains its coverage ratio dynamically. Finally, in the evaluation section of this chapter,

we implemented the protocols in MATLAB and evaluated the proposed system against two recent developed approaches. The simulations demonstrated that by locating the sensor nodes uniformly in the sensor field, the energy consumption of the network is more efficient. Moreover, the coverage ratio of the proposed protocols has been higher than the other two developed approaches.

Chapter 7

SUMMARY AND FUTURE RESEARCH DIRECTIONS

The purpose of this thesis is to develop solutions for the existing research problems in WSNs that negatively influence QoS in their performance. We firstly introduced an energy efficient clustering deployment method for the sensor nodes. Next, a quality based data fusion mechanism was proposed. Third, two data routing protocols with the purpose of enhancing efficiency of energy consumption were developed. Finally, a coverage maintenance in WSN was developed.

A. Conclusion

In this thesis, we developed a formal quality aware data collection framework using a WSN. To achieve this, five steps were explored very carefully. Firstly, a deep exploration and study was managed on many of the existing frameworks available in the literature. That

deals with analysing the advantages and disadvantages of the proposed solutions for WSN QoS control. As a result, four existing research gaps were introduced as research problems. First, an energy efficient sensor node deployment method always plays an important role in enhancing QoS in WSNs. Unreliable or even not suitable deployment for a WSN can cause the network to waste their limited energy. To enhance the efficiency of energy consumption we proposed a self-configurable clustering approach. In the proposed scheme, we thoughtfully considered predictable and unpredictable CH failure. In the both cases, the cluster members (CMs) are required to be re-clustered. Otherwise, the more they do not have a CH the more they are in the risk of losing their data. However, re-clustering the sensor nodes is a time consuming process that does not allow the sensor nodes to collect and transfer data. Therefore, we suggested to assign a backup CH (BCH) for each determined CH. Consequently, the sensor nodes ensures that there is always a CH for them during the network lifetime. To switch the CH, CMs need to firstly notice about the permanent failure of the node. The failure however, could be due to a sudden physical damage. In the case, the sensor nodes are able to assess whether their CHs are permanently or temporary failed. If their CHs permanently failed, they will automatically switch to their determined BCH. Our approach performs better in terms of reducing communication overhead by the average ratio of 32% as well as prolonging the network lifetime by the average ratio of 46%. In addition to results comparison between the proposed approach vs DBCH and PDDA, root means square error (RMSE) is also calculated. To calculate RMSE, the most optimum result (100%) is considered as the predicted result in each call. RMSE for the proposed approach is less than that for DBCH and PDDA, which are 0.1, 1.6 and 3.2 respectively.

The second addressed research problem was to aggregate the received data with the aim of reducing data duplication as well as energy consumption. The main and the first cause that makes a WSN to produce and process unvalued data and consequently become unreliable is missed behaviour sensor nodes. Usually, missed behaviour sensor nodes are not detectable unless the history of their collected data is analysed. Therefore, we suggested to monitor current condition of the sensor nodes to ensure that their data are true values. To achieve that, we developed a fuzzy system that calculates the confidence factor of the produced data. Based on the factor, each sensor can group the collected data into valued and unvalued data. Clearly, the valued data are sent to CHs for further process. The CHs were responsible to fuse the received valued data. They were also required to calculate the probability of occurring the target in their monitored areas. Thus, the CHs are sending only the probability of the events, instead of sending the fused data to the BS. To calculate that, each CHs were equipped with a fuzzy inference system with the inputs of the fused data and output of target possibilities. In case of noticing any changes in the calculated possibility, they sent the fuzzy output to the base station (BS). However, the BS still needed to process the received data with the aim of assessing whether the detection is accurate enough. If the BS determines that the event is occurred, it records the event to alerting subsystem. The proposed approach enhanced the performance by the average of 17%. In addition to results comparison between the proposed approach vs FIM and VWFFA, RMSE is also calculated. To calculate RMSE, the most optimum result (100%) is considered as the predicted result in each call. RMSE for the proposed approach is less than that for FIM and VWFFA, which are 3.67, 5.13 and 5.9 respectively.

After collecting and fusing data packets from different sources, they need to be transferred to the assigned BS. To transfer the data, we proposed a fuzzy logic based reactive routing

protocol for a WSN with stationary sensor nodes and a BS. In that, source nodes were required to establish a route to the BS. To establish data routes, we carefully considered the balance of energy among the deployed sensor nodes. The obtained results proved that our system increased the efficiency of energy consumption and buffer usage as well as reliability of the system. Then, we extend our proposed approach by replacing the stationary BS with a mobile BS (MBS). Then, we proposed IDCS (data collection scheduling) that is a data routing protocol with a controlled MBS. In the proposed scheme, location and the visiting time of the MBS are cautiously determined using local information of the deployed sensor nodes. In fact, the MBS is able to prioritise the clusters to be visited. Thus, it can visit the most prioritised clusters at a time, instead of visiting them randomly or in a fixed way of moving. That is determined based on the important of data in the clusters. The MBS was also authorised to define CHs for the clusters. That is because it moves across the network in different ways. Therefore, in some locations it can collect data from more than one clusters at the same time. Therefore, selecting the closest node to the specific location as a CH can reduce the energy consumption. However, to make the decision residual energy of the nodes also significantly important. Simulation results showed our scheme prolonged the network lifetime by the average ratio of 25% and also reduced the time delay in delivering data packets by the average ratio of 30%. In addition to results comparison between the proposed approach vs SDD and HCDD, RMSE is also calculated. To calculate RMSE for the proposed approach is less than that for SDD and HCDD, which are 0.9, 1.6 and 1.9 respectively.

Finally, maintaining the maximum coverage of the deployed nodes in the area of interest has a direct relation to the QoS maintenance. To maintain the coverage, we firstly formulated an optimal sensor node deployment problem. The computation requirement of

solving the problem exceeded the capability of typical sensor nodes. So, we proposed to use type-2 fuzzy logic system that has low computation requirements and also robust to incomplete information. Next, we introduced a protocol to distribute the deployed nodes uniformly. In this approach, disordered sensor nodes as well as noisy sensor nodes were firstly detected. Then, the other neighbours were required to move toward the position of the failed node. As a result, the network maintains its coverage ratio dynamically. The simulations demonstrated that by locating the sensor nodes uniformly in the sensor field, the energy consumption of the network is become more efficient that is about 20%. Moreover, coverage ratio of the proposed protocols has been higher than the other two developed approaches by 15%. In addition to results comparison between the proposed approach vs DCM and EFOA, RMSE for coverage ratio is also calculated. RMSE for the proposed approach is less than that for DCM and EFOA, which are 0.1, 0.3 and 0.4 respectively.

B. System Implications

Generally sensor nodes, sink and monitored events are the three main components in a WSN need to be considered properly to deploy a dynamic WSN. In the deployment process, the main issue is the mobility of the BS and the sensor nodes that need to be taken into account thoughtfully. In that, routing methods play important roles as route stability becomes an important optimization factor in addition to energy and bandwidth usage in the networks. Another consideration is the topological deployment of nodes. This is application dependent and influences the performance of the routing protocols. Next, efficiency of energy consumption that is influenced during the creation of an infrastructure. The process of setting up the routes is greatly influenced by energy considerations. The transmission

power of a wireless radio is proportional to distance squared or even higher order in the presence of obstacles, multi hop routing will consume less energy than direct communication. Finally, node capabilities is another considerable point in developing a dynamic WSN. All sensor nodes are assumed to be homogenous, having equal capacity in terms of computation, communication and power. However, depending on the application a node can be dedicated to a particular special function such as relaying, sensing and aggregation since engaging the three functionalities at the same time on a node might quickly drain the energy of that node. Inclusion of heterogeneous set of sensors raises multiple technical issues related to data routing. The results generated from these sensors can be at different rates, subject to diverse quality of service constraints and following multiple data delivery models.

C. Future Directions

Our extensive study on QoS control in WSNs identified a number of research problems that we could not solve in this thesis due to time and other limitations. We list out a number of future research directions in line with the problems discussed in this thesis. There are opportunities to enhance the proposed solutions and explore other potential issues to ensure the technology can performed at its best to benefit the users.

In this thesis we consider missed behaviour sensor nodes in data fusing process. To detect the missed behaved sensors, we considered the current condition of each of them. We checked the temperature and humidity of the environment around the sensor nodes and then compared them against the provided information in their datasheets. Next, we assigned a confidence rate (weight) for each collected data. Therefore, we could detect and disregard

the not true value of collected data from the fusion process. However, temperature and humidity are not the only factors that can negatively influence the performance of the nodes. There are many more factors that need to be considered to create a more accurate weights for the collected data in each round.

In this thesis we used one stationary BS and one MBS individually in different protocols. We enhanced QoS in our proposed schemes however, we believe that using multiple sinks, either fixed or mobile, can significantly enhance QoS in WSN. There is considerable opportunity for research of these areas to extend the current approaches.

Traditionally, sensor fields are considered in two dimensional, where location of any event can be defined using only two co-ordinates. However, monitoring systems using WSN can be installed in underwater or even in some applications in space. In these environments, the occurred event locations need three dimensional locations to be determined. Based on that, more complicated geometric factors are required to be taken into account. The change in WNSs from 2D to 3D is the extension of our QoS aware of coverage presented in chapter 6. In addition, our dynamic coverage scheme can be extended by considering the movement delay.

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