UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

FACULTY OF PHYSICAL AND MATHEMATICAL SCIENCES

# A STUDY INTO LIFETIME MAXIMIZATION OF WIRELESS SENSOR NETWORKS FOR WATER QUALITY MONITORING

BY

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THIS DISSERTATION IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF PHD IN COMPUTER SCIENCE DEGREE

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# DECLARATION

I, Kofi Sarpong Adu-Manu, hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 64,200 words including appendices, bibliography, footnotes, tables, and equations and has fewer than 129 figures. This dissertation was under the supervision of the Supervisory Committee as detailed below:

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(Supervisor)

# DEDICATION

I dedicate this dissertation to my wife, children, and mother. To God, be the Glory!

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# ABSTRACT

Freshwater sources represent only about 2.5% of the world's water bodies, hence, maintaining and monitoring its quality is vital. Several deaths reported across the world is as a result of contaminated and polluted water. Among the various methods proposed for monitoring water quality, the use of wireless sensor networks appear to have gained currency. Advances in Wireless Sensor Network (WSN) technology and the emergence of the Internet of Things (IoT) is engendering significant improvements in the operation and delivery of services in many developing countries, including Ghana. One application area of WSNs is in Water Quality Monitoring (WQM). Measuring and monitoring water quality parameters to obtain quality data has been of great concern to governments, researchers, stakeholders, policymakers, and the community at large. WQM systems seek to ensure high data precision, data accuracy, timely reporting, easy accessibility of data and completeness. The conventional monitoring systems are inadequate when used to detect contaminants/pollutants in real-time and cannot meet all the requirements of WQM systems. Collecting water samples for lab analysis is expensive, time-consuming, and a repetitive process. This approach lacks sufficient data for trend analysis for the development of appropriate models. The traditional/conventional approach to monitoring water quality does hence not achieve the set objectives for real-time WQM. There is, therefore, the need to adopt an approach which is efficient and cost-effective and overcomes the problems associated with the conventional methods. In recent years, wireless sensors capable of detecting the presence of pollutants and heavy metals in water bodies have been developed and commercialised. Wireless Sensor Networks for environmental monitoring applications require long battery life and low power consumption to enable them to operate over a prolonged period. An essential requirement for such networks is that the energy consumption of the nodes should be kept minimal to increase the lifetime of the wireless sensor network and to improve the performance of sensor nodes and the wireless network. The dissertation in addressing the energy consumption and lifetime maximisation problems proposes a novel transmission range adjustment algorithm based on the position of the sensor nodes. The dissertation is organised broadly in three phases. In phase 1, a systematic review of current trends in water quality monitoring using wireless sensor networks and future developments are discussed. This top-down study surveys the different water quality monitoring approaches ranging from traditional manual approaches to more advanced technological approaches. Also, this specific contribution highlights recent advances in the design of sensor devices, data acquisition procedures, communication and network architectures, and power management schemes to maintain a long-lived operational WQM system. In phase 2, an improved Ad-hoc On-Demand Distance Vector (AODV) protocol that takes into consideration the distance from neighbouring nodes and adjusts the transmission power accordingly is presented. The Euclidian distances between the nodes are calculated, and data packets are transmitted using the absolute value of the Euclidian distances as the transmission range between the nodes to minimise energy consumption and maximise the lifetime of the node and the network. Network Simulator 3 (NS3) is used to simulate the Packet Delivery Ratio (PDR), the energy consumption of the nodes, average delay, and other parameters for performance evaluation of the WSN using the improved AODV. To verify and validate the operation of the algorithm, a simulation was performed, and results from the evaluation were presented. Finally, in phase 3, an automatic monitoring system using real testbeds in real-time is presented. The sensor nodes can collect data with high integrity and accuracy at different sampling locations and with the desired temporal granularity. The study was conducted at the Weija intake in the Greater Accra Region of Ghana. The Weija dam intake serves as a significant water source to the Weija treatment plant which supplies treated water to the people of Greater Accra and parts of Central regions of Ghana. Smart water sensors and Smart water ion sensor devices from Libelium were deployed at the intake to measure calcium ion (Ca2+), conductivity, pH, dissolved oxygen, silver (Ag+), fluoride ion

(F), nitrate ion (NO3-), oxidation-reduction potential (ORP), and temperature. The results do indicate significant fluctuations over time in of all the parameters that were monitored. These changes may be attributed to pollution from upstream, which are time varying.

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| | |
|---|---|
| AATR | Automatic Adjustable Transmission Range |
| Ag+ | Silver |
| ALERT | Anonymous Location-Based Efficient Routing Protocol |
| AODV | Ad-Hoc On-Demand Distance Vector |
| AR | Autoregressive |
| ARIMA | Autoregressive Integrated Moving Average |
| ARMA | Autoregressive Moving Average |
| ASCII | American Standard Code for Information Interchange |
| AUV | Autonomous Underwater Vehicles |
| BOD5 | Biochemical Oxygen Demand |
| BVGF | Bounded Voronoi Greedy Forwarding |
| BVGF | Bounded Voronoi Greedy Forwarding |
| Ca2+ | Calcium Ion |
| CH | Cluster Head |
| CTP | Collaborative Task Processing |
| DB | Database |
| DO | Dissolved Oxygen |
| DPSR | Data Processing, Storage and Retrieval |
| DSA | Density Search Algorithm |
| DSDV | Dynamic Destination-Sequenced Distance-Vector Routing |
| DSR | Dynamic Source Routing |
| DTS | Direct Transmission to Sink Node |
| EEGR | Energy-Efficient Geographic Routing |
| EEG-R | Energy Efficient Geographic Routing |
| EELIR | Location-Based Energy Efficient Intersection Routing |

| | |
|---|---|
| EELIR | Location Based Energy Efficient Intersection Routing |
| EH | Energy Harvesting |
| EM | Environmental Monitoring |
| E-PULRP | Energy Optimised Path Unaware Layered Routing Protocol |
| F- | Fluoride Ion |
| GAF | Geographic Adaptive Fidelity |
| GEAR | Geographic And Energy-Aware Routing |
| GEMS | Global Environment Monitoring System |
| GEMStat | Global Water Quality Data and Statistics |
| GeRaF | Geographic Random Forwarding |
| GF-ViP | Greedy Forwarding with Virtual Position |
| GIS | Geographical Information Systems |
| GPRS | General Packet Radio Services |
| GPS | Global Positioning System |
| GPSR | Greedy Perimeter Stateless Routing |
| GSM | Global System For Mobile Communication |
| GUI | Graphic User Interface |
| HABs | Harmful Algal Blooms |
| IHLAR | Improved Hybrid Location-Based Ad-Hoc Routing Protocol |
| InP | In-Node Processing |
| IoT | Internet of Things |
| IR | Infra-Red |
| ISFET | Ion-Selective-Field- Effect-Transistor |
| LAR | Location Aided Routing |
| LARP | Location Based Adaptive Routing Protocol |
| LBRP | Location-Based Routing Protocol |

| | |
|---|---|
| LEACH | Low Energy Adaptive Clustering Hierarchy |
| LMR | Location-Based Multicast Routing |
| MANET | Mobile Adhoc Network |
| MECN | Minimum Energy Communication Network |
| MEMS | Microelectronic Mechanical Systems |
| MI | Magnetic Induction |
| NL | Network Lifetime |
| NLM | Network Lifetime Maximization |
| NO3- | Nitrate Ion |
| NS3 | Network Simulator 3 |
| OPNET | Optimized Network Engineering Tool |
| ORP | Oxidation-Reduction Potential |
| OS | Optical Sensors |
| OSI | Open Systems Interconnection |
| PDR | Packet Delivery Ratio |
| PEGASIS | Power-Efficient Gathering in Sensor Information Systems |
| QoS | Quality of Service |
| RERR | Route Error Message |
| RF | Radio Frequency |
| RNM | River Network Monitoring |
| RoI | Region of Interest |
| RREP | Route Reply |
| RREQ | Route Request |
| RSNs | River Sensor Networks |
| RSSI | Received Signal Strength Indication |
| SBZRP | Selective Bordercast In Zone Routing Protocol |

| | |
|---|---|
| SEEC | Sparsity-Aware Energy Efficient Clustering |
| SNR | Signal-To-Noise-Ratio |
| SSA | Sparsity Search Algorithm |
| TBF | Trajectory-Based Forwarding |
| TEEN | Threshold Sensitive Energy Efficient Sensor Network Protocol |
| TMIS | Traditional Manual In-Situ |
| TMLB | Traditional Manual Lab-Based |
| TORA | Temporally Ordered Routing Algorithm |
| TR | Transmission Range |
| UASNs | Underwater Acoustic Sensor Networks |
| UNDESA | United Nations Department of Economic and Social Affairs |
| USGS | Us Geological Survey |
| WCDMA | Wideband Code Division Multiple Access |
| WDNs | Water Distribution Networks |
| WDSs | Water Distribution Systems |
| WHO | World Health Organization |
| WMSNs | Wireless Multimedia Sensor Networks |
| WQM | Water Quality Monitoring |
| WSN | Wireless Sensor Network |
| WUSN | Wireless Underground Sensor Networks |
| ZRP | Zone Routing Protocol |

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# CHAPTER 1

# INTRODUCTION

## 1.1. Background of the Study

The growth of the world's population, together with the economic, industrial, and social developments, has led to increased pressure on natural resources, including water. When natural resources such as water are inadequate and do not meet the needs of populations, then opportunities for growth and development diminish [1]. Moreover, globalization, climate change and human activities such as dumping of refuse into water bodies, defecating near riverbanks, fish farming, commercial cattle farming, and illegal mining have had adverse effects on water resources. High volumes of waste created by individuals, industries, and businesses are channelled into water bodies, rendering them unsafe to drink and may lead to diseases such as cholera. It is known that of all the water in the world, only 2.5% constitute freshwater [2]. Thus, measures must be taken to preserve and protect these freshwater sources now and into the future. One possible solution is to undertake continuous monitoring of the desired water quality parameters to enable decision-makers to keep track of changes over time [2].

The frequent occurrence of water-borne diseases in many developing nations, mainly in Africa, may be attributed to the lack of access to potable water. The crucial role that freshwater supplies can play in supporting the economy of the African continent and the development of its human capital, including combating poverty and food insecurity is widely recognized [3]. The provision of access to potable water in many urban centres in Africa continues to remain a challenge [4]. This has led to a growing demand around the world to manage water resources sustainably. Recently information technology tools have been proposed for use in providing reliable and real-time water quality parameters. Water Quality Monitoring (WQM) may be done in freshwater bodies such as rivers or in Water Distribution Systems (WDSs).

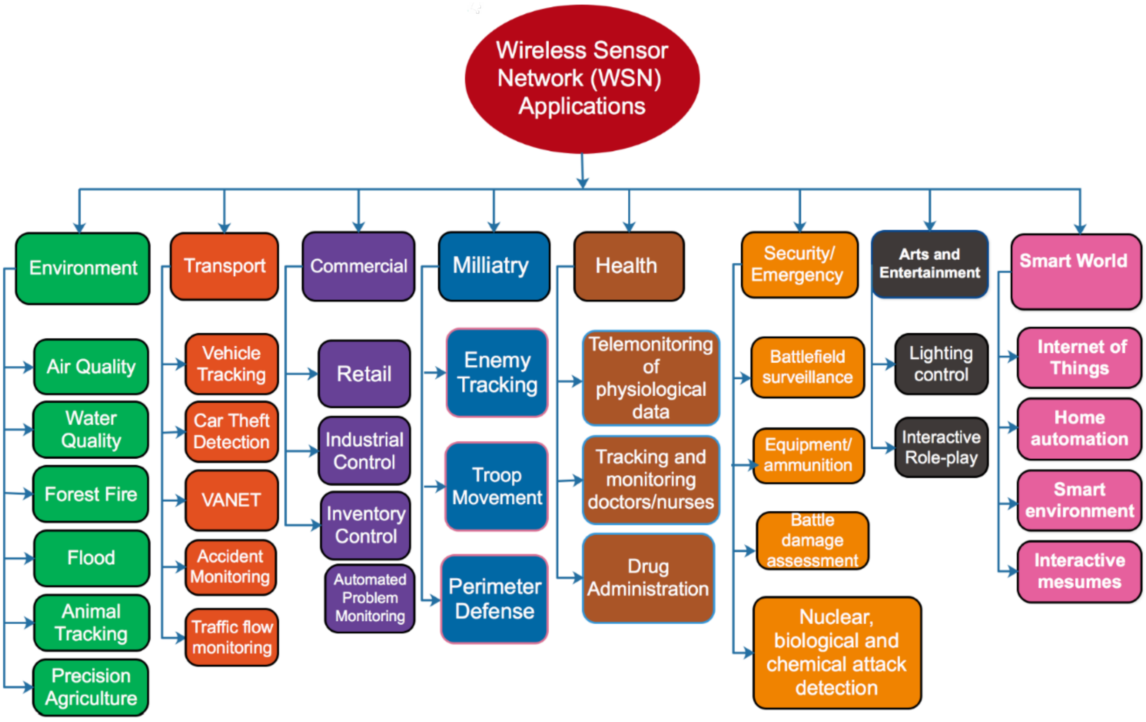


Figure 1. 1 Wireless Sensor Network Applications

Two broad approaches can be adopted for monitoring water quality in freshwater sources. The first and most common of these approaches are popularly known as the Traditional methods. These methods are typically manual and have been shown to produce experimental results with significant inaccuracies [5]. The second and more recent freshwater quality monitoring approaches employ smart sensors equipped with wireless transceivers to measure and transmit water quality parameters such as temperature, pH, conductivity, dissolved oxygen, etc. The smart wireless sensor nodes are autonomous and require no human intervention in their operation [6], thus, they are efficient and capable of providing reliable measurements.

In recent years, the use of smart wireless sensor nodes to form a distributed network of communication popularly known as Wireless Sensor Networks (WSN) is gaining significant research interest. This is because such networks provide unique opportunities such as self-organizing, autonomous, and spatial distribution and can be used to gather information and to detect environmental phenomenon ranging from health to military applications, as illustrated in Figure 1.1. Despite the enormous opportunities provided by WSNs, they are faced with a number of implementation and deployment challenges which include poor coverage and network connectivity, delay in data collection and processing, inefficient data compression approaches, unbalanced energy consumption, and shortened network lifetime. For most practical applications, the sensor nodes are deployed in remote, inaccessible, and inhospitable locations. This poses a huge challenge for the lifetime of the sensor nodes and ultimately the network since the nodes are battery powered. In a wireless sensor network, the distribution of the nodes may significantly impact the network lifetime.

Network lifetime (NL) has been defined differently by several other researchers [6]–[9]. In [9], NL has been defined as the time any of the nodes runs out of energy. Other alternative definitions have been provided and classified according to the node's lifetime, coverage and connectivity, transmission, and other parameters (e.g., node availability, data collection, etc.) [6]. Network lifetime is considered as the key characteristic to evaluate the performance of sensor networks based on the number of nodes that are alive, node connectivity, quality of service requirements [7], [8].

It is important to note that network lifetime as a performance metric is a function of the residual energy in the sensor nodes. It is therefore important to therefore pay attention to how the nodes are distributed in a network to help maximise the network lifetime. In this dissertation, network lifetime is defined as the time until connectivity is lost, and data packets can no longer reach their destination.

Network lifetime is a key parameter of any network, and, as such, several methods have been proposed to maximize it. Network lifetime may be maximized and extended by the use of certain application-specific techniques such as beamforming [10]–[12] energy harvesting [13]–[16], data correlation [17]–[19], network coding/data gathering [20]–[22], connectivity and coverage [13], [23], [24] mobile relays and sinks [8], [25], clustering and routing [26]–[29], sleep-wake-up scheduling [30]–[32], and resource allocation with cross layer designs [31], [33]

Figure 1.2 shows the various Network Lifetime Maximization (NLM) techniques that have been proposed since 2005 [34], [35].

Figure 1. 2 Network Lifetime Maximization Techniques (NLM)

This dissertation makes use of some of the NLM techniques stated in Figure 1.2 but focuses on the node transmission range (TR), routing and energy harvesting (EH) techniques. Transmission range (TR) for most sensor nodes is fixed to a minimum value for energy conservation. In the application domain under study, the node's transmission range is required to vary to minimize the amount of energy consumed by the node. The distance between nodes has a significant impact on the energy used to transmit the data packets. Routing aims at extending the network lifetime based on the transmission range. Energy harvesting (EH) increases the node energy level, thereby extending the sensor node and the overall network lifetime. These three techniques are closely related to network connectivity; hence, once implemented, they serve as useful approaches for improving the network lifetime in WSNs. Hence, the choice of these techniques in this dissertation over other techniques presented in Figure 1.2.

The transmission range (TR) of wireless sensor nodes is defined as the maximum communication distance between a wireless sensor node's transmitter and receiver to deliver a packet. In WSNs, the transmission range of wireless sensor nodes may differ depending on the signal strength, attenuation, and transmission power [36]. Transmission range occurs between two wireless sensor nodes (i.e., sensor to sensor) or between a wireless sensor node and a sink node (i.e., sensor to sink).

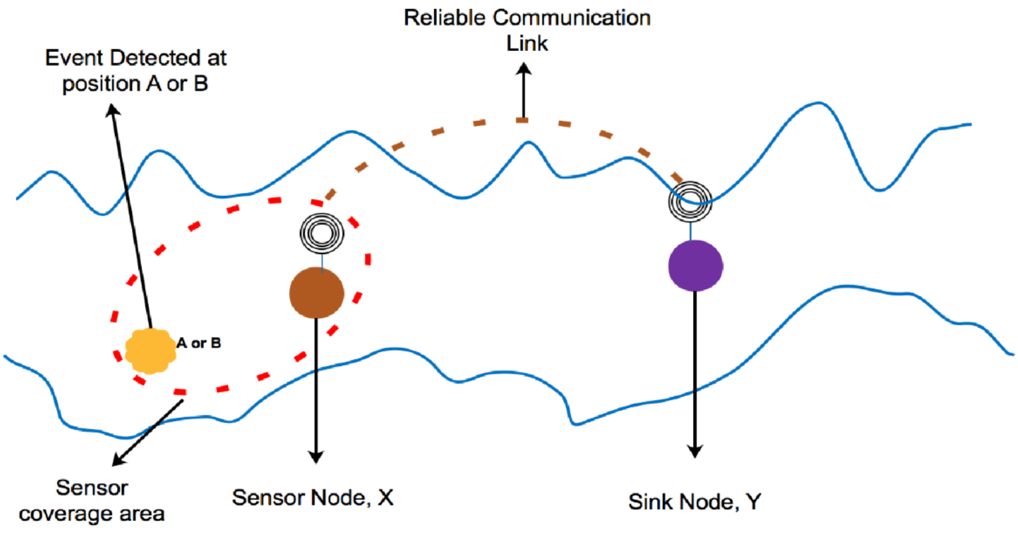


Figure 1. 3 Event detection and transfer process

Wireless sensor nodes generally have short-range communication capabilities. The nodes have limited energy which imposes restrictions on the communication distance between the source node and the destination node. Due to these limitations, single-hop communication is not suitable for some application domains, hence, multiplehop communication is used to overcome this limitation [36]. For example, in a river monitoring environment, the sensor nodes may be placed at different locations to achieve optimal coverage for detecting contaminants, hence, there is a need to determine the optimal transmission range for the sensor to sensor communication and for the sensor to sink communication.

In a wireless sensor network for WQM applications, an event detected at a certain position, say $A$ in close proximity of a node $X$ can be transmitted to a *sink node* $Y$, if there is reliable connectivity between the *source node* $X$ and the *sink node* $Y$ as shown in Figure 1.3. For energy saving purposes, the TR may be optimized and still maintain connectivity between nodes in a manner that maximizes the lifetime of the network.

In freshwater sources, static and mobile wireless sensors are deployed to sense and measure water quality parameters (e.g., pH value, dissolved oxygen, electrical conductivity, oxidation-reduction potential, nitrogen, etc). Previous works carried out in this application domain employed fixed-network topology [37]–[40]. Mobile sensors are beneficial in freshwater sources when combined with static sensor nodes to detect contaminants that are out of the sensing range of the static sensors.

This dissertation proposes a new approach in this application domain in which the source nodes are assumed to be mobile, with the goal of improving connectivity, coverage, and energy efficiency. The combination of mobile source nodes and static sink nodes allow the mobile source nodes to continuously sense and measure the water quality parameters along the flowing river.

It is assumed that the mobile wireless sensor nodes move along the river with velocities relative to that of the river. As they do, their positions change with respect to each other since the speed of the river at various locations is not uniform [41]. The change in relative positions have implications for data transfer within the network. Typically, a node that requires a single hop to reach the sink node may now require a multi-hop communication link to reach the same sink node. In addition, a node’s current position may now be irrelevant to other nodes that might previously have used it as a hop to the sink node. A new route may therefore be required to detect next-hop neighbours for packet transmission.

To overcome this issue, this dissertation proposes a novel algorithm which dynamically adjusts the transmission range of a node using local topological characteristics. In other words, the transmission range of the transmitting node is either increased or decreased based on the topological characteristics of its immediate neighbours. The proposed algorithm significantly reduces the cost associated with routing control overhead by mitigating the over reliance of network-wide or global topological information required for making routing decisions.

## 1.2. Motivations

According to the United Nations Department of Economic and Social Affairs (UNDESA), 115 people in Africa die every hour from diseases linked to poor sanitation, poor hygiene and contaminated water [2]. It is therefore extremely important to implement methods that can effectively manage and monitor water resources. Currently, the most common methods used to test water quality parameters in some African countries such as Ghana include manually collecting water samples and then transporting these samples to a laboratory for testing using equipment such as atomic absorption spectrophotometers, ion chromatographs, microwave digesters, UV spectrophotometers, flame photometers, and carbon surfer analysers. Although these approaches can detect contaminants in the water, the over reliance of manual systems and human interventions is expensive and may sometimes lead to inaccuracies of the results and reporting delays. For example, according to the American Public Health Association, the turbidity of water sample should be determined on the day the sample is taken, otherwise, the test results may be considered unreliable [2]. Recently, several sensor products have been specifically designed to provide accurate and timely measurement of water quality parameters. Some of these products include Waspmote Smart Water from Libelium [42], Multiparameter Sonds from In-Situ [43], etc. Some of these devices are equipped with communication capabilities to enable them to transmit the measured water quality parameter to a remote monitoring station. Although these devices can provide accurate and timely measurements of water quality parameters, their enormous potential in the formation of distributed wireless sensor networks for monitoring large water bodies such as rivers is yet to be explored. In other words, although there has been a tremendous amount of research work in Wireless Sensor Networks (WSNs) and their applications in ubiquitous computing, very little effort has been made towards using large scale WSNs to provide real-time monitoring of water quality parameters in freshwater bodies such as rivers. This dissertation makes novel contributions towards providing real-time monitoring of water quality parameters in freshwater bodies using WSNs and focusing on lifetime maximization of the wireless sensor nodes. We achieved this by employing novel algorithms that seek to minimize the nodes' energy consumption whiles maintaining acceptable levels of network throughput and end-to-end delay of data transmission using local topological characteristics of the nodes in the WSN.

### 1.3. Static Wireless Sensor Network for WQM

Different approaches may be used to perform the monitoring process, that is employing static sensors or mobile sensors or both. To better understand the design of WSNs for WQM, we consider the nature of the freshwater source (river, lake), the sensor node properties (energy consumption, storage, and communication), the monitoring task of the sensor network (i.e., chemical, physical, and biological observation), the environmental status (water status or level of contamination, and the area of interest), and the sensor network states (sensing, energy consumption, and networking states) [44]. In WQM, huge amounts of data are collected, processed, and transmitted, hence efficient routing algorithms designed to minimize the amount of energy consumed for sensor node operations are required.

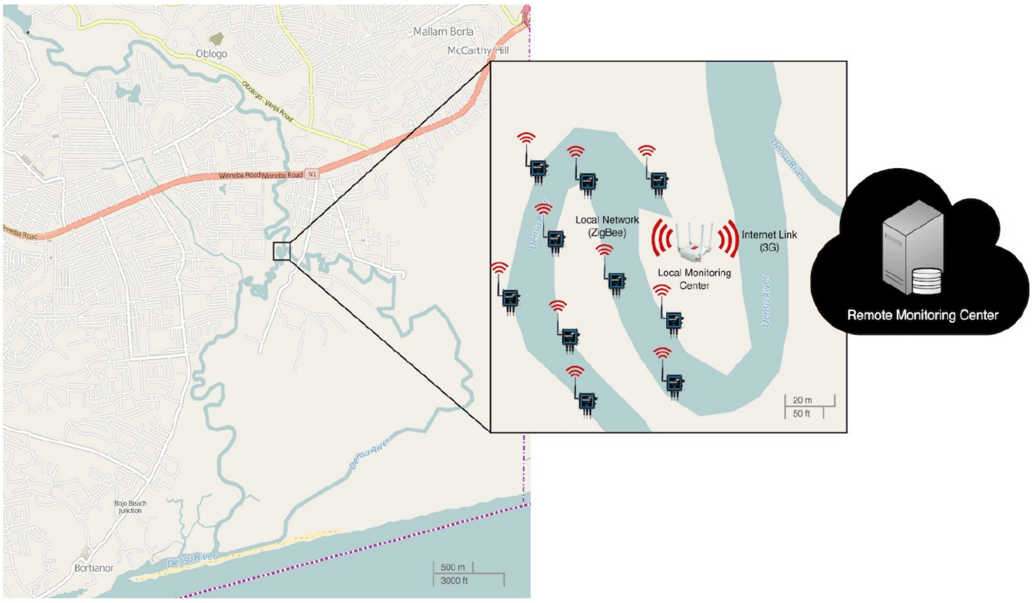


Figure 1. 4 Static sensor nodes deployed in a river

Researchers have different ways of approaching the monitoring of freshwater sources to have first-hand information when contaminants are detected because water quality changes at different times. In static WSNs for WQM, the sensor nodes are placed along the freshwater path or inside the freshwater to monitor different water quality parameters. The sensor nodes send the measurements obtained to a sink node and then to the Internet for data analysis and reporting. In static sensor networks (see Figure 1.4), node placement is challenging since coverage holes are likely to be created [45]. Depending on the application objective, the positions of the nodes could be optimized based on the detection time and the monitoring region [44].

In WQM networks, static nodes are fixed to the river/lakebed to collect data and transmit the data to a sink placed somewhere at the bank of the freshwater source. For example, the InWaterSense project in Kosovo deployed a WSN to monitor water quality parameters and transmit the data to a remote server via a GPRS network [37]. In the Savannah River in the southeastern USA, dissolved oxygen and temperature data was collected using intelligent river sensors for water quality analysis [38]. In Brazil, a reliable environmental sensing standard based on WSNs was adopted to monitor river depth [40].

In Iraq, a system to monitor the water quality in fish farms was designed and implemented. Sensors adapted in this projected included turbidity, temperature and humidity sensors [39]. Finally, in Kigali, a WSN for WQM and control was implemented at the Lake Victoria basin to detect pH, dissolved oxygen, temperature, and electrical conductivity. The sensors collect data and transmit to a web-based portal and a mobile phone platform [46].

## 1.4. Mobile Sensor Nodes for WQM

In mobile sensor networks, sensor nodes can move within an area of interest to sense environmental parameters. They may connect dynamically with static sensor nodes within the monitoring area to transfer data to a central office [44]. The inclusion of waterproof mobile sensor nodes in WQM makes it possible to cover a wider area as well as monitor the pollutant concentration downstream. Therefore, the use of mobile sensors in WQM provides a better readings/results of pollutant distribution and overcomes the coverage-hole problem created by static sensor networks. In Mobile Wireless Sensor Networks for WQM, sensors may be released at a particular location at any given time to travel in the direction of the water-flow to reach the desired final destination [47], [48].

Mobile sensors deployed in a river can be assumed to travel at the velocity of the river, and this can either be constant or with rapid variations depending on the type of river [48]. A mobile sensor completes its travel when it reaches a dead-end or the destination. When a contamination occurs in a river, it is assumed to spread downstream overtime and be carried along with the river flow. A mobile sensor which is carried with the river flow is therefore able to track the concentration of contaminants with time and track the location where the measurement was taken. Sensors deployed in a river are subject to varying degrees of turbulence and hence, may take different routes and time to arrive at a designated point when they are released at any given time and location. This implies that the mobile sensor nodes travel down the river path with varying velocities [48].

In [44], mobile sensor nodes have been implemented in water distribution networks (WDNs) to measure water quality and detect leakages in pipes to ensure a clean water supply and avoid wastage of water due to leakages in pipes. A prototype wireless sensor network system known as TriopusNet is designed to automatically monitor water in pipes [49]. TriopusNet was designed to cover sensing areas with fewer sensor nodes, maintain network connectivity among the mobile sensor nodes, employ a sensor node replacement algorithm to replace nodes whose batteries are depleted and ensure no disconnects in the network by releasing a fresh node to keep the network connectivity. In [49], the authors presents PipeProbe, a mobile sensor system that determines the spatial topology of pipelines hidden behind walls by dropping small sensor capsules at the source of the water flowing into the pipelines. PipeProbe moves in the pipelines and gathers measurements (i.e., pressure and angular velocity) for spatio-temporal analysis. Mobile sensor nodes support water distribution networks (WDNs) to monitor flow and other parameters in pipelines. Other implementations of mobile sensors for monitoring water distribution in pipes can be found in [47], [48].

## 1.5. Problem Formulation

In WSNs, sensor nodes are mainly battery-powered, and for monitoring water quality in freshwater sources, the sensor network should be able to operate for a long time without battery replacement. Energy is of major concern because all the components (i.e., sensing unit, transceiver unit and power unit) in the sensor node consumes energy [50]. In the past decade, there has been a growing research interest aimed at designing models and communication protocols to extend the lifetime of WSNs [51], [52]. In general, a sensor node's energy is consumed during packet transmission, packet reception, sensing, data processing and aggregation and even when the sensor node is put into sleep mode. It is a well-known fact that the node consumes most of its energy during data transmission activities when compared with other activities such as environmental sensing, data processing and aggregation [5], [50], [52].

Consequently, the continuous depletion of a node's energy will eventually run down the battery power. When a node's battery runs out of power, it remains dysfunctional and may affect the operation of the entire network. In particular, the network loses connectivity among nodes and eventually fails to transmit data. However, in WQM, the peculiarity of the deployment environment makes it nearly impossible for node's battery to be replaced. In this dissertation, a careful but detailed study has been carried out to review various contributions proposed in the literature towards decreasing the energy consumption rate, thereby improving the network lifetime. The dissertation also proposes and implements a novel approach towards mitigating the energy consumption rate by dynamically adjusting the transmit range of a node, thereby reducing the energy required to transmit data.

### 1.6. Dissertation Objective

In this dissertation, a novel adjustable transmission range algorithm for energy saving is proposed. The new algorithm considers the position of the sensor nodes and calculates the Euclidian distances between client nodes and their neighbor nodes and client nodes to sink nodes. The network lifetime maximization problem works using a greedy algorithm. The goal is for the client nodes to choose different transmission ranges to save energy and improve their lifetimes.

The dissertation proposes a lifetime maximization algorithm with an adjustable transmission range scheme. The adjustable transmission range scheme checks the distance between nodes during packet transmission and reception. Based on the distances between these nodes, the transmitting node chooses the appropriate minimum or maximum distance with which the data packet will be transmitted to maximize the network lifetime. The adjustable transmission range algorithm can maximize the node and network lifetime and optimizing the energy consumption of the entire network by considering the Euclidian distances between the nodes and the position of the node. The transmission range adjustment algorithm further aims at adjusting the transmission ranges, thereby reducing the energy budget of transmitting data packets to neighbours and the sink to maximize the network lifetime. The appropriate distance is chosen so that minimum energy will be consumed.

## 1.7. Main Contributions

In this dissertation, sensor nodes that can measure single and multiple water quality parameters are placed at an initial location within the water body. The sensor devices measure physical, chemical, and biological parameters of the water. These data are transmitted to a remote monitoring site for analysis and evaluation for long-term monitoring of the water body. A fundamental limitation of sensor nodes is their energy constraint leading to shortened network lifetime. This dissertation proposes a new solution to improve the network lifetime of sensor nodes in a moving water body based on automatic adjustment of the node transmission range.

In the first part of this dissertation, we start with a systematic review of current trends in water quality monitoring using wireless sensor networks and future developments. This top-down study surveys the different water quality monitoring approaches ranging from traditional manual approaches to more advanced technological approaches. In addition, this specific contribution highlights recent advances in the design of sensor devices, data acquisition procedures, communication and network architectures, and power management schemes to maintain a long-lived operational WQM system.

The second part of the study also provides detailed discussions on the energy issues in WSNs by emphasising the energy management schemes and energy consumption techniques. After that different approaches to addressing the energy concern are presented. Energy approaches related to energy harvesting techniques and protocol management techniques are highlighted in this section. Moreover, the choice of the methodology and its justification, as well as the performance metrics, are also presented in this section of the dissertation.

The third part of the study provides detailed discussions on Wireless Sensor Networks in environmental monitoring applications. In this same part, a description of the energy consumption challenges in WSN, the deployment environment, mobility models, and the detail description of the network simulation adopted for modelling the network scenario in this dissertation are presented.

The fourth part of the study highlights the network maximisation techniques with an adjustable transmission range.

In the fifth part of this dissertation, a new distance-based energy aware routing protocol is proposed to extend the network lifetime based on the transmission range adjustment technique. The distance between nodes has a significant impact on the energy consumption of the nodes, as the energy expended in transmission is proportional to the distance between the communicating nodes. The algorithm proposed in this work considers the actual separation of the nodes and adjusts the transmission power to achieve optimal performance of the network. Also, the position of the mobile sensor nodes is exploited to determine the route for data packet transmission. In this case, the nodes in the network are location aware as they move in different directions in the freshwater body. The AODV routing protocol is implemented in such a way that the routing tables keep track of the position of each node in the network. Finally, to assess the performance of the approach discussed in this dissertation, a prototype implementation is designed using sensor nodes from Libelium.

The sixth part presents the experiences with Experimental Testbed of WSN for WQM.

## 1.8. Definition of Terms

**Definition 1** Sensor Node: A sensor node $n_i$ is a node that has detected an event for forwarding to the sink node $s_k$.

**Definition 2** Region of Interest (RoI): The deployment region where mobile or static sensor nodes are placed to monitor specified phenomenon within the region. The region of interest is the area that needs to be covered.

**Definition 3** Transmission Range: The maximum distance a node can send data to neighbour node ($n_r$) or the sink node $s_k$.

**Definition 4** Transmission Route: The path a node takes to reach the sink node.

**Definition 5** Neighbour Node: The neighbour node ($n_r$) is the next-hop node chosen by $n_i$ as the best route to reach node $s_k$ based on $n_r$ current location information. Sensor node $n_i$ obtains the location information of all $n_r$ nodes based on the information in its routing table in the quest to reach the destination node $s_k$.

**Definition 6** Sink Node: Aside from the sensor nodes (i.e., $n_i$ and $n_r$), a sink node $s_k$ may be deployed as static or mobile. All the nodes at the beginning of the simulation obtain the location information of the sink. The reception rate of the sink remains the same, and the positional algorithm is used to determine the exact location of the nodes. When a mobile node is used as a sink node it possesses three main problems: a) the near-sink problem; b) the far-sink problem and c) the trailing-sink problem.

## 1.9. Outline of the dissertation

This dissertation is organised as follows. In Chapter 2, a review of WSNs for WQM applications with emphasis on the general WQM architecture and WSN-based WQM architecture are described. Chapter 3 proposes and evaluates energy efficient techniques that aim to improve the network lifetime in WSNs and provides the methodology of this dissertation. The proposed protocol dynamically adjusts the transmission range of nodes thereby reducing the overall transmit power required for data transmission. Chapter 4 presents a network lifetime maximization technique for improving the wireless sensor network performance. In Chapter 5, a variant of the AODV routing protocol that takes into consideration the position of the nodes to make routing decisions is presented. Chapter 6 presents a performance analysis of an experimental testbed deployed at the Weija Dam in Accra. In addition, the chapter presents experiences gained through the deployment of WSNs for real-time WQM. Finally, in Chapter 6, a real-time implementation of an energy-efficient online river monitoring application is provided based on the architecture presented in Chapter 2.

# CHAPTER 2

# REVIEW OF WATER QUALITY MONITORING USING WIRELESS SENSOR NETWORKS

## 2.1. Introduction

Quality water is indispensable for existence on this planet. Without freshwater, life on earth would be extremely difficult. The water quality monitoring process is crucial in safeguarding water from contaminants which result from animal and human activities. There are three (3) different approaches that have been used for monitoring water resources: Lab-Based Approach (i.e., a traditional approach performed manually), In-Situ Approach (i.e., manually performed in the traditional manner), and Wireless Sensor Network-based WQM approach.

Beginning from the 1960's to early parts of the year 2000, Water Quality Monitoring primarily depended on traditional approaches for sampling and evaluating water. In this approach, individuals travel to the freshwater (e.g., river, lake, etc.) sites to collect water samples for evaluation. The samples collected are physically transported to research labs for possible evaluation of contamination levels and the amount of physical and chemical parameters in the water. Presently, researchers in the area of WSNs for WQM applications have focused their discussions referencing the general WQM framework. The general WQM framework includes a description of the goals and approaches, and explicit procedures employed for freshwater evaluation and interpretation.

In the traditional methods, the design stage includes obtaining the number of the quality parameters to be used in the analysis, the areas allocated for the sampling, and the number of times to perform the sampling (i.e., the sampling frequencies) [53]. There are several shortcomings in the traditional WQM systems. These shortcomings are due to the variability in the water source over time, physical parameters, chemical parameters and levels of microbial [54]. In addition to these limitations, other specific errors are likely to hinder the successful implementation of the traditional approaches for measuring water quality. These errors consist of human error that arise during the process of collecting the samples to the laboratory (e.g., misidentification errors); data analysis and recording errors; the errors added during the time the sample was collected and transported from the site (especially the transportation apparatus); the presence of reagents and other possible environmental contamination; errors introduced due to equipment or instrument malfunctioning; and finally errors introduced due to variables such as temperature. Apart from the errors presented above, data errors during data use, data manipulation, and data reporting (such as statistical, round-offs, and omissions) may be discovered in the measured values at the laboratory [55]. In order to overcome the limitations in the traditional manual methods for monitoring water sources, new technologies were introduced in the early parts of the year 2000. New sensors that used laser technology, fibre optics, biosensors, Microelectronic Mechanical Systems (MEMS), and optical sensors were particularly introduced to support the monitoring process. These new sensor technologies were capable of detecting different water quality variables in-situ [56], [57]. Also, the introduction of advanced computing devices and telemetry electronic technologies in the year 2000, served as a breakthrough in the industry to support the monitoring process for easy acquisition of data in the monitoring processes. Furthermore, new approaches in the way of collecting data with the use of satellite imagery technologies supported the retrieval of data at sampling locations were also proposed. These approaches were capable to assess water quality parameters from a remote location [57]. Advances in software architectures and the introduction of simulation and visualization tools aided researchers to visualise the parameters over the web to monitor most freshwater sources and marine water sources with much simplicity and clarity [58]. The introduction of these newer technologies and software architectures enhanced the overall data acquisition process and reporting in the conventional methods of measuring quality parameters in WQM. These newer systems will provide a shift from fixed sampling stations to automated monitoring stations. With these technologies, water sources could be monitored constantly or occasionally to detect contaminants for further analysis. The automated approach is widely used in recent times [57], [59]–[61].

Advances in Water Quality Monitoring (WQM) systems came with the introduction of sensor devices equipped with wireless transceivers in early 2000. These devices when connected forms a Wireless Sensor Networks (WSN) that are capable of measuring and transmitting water quality parameters wirelessly. The use of WSNs for WQM has gained increasing interest from researchers. This is partly due to the improved wireless communication technologies and the miniaturization of the microcontrollers. WSNs supports the capturing, analysing, and transmission of environmental phenomena. Hence, WSNs has proven to be of a useful tool when gathering ecological data in modern times. WSNs for WQM-based applications is particularly attractive because wireless sensor nodes are of low-cost. WSNs provides a cost-effective solution and can acquire and processing data at many distributed sampling locations. WSNs can communicate with low-powered wireless communication technologies and techniques, which facilitates the acquisition of multiple data for decision-makers from several remote sensor devices promptly.

WSNs for environmental monitoring has been reported as the most convenient tool to overcome the challenges associated with the use of the traditional water quality monitoring techniques [5]. The technique can thus replace the expensive technologies used in the laboratories for water quality analysis. The lab-based equipment become old, out-dated, and outmoded over time rendering them inefficient. Wireless sensor networks are cheap, capable of performing an onsite investigation. The use of WSNs takes away transportation of field agents to collect water samples from the field to the research centres. The use of WSNs thus saves the time of human agents employed for site visits to collect water samples and the cost of procuring laboratory equipment and consumables. In designing and deploying WSNs to monitor water sources, the following factors are to be considered as reported in [5]. Researchers should evaluate the sensing range of the wireless devices, the preference of the underwater communication technologies, typically acoustic and radio, signal processing, and the physical arrangement of the sensor nodes.

In recent times, there have been many attempts by researchers to use wireless sensor networks to monitor different phenomena in the environment. For example, oceanographic/marine environment monitoring and sensing [5], [62], [63], water level sensing [5], [64], water pipeline monitoring [5], [65], fish farming monitoring [5], [66], and residential water management [5], [67]. Characteristics that distinguish various water monitoring projects and applications are primarily related to the goals set for the project and the dimension of the water targeted for monitoring. In these projects, different network topologies may be required depending on the application requirement. Also, such applications call for the adoption of specialised wireless sensor devices that can measure various water quality parameters. The total wireless sensor devices sufficient to cover the region of interest and the inclusion of specialised operational technologies is an essential requirement in the adoption process for monitoring water sources.

## 2.2. Classification of Water Quality Monitoring

Water monitoring represents a general term to indicate the action of evaluating the water condition over time. The monitoring is performed using standardised measurement to observe the aqua environment for trend analysis. According to [68], Water Quality Monitoring (WQM) is the quantifiable measure of water quality parameters over time to guarantee that safe and clean water is delivered to consumers using discrete, mechanical, and automated methods. In the automatic WQM process, wireless sensor nodes are placed in water to sense and identify freshwater and marine water quality, for example pH, DO, Calcium and others. Ocean/Marine Environment Monitoring requires keeping track of physiochemical, and biological variables in the ocean to monitor contaminants, assess changes in the environment, and monitor sea level over a period. Water Monitoring considers both fresh water sources (Water Quality Monitoring) and Ocean Environment Monitoring. The key difference is that WQM is performed to guarantee safe and clean water among freshwater sources whereas marine/ocean monitoring focuses on detection of climate changes or pollution of the marine environment, which mainly affects human and animal habitat [68], [69]. The thesis aims at proposing efficient WNSs deployment strategies for monitoring freshwater sources as well as optimizing the communication bandwidth while maintaining acceptable battery energy consumption.

### 2.2.1 Monitoring Freshwater Sources with WSNs

Freshwater sources comprise of rivers, wells, lakes, underground water, surface water, ponds, etc. These freshwater sources are the main source of drinking water and for most human activities (i.e. washing, farming activities, etc.). As such Governments have instituted Ministries and Agencies whose mandate is to ensure that the freshwater sources are safe for human and animal consumption as well as farming and industrial activities [68], [70]–[74]. Freshwater monitoring is also used in reference to evaluating industrial or commercial activities [75]. WQM systems focus on applications related to drinking water, wastewater treatment, and aquaculture management [76]. Freshwater monitoring can be performed on moving freshwater sources (e.g. rivers) and static freshwater sources (e.g. well, lake etc.). With moving water sources, the sensor nodes can either move freely or they are anchored to buoy, wood, tree or any other object to allow it to move at a certain point. Freshwater monitoring may also differ from one source of water to the other based on the depth of the river to which the monitoring process is to be conducted. Conducting studies in shallow/surface or deep freshwater sources will require different sensor technologies [68], [74], [77]. In freshwater quality monitoring, the wireless sensor nodes may transmit data packets using radio transmission technology for surface monitoring station. For deep freshwater sources, the monitoring may require wireless sensor nodes to be immersed underwater. The communication architecture required in such instances may be acoustic. For example, the LakeNet project in [78] used an acoustic communication technology for underwater communication over wireless sensor nodes. The testbed of the LakeNet project was carried out at the St. Mary's Lake. The project comprised of embedded wireless devices which formed a wireless sensor network to measure physical water quality parameters at the deployment site.

### 2.2.2 Ocean/Marine Sensing and Monitoring

Marine Environment Monitoring (MEM) applications have been designed in recent times to observe different phenomena in the oceans. MEM is also referred to as oceanographic or underwater monitoring. MEM or Oceanographic monitoring is used to determine the amounts of various contaminants within the ocean environment, and appropriate models are designed to provide information about the different ocean parameters. MEM also includes monitoring marine fish farming [62], [63]. Classical methods such as using ships and fixed buoys placed at the bottom of the ocean are used mainly for measuring marine parameters. Other methods include using satellites to measure the temperature and the sea level [69].

Parameters measured in ocean monitoring are classified into physio-chemical parameters such as Nitrate, DO, pH, temperature, pressure, salinity, water, turbidity, and chlorophyll. In this type of water monitoring, different wireless communication technologies are adopted for data transmission on land and acoustic communication is used for underwater communication. Apart from the classical methods, WSNs have been employed to monitor the marine environment [5]. The main factors when deploying WSNs for MEM include a combination of radio/acoustic communication technologies, network topology, routing mechanisms, and power management of underwater sensors. Sensor platforms are designed to meet requirements of specific sensor applications. The communication may be done using an off-shore base station or a fixed ship may be used as a base station to communicate through a satellite [69].

### 2.2.3 Attributes of Water Quality Monitoring

In this dissertation, we outline the key attributes of Freshwater Environment Monitoring (FEM) that makes it different from Ocean/Marine Environment Monitoring. The attributes/factors that differentiate between these two water quality monitoring environments relates to the size of water source, network density, network mobility, energy consumption, network topology, data acquisition and measurement parameters, and the cost of the nodes, application of appropriate treatment technologies. In Table 2.1, we provide a brief comparison pointing out the differences between these attributes of FEM and MEM.

Table 2. 1 Comparison of FEM and MEM, Adapted from [5].

| Attribute | Freshwater Environment Monitoring (FEM) | Marine Environment Monitoring (MEM) |
|---|---|---|
| **Size of water source** | Forms about 2.5% of all the water on the surface of the earth | Forms about 97.5% of the water on the surface of the earth |
| **Network density** | Smaller Area of coverage but many nodes can be deployed | Larger area of coverage but fewer nodes maybe deployed |
| **Network mobility** | Mostly Static Nodes | Mostly Moving Nodes/Self organized Nodes |
| **Energy consumption** | Low energy usage | High energy usage due to communication distances |
| **Network topology** | Usually predetermined | Unknown/ Self organized network |

| | | |
|---|---|---|
| **Data acquisition (purpose)** | Data sent to consumers to alert them on condition of the water | Assessment of status or marine conditions across a specified area to plan pollution control policies |
| **Relevant Measurement parameters** | Chemical contaminants such as hardness, alkalinity, and chemical oxygen demand COD, pH, temperature etc. | Physical contaminants, for example, humidity, temperature, wind speed and direction.<br>Chemical contaminants, for example, pH, salinity, turbidity, nitrate, chlorophyll, and DO. |
| **Coverage (Communication type)** | Shorter distances (radio frequencies) | Longer distances (acoustic waves) |
| **Cost of sensor node** | Cheap | Expensive |
| **Application of appropriate treatment technologies** | Performed to obtain safe drinking water | Performed to assess marine health and safety levels |

### 2.3. WQM Physio-Chemical Components in Water Resources

Over the years, researchers have given much attention to discovering different ways of identifying physio-chemical parameters in water resources. In general, the measurements of physio-chemical parameters in water sources are used to determine the water quality. In this section, an overview of some physio-chemical parameters of interest are highlighted. These quality parameters have been recommended for measurement by most credible agencies and government institutions such as USGS. The section further describes the way wireless sensor devices can be used to measure the WQM parameters. A well-studied into recent literature revealed the results shown in Table 2.2. The table specifies how each quality parameters required in FEM or MEM, their description, standard values as enlisted by the World Health Organization (WHO) on their websites. It also makes references to specific projects around the globe that have used these values as a yardstick to confirm values obtained from their experimental studies. The threshold values set for each parameter is to ensure that the quality parameter shows researchers and consumers the safety limits available for freshwater sources [79]. In events where the quality parameter falls outside of the safety boundaries set by WHO, the system is capable to send warning triggers to stakeholders and consumers.

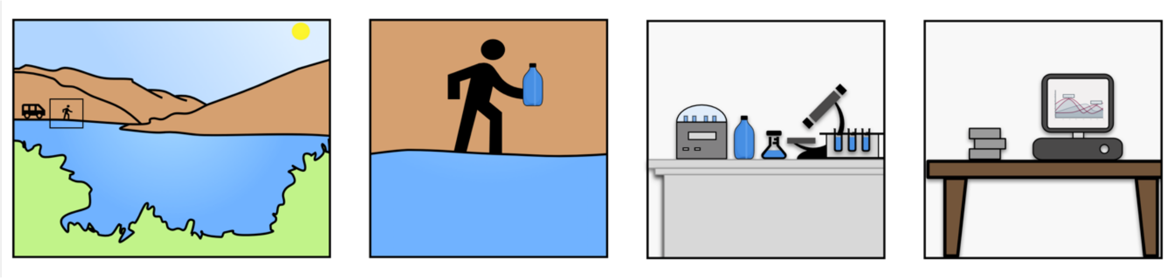
Table 2. 2 WHO standard values prescribed for drinking water, Adapted from [5], [79]–[81]

| **Measurement Parameter** | **Description** | **WHO Standard Values** |
|---|---|---|
| **pH** | pH is described as functional hydrogen-ion content, i.e., pH is equated to −log [H+] | 7–8.5 (preferably ≤ 8) |
| **Turbidity** | Turbidity is quantity of solid matter placed in water that disturbs the movement of light | 1–5 NTU |
| **Dissolved oxygen (DO)** | Total of dissolved oxygen | 5–6 mg/l |
| **Residual chlorine detection (RCD)** | Total of chlorine (the remaining chlorine after chlorine-based freshwater purification) | 2–3 mg/l |
| **Calcium Hardness** | Hardness of Calcium is the quantity of calcium salts that reacts with other substances. This reaction reduces the efficiency in cleansing procedures) | 75–100 mg/l |
| **Temperature** | The level of hotness or coldness refers to temperature. Temperature value affects the DO values measured in water | Temperature for drinking water supply is around 15◦C |
| **Fluoride** | Salts in fluoride combine with other minerals in different soil mediums and rocky areas | 4mg/l and 2mg/l in soil/rocks |

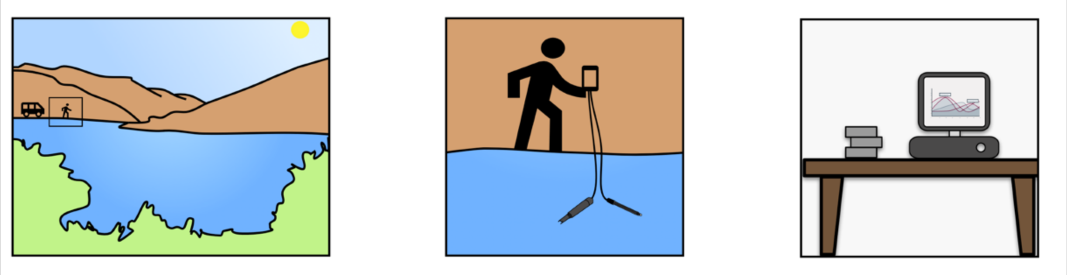
| | | |
|---|---|---|
| **Conductivity (also Salinity)** | The potential of water solution to transmit an electrical impulse (a test for the amount salt) | 25◦C |
| **Total Dissolved Solids (TDS)** | The quantity of inorganic levels of salinity content and other smaller organic matter in water | 600 mg/l – 1000mg/l |
| **Magnesium Hardness** | The total of magnesium of levels of salinity (this brings an unwanted flavour and discolour clothes) | 50 mg/l –100 mg/l |
| **Manganese** | Mineral occurs in a natural manner in rocks near riverbanks and the different soil mediums in the area. Manganese is a normal component of person's food | < 0.1 mg/l |
| **Sodium** | Sodium is an important mineral found in freshwater sources. Sodium is in referred to as salt. | ~ 200 mg/l |
| **Hydrogen sulfide** | Created or manufactured by sulfur chemical and sulfate chemical reducing bacteria which happens in a natural manner in freshwater sources | 0.05–0.1 mg/l |
| **Oxidation reduction potential (ORP)** | It is the capability to send or accept electrons from chemical Compounds reacting together. ORP has the potential to alter the length of time some bacteria spend in freshwater. | 650–700 mV |

### 2.4. Advances in Water Quality Monitoring Systems

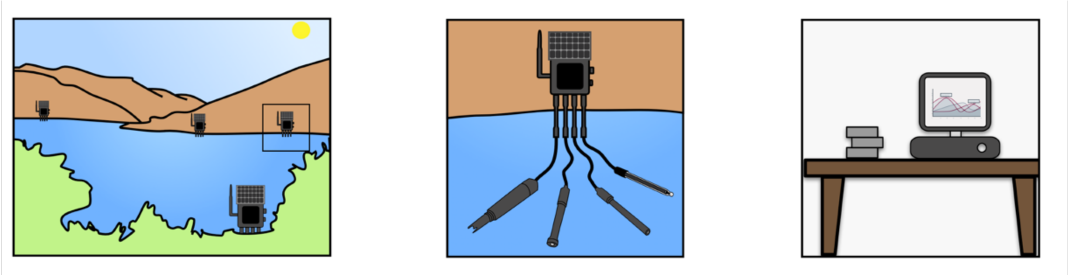
Water Quality Monitoring has seen several advances in the past years, many of which has been highlighted in earlier sections. This section provides thematic insights into how WQM systems have evolved over the years. There has been a shift from two traditional manual (TM) systems. First was the manual approach in which results of water parameters were determined in the Lab-Based (TMLB) and then the monitoring technique based on In-Situ (TMIS). From these two monitoring approaches emerged the most recent monitoring approach referred as Wireless Sensor Networks (WSNs).



(a) Traditional Manual Lab Based (TMLB) WQM approach



(b) Traditional Manual In-Situ (TMIS) WQM approach



(c) Wireless Sensor Network-based WQM approach

Figure 2. 1 Evolution of Water Quality Monitoring systems.

In the past, the water quality test flow includes field agents go to the water site and collect water samples in bottles and other containers. The collected water samples are transported to water quality testing laboratories. The laboratory technicians conduct testing and analysis on the sample to detect the presence of bacteria, chemicals, and microbial pollutants in the water sample [53], [56], [90]. This process is clearly shown in Figure 2.1. While the TMLB shown in Figure 2.1a technique provides some WQM data, the data generated is woefully inadequate although this is the main approach used many years in most parts of the world. TMLB has been known to have many shortcomings, which includes: 1) The use of special equipment, chemical reagents and the high cost associated with the hiring and training of field agents.; 2) TMLB lacks quality control measures. The loss of these quality control measures increases the time spent in the entire operation. There is also too much human involvement in TMLB from start of the process to finish. Laboratory results may be staled and inaccurate since they are subjected to human interpretations; 3) The analysis of the sample is in most instance, based on archaic or outdated machineries and tools [55], [56]. Thus, the traditional approach is costly in terms of resource investment, time, and effort in the entire process in TMLB as a monitoring system.

In addition, the results obtained from samples collected may not reflect the prevalent water conditions. These challenges influenced the drift towards a more accurate, sustainable, and cost-effective water monitoring quality approaches. In other words, the design of in-situ sensors was a suitable option to measure contamination in water bodies on the field and in real-time. These special sensors led new paradigm where sensors were used along the pure traditional method to monitor water parameters.

Traditional Manual In-Situ (TMIS) WQM approach became well known because most of the challenges discussed in TMLB were addressed in TMIS. Figure 2.1b shows the operation of TMIS. Here, the field agents may perform two activities. First, send the in-situ sensors to the location they want to conduct the experimentation. At the site, the field officers use the in-situ sensors to gather or collect measurements in real-time from specific locations in the river using specific sensor devices. In recent adoption of TMIS, researchers and developers adopt TMIS for variety of applications. For example, the Micro Electronic Mechanical Systems (MEMS) which are sensors used for recording water quality parameters at a chosen site for experimentation [56]. MEMS sensors employ aircraft or satellites to record pictures for evaluation. MEMS sensors finally employ optical sensors to monitor aquatic ecosystem in-situ [92]. Although TMIS has shown strength over TMLB systems when it comes WQM applications, the technique still has some challenges. TMIS is capable to measure and record quality parameters on site but does not resolve the challenge of continuous uninterrupted evaluation of water quality parameters. TMIS does not also transfer the data to any other location for future use. In addition to the problems with TMIS, it lacks also a critical aspect in the monitoring process which is feedback control. TMIS mostly do not permit feedback control making it impossible for new data to be attained in response to earlier data collected for analysis.

To this end, we have shown clearly that the two main approaches (TMLB and TMIS) discussed have challenges when adopted for water quality monitoring projects. To overcome the challenges in both traditional methods, a recent and a modern approach with capabilities is introduced in as a smart alternative for water quality monitoring. The introduction of Wireless Sensor Networks came with the following design objectives: 1) capable to detect contaminants in real-time at the deployment location; 2) capable to provide distributed sensing within a wider area of interest and provide local or analysis on the sensor node and also capable of collecting data from other distributed sensors; 3) attain high responsiveness and high-level of selectivity; have a longer lifetime whilst in operation; and 5) provide sensors with autonomy, self-configurable capabilities, robust, self-powered and perform data processing instantaneously. With these capabilities of WSNs they are considered as the best choice for environmental monitoring applications due to wide range of advantages it brings to fore. The operation of WSNs have been illustrated in Figure 2.1c. Wireless sensor nodes are autonomous and do not require human intervention to regulate. They are robust to the extent that they perform well in very harsh environments [93], [94], [95]–[97].

### 2.4.1 Operation of TMLB in WQM Applications

In this section, a detailed analysis of TMLB is discussed. The framework for data capturing and evaluation of the TMLB approach is depicted in Figure 2.2. In this approach, different laboratory tools are employed to capture and measure pollutants in freshwater. As shown in Figure 2.2, the TMLB approach for water quality monitoring is usually broken down into six stages. These stages are: 1) design stage; 2) sample collection stage; 3) laboratory evaluation and analysis; 4) data handling; 5) data analysis and evaluation and 6) information processing and utilization [53], [90].

At the design stage, three activities are considered. Firstly, the sampling locations are identified. Secondly, the water quality parameters for monitoring which includes the laboratory-based sensor devices for measuring pollutants are selected. Finally, the rate of collecting the water samples that guarantees precise and accurate detection is determined [5], [98].

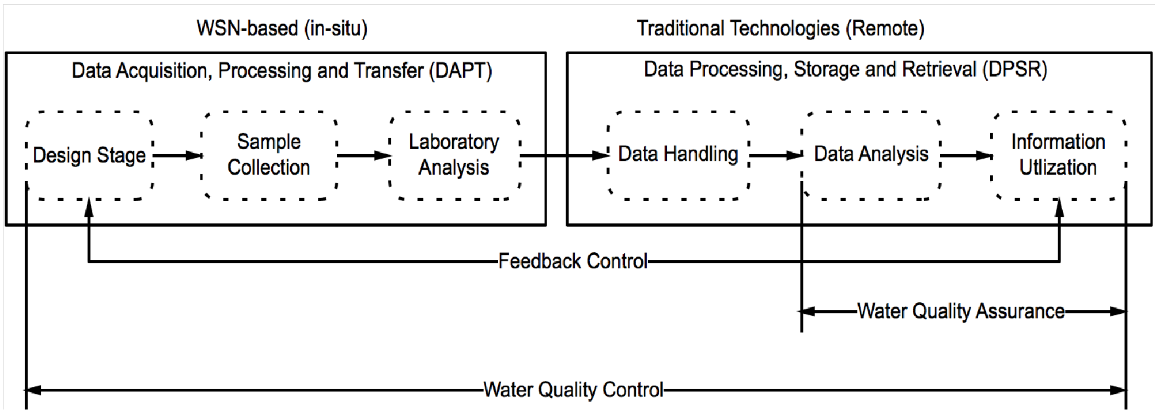


Figure 2. 2 Traditional water quality monitoring framework [53].

The next stage in the traditional monitoring phase is sample collection stage. The *sample collection stage* entails the determination of specific sampling techniques. It also involves the final measurement performed at the deployment site/location. The right technique is required when transporting the sample to the laboratory for critical evaluation and analysis. It is indispensable to note that each of the variables requires a sampling selection method. These sampling selection methods or procedures differ from one parameter to the other and may not be the same from site to site [5], [99].

The principal activity in Figure 2.2 is the *laboratory analysis*. The laboratory analysis stage in the monitoring process consists of several procedures (i.e., physical, chemical, and biological). Particularly, the essential operations at the laboratory analysis phase include operational methods, quality assurance control, and data recording [5]. These approaches together defined the required water quality parameters at the design stage.

The second compartment in Figure 2.2 illustrates three main activities in the traditional method. These are mainly concerned with activities after the data has been transferred to the laboratory. These activities include handling the data, analysing the data and using the resulting information [5], [53], [90]. To achieve the set goals for the monitoring programme, the guidelines in Figure 2.2 (i.e., design stage, sample collection, and laboratory analysis) should be followed conscientiously.

This compartment in the entire process depends on the results from the components in the first compartment. In principle, Water quality monitoring is intended to take data from the source, obtain precise information from this data and to use the information to achieve specific goal by companies that supply freshwater efficiently [5], [90].

### 2.4.2 Operation of TMIS in WQM Applications

Wireless sensor devices are used to monitor specific variables in water quality projects. The advances in the TMLB to TMIS sensors technology brought great improvements in the monitoring process. Examples of TMLB sensors on the market today are ion-sensitive electrodes, mass spectrometry, potentiometric, conductometric and amperometric sensors.

TMIS-based sensors have the capability to measure in real-time from the deployment location. TMIS-based sensors are accessible today on market. The most prominent ones are electromagnetic wave sensors, biosensors, lab-on-a-chip sensors, fibre optic sensors, infra-red (IR) sensors and fluorescence detection [5], [100], [101].

Table 2. 3 Data processing in a WQM system guideline. Adapted from [5]

| **Notation** | **Description** |
|---|---|
| Preliminary data evaluation | The purpose of preliminary data evaluation is to authenticate the accurate transfer of raw field data to the database and to assess and identify erroneous data. A diversity of formats is available to store raw field data, subject to the recording sensor node and the means of retrieving data from the recording sensor node. |
| Apply data corrections | The application of data corrections permits recorded data to be harmonised or adjusted for calibration drift and biofouling errors that occur between subsequent servicing visits. These are because of environmental or instrumentation effects, and variability in cross-sectional areas of the sensor devices. |
| Apply and evaluate cross-section corrections | If the values at the measuring location is not characteristic of the freshwater source, the point of measurement should be relocated to a measuring point that represents the cross-section. |
| Data Evaluation (final stage) | At the final data evaluation phase, the data record is reviewed and checked for corrections (i.e., making sure any required final revisions are done). When the review document is finalised, the data are verified for publication and rated for quality. |
| Record Computation | The record computation process verifies the data and overall report quality. Accurate field notes and calibration logs are essential in processing the record. |
| Record Review (Final Stage) | Review of a continuous water-quality record involves analysis of the tables of the measured field parameters. |

TMIS-based sensors require calibration in the laboratory before they are installed at a monitoring site. The in-situ sensors may be calibrated at the site. It is required that the data from the sensors be processed to ensure an acceptable quality by following procedures outlined in Table 2.3. It is expected that the data to be communicated to the stakeholders and public should be verified and formatted in a way that they can easily be accessed and interpreted. Researchers should preferably stipulate a standard graphical user interface (GUI) to present the data at the data reporting stage [79]. The United State Geological Survey (USGS) [2], [5], and the United Nations Global Environment Monitoring System (GEMS) are two notable organisations known for publishing much water quality data for public use [99]. Standard sensors for measuring the various water quality parameters are commercially obtainable from several manufacturers (e.g. Analytic Technologies [102], Technical Associates [102], CENSAR Technologies [103], Hach [104], In-Situ [105], Libelium [115], Scan [106], Technical Associates [107], YSI [108] and Zap Technologies [109]). In Table 2.4, some new water quality sensors commercially available and their capabilities are presented.

Table 2. 4 Water quality sensors and their capabilities commercially for measuring the water quality parameters. Adapted from [5], [58], [91].

| Sensor Model | Water Quality Parameter |
|---|---|
| ATI | Free Chlorine |
| Hach model A-15 Cl-17 | Free/Total chlorine |
| Hach 1720 D, WQ730, WQ720 | Turbidity |
| GLI Model PHD, WQ201, WQ101 | pH |
| GLI Model 3422, WQ-Cond | Specific conductance |

| | |
|---|---|
| Hach Astro TOC Ultraviolet /Process analyser | Total organic carbon |
| WQ401 | Dissolved oxygen |
| WQ600 | Oxidation reduction potential (ORP) |
| **Sensor Model** | **Water Quality Parameters** |
| Dascore six-sense sonde | Temperature, Specific Conductance, DO, ORP, Free Chlorine |
| YSI 6600 Sonde, 6820 V2, 600XL, WQMS | Turbidity, Temperature, Specific Conductance, DO, ORP, Free Chlorine, pH, Ammonia-nitrogen, Chloride, and Nitrate-oxygen |
| Hydrolab Data Sonde 4a | Turbidity, Temperature, Specific Conductance, DO, ORP, Free Chlorine, pH, Ammonia-nitrogen, Chloride, and Nitrate-oxygen |
| Smart Water (Libelium) | Turbidity, Conductivity, DO, ORP, pH, Temperature, Nitrates, Dissolved ions |

However, several researchers have focused on improving the sensors for water quality measurements. For instance, in [56], an overview of modern sensor devices is provided by the authors that was used for monitoring water quality, such as microelectronics mechanical systems (MEMS), optical sensors (OS), and bio-sensors, and discussed the benefits of these current in-situ sensor technologies over the traditional lab-based sensors. While these modern sensors present several advantages such as high sensitivity, excellent response time, and high selectivity, they are associated with some key limitations such as high rate of energy consumption.

Comparing the devices used in the traditional methods such as Ultraviolet sensors, spectrometry and ion sensitive electrodes to the modern sensor technologies, the latter requires electronic transducer unit which consumes additional power. Also, these sensors need routine maintenance to ensure their proper operation [56].

Recently, a low-cost autonomous optical sensor for monitoring a range of water quality parameters was designed by the authors in [92]. The authors developed a robust, easily deployable optical sensor that is simple to operate.

### 2.4.3 Wireless Sensor Network-based WQM approach

Wireless sensor nodes are the current generation of sensor devices for monitoring water quality parameters. They can measure water parameters in-situ, locally process and transmit the measured data. WSNs facilitate the automatic transfer of this data while in some instances provides a feedback mechanism to refine the granularity of data collection.  A wireless sensor node typically consists of the sensor unit, the interface circuitry, a processor, a transceiver system, and a power supply unit [110]–[112], as shown in Figure 2.3.

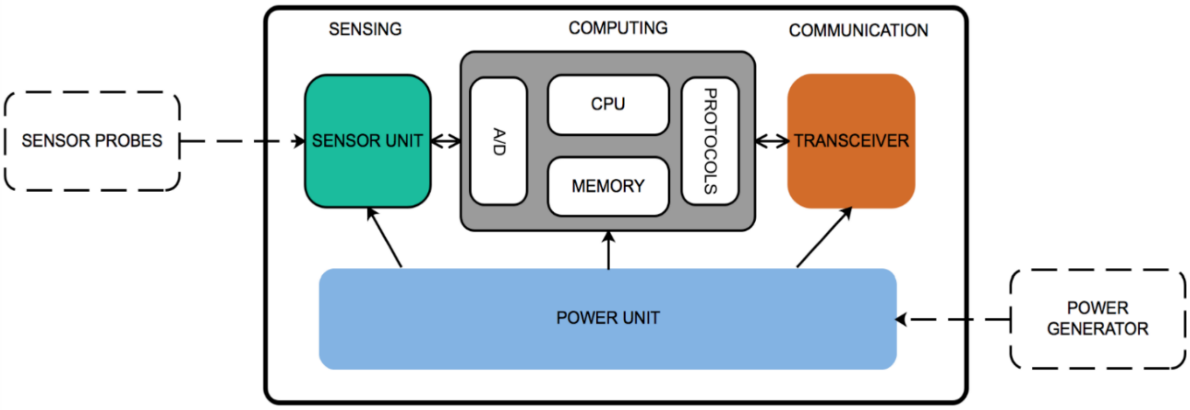


Figure 2. 3 Generic wireless sensor node hardware architecture

A number of commercially available wireless sensor nodes are available for measuring water quality parameters [5]. The wireless sensor nodes are intended to accommodate a diversity of situations, from short term or spot sampling of the water quality parameters to long-term, unattended monitoring and analysis [5], [113].

Table 2. 5 Wireless sensor nodes supported by specialized wireless sensor nodes. Adapted from [5].

| **Sensor Devices** | **Communication** | **Deployment** | **Advantages** | **Disadvantages** |
|---|---|---|---|---|
| Digital Videos | ZigBeeand CDMA | Uses three monitoring points along a water body (river) | Multi-hop, ability to monitor a large area. It is flexible and easy to extend to a three-layer architecture | Here data acquisition was not clearly defined |
| Automatic Underwater Vehicles | GPRS (multi-hop routing) | 3D grid of sensors | high performance was seen in the proposed algorithm | AUV navigates only in one direction |
| Fish Robots | Infrared, ZigBee, and GPS | Swimming pool testing with sonar localization | Sonar localization proved to be more efficient than GPS, it is an autonomous system | Battery operating devices with short lifetime |
| Battery operated miniboat | Wireless link (the type not specified) | Simulation studies | It is cheap to implement and to maintain | The Performance depends on some parameters. Battery operating devices with short lifetime |
| Buoys mounted with probes | Wireless and wired links (type not specified) | Simulation studies | Cheap to implement and maintain | Performance depends on several parameters |

| | | | | |
|---|---|---|---|---|
| Air boat | GPS | Experiments on a mire pool | Using grid sampling, the boat was able to obtain fine-resolution water-quality distribution maps | The design of the boat can be improved to reduce side to side oscillation. Complex to determine the optimal control parameters |

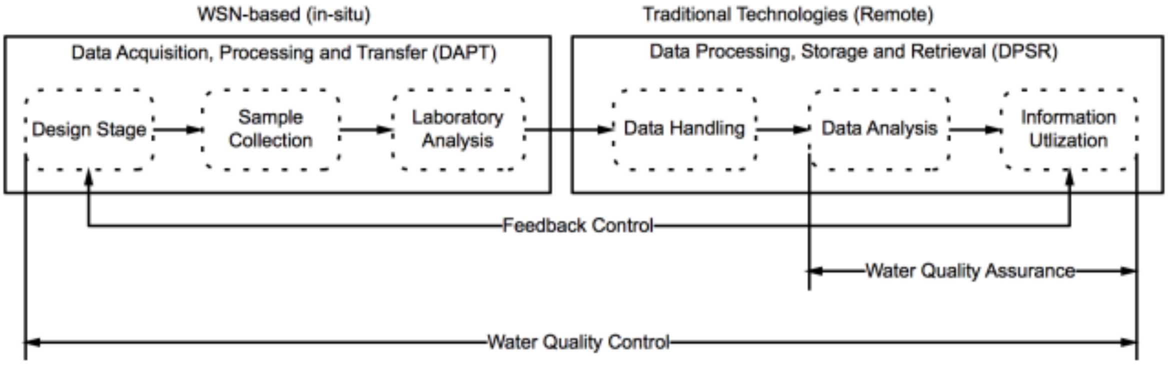
Wireless sensor devices commercially available are presented in Table 2.5. The sensors may be capable of measuring single or multiple parameters. The choice of single or multiple sensing sensor devices are dependent on the number of parameters intended to be measured in the project. The following studies proposed the use of specialized hardware devices to support the monitoring process. For example, fish robots [116], Autonomous Underwater Vehicles (AUVs) [115], mini-boats [117] unmanned airboats [118], and digital cameras [119].

## 2.5. Using WSN to Monitor Water Quality Parameters

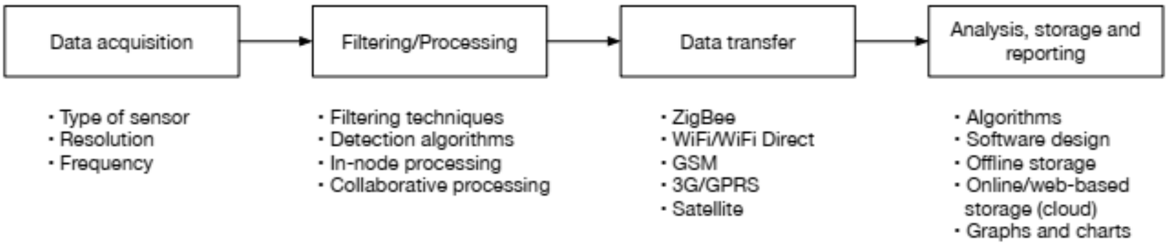
WSN infrastructure supports WQM projects in the following ways: WSNs enables the sensors to be placed in fixed positions to gather water samples continuously; measurements for water quality may be sent to an end-user for concurrent analysis; and end-user feedback influences the frequency of sampling in the event of more or fewer measurements [5], [79], [80], [90], [98]. Different techniques proposed in literature provides description of energy management, communication technology, and data processing in WSN-based WQM systems [5].

### 2.5.1 Framework for WSN-based WQM Applications

The traditional WQM framework presented in Figure 2.2 is categorized into two key activities, represented by Figure 2.4a and Figure 2.4b when implementing it in WSNs. The initial process is achieved in-situ by WSN and is comprised of activities such as Data Acquisition, Processing and Transfer (DAPT). In DAPT, the sensor devices are dispersed in or at the banks of the freshwater source. Local processing of sampled data has implications on the energy consumed by the sensor nodes. At the local monitoring station, the processed data is transferred through a long-range communication technology to a remote monitoring centre. The data may be stored in a database locally at the monitoring centre for evaluation by a user [5].



(a) Adaptation of the TMLB framework for DAPT in WSN.



(b) WSN pipeline for water quality monitoring.

Figure 2. 4 WSN-based WQM framework and relative sequence of operations, with examples of operation specific techniques

Systems that are used to primarily transfer data include VANETS and satellites. Data Processing, Storage and Retrieval (DPSR) operations is the final phase in WSN, and it is completely automated. An example is illustrated in Figure 2.5. The WSN-based WQM framework represented in Figure 2.5 could be described by the various building blocks in Figure 2.4b. The blocks are data acquisition, filtering/or processing, data transfer block. These blocks are responsible for performing the final analysis, storage and reporting [5]. To increase the level of correctness for collecting the data, distributed sensors are used because the data from the distributed sensors may be required for investigation.

The *filtering/processing block* obtains data from the acquisition phase for processing. It involves special computations that relies on computationally intensive devices. Efficient algorithms used in filtering techniques detect essential water quality variables. For the purposes of efficient data processing, collaborative task processing (CTP) and in-node processing (InP) are two basic approaches that may be employed.

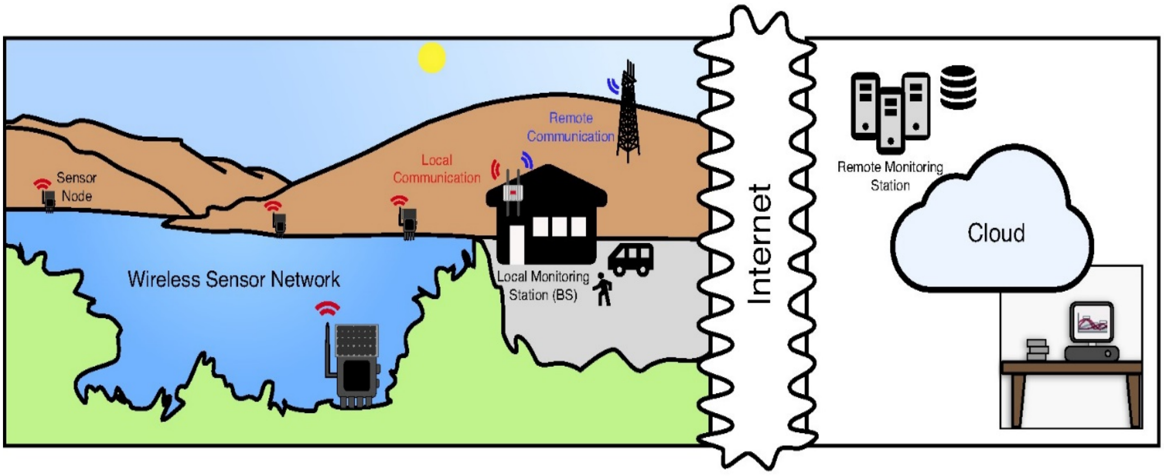


Figure 2. 5 WQM system using a WSN for data acquisition and transfer.

When a node processes its samples, then In-node processing (InP) is said to have occurred. It could be individually or over some period. In Collaborative task processing (CTP), nearby nodes share data, and then based on the spatial distribution of the samples from the various nodes processing is performed. WSN may be configured to use either CTP or InP for the separate nodes to work locally on their data and share the worked-on data with their neighbours for further collaborative task processing. Often when there is a need to be acquainted with the state of the freshwater source, an overall or an average value is provided by CTP. On the other hand, an indication of the freshwater state at specific points or locations values is obtained from InP.

Data transfer signifies the subsequent functional block which defines the manner of data transfer from the source to the destination. The network architecture mainly influences the data transfer. The efficiency of the selected routing protocol is worth considering. There are a good number of technologies that exist, including WIFI-Direct, WI-FI, ZigBee, GSM, WiMAX, and LTE. Finally, there is the data analysis, storage, and reporting block. This section of the system does extra processing, organizes, and categorises the data obtained from the WSN. Such processed data may be kept in storage media such online portals, offline storages or the cloud. The graphs, charts and tables present the data collected.

### 2.5.2 Communication Techniques

Designing the communication network is essential to the success of WQM systems based on WSNs. The network architecture may be divided into two parts. The first part is a local network communication infrastructure (i.e., transmitting data to a local monitoring centre from sensor node or base station). The second part is remote network communication. This is the transfer of data from the local centre to the remote monitoring centre.

ZigBee, WIFI-Direct and WIFI are some wireless communication techniques often used in the local network. Direct or multi-hop communication may be employed which is dependent on location of spatial difference of the wireless sensor nodes. When multi-hop communication is utilized, one can use a cluster-based approach. In this case, local clusters are formed from wireless sensor nodes. Each local cluster selects a cluster head (CH) and transmits its local data to their CH. Then the CH transfers the aggregated data to the local monitoring centre. Researchers, in recent years, have proposed local network communication systems [6], [7].

Long-range communication architectures are used in remote network communication to transfer the data from the monitoring centre locally to a monitoring centre remotely or the cloud (see Figure 2.5) [5], [8]–[12].

Table 2.6 presents the features of various wireless technologies for local communication such as WIFI, ZigBee and WIFI-Direct and remote communication (RF Module, WiMAX, LTE and GSM) [5]. Terrestrial communication standards such as LTE, GSM, and WiMAX ranges from 5 to 100Km, which is required for remote monitoring in WQM environments. For local monitoring, ZigBee, WIFI-Direct and WIFI, are usually used for shorter distances, ranging between 50m and 20m.

Table 2. 6 Technologies for Wireless Networks. Adapted from [5].

| **Protocol** | **Coverage** | **Regularity** | **Speediness** | **Merits** | **Demerits** |
|---|---|---|---|---|---|
| ZigBee | 50 m | 2.4–2.48 GHz | 20/40/250 Kbps | Low power consumption, Low cost, ad hoc, has the potential to support many users | permeability to buildings is not good, low speed |
| WiFi (a/b/g/n) | 200 m | 2.4 and 5 GHz | up to 150 Mbps | High speed, low cost, wide distribution, a common standard | Consumes high power, needs a centrally placed access point, not scalable |
| WiFi Direct | 200 m | 2.4 and 5 GHz | up to 150 Mbps | low cost, Ad hoc, high speed, easy to set up | Consumes high power, has limited platform support, not scalable |
| RF Module | 8 Km | 2.4 GHz | 250 KBs | It is resilient to noise and variations in the signal strength | It requires complex demodulator, low speed |
| GSM | 10 Km | 900–1800 GHz | 9.6 Kbps | Wide distribution, 2-factor authentication, support for roaming | High energy consumption, Low speed, needs special processing handling hand-offs |
| WiMAX | 5–100 Km | 2–11 GHz<br>10–66 GHz | up to 80 Mbps | Relative low cost to deploy, high speed and coverage, secure and reliable, | Limited access to spectrum, Trade-off between bit rate and coverage, limited diffusion |
| LTE | 100 Km | 698–960<br>MHz UL | 300 Mbps<br>DL; 75 Mbps | High speed, backward compatible, Low latency, high capacity, | Expensive equipment, high energy consumption |

Additionally, Table 2.7 provides an overview of several different communication and networking architectures that have been proposed specifically for WSN-based WQM systems. Other technologies that have not been fully explored in WQM are underwater communication technologies such as acoustic communication and optical communication. These technologies can support high performance in WQM communications. For example, acoustic communication provides long-range communication distances with low data rates, while underwater optical communication has very high data rate over a short range communication distance [21], [22]. The communication range for radio in freshwater sources is above 100m, while the communication range for radio in marine sources is between 10m and 100m. Acoustic communication spans across several kilometres, whereas optical communication ranges between 10m to 100m [21].

Table 2. 7 Comparison of Network Architectures. Adapted from [5].

| Communication Technology | Network Design | Routing | Sensor overlay | Network Type |
|---|---|---|---|---|
| ZigBee | Sensors send data to the local monitoring centre through the ZigBee network | Multi-hop | None | Local |
| Hierarchical WSN | Sensors are connected to a central fusion centre via local fusion centres | Multi-hop | Clustering | Local |
| ZigBee | Sensors transmit data through the base station to data centre | Not specified | Not specified | Local |
| ZigBee | Sensors are connected to a local host computer through a ZigBee/Ethernet gateway | Not specified | Not specified | Local |
| ZigBee | Sensors connect to a gateway and then to the field servers | Multi-hop | Clustering | Local |

| | | | | |
|---|---|---|---|---|
| ZigBee, CDMA | Sensors transfer data to a local base station (ZigBee/CDMA gateway) | Multi-hop | Three layers | Local and Remote |
| ZigBee, CDMA | Sensor nodes are connected to the remote monitoring centre through a cluster head that acts as a ZigBee/CDMA gateway | Single hop | Clustering | Local and Remote |
| ZigBee, WiMAX | Sensors are connected to a remote station through a local ZigBee/WiMAX gateway | Single hop | Star topology | Local and Remote |
| ZigBee, GPRS/GSM | Sensors transfer data to a local base station (ZigBee/GPRS gateway) | Single hop | Clustering | Local and Remote |
| GSM | Sensors are connected to the remote monitoring centre via GSM | Direct connection | None | Remote |

Presently, very little has been reported on WQM quality of service (QoS) performance metrics such as throughput, delay, security, etc., as far as the actual network is concerned. Over the past ten years, research in WSNs for WQM has focused mainly on collecting data from sensor nodes and storing them in a database (DB).

An example is the design and deployment of a smart system for gathering data in estuaries using WSNs. In this instance, a server is used to request and collect data from several nodes and stored in a database [30]. Likewise, in [31], the authors present a design of an energy efficient environment monitoring station and data collection network based on ubiquitous WSNs. In this work, different climatic parameters from the sensor nodes were sent through the sensor network to the base station. Data is sent from the base station to the sensors, performs data processing, and transmits data packets to the remote monitoring centre via a

GPRS/3G data network. Another related work is found in [21], where the authors proposed an energy efficient network for WQM in Subterranean River in China. In this work, the authors evaluate the network communication architecture by placing emphasis on the node energy consumption in the network building stage, the data acquisition stage, and the transmission stage. Different node numbers were assigned to each node in the network, and their results indicated that the maximum energy consumed in the data acquisition and transmission phases takes place in the node with the largest node number.

Routing is also key in the network communication because the sensor network plays a role on sampling the environmental data and transferring the data to the base station [31]. WSN routing protocols can be adapted for use in WQM applications by studying into ways the protocol could improve to minimize the amount of energy consumed in the network to increase the network lifetime. In [22], a throughput optimal underwater routing protocol was proposed to maximize the network throughput by utilizing all possible link capacities.

In [32], the authors proposed a hydraulic pressure-based anycast routing protocol that exploits the measured pressure levels to transport data to the surface sonobuoys at sea level using acoustic multi-hopping technique. Also, a distributed underwater self-deployment algorithm was proposed [33]. Here, each node uses an uneven clustering algorithm based on the distance on the water surface and then the cluster head adjusts its depth while maintaining the layout formed by the uneven clustering and finally adjusts the positions of in-cluster nodes [33].

The adaptation of these routing protocol in WQM could enhance the communication among the sensor nodes, the local monitoring centre, and the remote monitoring centre. The design of an efficient routing protocols should be realized to reduce the energy consumption without compromising on network operation [34]. In designing protocols for WQM, researchers should take into account the possibility of sensor drifting and biofouling since these conditions may affect the behaviour of the sensor device.

### 2.5.3 Data Storage and Retrieval Techniques

Several authors have provided different schemes for data storage and retrieval within WSN-based WQM systems. This task tends to be one of the most important aspects of the WQM process, as the energy consumed by the devices greatly depends on the amount of data to be acquired and the frequency of data acquisition, as does the quality of the WQM process. Many existing implementations, rely on memory cards for data storage on the local node, while remote reporting is triggered by specialized commands transmitted from the local monitoring station [35]–[38]. While this delay-tolerant data collection does not allow for real-time access to the water quality measurements, in some cases, it is considered more convenient due to its cost effectiveness [36]. To reduce the energy consumption of the data transmission, the authors in [10], present a data fusion technique that enables a reduction in the amount of data that need to be transmitted to the remote monitoring station.

The remote monitoring centre may use a database management system for storing the water quality data. In current implementations, these databases are mostly national databases, which are most of the time available online. For example, the United Nations Global Environment Monitoring System (GEMS) programme is committed to provide water quality data of the environmental and information of the highest integrity, accessibility and interoperability through its database referred to as the Global Water Quality Data and Statistics (GEMStat) [39]. An additional dataset is operated by the US Geological Survey (USGS) [40]. It is important to note that these databases are only repositories for storing the acquired data and, as a recent study points out, the data become less actively accessed over time [41].

Hence, there is a need to explore ways to perform real-time trend analysis of the data collected and compare it continuously with the previous data collected and stored in repositories over the years. In this perspective, a common platform that integrates historical and real-time water quality data has recently been proposed in [42].

## 2.6. Chapter Summary

In this chapter, a survey of the current state-of-the-art in the design and implementation of WSN-based WQM systems is discussed. The chapter also described a framework for WSN-based WQM systems, and the technologies used at each stage in the monitoring process. The communication techniques, energy management schemes and data processing approaches employed in these systems are also explored.

In addition, the chapter enumerated various open implementation issues that still need additional research to advance the use of WSN-based WQM systems.

# CHAPTER 3

# WIRELESS SENSOR NETWORKS IN ENVIRONMENTAL APPLICATIONS

## 3.1. Introduction

This chapter provides background information on Wireless Sensor Network (WSN) for Environmental Monitoring (EM) applications. It also focuses on sensor node energy issues in WSNs. Section 3.2 of the chapter describes the energy consumption challenges in wireless sensor networks. The chapter places emphasis on the type of deployment environments, the network topology, and the deployment techniques. Section 3.4 provides descriptions of the mobility model used to simulate node mobility to mimic mobility in the aquatic environment. Section 3.5 presents a description of the network simulator (NS-3) and provides some general assumptions and justification for the choice of simulation as a methodology. This section also provides performance metrics for evaluating the proposed algorithm. Section 3.7 discusses performance analysis of hop distance adjustment in AODV. Finally, Section 3.8 provides a summary of the chapter.

## 3.2. Wireless Sensor Networks

Wireless Sensor Networks (WSNs) consist of sensor nodes that are capable of sensing environmental phenomena and cooperatively transfering the sensed data to a base station. The sensor nodes are spatially distributed in an environment to observe some phenomena within their immediate neighbourhood. They can be deployed in the tens, hundreds or thousands depending on the application requirements. These smart devices can be used in to monitor the home, inventory, transportation, traffic situation, health of humans, structural health, track animals, air quality, water quality, military, and may even serve as surveillance systems [147]. Over the years, WSNs have proven to be the technology of choice by researchers for environmental monitoring (EM) applications taking into account the number of advantages that comes with its use [147]–[149]. For example, a WSN is resilient (i.e., adaptive to node failures), scalable (i.e., easy to add nodes to the network), robust (i.e., can withstand harsh environmental conditions), flexible to setup and deploy, cheap, and the network requires no infrastructure. Despite the large number of advantages, WSNs are challenged with several issues. These include but are not limited to communication, memory size, energy, processing capacity, and security [150].

## 3.3. Types of Deployment Environments

Wireless Sensor Networks may be classified according to the deployment environment. Figure 3.1 shows the classification of WSN according to the deployment environment. WSNs may be deployed underwater or underground. They may also be classified according to the type of data being acquired, including multimedia (when deployed to capture videos, images, and audios) or simply numeric data.

WSNs have also been classified according to their mobility, mobile (when the sensor nodes move in their deployment environment) [151] and stationary. In both underground and underwater wireless sensor networks (Figure 3.1), the sensor nodes are buried either in the soil or placed underwater to measure the condition of their respective environments. The buried sensor nodes communicate with a sink above ground and send data through it to a monitoring station [152].

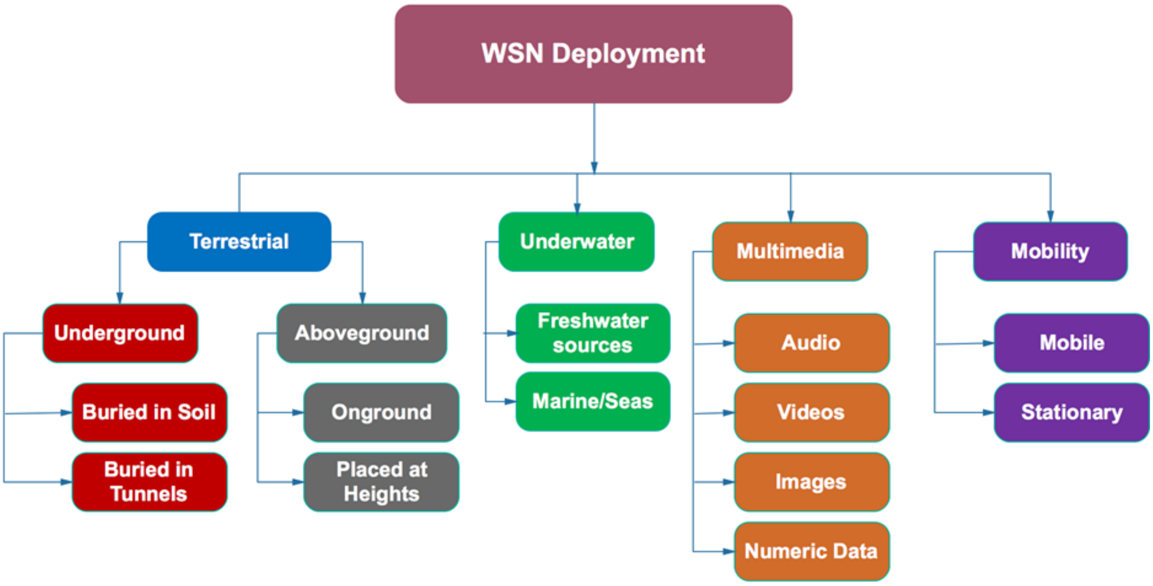


Figure 3. 1 WSN deployment types.

### 3.3.1. Wireless Underground Sensor Networks (WUSN)

Wireless Underground Sensor Networks (WUSN) as shown in Figure 3.2 is a well studied area [153]–[157]. They are used in different applications which include intelligent agriculture, power grid maintenance, pipeline fault diagnosis, etc. [156], [158].

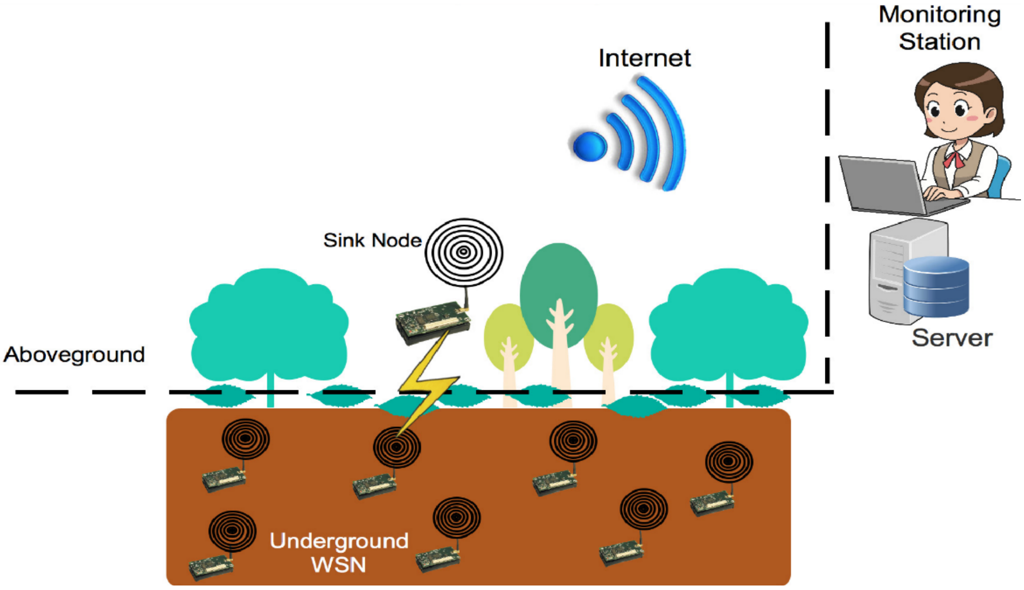


Figure 3. 2 WSN deployment techniques

Compared with traditional terrestrial Wireless Sensor Networks, WUSNs suffer special communication challenges characterized by the weak signal propagation in soil, rocks and other underground materials. Underground signal propagation is challenged with strong attenuation and signal losses [152]. Traditionally, WUSNs use electromagnetic (EM) waves to establish connection among transceivers underground. However, EM waves have several shortcomings; antenna sizes, short communication range, and the channel conditions are highly unreliable. There are new techniques such as magnetic induction (MI) that have the potential to overcome the challenges posed using EM waves in WUSNs. Underground sensors are equipped with batteries which are difficult to charge or replace when the sensor nodes energy is depleted. Conserving underground sensor nodes' energy is crucial to extending the lifetime of the network and to achieving optimal performance.

### 3.3.2. Wireless Underwater Sensor Networks

Wireless Underwater Sensor Networks (Figure3.3) is an area that has caught the attention of researchers in recent times [159], [160]. Underwater Sensor Networks are useful due to their several implementation areas which include marine pollution monitoring, marine data gathering, tsunami detection, threat detection at seaports, and underwater telemetry. The monitoring is usually performed using navigation assistance such as autonomous underwater vehicles (AUV) and vehicle surveillance. Wireless Underwater Sensor Networks (e.g., marine monitoring) suffer from limited bandwidth, node failures due to harsh environmental conditions, signal fading, and propagation delay [151].

Underwater sensor nodes normally communicate using acoustic waves to a surface buoy or sink above the water. It is also possible to employ non-acoustic communication techniques such as radio frequency (RF), magnetic induction (MI), and underwater free-space optics in underwater sensor networks [161].

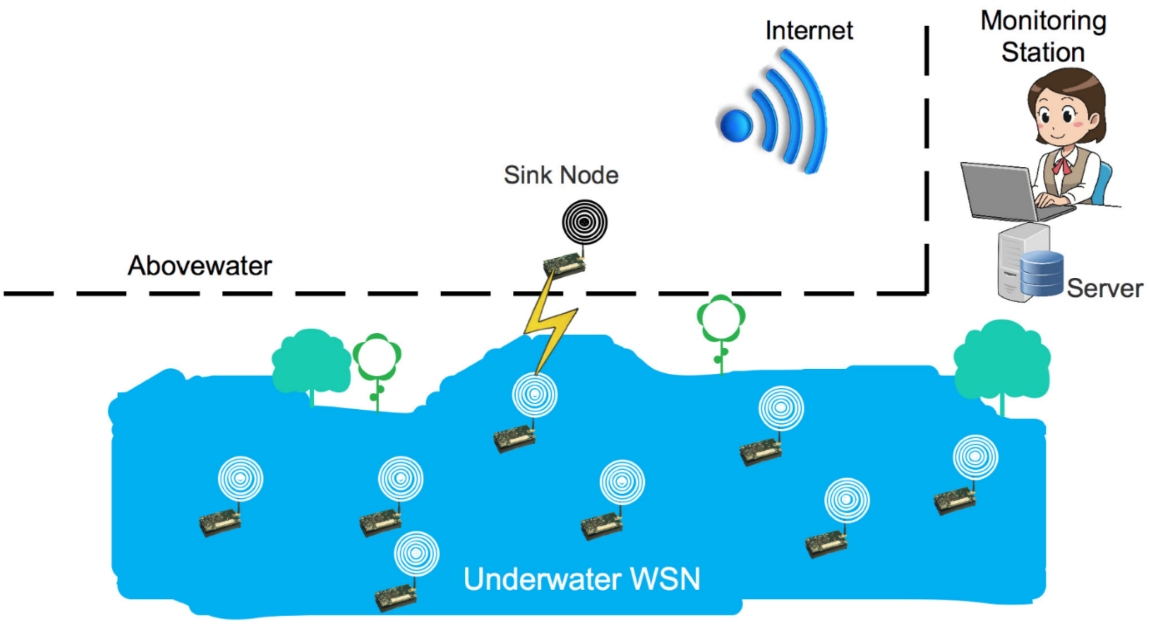


Figure 3. 3 WSN deployment techniques.

The dynamic nature of the water environment is related to the content salt, and its turbidity. Hence, the communication channel also becomes dynamic. RF signals, when exposed to these environmental characteristics, suffer high attenuation. Magnetic Induction may also be used for underwater propagation but requires the use of large-sized antennas which is somewhat impractical in such environments. Acoustic communication is the preferred method for underwater communication since acoustic waves suffer less attenuation and can travel long distances due to their low frequencies. Nodes that are connected using acoustic waves constitute underwater acoustic sensor networks (UASNs). UASN nodes are energy hungry nodes which consume a great deal of power compared to sensor nodes deployed to monitor environmental conditions on land. There are several techniques discussed in the literature to overcome the energy problem in UASN and to minimise the energy consumed by the UASN to improve on the network lifetime. Energy efficient routing protocols [159], [162]–[165] and clustering protocols [161], [166]–[168] are two such techniques adopted to minimize the energy consumed by sensor nodes deployed in WUSNs and UASNs. Current existing routing protocols are group into receiver-based and sender-based which are further categorized based on energy, geographic information, and hybrid routing protocols [159].

An Energy Optimised Path Unaware Layered Routing Protocol (E-PULRP) that minimises the energy consumed in a dense 3D-WUSN is described in [169] as a typical example of an energy-based routing protocol. E-PULRP uses on the fly routing to report events to a stationary sink node. E-PULRP has two phases: layering and communication. Nodes occupy layers in a concentric shell around the sink node in the layer phase. The nodes within one layer have the same number of hops counts to the sink node. The E-PULRP protocol is designed to follow a network model in which the total volume in interest is subdivided into small-sized cubes with a binomial probability distribution for a node occupancy. The protocol assumes that the number of cubes is large. Following Poisson approximation to the binomial distribution, we can calculate the probability of k nodes occupying a volume V as:

$$Pr[x = k] = \frac{\left(\int v\rho dv\right)^{k}}{k!} exp - \int v\, \rho dv \tag{3.1}$$

where:

$\rho$ = is the volume density of the sensor nodes

$\int v$ = indicates integral over the volume V

Physical properties such as temperature and chemical properties affect underwater communication. Another key factor that affects underwater communication is the depth of transceivers. In E-PULRP, for a transmitted energy of $E_T$, the received energy $E_R$ at distance $R$, is modeled as follows:

$$E_R = \frac{E_T}{R^{(B/10)} 10^{(\alpha R+\beta)/10}} \tag{3.2}$$

where:

$B$ = takes values 10, 15 or 20 depending on the type of propagation

$\alpha$ = is a range-independent absorption coefficient

$\beta$ = is a constant independent of range

$E_T$ = the transmitted energy

$E_R$ = the received energy/power of the control packet

In this layering phase, the protocol allows communication to occur only when energy levels of layers close to the sink are chosen. Concentric circles are formed around the central sink and the structure ensures packet forwarding towards the central sink. The layers in this phase are formed as follows: 1) Layer 0 initiates a probe of energy; 2) Nodes with energy equal to the detection threshold ($E_D$) assign layer 1 to themselves; 3) The nodes in layer 1 communicates with the sink using a single hop and 4) waits for time $k$ to transmits a probe with energy to create layer 2 (i.e., made of nodes in layer 1 with energy equal to $E_D$.

The detection threshold, ($E_D$) and the waiting time $k$ are calculated as follows (see Equation 1, Equation 2 and Equation 3):

$$E_D = \frac{E_{pl}}{{\alpha_l}^{(B+10)} 10^{(\alpha \alpha_l + \beta)/10}} \tag{3.3}$$

where:

$E_{pl}$ = the probing energy

$l$ = the layer

$$k = \frac{\lambda_{min}(E_R - E_D)}{\gamma} \tag{3.4}$$

$\gamma$ = energy dependent factor which is the ratio of the energy remaining in the node to the totalinitial energy

$\lambda_{min}$ = constant

In the communication phase, intermediate relay nodes are selected to send packets to the sink using multiple hop routing path to determine nodes *on the fly*. In this phase, nodes at the lower layers nearer to the source node are first identified as potential forwarding relay nodes. For example, if a source node, $S$ in layer $l$ sends a control packet, a node, $N$ in the network who receives this control packet may declare itself as a potential forwarding node. This self-declared potential node waits at a time given in Equation 3.4 to listen if any other node has not declared itself as a relay node. It does this by comparing its signal strength Resceived Signal Strength Indication (RSSI) with other nodes' RSSI.

Once its RSSI value is less than all others, then it forwards the data packet, otherwise it will go into silent mode. A classic example of a cluster-based energy efficient UWSN is SEEC: Sparsity-aware energy efficient clustering protocol for underwater wireless sensor networks. SEEC was proposed by [170] to search sparse regions in the network. The network is divided into subregions of equal sizes. With the use of sparsity search algorithm (SSA) and density search algorithm (DSA), sparse and dense regions in the network. The lifetime of the network is improved through sink mobility in the sparse regions and through clustering in the dense regions. SEEC minimises the energy consumed in the overall network by balancing the two-sparsity search algorithm (SSA) and density search algorithm (DSA). In SEEC, random nodes are deployed underwater and the network formed is divided into 10 regions. The position of each node in the network is dynamic due the dynamic nature of the deployable environment. The 10 regions are created to determine the sparse and dense regions. SEEC employs three sinks (i.e., a static sink at the top of central point of the sensor network field and two mobile sinks positioned at the sparse regions). Each sensor nodes coordinate is first determined to know its current region in the network field (i.e., sparse or dense). A simple algorithm that checks the number of nodes in a region is used to determine a sparse or a dense region. If the number of nodes is minimum, then then node is in a sparse region other the node is in a dense region. When the searching is completed, then the nodes in the dense region are placed into clusters. To conserve energy and increase the lifetime of the network, SEEC is designed to cluster the top four (4) densely populated regions. Nodes in a dense region collaborate to select their cluster head (CH). The CH is the node with low depth and high residual energy as shown in Equation 3.5.

$$E_{ave} = \frac{TotalResidualEnergy}{NumberofAliveNodes}$$

$$rand <= Th \tag{3.5}$$

$$Th(i) = \frac{p}{1 - p(mod\ (r, \frac{1}{p}))}$$

### 3.3.3. Wireless Multimedia Sensor Networks (WMSNs)

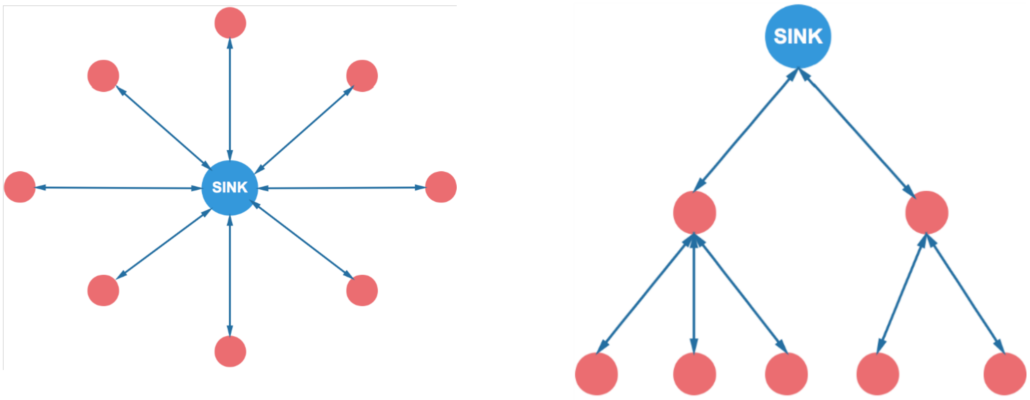
Another type of WSN is the Wireless Multimedia Sensor Networks (WMSNs). These types of sensor networks are designed to monitor multimedia events and can retrieve images, videos, audios, and scalar wireless sensor data. WMSNs come with additional challenges on top of the challenges of traditional WSNs. WMSN challenges include real-time delivery, high bandwidth demand, security, tolerable end-to-end delay, coverage, and proper jitter and frame loss rate [171]. Video streaming requires high bandwidth for it to be delivered. Streaming at high date rate also means that more energy will be consumed. Several approaches have been proposed to also reduce the amount of energy consumed for delivering the content. Current studies have looked into the design of energy efficient MAC and routing layer protocols that are capable of handling low data rates [172], [173]. Also, to overcome the other challenges apart from the amount of energy utilized during content capturing and delivery, new approaches have been proposed in WMSNs to ensure data sharing security, quality of service assurance in providing real-time multimedia data and to ensure algorithms are designed to compress the images, videos, and audios before transmission to reduce the amount of energy consumed for such operations [174]–[177].

### 3.3.4. Mobile Wireless Sensor Networks (MWSNs)

There are some application domains that static wireless sensors may not be a good option to deploy, hence, the introduction of Mobile Wireless Sensor Networks (MWSNs). Mobile sensors can move freely in their environment. This type of WSNs are good for deployments that require maximum coverage to monitor the physical environmental conditions since the mobile nodes can spread out when gathering information and reposition themselves. Mobile sensors improve coverage, energy efficiency, and channel usage [151]. In the last decade, studies into MWSNs has focused on sensor node coverage [178], energy efficiency [179]–[182], sensor relocation and deployment [183]–[185]. Following the studies conducted, the energy efficiency schemes discussed in this area is of key interest. There are two main approaches of improving the energy efficiency in MWSNs: reducing the energy consumption and harvesting energy to power sensor nodes.

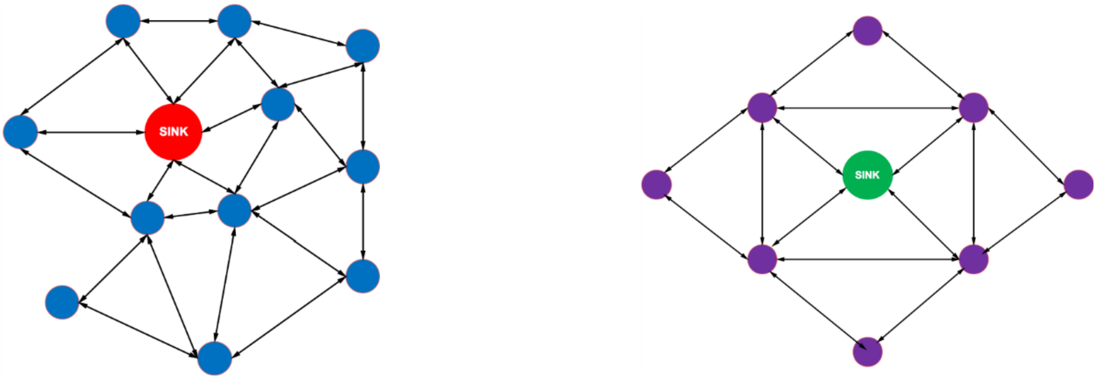
### 3.3.5. WSN Topologies

The arrangement of wireless sensor nodes in a Wireless Sensor Network is critical for maximising the network lifetime. The network topology adopted in a deployment environment affects factors such as network connectivity. Network connectivity becomes more reliable if the proper topology is chosen for the deployment [161]. The topology also affects the energy consumed by nodes in network. For example, if a network is designed in such a way that the wireless sensor nodes are distributed far from their neighbors and the sink, the nodes will require high energy budget to establish connections and communicate [161].



(a) Star Topology (b) Tree Topology

Figure 3. 4 WSN Topogies



(a) Mesh Topology (b) Star Mesh Topology

Figure 3. 5 WSN Topologies

Wireless Sensor Networks employ mesh (also known as peer-to-peer), star, star-mesh, and tree topologies, as show in Figures 3.4 and 3.5. Static network topologies do not suffer from topological changes, but they suffer from minimum battery power and MAC layer problems. In a star topology (Figure 3.4a), the nodes are one-hop away from the sink. The sink or base station is at the central point and all the nodes in the network broadcast data through the sink to other nodes in the network. The star topology is energy efficient when adopted in WSN projects. But in situations where the sensor nodes are far from the sink node, the sensor nodes in the star topology requires a ton of energy compared to multi-hop through mesh. The challenge with this topology is that it is susceptible to failures when the sink node fails [186].

In Figure 3.4b, the sink serves as the root of the tree and all other nodes are considered as child nodes. In Figure 3.5a, the sink or base station is a hop away from some of the nodes, which are its nearest neighbors. The other nodes require multiple hops to reach the sink. In a full mesh, every sensor node is connected to every other sensor node in the network. Finally, in Figure 3.5b, the sink node is at the central point. Some nodes broadcast to the sink directly whilst other nodes require a hop to reach the sink.

### 3.3.6. WSN Deployment Techniques

In WSNs, sensor node deployment is the process of setting up or positioning wireless sensor nodes to be fully functional and operational in either real-world using testbeds, laboratory or simulated environments [187], [188]. Deploying sensor nodes in the environment (i.e., land, air, water) may differ from one application domain to the other. In some cases, deploying the sensor nodes to communicate from one medium to the other (i.e., air/land to water, water to air/land, water to land and vice versa, and water to water) require the right selection of the deployment strategy [189].

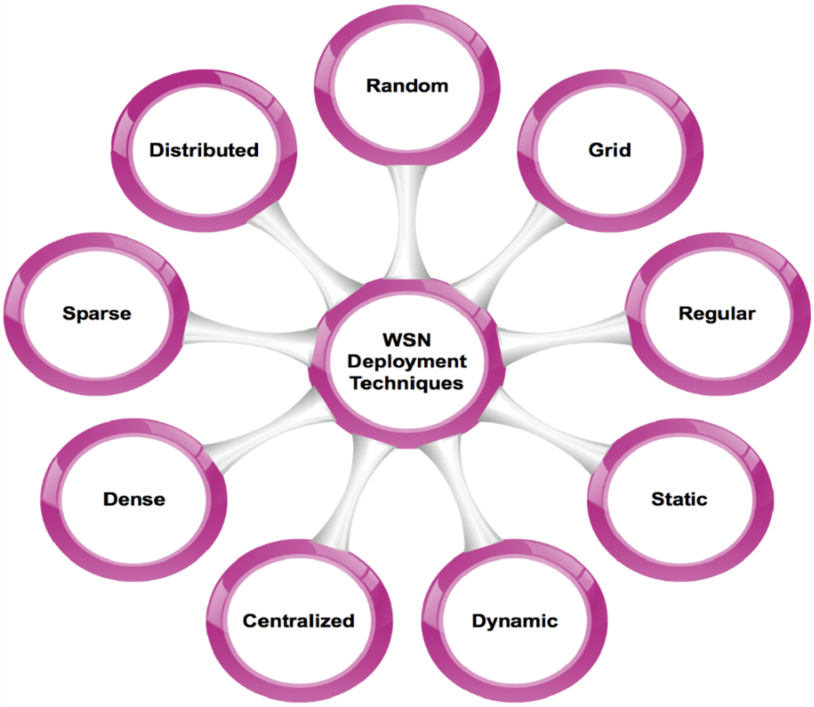


Figure 3. 6 WSN deployment techniques.

The sensor nodes are deployed to collect data/information about their environment and transmit to a base station for onward processing. Nevertheless, the primary objective for node deployment consideration in WSN is to gain energy advantage since the sensor nodes are low powered devices. There are several deployment strategies for static and mobile sensor networks (Figure 3.6). Sensors in their physical environment play several roles in the network (i.e., act as a source node, relay node, cluster head, or sink/base station node) are deployed with any of the approaches or methodologies in Figure 3.6.

The objective function for selecting the desired methodology or approach should be based on the coverage area, network connectivity, network lifetime, and data fidelity (ensuring that the data gathered is credible) [190]. Unlike static environments, placing and controlling sensor nodes in mobile environments is challenging. Similarly, node replacement is also a difficult task. The best deployment strategy for any implementation must meet the following criteria: 1) have clear objectives to meet the application requirements; 2) improve system performance and maximisation of network lifetime; 3) enable the detection of failures and errors in the network topology [161], [190]. Sensor node deployment techniques in WSNs may also be determined based on the algorithms used. Current algorithms that have gained proper consideration for sensor node deployment include greedy, adaptive, probabilistic, centralised, distributed, incremental, and genetic algorithms [189].

In [188], the authors classified four (4) possible WSN deployment problems that are likely to be encountered during the lifetime of the wireless sensor network (Table 3.1). The deployment problems were classified into: 1) node problems which general involve only one node; 2) link problems which occurs between two neighboring nodes; 3) path problems which typically occurs in a multi-hop environment (i.e., where paths are formed by more than three sensor nodes within the network); and 4) global problems affecting the entire sensor nodes in the network. Advances in algorithms for reduction in energy consumption, bandwidth utilization, routing and clustering, quality of service have seen the improvement of sensor node deployment issues related to coverage, network connectivity, energy efficiency, and data fidelity. A recent survey conducted by [191], has provided the state-of-the-art in four main wireless sensor node deployment strategies mentioned earlier in this dissertation and provides the approach, the load balance strategy, the lifetime, cost, redundant nodes, deployment space (i.e., 2D or 3D), the energy distribution, sensor range, and scalability of some of the work done so far in the area.

Table 3. 1 Sensor Network Deployment Problems. Adapted from [5], [188]

| **Sensor Deployment Problems** | **Causes** | **Effects** | **Possible Solution** |
|---|---|---|---|
| Node Problems | Low Battery, Increased network traffic, Software bugs, and Sinks acting as gateway between WSN and the Internet | Wrong sensor readings which affects the performance of the network; Battery depletion due to overhearing, Bugs results in hanging or kill threads, Data loss | Node duty cycle<br>Energy Harvesting<br>Power Management Schemes |
| Link Problems | Network congestion due to traffic bursts, Neighbor nodes frequently changing, Asymmetric links | Message loss, broadcast to discover and maintain links | Efficient MAC protocol |
| Path Problems | Bad path to sink bad path to node, Routing loops, Asymmetric paths | Greedy nodes not forwarding packets received<br>Message loss, Inconsistent paths | Direct Diffusion<br>Rebooting nodes to clear cached data |
| Global Problems | Low data yield<br>High reporting latency<br>Short network lifetime | Network delivering insufficient data<br>Message loss<br>Node dies | Energy Efficiency Schemes<br>Energy Harvesting |

### 3.4. Mobility Models

The design, deployment, and evaluation of sensor nodes in WSNs depend on the environment and the designed objectives for the intended application (e.g., water quality monitoring, fire detection applications, etc.). The sensor network in their deployable environments become successful when the stakeholders consider the network size, the topology, and the communication models used for achieving the application goals. Mobile sensor nodes move to form mobile sensor networks and reposition/reorganise themselves in the sensor network. For example, nodes placed in the ocean are capable of measuring parameters such as ocean current speed, temperature, salinity, pressure, and other chemicals. These sensors move about collecting data in real-time and transmitting the data to a central repository for real-time data analysis [192].

Terrestrial WSNs mobility occurs differently from aquatic WSN mobility. For example, sensor nodes deployed in freshwater sources are affected by the water current. The node movement affects the sensor network design, the distance between the nodes (i.e., during route discovery), propagation, energy utilisation, among others. In an aquatic environment, electromagnetic wave propagation to sinks above water is challenging. Energy conservation and mobility in this type of network create challenges in the design of routing protocols. Routing protocols that can minimise the energy consumed by nodes, managing the random variation in the network topology, and minimising the delay in communication are therefore required in an aquatic environment.

In designing and evaluating mobility models for aquatic environments, our work took into consideration the conditions and characteristics of freshwater sources. Freshwater sources such as rivers are in constant motion. The velocity of the river depends on the slope of the land, the size and shape of the bed, and the quantity of water in the river [193]. Sensor nodes may be deployed in one of the following environments: 1) slow but deep water bodies, 2) swift but deep water bodies, and 3) swift but shallow water bodies. Freshwater sources are characterised by three key factors: velocity, gradient, and discharge. Velocity is the distance that the water in a river travels in each amount of time. The velocity relates to the energy levels of the water in the river. For example, objects (small or large) deposited in a swift or fast-moving river are carried downstream or along the river path quickly as compared to slow-moving rivers. The velocity of a river is affected by the gradient, discharge, and the shape of the river path that the water travels [193]. The gradient is a measure of the steepness of a river, and a river's discharge is expressed as the quantity of water that moves through the different points along the river path at any given time. The discharge varies along the length of the river [193].

Mobile sensor nodes continue to move with water currents after the initial deployment. There are different mobility models used to simulate WSN projects. These include constant acceleration, constant position, constant velocity, Gauss Markov, hierarchical, random direction 2D, random waypoint, steadystate random waypoint, random walk2D, and waypoint mobility models. Although these mobility models are designed for terrestrial WSN projects, they may be modified for use in aquatic WSN projects. In considering the random walk mobility model, the mobile sensor node after the initial travel time stays at a point for a given period known as the pause time. In other models, the mobile sensor node chooses a new direction and a new speed throughout the travel time and travels towards the destination with this new direction and speed. A comparison of some random mobility models and their characteristics are presented in Table 3.2.

Table 3. 2 Random mobility models compared.

| Terrestrial Environment | | | | Aquatic Environment |
|---|---|---|---|---|
| **Parameters** | **Random Waypoint** | **Random Walk** | **Random Direction** | **Modified Random walk** |
| Selection of destination | Node selects destination (uniformly distributed) | Pre-defined destination (uniformly distributed) | MN travels to boundary of scenario (destination) | Region of interest |
| Selection of destination | To specified destination in environment | Selects a direction (uniformly distributed) | Selects uniform direction from boundary | Depends on water current (randomly chosen directions) |
| Selection of Speed | Selects speed (uniformly distributed) | Pre-defined speed (Uniformly distributed) | Selects uniform speed | Depends on river current/speed |
| Moving to destination | Moves until it reaches the destination | Node moves until reaching the boundary/a certain distance | Moves until it reaches the boundary | Nodes move to boundary and redirected by bouncing effects to change course (x, y) |
| Waiting time | Stays in a location for a period (Uniformly distributed)/Pause time | Wait a certain amount of time | Wait a certain amount of time | No waiting time since node movement is dependent on the flow motion |
| Next destination | Stays in a location for a period (Uniformly distributed)/Pause time | Node selects new direction after reaching boundary/a certain distance | - | Node floating to the bank (Boundary) and bouncing effects determines (x, y) destination |

Random Walk mobility model is designed in a way that the mobile sensor nodes move freely and randomly in the defined simulation field. In our application domain (i.e., river network monitoring), the mobile sensor node's movement is affected by the characteristics of the water environment. Notably, the movement is affected by the velocity of the water. Therefore, the sensor nodes are not expected to move in a predefined manner. Random Walk mobility has the following limitations:

- The time and distance that a mobile sensor node moves are short.
- The node's movement pattern is limited to an only small area in the simulation environment
- The node's directional movement is randomly generated
- The mobile sensor node moves independently of other nodes

Hence, there is a need to design models that have different mobility characteristics (i.e., such as destination, velocity, and direction). In our model, the speed increases incrementally and the change in direction may not be smooth but fraught in some scenarios. The Random Walk mobility model defined proposes node movements that depend on speed, discharge and gradient of the river.

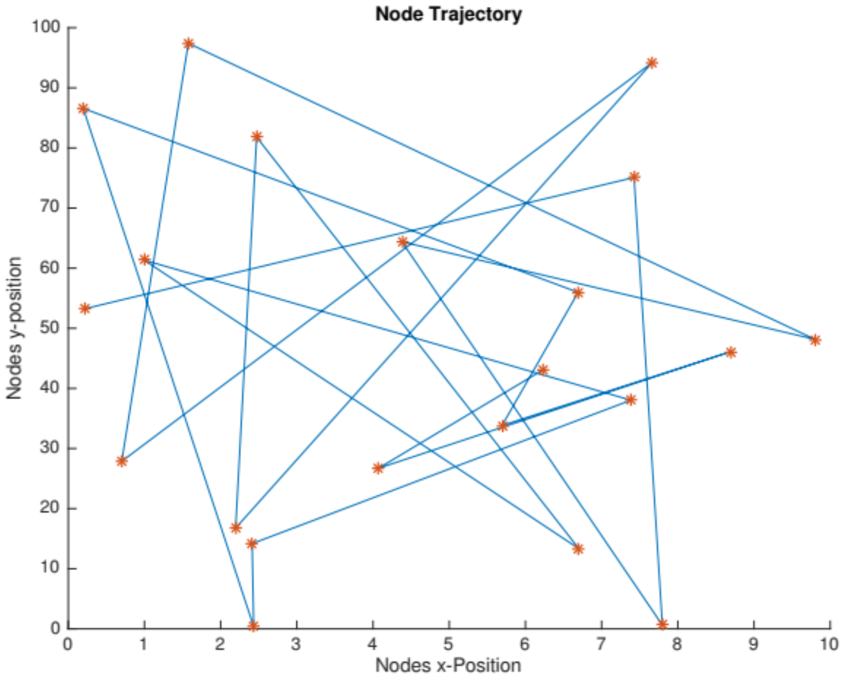


Figure 3. 7 Example of Mobile Sensor Node Movement in Random Walk Mobility Model

In the simulation environment, the node's direction and speed change as the sensor node travels from a point at the beginning to the end of the simulation, as shown in Figure 3.7. Figure 3.7, shows an example of a mobile sensor node's trajectory pattern using Random Walk 2D mobility model where a mobile sensor starts its movement process at a randomly chosen position, speed, and direction. The speed and direction of the mobile sensor nodes are critical parameters that aids in the determination of a sensor nodes' mobility behaviour.

### 3.5. Simulation

A simulation is a standard approach to model real-world scenarios. In recent times, simulation has shown to be a valuable tool in modelling network scenarios and analytic methods when experimentation isn't feasible and applicable. In energy modelling, the objectives of communication protocols focus on minimising the maximum energy and adapting the operations according to the residual energy. As a result, the need for a simulation framework for evaluating the performance of energy-aware wireless networks is studied. There are several network simulators and emulators proposed in the literature for conducting network performance analysis. For example, OMNeT++ a discrete event simulator that was developed based on the C++ language for modelling network communications comes with a graphical user interface [194]. Optimized Network Engineering Tool (OPNET) built on C/C++ is used to model both wired and wireless communication networks. OPNET is mainly used for creating network scenarios, collecting data and performing analysis [194].

Castalia is designed to test the performance of network protocols and other distributed algorithms. Castalia supports analysis of sensor node energy consumption [195]. PASES is designed based on the SystemC framework. PASES is an event-driven simulation designed for energy consumption analysis [196]. COOJA runs on the Contiki OS which supports network-wide simulation. COOJA does not have energy modules and parameters for energy consumption analysis [197]. The NS-2 simulator is designed using C++ and C++ bounded to an Object-Oriented Tool Command Language (OTcL) together with TcLCL. NS-2 supports energy consumption analysis in a network scenario [198]. A more recent network simulator that supports a variety of network scenarios is NS-3. NS-3 supports parallelism, scalability, extendibility, emulation, and extensive documentation support [199]. In what follows, a detailed description of NS-3 is provided.

### 3.6. Network Simulator 3 (NS-3)

In this work, extensive simulations are performed to show the performance of a new protocol (i.e., an adjustable transmission range protocol). To achieve this the network simulator 3 (NS-3) is employed. The NS-3 simulator was developed using C++ and Python. Although the simulator is limited in its GUI functionality, it is scalable, comes with excellent documentation and support, is highly extensible, supports emulation and is open source. NS-3 is a research tool widely accepted by both academia and industry for evaluating the performance of a network. It is reliable, accurate, and results can be easily validated. NS-3 is composed of several modules which support the simulation of different network scenarios. The modules include a network module, energy module, propagation module, WIFI module, mobility module, and many more. In this work, we provide a brief description of the energy module.

The energy module in NS-3 is made up of an Energy Source and the Device energy model. The energy source is an abstract base class that provides an interface for updating/recording total energy consumption on a node, keeping track of the remaining energy, decreasing energy and tracking when the energy is depleted. The device energy model monitors the state of the device to calculate its energy consumption. It provides an interface for updating the residual energy in the energy source and gives notification from the energy source when energy is depleted and maintains a record of the total energy consumed by the device. NS-3 provides energy models for WIFI Radio with states *idle*, *CCA busy*, *Tx*, *Rx* and *switching*. Developers may extend the models in NS-3 to model different scenarios that may not be present in current releases.

NS-3 allows for the definition of new energy sources that incorporate the contributions of an energy harvester. It provides the addition of an energy harvester component with existing energy as well as the possibility of evaluating the interaction between energy sources and the different energy harvesting models. In [76], the authors provided an extension of the current energy models in NS-3 introducing the concept of energy harvesting. Two energy harvesting models are provided: the basic energy harvester, providing time-varying, uniformly distributed amount of energy and the energy harvester that recharges the energy source. It also provides a model for a super capacitor energy source and a device energy model for energy consumed by a sensor node. A model for an energy predictor was introduced that is supposed to predict the amount of energy that will be available in the future based on information from the basic energy source and energy harvester.

### 3.6.1. Justification

In this work, extensive simulations have been conducted in NS-3 to evaluate the performance issues such as end-to-end delay, normalised throughput, packet delivery ratio, and energy consumption in WSNs. The automatic transmission range adjustment for improving the lifetime of the sensor node is explored taking into account the end-to-end delay, normalised throughput, packet delivery ratio, and energy consumption. In particular, we are simulating a network to mimic the application environment (i.e., water quality monitoring). For our work, we make the following assumptions:

- Sensor nodes position are randomised, and they move independently in randomly chosen directions.

- At the start of the simulation the sensor nodes are uniformly distributed.
- The speed of the sensor depends on the flow rate of the freshwater source.
- Sensor nodes may be tethered or allowed to float.
- Depending on the river current, wind direction or tide, the sensors may move in the x-y direction.

The *direction* variable defined in the Random Walk mobility model is used for setting the direction of the sensor node. It is measured in radians. This variable was changed to enable the sensor nodes move only in the x-y direction.

In mobile networks, discovering routes of sensors placed underwater is challenging due to the dynamic nature of the environment. The sensor nodes may move at different speeds making it difficult to discover routes in the network. The variable characteristics in the aquatic environment pose constraints on the sensor nodes' energy utilization and data packet transmission. Therefore, to efficiently model the network in a simulation environment requires a multi-layered simulation environment that supports a wide variety of models (e.g., energy model, communication model, etc).

Simulators such as NS-2, OMNET++, OPNET, and the like are not suitable for modeling the aquatic environment. Although NS-3 is not a perfect simulator is this regard, it is the most appropriate. The choice of NS-3 is due to the fact that experimental test-beds are expensive. The simulator gives a reasonable level of accuracy. The analysis shown in this dissertation is based on NS-3 version 3.6. The proposed protocol was evaluated to ensure that it is functioning as expected. To evaluate the simulation results discussed and presented in this dissertation, validation tests were performed using existing MANET routing protocols in NS-3 (AODV, OLSR, DSDV). First, we test the different routing protocols (AODV, DSDV, OLSR) with various distances and record the packet delivery ratio (PDR) as shown in Figure 3.8. Next, we perform validation test to explore the impacts of node density on the number of packets received when each MANET routing protocol was implemented, as shown in Figures 3.8 to 3.10. This validation test was performed using static and mobile network topology. A network of about 20-100 wireless sensor nodes was employed in the simulation setup. Increasing the number of nodes (>100 nodes) increases the number of generated packets by each node, hence, increasing the contention in the channel. Channel contention increases collision and end-to-end delay, thereby affecting the number of received packets. For the sensor nodes to move in one direction depicting river flow, the Random Walk mobility model's direction parameter was modified to mimic river flow. Typically, the nodes move in the x-direction. The sensor nodes, in most cases, formed a tree or mesh topology. From Figures 3.8 to 3.10, the source nodes were mobile, and the sink nodes were static throughout the simulation.

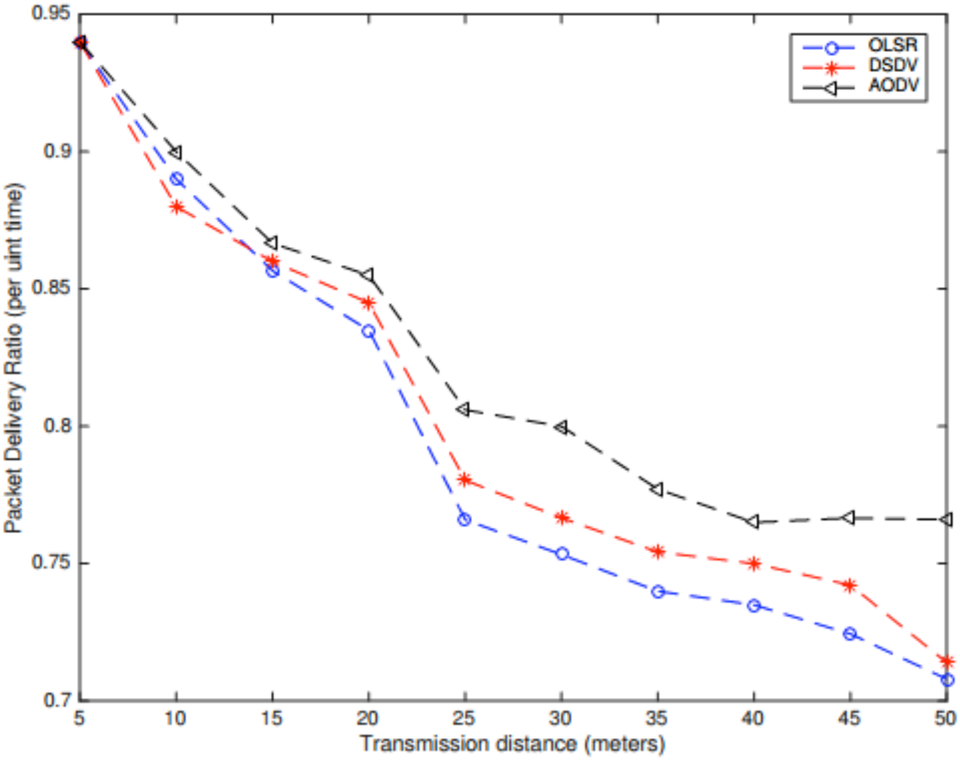


Figure 3. 8 MANET Routing Protocol Performance - PDR vs. Transmission Distance

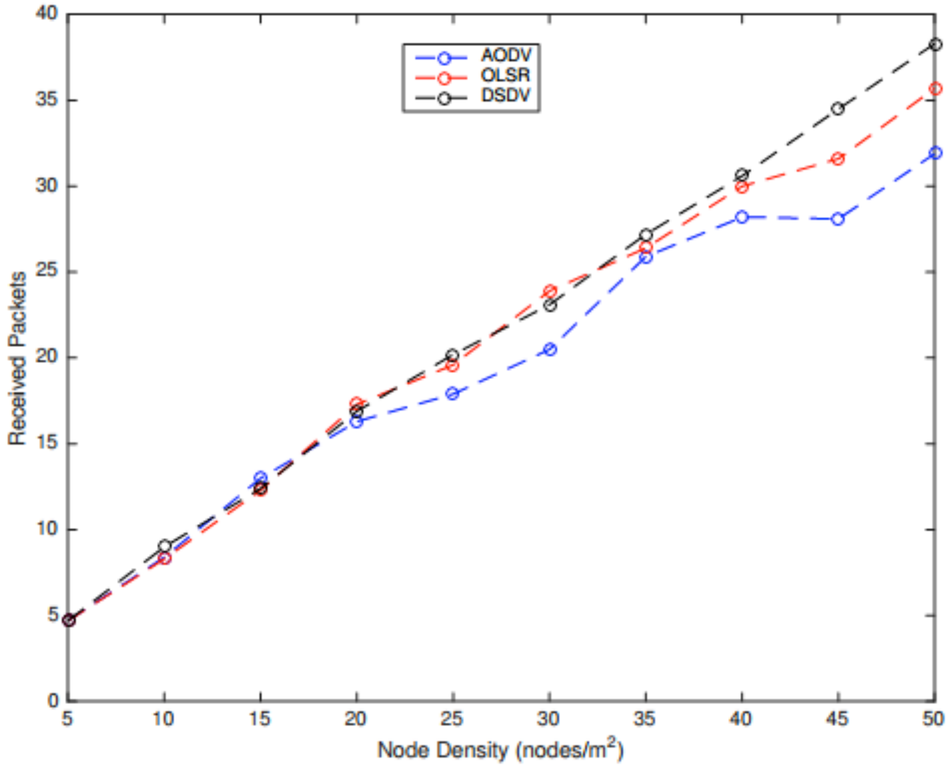


Figure 3. 9 MANET Routing Protocol Performance - Received Packet vs. Node density

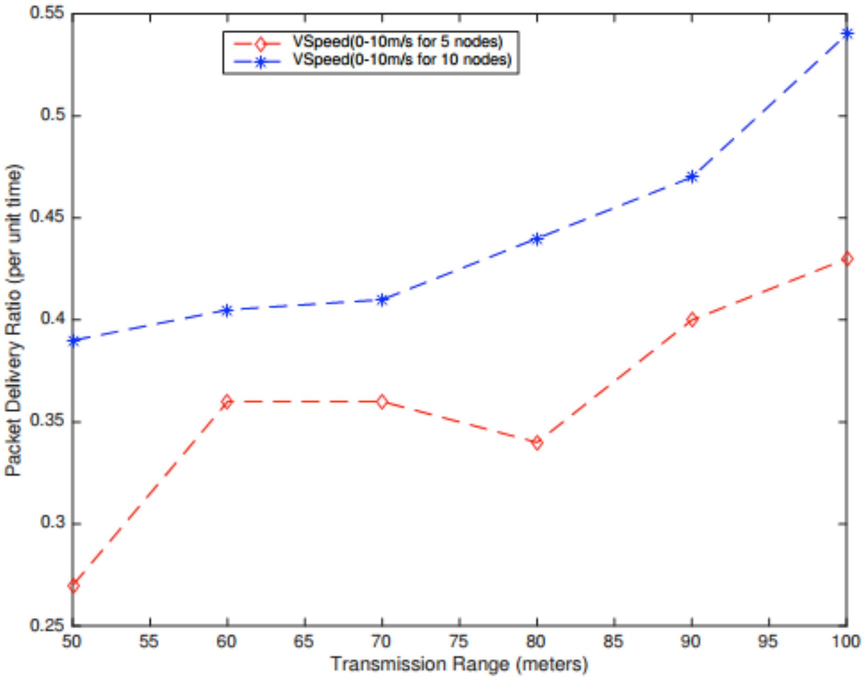


Figure 3. 10 AODV Routing Protocol Performance - TX Range vs PDR

### 3.6.2. Performance Metrics

A metric is a measure for quantitatively evaluating the performance of a system [200], [201]. In computer networks, metrics are essential as design factors, and the network performance is generally assessed based on specific metrics for each network layer [202]. In traditional wireless sensor networks, the crucial metrics contributing to the design and performance evaluation are quality of service (QoS) and network lifetime [203], [204].

Network lifetime is the period from the deployment of the WSN to the instant when the network is considered nonfunctional [35]. Concerning QoS, network lifetime can be determined based on how long the network can meet the QoS requirements of the end user/application. Thus, network lifetime is the time until which the network stops providing the required QoS in each network.

In [205], network performance metrics such as routing overhead, route discovery delay, end-to-delay, network connectivity success ratio, collisions rate, and normalised throughput are discussed in detail. The results in this work were evaluated based on the following performance metrics: lifetime [7], [35], normalised throughput, end-to-end delay, energy consumption, and packet delivery ratio. Throughput is the total number of packets delivered over the total simulation time. Packet delivery ratio in this work is defined as the ratio of packets received at the sink to the data packets generated at the source. A node’s total energy consumption is calculated as the amount of energy spent for transmitting packets, receiving packets, and when in an idle state [206].

In mobile sensor networks, mobility performance metrics are meant to capture and quantify the type of node movement relevant for an ad-hoc routing protocol [207] and is represented by network topology changes that it is due to node mobility [208]. The derived mobility parameters are obtained through mathematical modeling and they consist of parameters related to link, path, node and network connectivity, and quality of service [209], [210]. WSNs designed and deployed for aquatic monitoring (such as rivers, lakes, oceans, etc.) applications poses new demanding and challenging situations exceptional to those that are designed and deployed on land [62]. This is because the impact of aquatic environments on the wireless sensor network normally limits and affects their performance.

### 3.7. Hop Distance Adjustment in AODV

Following the discussions in the previous sections, it is clear that the sensor node's battery has limited energy and therefore, requires the use of different strategies to efficiently utilise the limited energy to improve the lifetime of the sensor node. The energy depletion problem is a concern for all the types of WSNs discussed in section 3.3.

The energy efficiency in WSNs can also be improved based on the kind of network topology formed by the nodes in their deployable environment. In a sensor network, nodes with no energy (i.e., a dead node) may cause a break in links which affects the connectivity. Apart from dead nodes causing a break in communication links, node mobility is known to cause a break in network connectivity or route establishment. The break in communication link affects the performance (i.e., throughput and packet delivery ratio) of routing protocols and the network as a whole. In a mobile sensor network (MSN), mobile sensor nodes get connected to other neighbour nodes until a destination node is reached. In such networks, locating the position of a node on a transmission route is essential since it reduces the amount of energy wasted to send broadcast messages (using RREQ) to locate neighbour nodes to be able to establish routes to the destination.

In routing protocols, each node maintains changes about its topological characteristics in a routing table and these updates occur throughout the lifetime of the network. Routes are either requested on-demand (AODV and DSDV) or proactively (DSR and OLSR). To obtain the position of sensor nodes on their transmission route, a modified AODV has been proposed that allows a sensor node to obtain the position information of neighbours periodically using the Hello messages as the nodes move along already established routes/paths. The position information acquired may be used to minimise the energy consumed by sensor nodes to transmit the data packet to a destination node. A detailed discussion of this protocol is provided in Chapters 4 and 5, where the lifetime of the sensor network is maximized using an adjustable transmission range algorithm and calculating the Euclidian distance between the nodes.

In what follows, the operation of one of the popular on-demand routing protocols (i.e., AODV) is provided. The description is followed by a sensitivity analysis which aided us to arrive at an optimal distance required to evaluate the performance of the algorithm proposed in the following chapters. The Ad-hoc On-Demand Distance Vector (AODV) Protocol is a reactive protocol. AODV is multihop and is suitable when implemented in a mobile environment. The AODV routing algorithm enables nodes to establish and maintain a mobile ad-hoc network. In AODV, mobile nodes respond to breaks in communication links and changes in topological characteristics as they occur. AODV is designed to maintain routes that are actively engaged in communication. The message types defined in AODV are Route Request message (RREQ), Route Reply Message (RREP), Route Error Message (RERR), and HELLO Message.

RREQ is issued by a sensor node that is ready to send a data packet but does not have the routing information of a destination node or a sink; then the sensor node is required to discover a path to transmit the packet. The sensor node will broadcast the RREQ to all its neighbours to find possible routes to the destination node. RREQ is a continuous message sent across the network until a destination node is found. RREQ consists of the following fields: Request ID, Destination IP Address, Destination Sequence Number, Source IP Address, and Source

Sequence Number, and Hop Count. Once a source node sends a RREQ to all the nodes, a neighbour node that has a route to the destination node informs the sender through a unicast Route Reply (RREP).

The RREP field consists of source IP Address, destination IP Address, destination Sequence Number, Hop Count, and Lifetime. If due to mobility some nodes leave the network or if links may not be available, a message called Route Error (RERR) is invoked to inform the source node of the break in the route and the inability to reach the destination node. When there is a break in communication between sensor nodes, but the source node still requires the path then route discovery can be re-initiated to find an available route to send the packet to the destination. The RERR field consists of the following fields: unreachable destination IP address, unreachable destination sequence number. Additional unreachable destination IP addresses and sequence numbers may be required whenever a link break causes one or more destination nodes to become unreachable from neighbour nodes in the network. In the process of route discovery, AODV uses local broadcast messages called Hello messages to find a node’s neighbours. The Hello messages inform neighbour nodes about existing routes that are still important for packet transmission.

In WSN, energy utilisation prolongs the network lifetime. Network lifetime may be achieved by minimising the amount of energy consumed by the radio during transmission. One way to do this is to estimate the appropriate distances between the source node and its neighbour node and source node and sink node during the transmission to optimise the performance of the network. In chapter 5, distance estimation calculation using euclidian distance calculation is performed by the source nodes to adjust their transmission range to decide on the appropriate distance for data packet transmission.

### 3.7.1. Modification of routing table, RREQ and RREP packets

The AODV routing protocol is implemented in NS-3. The different modules in this protocol have been studied, and changes or modifications have been made in some of its modules. The AODV protocol was modified to include position and distance parameters in the routing table, RREQ, and RREP packets. The routing table fields have been expanded to include the source node's position, the destination node's position, and the nexthop's position. Destination and routes in the traditional AODV routing table entries are categorised by the hop-count. Therefore, the best route to a specified destination is the route with the least hop-count. In the modified version, the sensor node's position and distance to the destination node are considered in the categorisation. The transmission route with the shortest transmission distance is regarded as the best route. In the modifications of RREQ and RREP packets, the source node and destination node positions are introduced as fields to allow the sending node to include its current position to its immediate neighbours. The calculated distance is passed as a parameter in the RREQ packet to aid the source node to choose the best and optimal route.

AODV-PD is an energy saving protocol. To minimise energy consumed by the nodes during packet transmission and reception, the position information is used for calculating the distances.

For example, in Figure 3.11 source node *S* sends a broadcast RREQ to neighbour nodes as indicated in step 1. As shown in Figure 3.11, the immediate neighbours to node *S* are node *A* and node *B*. Both nodes receive the RREQ and send an RREP including their current position which has been updated in their routing table. The source node *S* calculates the distance between itself and node *A and B* to choose the minimum distance and transmits the data to the selected node (in this case node *A*). Node *A* rebroadcasts to forward the packets received from *S* (in the case of step 2).

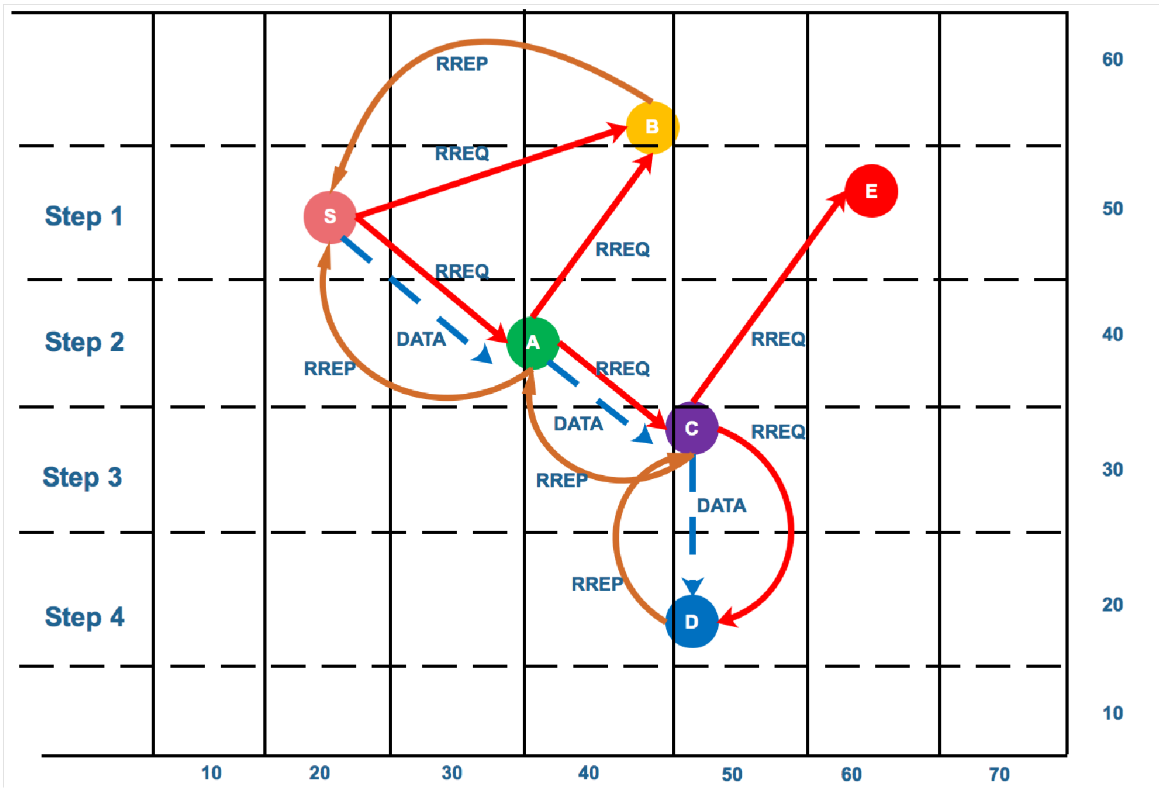


Figure 3. 11 RREQ and RREP packet exchange using AODV-PD Message Format

The immediate nodes that receive RREQ from node *A* are nodes *B and C*. Both nodes *B and C* sends RREP with their position information to node *A*. In step 3, node *C* receives the data from A, rebroadcasts and finds the destination node *D* and passes the data packets to the destination node as indicated in step 4. When the RREQ reaches the destination and then the destination chooses the shortest path and sends the RREP back according to that path. So it would choose A-C-D rather than A-B-E-C-D, as would be done if each hop selected the closest next hop.

### 3.7.2. Modified Routing Table Entry

In a mobile sensor network, when a sensor node receives an RREQ from a neighbour node, or when a sensor node creates a route or updates its route of a particular destination node, its routing table entry is automatically updated for that particular destination. The sensor node creates a table entry in case there is no such information in its routing table. If a sensor node receives RREQ, it updates its routing table with the position of the node that sent the RREQ. This would enable the node receiving the RREQ calculate the distance between them. In the routing table entry, parameters such as the position of the source node (srcPoz), the position of neighbour nodes (srcNextHopPoz), and the position of the destination node (dstPoz) have been included as fields in the routing table entry as indicated in Code Listing 3.1.

---

**Code Listing 3.1 Determining the position of a node in a routing table**

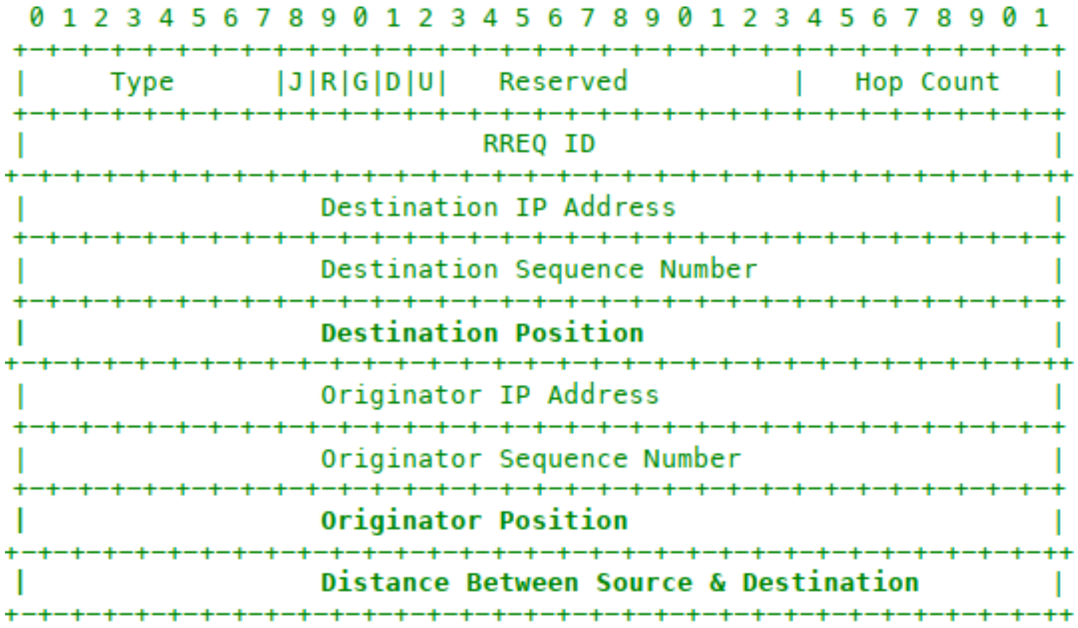
---

```
   class RoutingTableEntry
   {
   static RangePropagationLossModel range;
      public:
   ///Modified Routing Table ENtry
   RoutingTableEntry (Ptr<NetDevice> dev = 0, Ipv4Address dst =
Ipv4Address (), bool vSeqNo = false, uint32_t m_seqNo = 0,
   Ipv4InterfaceAddress iface = Ipv4InterfaceAddress (), uint16_t
hops = 0,
   Ipv4Address nextHop = Ipv4Address (), Time lifetime =
Simulator::Now (),
   Vector srcPoz = range.GetPosition(),
   Vector srcNextHopPoz = range.GetPosition(), // positions of src
nxthop dst
   Vector dstPoz = range.GetPosition(), double distance = 0.0); //
distance to nxthop dst
   ~RoutingTableEntry ();
```

```
   // new fields on positions (src, dst) and the distance between nodes.
   void SetSrcPoz (Vector xy) { m_srcPoz = xy; }
   Vector GetSrcPoz () { return m_srcPoz; }
   double GetSrcPow () { return m_srcPow; } ///<     Source     node information ends here
   void SetDstPoz (Vector xy) { m_dstPoz = xy; }
   Vector SetDstPoz () {return m_dstPoz; } ///< Destination node info ends here
   void  SetDistance  (double  d)  {  m_distance  =  d;  }  //distance functions
   double GetDistance () { return m_distance; }
   }
```

### 3.7.3. Modified RREQ packet format

Figure 3.12 shows the message format for the modified AODV Transmission Adjustment Protocol (AODV-TP). Position vectors are set to obtain the positional information from mobile sensor nodes are they move freely to observe phenomena. Parameters such as destination position, originator position, and the distance from the source to the destination. The modifications shown in Code Listing 3.2 were made in RREQ header.



```
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |J|R|G|D|U|   Reserved          |   Hop Count   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            RREQ ID                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-++
|                    Destination IP Address                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination Position                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-++
|                    Originator IP Address                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Originator Sequence Number                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Originator Position                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-++
|                    Distance Between Source & Destination      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-++
```

Figure 3. 12 Route Request (RREQ) Message Format

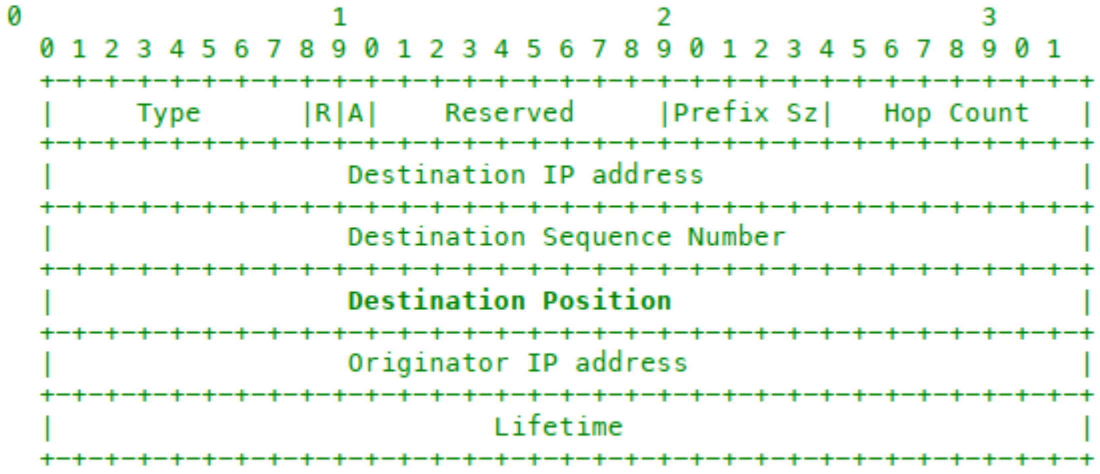
**Code Listing 3.2 Position parameter set in the Route Request Header**

```
class RreqHeader : public Header
{
   public:
   //Addition of position and distance fields in RREQ header
   RreqHeader (uint8_t flags = 0, uint8_t reserved = 0, uint8_t
hopCount = 0, uint32_t requestID = 0, Ipv4Address dst = Ipv4Address
(), uint32_t dstSeqNo
   = 0, Vector dstPosition = range.GetPosition(),
   Ipv4Address origin = Ipv4Address (), uint32_t originSeqNo = 0,
   Vector originPosition = range.GetPosition(), double distance =
0.0);
   //fields
   // methods about extra fields for RReq Messages Format.
   void SetSrcPosition (Vector x) { m_srcPoz = x; } // source x
   Vector GetSrcPosition () { return m_srcPoz; }
   void SetDstPosition (Vector x) { m_dstPoz = x; } // destination x
   Vector GetDstPosition () { return m_dstPoz; }
```

```
double    GetDstPower    ()    {    return    m_dstPower;    }    void
SetNxtHopPosition (Vector x) { m_nxtHopPoz = x; } // next-hop x
Vector GetNxtHopPosition () { return m_nxtHopPoz; }
void SetDistance (double d) { m_distance = d; } // distance
double GetDistance () { return m_distance; }
}
```

### 3.7.4. Modified RREP packet format

In a mobile sensor network, a source that receives RREQ issues a Route Reply (RREP) control packet to the sender in response to the request received. RREP packets are sent when intermediate nodes have a route to the destination node in the network. RREP packets contain all the information requested by the RREQ packet. An intermediate node without the required information rebroadcasts RREQ until the packets reached the destination node. Figure 3.13 shows the modified message format for RREP. The destination node upon receiving route request from a source node replies with its current position. The positional information sent to the RREQ node will enable the source node take decisions to adjust its distance to meet the topological changes in the network as shown in Code Listing 3.3.



```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |R|A|    Reserved     |Prefix Sz|   Hop Count   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Destination IP address                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Destination Position                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Originator IP address                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Lifetime                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3. 13 Route Reply (RREP) Message Format

**Code Listing 3.3 Position parameter set in the Route Reply Header**

```
   class RrepHeader : public Header
   {
   public:
   ////Addition position and distance in RREP header
   RrepHeader  (uint8_t  prefixSize  =  0,  uint8_t  hopCount  =  0,
Ipv4Address dst =
   Ipv4Address (), uint32_t dstSeqNo = 0,
   Vector dstPosition = range.GetPosition(),
   Ipv4Address origin = Ipv4Address (), Time lifetime = MilliSeconds
(0));
   //fields
   // extra fields about destination xy positions
   void SetDstPosition (Vector x) { m_dstPoz = x; } // destination x
   Vector GetDstPosition () { return m_dstPoz; }}
```

## 3.8. Chapter Summary

In this chapter, energy-related issues about WSNs and how they are affecting river monitoring network systems are provided. The chapter focuses on the various deployment environments and the challenges that the implementation of WSNs brings about when adopted for use. The chapter also discussed WSN topologies and explored ways in which network topology impacts energy consumption and communication issues. The chapter highlights the different techniques mainly used when implementing WSNs to maximise lifetime, coverage, and connectivity while ensuring data fidelity. The rationale for choosing NS-3 to evaluate the proposed algorithm in this dissertation is presented. The next chapter examines ways to maximise the lifetime of a network of mobile nodes in WSNs as they are affected by the state of the river (i.e., speed and depth). The next chapter discusses the types of river network monitoring, coverage and connectivity issues in river network monitoring systems and discusses the automatic adjustable transmission range algorithm. Performance analysis of the automatic adjustable transmission range algorithm takes into consideration the types of river network monitoring. The evaluation is considering the node density, connectivity and node mobility.

# CHAPTER 4

# NETWORK LIFETIME MAXIMIZATION

## 4.1. Introduction

Sensing coverage and data communication are improved when wireless sensor networks are adopted in place of the traditional methods when monitoring rivers to detect contaminations [211]. Depending on the application requirements, sensor networks can be designed in a way to collect high-precision data from a particular region of interest (RoI) or across a wide geographical area to measure the extent of pollution and the level of concentration of contaminants in the water bodies [212].

Contamination in river bodies can occur at any given place of the river and at any time [213]. Therefore, building WSNs with mobile sensor nodes is the best solution when monitoring a river network. Although WSNs with node mobility capabilities have great potential in contaminant detection, the sensor nodes are challenged with managing data communication, dealing with limited energy supplies, energy consumption, and maintaining coverage. These issues affect the network lifetime and performance. To minimise the amount of energy spent on data communication (i.e., the energy spent on route establishment due to changes in topological characteristics), an adjustable transmission range protocol is proposed in this dissertation.

The philosophy guiding the design and implementation of an adjustable transmission range routing protocol in WSNs for River Network Monitoring (RNM) systems is achieving energy efficiency and optimal network performance between mobile nodes communicating with sink nodes deployed in rivers. Mobile nodes consume much energy sending broadcast messages to the network to reach next-hop neighbours or the sink nodes during data packet transmission. The cost of communication affects energy consumption. Hence, we provide a new approach that reduces the energy budget during data transmission. The movement of the sensor nodes in the deployment area affects communication in WSNs for RNM systems. Node mobility is because of the different velocities at different parts of the river which may cause a break in the communication link between neighbouring nodes and sink nodes. Link breaks dramatically affects network performance. One approach to overcome the communication link problem is to balance the energy consumed during data transmission in the network.

Sensor networks for river network monitoring (RNM) may be of three types:

1. A river sensor network where the sensor nodes are pre-installed in the river and along its banks (i.e., using stationary sensor nodes to form the sensor network).
2. A river sensor network where the sensor nodes are released at a particular location and allowed to float freely along the river path (i.e., using mobile sensor nodes to form the sensor network).
3. A hybrid river sensor network system where a combination of stationary and mobile sensor nodes is used.

In all cases, fixed or mobile sink nodes may be used to collect the data from the mobile nodes. The way the nodes are deployed may result in coverage and energy problems and eventually affect the network lifetime. To maximise the network lifetime, an efficient design that considers uniformity in coverage and energy is proposed. In this chapter of the dissertation, we investigate a network lifetime maximization strategy, an adjustable node transmission range that automatically adjusts the transmission range based on a non-corona model, thereby focusing more on the coveragehole problems and not the energy-hole problem. In WSNs, the rate of energy depletion in sensor nodes leads to shorter network lifetimes. The performance of sensor nodes depends on the available energy for detecting contaminants over a period since most of the sensor nodes are battery powered. The battery life depends on the amount of energy used by the nodes during transmission, reception of data, and the type of routing protocol used.

Routing protocols are essential to the optimal performance of networks. Many routing protocols have been proposed for use in mobile networks. Sensor nodes that float with the river may be considered as constituting a mobile adhoc network (MANET). MANETs are rapidly deployable, self-configuring networks in which nodes connected by wireless links can freely move [214]. The network topology formed in MANETs is dynamic (i.e., change continuously) and the nodes communicate through multi-hop. The nodes are autonomous and do not require any specific infrastructure, and the network is designed to achieve particular objectives [215].

The operation of River Sensor Networks (RSNs) is like Mobile Ad-hoc Networks (MANETs) albeit with some key differences. The RSNs and MANETs are both distributed wireless networks in which data packets are routed through intermediate nodes. Each network supports multihop routing algorithms. They are energy-constrained, and their primary concern relates to minimising energy consumption. MANETs are constrained by limited bandwidth and physical security whereas RSNs are constrained by data reliability, cost, transmission range, data rate, data latency, physical size, and data security [215]. Most MANET routing protocols are designed to improve the efficiency of the network. Typical among them is Dynamic Source Routing (DSR), Dynamic Destination-Sequenced Distance-Vector Routing (DSDV), Temporally Ordered Routing Algorithm (TORA) and Ad-hoc On-Demand Distance Vector Routing (AODV). MANET routing protocols are used to save bandwidth and increase the remaining battery power in large and dense and mobile networks. AODV sends route error (RERR) messages whenever a link breaks and reestablishes a new route after the old route breaks. A route that breaks halts communication rendering the network inefficient and affecting its lifetime [216], [217].

Routing protocols in RSNs are classified based on the network structure, the process of route discovery, the operation and route selection. The protocols are mainly intended for data transmission and aggregation between the source and destination nodes. Examples include Low Energy Adaptive Clustering Hierarchy (LEACH), Power-Efficient Gathering in Sensor Information Systems (PEGA-SIS), Threshold sensitive Energy Efficient Sensor Network protocol (TEEN), Greedy Perimeter Stateless Routing (GPSR) and Location Aided Routing (LAR). These protocols route data packets by taking advantage of location information of the sensor nodes and managing energy efficiently through multihop communication [217], [218]. Routing protocols in WSNs and MANETs ensure quality communication among sensor nodes to increase the network lifetime. The network lifetime depends on the available battery power of each sensor node in the network. Node and network lifetime maximisation in WSNs are of great concern because the nodes have limited energy capacity for extended operation [50].

A key reason MANET protocols adopted for use in River Sensor Networks (RSNs) require some modification has to do with the high level of mobility of sensor nodes in RSNs which causes breaks in communication links. MANET routing protocols implemented in RSNs are needed to improve packet delivery between the source and the destination nodes whenever the intermediate nodes are out of range of their neighbours.

In this dissertation, we are motivated to extend the network lifetime to maximize the performance of the network by automatically adjusting the nodes' transmission ranges. The rest of the chapter is organised as follows. Sections 4.2 to 4.5 focus on MANET routing protocols. This section describes GPS-based location routing protocols such as Geographic Adaptive Fidelity (GAF), Minimum Energy Communication Network (MECN), and Location-based energy efficient intersection routing (EELIR). This section further describes non-GPS-based routing protocols implemented in a mobile network environment and a static network environment when they are in operation. For example, Bounded Voronoi greedy forwarding (BVGF), SPAN: An Energy-Efficient Coordination Algorithm, the Locationbased adaptive routing protocol (LARP), and Location-based multicast routing (LMR). Section 4.6

describes in detail WSNs for river network monitoring. Section 4.7 describes in detail the proposed automatic adjustable transmission range approach for maximising the lifetime of the sensor network. Section 4.8 describes the energy consumption during packet transmission and reception. Finally, Section 4.9 concludes the chapter.

### 4.2. Routing Protocols in WSNs

The development of routing protocols in WSNs has been given much attention in recent times because of the different application-specific domains in which they operate. In WSNs, routing protocols are categorised into five (5) main groups; location-based, data-centric, hierarchical, opportunistic, network flows, and quality of service aware protocols. The performance of routing protocols is measured based on the following parameters: data delivery, scalability, energy consumption, data aggregation, and other quality of service parameters.

The application-specific nature of WSNs does not allow the position of sensor nodes to be predetermined. Hence, most sensor nodes are deployed randomly in the application area. The nodes may be deployed in regions that are challenging so in these cases they are left unattended. Therefore, routing protocols developed for such applications should be capable of self-organization during data transmission, reception and computation between the source and sink nodes. Designing routing protocols for WSNs posses a lot of challenges due to the unpredictable nature of WSN. These problems include: limited energy (e.g., during transmission, reception), random deployment (i.e., no global addressing system), data packets flow from source to sink nodes, and data redundancy (multiple sensors may generate same data within the same region of interest) [218].

The concept of location-awareness has gained an essential consideration for improving the lifetime of WSNs. Location-based routing protocols use the position information about nodes in a network to communicate. Location information of two nodes is needed to calculate the distance between the nodes in order to estimate the energy required in establishing connection between the two nodes. When location information is acquired, it may be utilised in an energy efficient way to maximise the network lifetime [219]. The distance between a node and its neighbour are determined by using any number of methods including the incoming signal strength, the GPS location information, or any other non-GPS methods.

Route discovery and data packet exchanges between nodes are based on location information. To do this, the source node needs to know its location, the neighbours' locations, and the destination node's location information. The route with optimal energy consumption is selected to reduce the overall energy consumed by the node and the network [217], [220]. Many location-based routing protocols are proposed in the literature [217], [220]–[223]. A more recent work is found in [217], where the authors categorised the location-based routing protocols based on their topologies using mobile sensors and static (non-mobile) sensors. For example, the Minimum Energy Communication Network (MECN), Geographic Adaptive Fidelity (GAF), Geographic and Eenergy-Aware Routing (GEAR), Location based Energy Efficient Intersection Routing (EELIR), and Anonymous Location-based Efficient Routing Protocol (ALERT) are designed for network topologies for mobile sensors.

The other location-based routing protocols include; Energy-efficient Geographic forwarding algorithm for wireless Ad-hoc and Sensor network (DECA), Improved Hybrid Location-based Ad-hoc routing protocol (IHLAR), Location-Based Routing Protocol (LBRP), Selective Bordercast in Zone Routing Protocol (SBZRP) and Location-based Selective Bordercast in ZRP (LBZRP). Also, a couple of the locationbased routing protocols based on static network topologies include Trajectory-based forwarding (TBF), Bounded Voronoi Greedy Forwarding (BVGF), Geographic Random Forwarding (GeRaF), Two-Tier Data Dissemination (TTDD), Energy-Efficient Geographic Routing (EEGR), Greedy forwarding with virtual position (GF-ViP), Loss-aware geographic routing for unreliable WSN (GWRR), and Energy Efficient Geographic Routing (EEG-Routing).

Despite a great deal of work published over the past decade on location-based routing protocols, only a few focused on mobile WSNs which are made up of multiple mobile source nodes and sink nodes in the network. Hence, designing location-based routing protocols for mobile WSN applications is critical. We provide a brief description of both GPS-based and non-GPS based location routing protocols in WSNs.

## 4.3. GPS-based Location Routing

The location-based routing protocols described in this section determines the position of nodes using GPS. A detailed description of two well known GPS-based location Routing protocols is presented. The GPS-based location routing protocols described in this section are energy-aware and can obtain location information about other nodes in the network.

### 4.3.1. Geographic Adaptive Fidelity

A Geographic Adaptive Fidelity (GAF) routing protocol was proposed [224] for use in MANETs and WSNs. GAF is an energy-aware location-based routing protocol designed to conserve energy in the network for optimal performance and to prolong node and network lifetime. The protocol is designed in such a way that it creates virtual grids and nodes use their location information to associate with these virtual grids. The nodes in a square grid are equivalent with respect to data packet forwarding and the nodes coordinate to determine the sleep and wake-up times of each other for a period to achieve load balancing. Generally, in GAF:

- Each node determines its equivalent node(s) in the same virtual grid
- Unnecessary (i.e., nodes not required for communication) nodes are turned off

- Constant level of routing fidelity (i.e., uninterrupted connectivity between two communicating nodes) is maintained if an intermediate node is awake
- The source and sink nodes remain on and intermediate nodes monitor to balance energy use in the network.

In GAF, a square virtual grid of size *r units* is created in a region of interest with each grid size calculated based on the radio transmission range, *R*. The distance between two nodes must be greater than the transmission range.

The grid size is computed as follows:

$$r^2 + (2r)^2 \leqslant R \tag{4.1}$$

$$r < R/\sqrt{5} \tag{4.2}$$

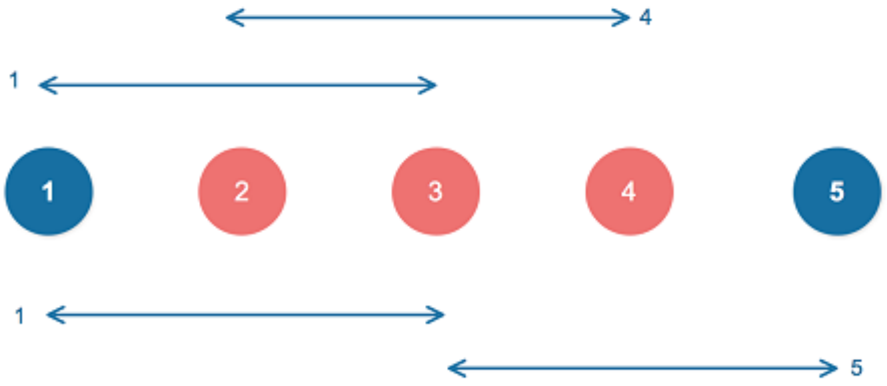


Figure 4. 1 Virtual Grid in GAF

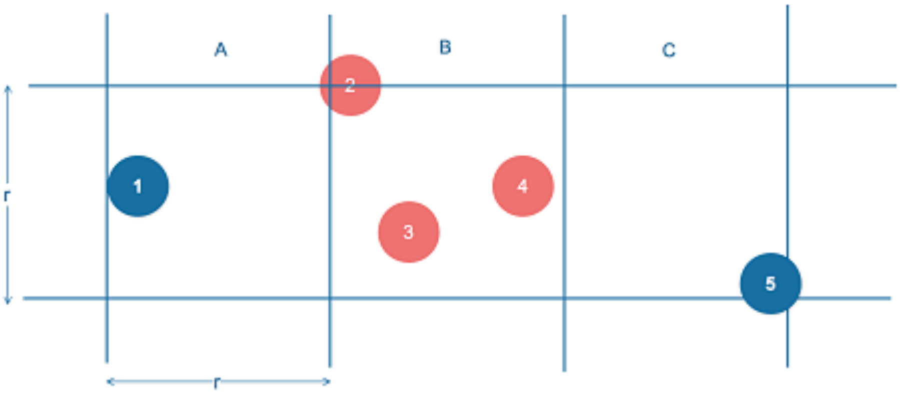


Figure 4. 2 The problem of Node Equivalence

When nodes have obtained the location information about other nodes, determining their equivalent nodes poses a challenge because nodes that may be equivalent with some nodes may not be equivalent for data packet forwarding between others. In Figure 4.1, given that node 1 wishes to establish communication with node 4, this can be done using either nodes 2 or 3 as intermediate nodes. Thus, nodes 2 and 3 are said to be equivalent in relation to the transmission from node 1 to node 4. On the other hand, for node 1 to communicate with node 5, it requires the use of node 3 as its intermediate node since it is the only intermediate node reachable from node 1 that can also communicate with the destination node, in this case node 5. The introduction of virtual grids in GAF was to overcome the problem of equivalence created in Figure 4.1. GAF divides the region of interest where the nodes are distributed into small *virtual grids* such that, for any two adjacent grids, nodes may communicate with each other. For example, in Figure 4.2, nodes in virtual grid A can communicate with all the nodes in virtual grid B and vice versa. Hence, in Figure 4.2, node 1 can forward data packets to *node 2* and *node 3*. Also, *nodes 2, 3 and 4* can communicate with node 5 since their virtual grids are adjacent. *Nodes 2, 3 and 4* are equivalent, and therefore two of these nodes in grid B may sleep to conserve energy in the network. Nodes periodically change their states (i.e., move from discovery-active-sleeping) to balance load in the network. In discovery or active state, the node can move to the sleeping state when it identifies another equivalent node performing the packet forwarding (routing) operations. GAF is adapted for both scenarios with and without mobility. GAF-basic tend to have fewer active nodes when the mobility is high within the virtual grid and therefore is suitable for energy conservation but observes higher loss of data packets. In GAF-mobility, each node computes its leaving time in the grid and sends this information to all the neighbour nodes. This information is used by nodes in the sleep-state to adjust their sleeping time to keep a good level of routing fidelity.

### 4.3.2. Minimum Energy Communication Network (MECN)

In the work presented in [225], the authors described a distributed position-based network protocol which focuses on minimising energy consumption in the network, taking into consideration a lowpower RF transceiver design. The protocol was implemented in a randomly deployed ad-hoc network and is designed to maintain a globally connected network regardless of possible module (i.e., the communication and sensing) failures.

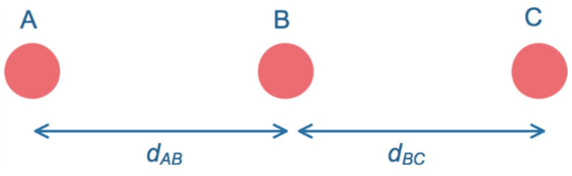


Figure 4. 3 Three colinear nodes A, B, C.

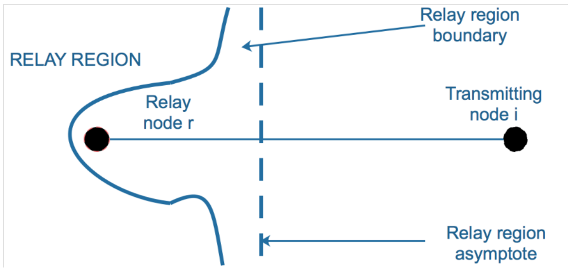


Figure 4. 4 Relay region of the transmit-relay node pair in MECN.

MECN is designed to be able to dynamically update its link to maintain strong connectivity. The protocol considers path loss based on the height of the transmission antennas. Hence, the protocol does not depend on the value of the path loss exponent *n*, but instead the distance-dependent path loss.

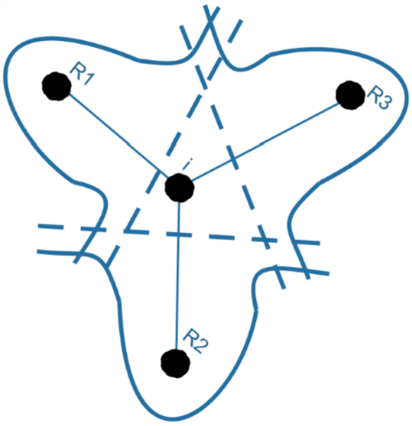


Figure 4. 5 Enclosure of node i

The protocol assumes mobile nodes to have similar antenna height, hence path loss is ignored. The position of the mobile nodes is obtained using a low power GPS. The challenge is that the nodes are unable to obtain the position of other nodes through the use of GPS. The protocol reduces the power consumption by relaying messages through a middle node as shown in Figure 4.3. On the other hand, if the node communicates directly to the sink (i.e., the master-site), it consumes more energy. For example, in Figure 4.3, if node *A* knows the position of nodes *B and C* and wants to send a message across to node *C*, node A may either transmit the message directly to C with high energy consumption or will relay the message to node *B* and then node *B* will forward the message to node *C* using minimal amount of energy to transmit the message. Since node B is acting as a relay node, its exact location could be an important determinant in minimizing power consumption during transmission. For this node then, a relay region can be defined. In Figure 4.5, the behaviour of relay nodes in the propagation region is shown. In this region, a finite set of nodes are deployed. Nodes outside this region are unable to communicate with nodes within the finite region. In Figure 4.4, node *i* finds neighbour nodes $R_1$, $R_2$, *and* $R_3$ within its range and may compute the relay region for each of the three nodes it has found. Beyond these regions, node *i* is no longer able to search for other neighbours.

The MECN protocol is divided into two phases: 1) search for the enclosure and 2) cost distribution. In the search for the enclosure phase, each node finds its enclosure and neighbour set by sending a broadcast with its search region to obtain the positions of nearby nodes. The nodes' transmission range or signal is available only in the nodes' finite region. The node must keep track of all neighbour nodes found within its search region.

In the first phase, a local search is performed by the node to find the enclosure graph and nodes within its neighbour set. The positions of nearby nodes are required for computing the enclosures. Each node broadcasts its location to the search region where other nearby nodes can detect the transmitted signals. Phase 1 is designed for link setup and configuration. In the second phase (i.e., cost distribution), the protocol is designed to find the optimal links on the enclosure graph. The Bellman−Ford shortest path algorithm was applied to the enclosure graph in phase 1 to determine the cost of each link (i.e., the power consumption). Each node broadcasts its cost to its neighbours and calculates the minimum cost to reach its neighbours.

### 4.4. Non-GPS-based Location Routing using Mobile Nodes

The location-based routing protocols described here determines the position of other nodes using other methods other than the use of GPS. In this it is assumed that the nodes are energy-aware and are mobile. Among the several protocols provided in the literature, the improved hybrid location-based ad-hoc routing protocol (IHLAR) and the anonymous location-based efficient routing protocol (ALERT) are both implemented with mobile nodes and without the use of GPS to determine the position of the nodes.

### 4.4.1. Improved hybrid location-based ad-hoc routing protocol (IHLAR)

The work presented in [226] is a hybrid location-based routing protocol that combines the strength of a topology-based (i.e., for intra-zone communication) routing protocol and a geographical-based (i.e., for inter-zone communication) routing protocol to reduce end-to-end delay in ad-hoc networks. The protocol is designed to enable each node to maintain a table of neighbours within a certain number of hops $\rho$, to form a zone with its neighbours in the table.

A node and its neighbours in the same zone communicate using hello messages. If a node does not receive *hello messages* from its neighbour, it deletes it from its table entry. Hence, to forward a packet to a destination node, the source nodes checks if the destination node is in the same table. Packets are routed to the destination node if it is $\rho$ hops away from the source node or the neighbour node using the AODV routing protocol. In Figure 4.6, the source node, $S$ is in the same zone (i.e., intra-zone routing) with destination, $D_1$, hence, the source node requires a maximum of $\rho$ hops to send packets to $D_1$. In the case of inter-zone routing, a source node, $S$ forwards data packets to the destination node, $D_2$ using the greedy forwarding approach since $D_2$ is out of the zone of $S$. With greedy forwarding, the source node forward packets to the node's closest node towards $D_2$, until the packet reaches an intermediate node which is within the same zone as $D_2$ and is a $\rho$ number of hops to the $D_2$. In situations where both the topology-based routing protocol and the greedy forwarding algorithm (i.e., geographic routing) are implemented but a node closer to $D_2$ is not found, the protocol then adapts the angular routing protocol presented in [227] to find other possible routes to the destination.

### 4.4.2. Anonymous location-based efficient routing protocol (ALERT)

ALERT [228], is a location-based routing protocol implemented in ad-hoc networks. This routing protocol partitions the network area into zones and chooses nodes randomly in the same zone as intermediate nodes to form unknown routes which are not traceable. In addition to the anonymous route creation, ALERT is also designed to hide the transmitter/receiver among the set of transmitters/receivers to increase the anonymity protection of the sources/sinks. For ease of illustration of the ALERT routing algorithm, a rectangular network area is employed. The nodes are positioned randomly in this network area. For nodes to identify the positions of other nodes in the network, they must be in the same zones, and new nodes joining the network are configured to join the network.

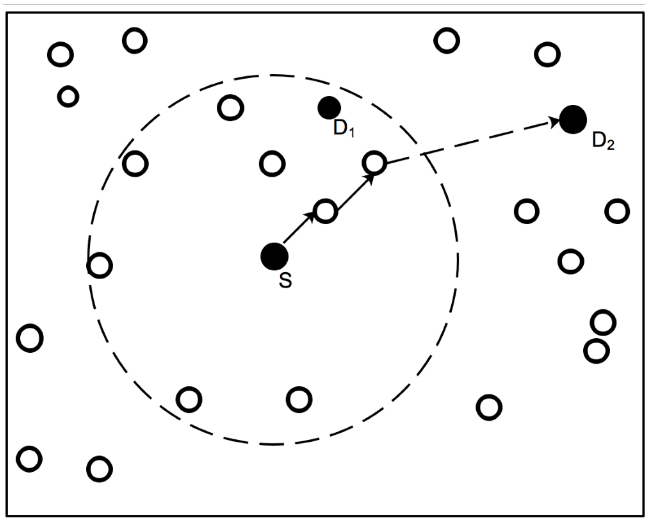


Figure 4. 6 Setting up route in IHLAR

Figure 4.7 depicts the operation of ALERT. It uses hierarchical zone partitioning to dynamically divide the network area into two zones (*Zone A and B*). Each zone is further partitioned vertically and horizontally into smaller zones. For example, *Zone A* is divided into Zone $A_1$ and $A_2$ and Zone $A_2$ into zones $A_{2A}$ and $A_{2B}$. This type of partition process is known as hierarchical zone partition. Zone $A_{2B}$ (i.e., the destination zone) contains the destination node, $Z_D$. Each data source, $S$ or forwarder, $RF_1$ executes the hierarchical zone partition to check whether is in the same zone at $Z_D$. The data source then divides the network into horizontal and vertical directions until it is not in the same zone as $Z_D$. The data source through a GPSR routing protocol chooses a position in the other zone (i.e., temporary destination, *TD*) and transmit the packet to a node closest (i.e., the random forwarder, $RF_1$) to *TD*. After a successful identification of a TD, the data packets are broadcasted to the nodes in Zone $A_{2B}$ for onward transmission to the destination node, $Z_D$.

Here, the assumption is that the position of the destination node, $Z_D$ does not change during the data transmission process. One essential contribution made with this protocol is to hide the data initiators among the number of initiators in the network to increase the anonymity protection of the sender, *S*.

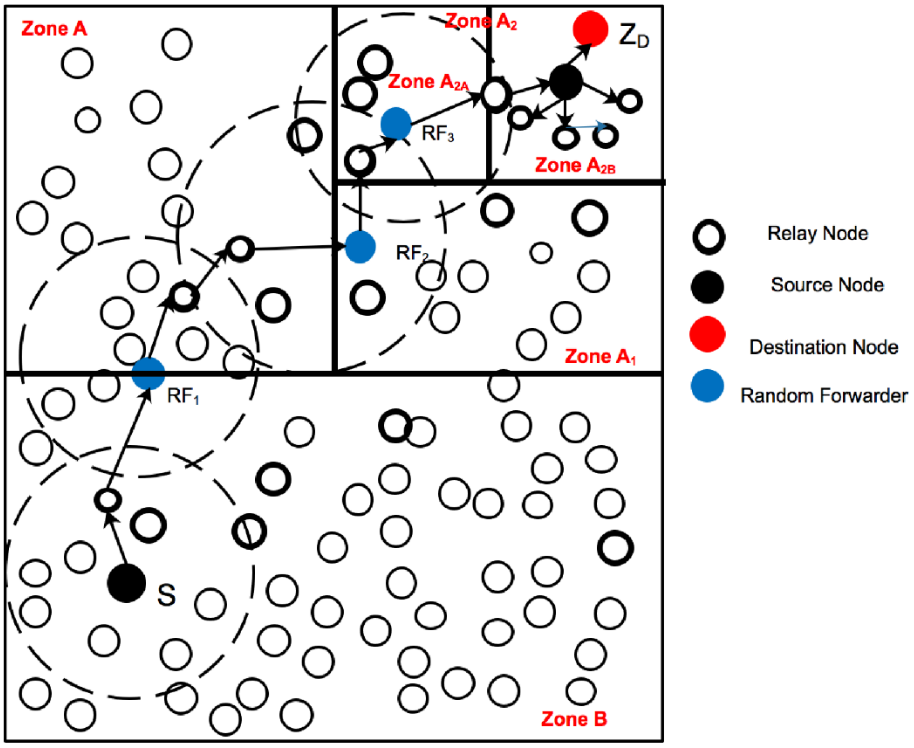


Figure 4. 7 Zoning in ALERT [5]

### 4.5. Non-GPS-based Location Routing using Stationary Nodes

A Non-GPS location-based routing protocol have been reported in literature [229]–[232]. The existing non-GPS-based location-based routing protocols discussed in this section include Bounded Voronoi greedy forwarding (BVGF), SPAN: An Energy-Efficient Coordination Algorithm, the Location-based adaptive routing protocol (LARP), and Location-based multicast routing (LMR). These existing protocols were implemented in a static network environment [229]–[232], but they are energy-aware.

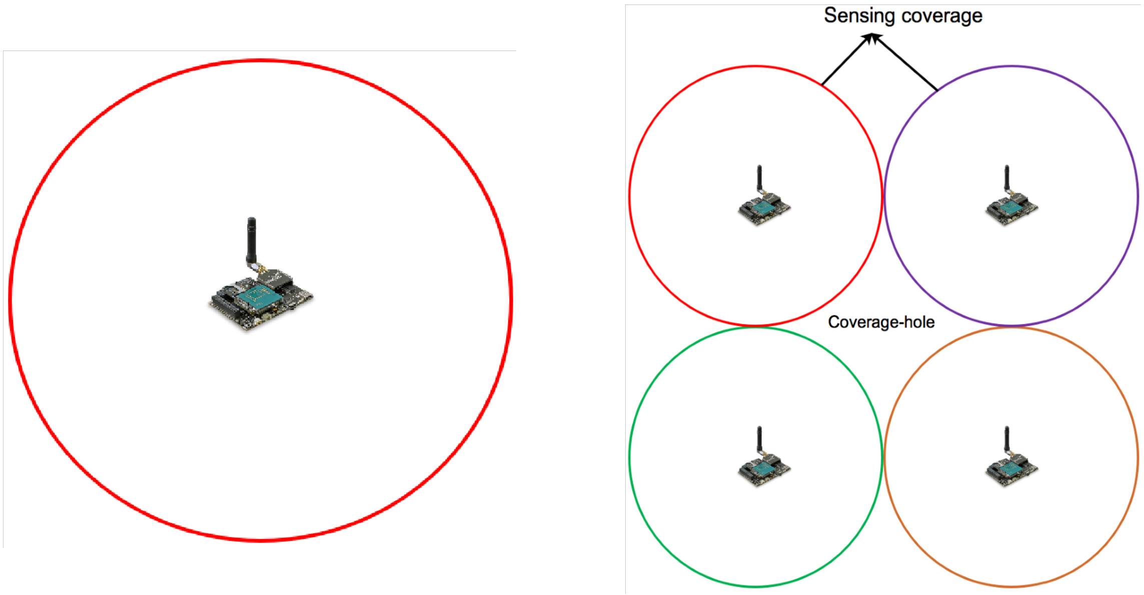
In [229], the protocol is designed to make greedy decisions based on neighbours located one-hop away. When a node *i* needs to forward data packet to node *j* which is one-hop away from *i*, then it is expected that the line segment joining the source and the destination node should coincide or intersect with one of the boundaries of the *Voronoi (V) map* or *j*. BVGF chooses a neighbour with the shortest Euclidian distance as the next-hop to reach the destination among all the eligible nodes. In instances where there are multiple neighbours likely to be chosen as the next-hop node to the destination, BVGF routing randomly selects one of these nodes. The likelihood that the same next-hop may be chosen to forward data to the sink makes such nodes suffers from high battery depletion.

In [230], a novel adaptive routing protocol based on the location of the nodes (LARP) in underwater is proposed. Packet forwarding is based on the characteristics of the environment and the data packet level. Data packets are in three different levels:1) emergent route, 2) intermediate route, and 3) regular route. The protocol employs the location of nodes to calculate the distance between the source and the destination nodes. LARP causes propagation delay when assigning the transmission path, but its energy consumption is efficient.

### 4.6. WSNs for River Network Monitoring (RNM)

In this section, we briefly provide a description of the three different kinds of river network monitoring systems in use. In River Network Monitoring (RNM), sensor node placement [233], [234], sensor node localization [235], [236] and node coverage [237] are factors that affect the performance of the RNM applications deployment. It is necessary to consider these factors in river networks when deploying sensors for efficient event (i.e., contamination) detection during the monitoring process. The deployment and topology of sensor nodes in WSNs contribute to the network performance during sensing and communication. Consequently, the random deployment of nodes may affect the coverage and limit the sensing of the targeted area. Random node placement may also lead to unbalanced traffic which eventually shortens the lifetime of the network [238]–[241].

In most instances, the problem that may arise in random sensor node deployment in rivers is that this may create coverage-holes and energy-holes in the network. When every point in the deployment area is not covered it give rise to the coverage hole problem. [242] defined coverage-hole as an area in the network that is not covered by any of the sensing nodes. Each sensor node when deployed will have a fixed range within which if an event occurs it will be able to detect it as shown in Figure 4.8a. When the nodes are deployed in such a manner as to use the least number of nodes this could result in a coverage-hole problem as shown in Figure 4.8b.



(a) Sensing Range of a wireless sensor node (b) Coverage-hole Problem in WSNs
Figure 4. 8 WSN Coverage Issues

The coverage-hole problem may also arise when sensor nodes within the network die due to energy depletion. In such situations, sensor nodes far from the sink may not be able to reach the sink or other intermediate nodes, resulting in interruption and non-functioning of the network. This problem may also cause essential events not to be detected and creates a break in data transmission. One way to overcome the coverage-hole problem is placing sensor nodes entirely within the region of interest (RoI) and at the same time balancing the energy consumption in the network for optimal performance. The coverage-hole problem may be overcome when the nodes are set up in a way that the sensing ranges overlap each other in the region of interest as shown in Figure 4.9.

An energy hole occurs when nodes are out of range of intermediate nodes and the sink and are unable to deliver data to the sink node on a certain path [240]. The uneven depletion of energy especially in routing-based environments where the nodes around the sink node die-off more quickly than expected may give rise to the energy-hole problem. These challenges affect the overall network lifetime [243].

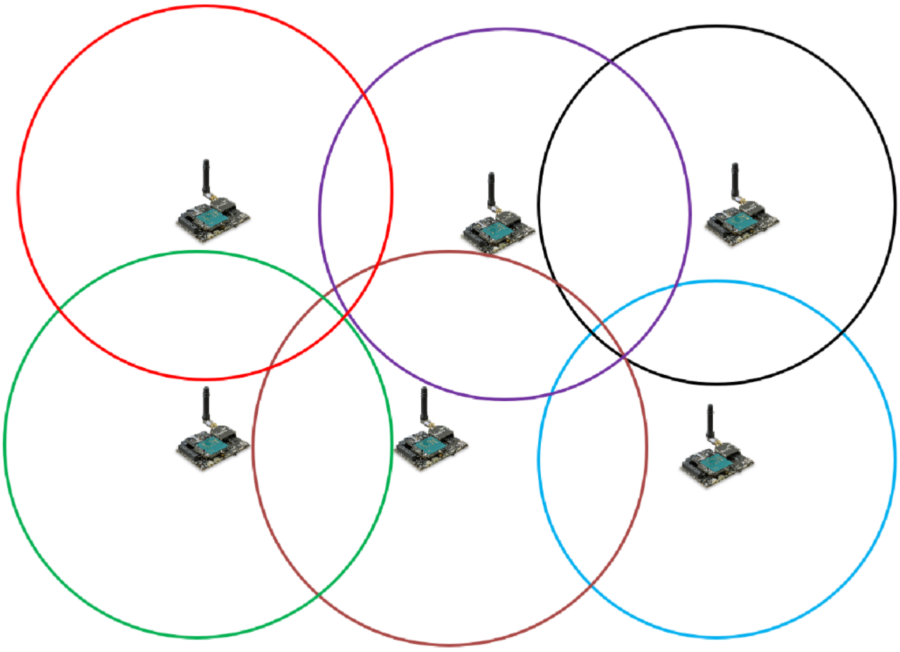


Figure 4. 9 Overcoming coverage-hole problem

To overcome the energy-hole problem and maximise the lifetime of the network, [24], [244] proposed a set of design guidelines that take into account uniform distribution. In [24], the authors proposed three deployment strategies that improve network connectivity, coverage and lifetime. The three interventions recommended by the authors to achieve maximum network lifetime and avoid energy-holes in WSNs are as follows. a) Balancing energy consumption in the node. In this strategy, the node density at the different deployment locations in the sensor network is expected to be a continuously varying function of the distance from the sink. This aids in energy balancing among the sensor nodes in the network system. b) In the case where energy balancing is not achievable in the entire network due to insufficient sensor nodes in the deployment locations, the lifetime threshold is used to determine the minimum number of nodes required at the deployment sites. c) Ensuring network connectivity and coverage. In this intervention, the nodes in the network are sufficient in the deployment area but only require optimal transmission to achieve maximum lifetime.

In [244], the authors proposed design guidelines for lifetime maximisation and avoiding energy-holes in WSNs using two strategies: a) uniform deployment of sensor nodes and b) uniform reporting. In uniform node deployment, the area is divided into sectors and each sensor node is likely to serve as a source or the next-hop when communicating to the sink from its sector. This approach is employed to balance the amount of energy spent within the sensor network and to maximise its lifetime.

### 4.6.1. Mobile Nodes with Stationary Sinks Nodes for River Monitoring

In this kind of river monitoring, the mobile sensors float along with the river current, and as they move, they sense water quality parameters and transmit data to the stationary nodes positioned along the river bank, as shown in Figure 4.10. The use of mobile sensor nodes will support the modelling of the spread of contaminants in the river over a period. For example, the nodes may be moving with the contamination; we aim to use these models to monitor the spread of the pollution as it goes down the river. The stationary nodes, which serve as sink nodes, perform in-node data analysis, and transmit the water characteristics of the river to the appropriate users. The mobile nodes also may provide additional information about their path whilst they are moving, such as their current velocity, direction, comprehensive coverage and high connectivity among the sensor nodes with minimum energy utilisation in the network [235].

The sensor network is said to have full coverage if the following conditions are met: 1) RoI is totally covered to enable the detection of all events occurring within the specified region, and 2) all the nodes within the network are able to reach the sink node either directly or through an intermediate node [245].

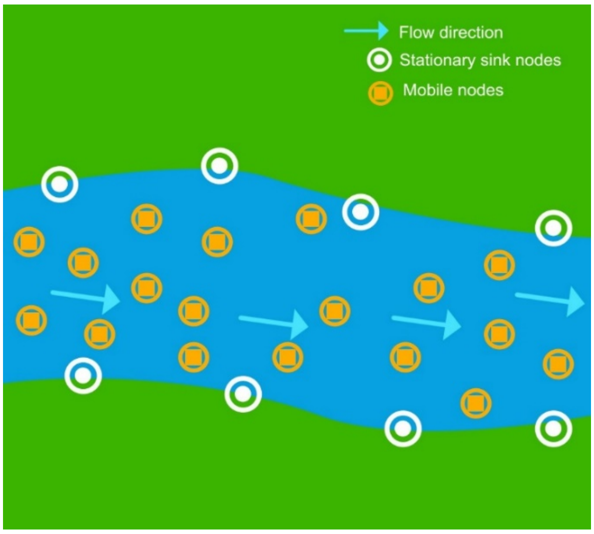
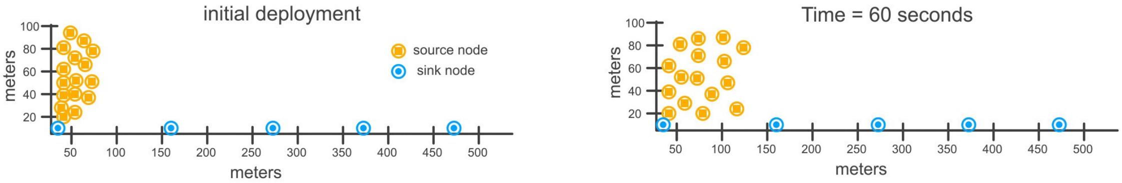


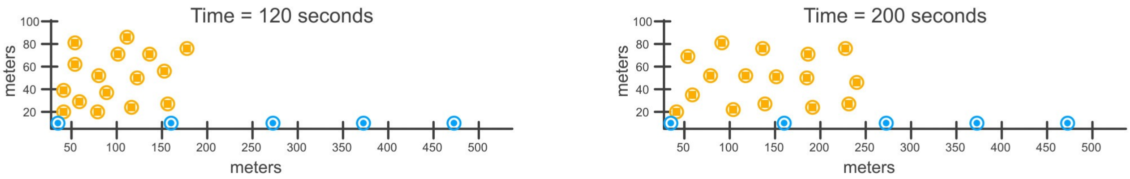
Figure 4. 10 River Network Monitoring with mobile sensors and static sink nodes

In river monitoring network systems, detecting every instance of pollution in the river is of great importance. Hence, full coverage is necessary. Full coverage of the region of interest improves network connectivity and reduces high rate of packet loss during transmission. In river monitoring networks, the levels of pollution at the origination point differ from other locations as pollutants travel along the river. In this situation, shallow levels of contamination may not be detected (i.e., appears to be a false alarm). Full coverage in the region of interest may improve the detection accuracy of events as and when they occur [246].



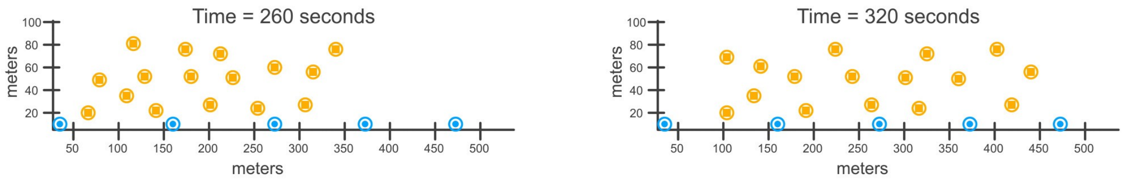
(a) Initial deployment (b) Nodes movement at time *t=100 seconds*.

Figure 4. 11 Time evolution of sensors at initial deployment



(a) Nodes movement at time *t=150 seconds* (b) Nodes movement at time *t=250 seconds*

Figure 4. 12 Time evolution of sensors over a period



(a) At tx=80m and at time t=350 seconds (b) At tx=80m and at time t=500 seconds

Figure 4. 13 Time evolution of sensors at end of simulation

The mobile sensors upon detection of an event will transmit the sensed data to a sink node in the river network. For the mobile node to transmit the sensed data, it must establish a path to the sink node. Typically, this is achieved through a broadcast message to find a path to any nearby sink node. The path may either be a direct path or one that is obtained through another mobile node. The sensor deployment is random, and the probes are immersed under the water to sense data as the mobile nodes move along the river path, as illustrated in Figures 4.11, 4.12, and 4.13. As the sensor nodes move, they collect water quality information from the river and transmit the data collected and their current position at any given time to the sink nodes along the banks of the river.

### 4.6.2. Mobile Nodes with Mobile Sink Nodes for River Monitoring

In this kind of river monitoring, the mobile sensors and mobile sinks float along with the river current, and as they move, the mobile sensors detect pollutants and transmit the data to mobile sinks also floating in the river, as shown in Figure 4.14. This kind of network improves the coverage/sensing area. The number of mobile sinks that may be deployed may depend on the river type (i.e., deep but slow-moving rivers, deep but swift moving rivers, and shallow but swift moving rivers). In slow, deep rivers, the velocity of the river is relatively low. Hence, the mobile sensor nodes move steadily with the mobile sensor nodes along the river path. In this type of deployment, the mobility of the mobile sensors and the sinks are controlled by the current of the river. In swift, shallow, and deep rivers, the movement is random.

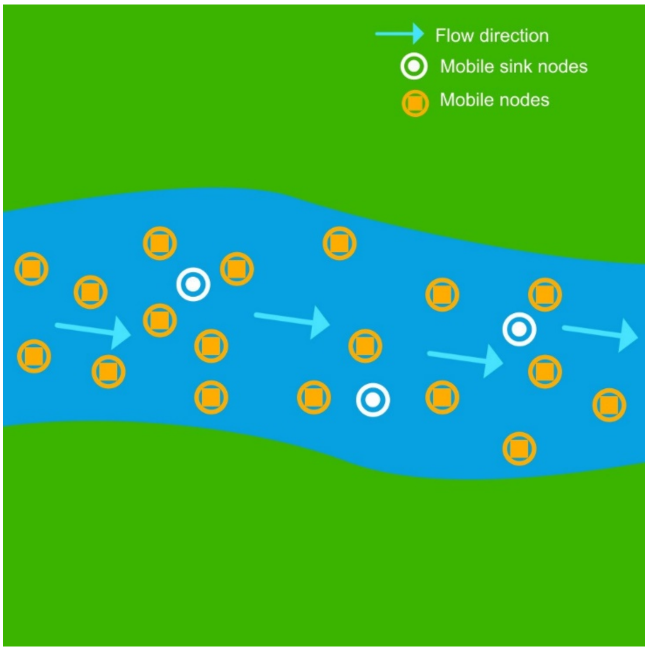


Figure 4. 14 River Network Monitoring with mobile sensors and mobile sink nodes

The sinks and mobile nodes follow a random path in the river. In most WSN applications, the mobile sinks are used to collect data from either static sensors or mobile sensors [247]. In such applications, the mobile sinks move to specific locations and collect the data from the source nodes. In river monitoring networks, sink movement is random and depending on the velocity of the river, the mobile sink may find itself: 1) trailing in the sensor network field on its mobility path (i.e., trailing sink problem), 2) moving among the mobile sensor nodes (near sink problem), and 3) moving ahead of all other mobile nodes due to high velocity and variability in mobility (i.e., far sink problem). Random mobility in river sensor networks makes it difficult to track the current position of the mobile nodes/sinks during packet transmission and reception, discovering and maintaining routes, thus increasing the energy consumed by mobile nodes/sinks during packet transmission and reception. The use of mobile sinks in WSNs requires the design of novel strategies that support multi-hop communication.

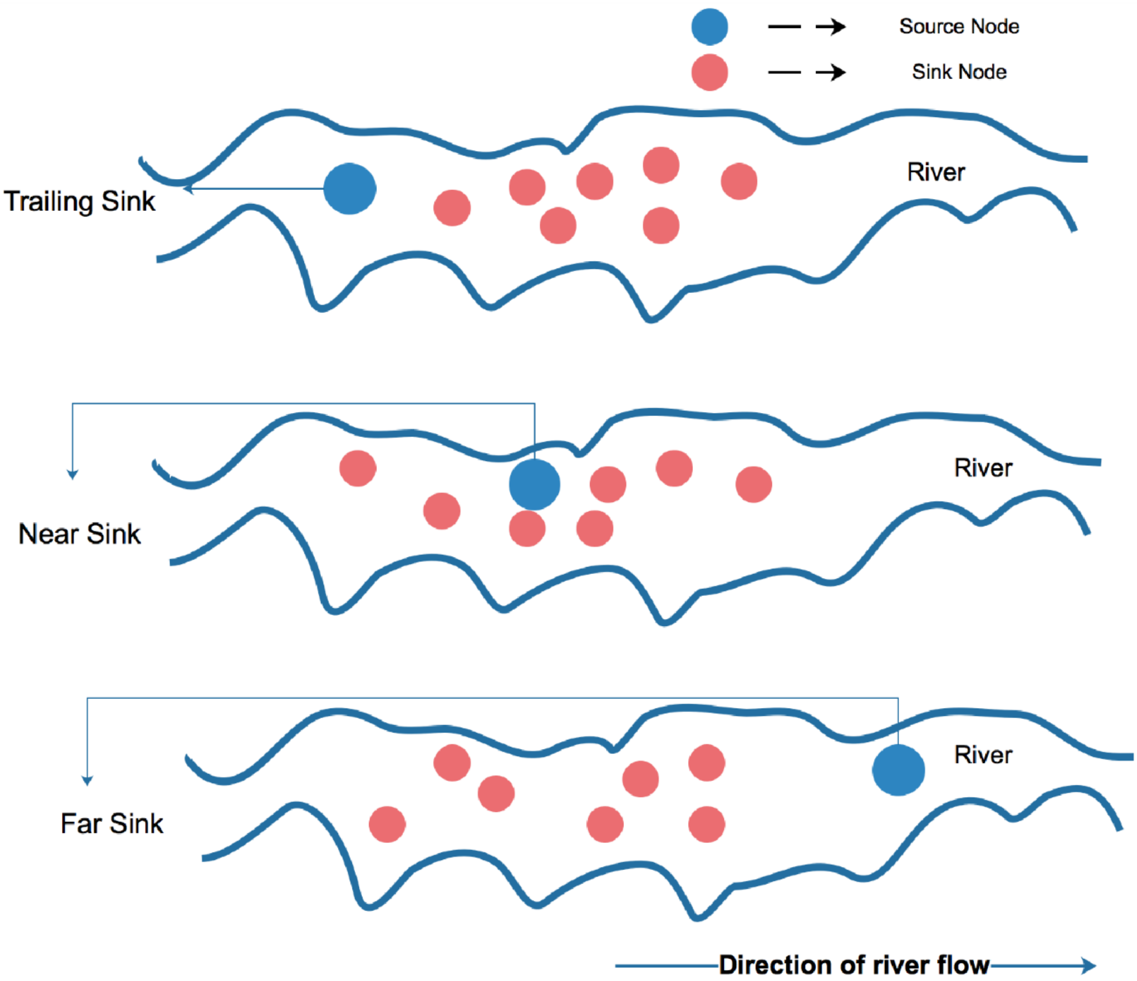
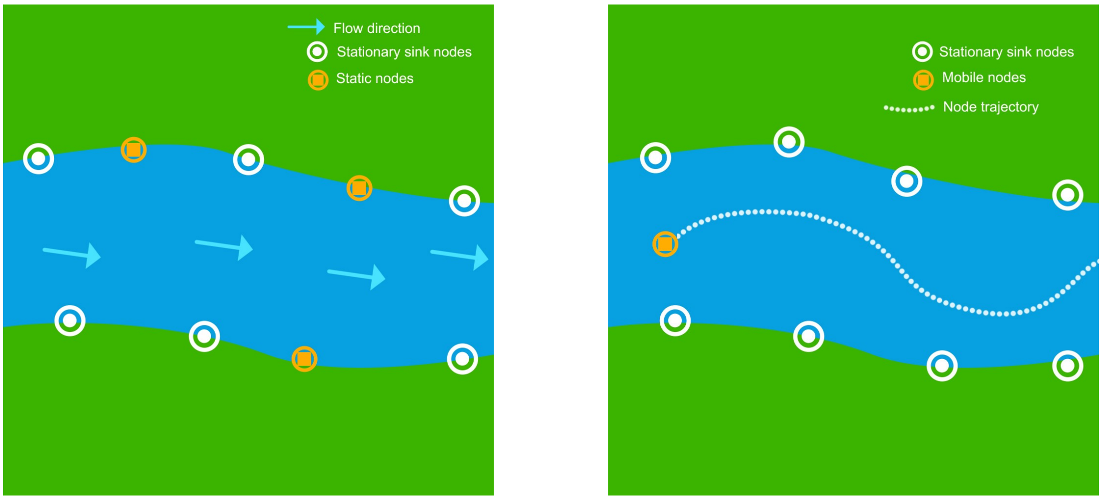


Figure 4. 15 Mobile sink problems in River Monitoring Networks

### 4.6.3. Static WSN for River Network Monitoring

Depending on the application requirements and objectives, specific RNM systems may be deployed. Static WSNs for River Network Monitoring are designed for use when it is required to know the state of the river at a particular location. Static nodes deployed in specific areas in a river monitor only that region, leaving the other regions unattended and uncovered. With static WSNs, it is difficult to know how the pollutant is spreading in the river body.



(a) RNM with static nodes and static sinks (b) RNM with static sensors and mobile sinks

Figure 4. 16 Kinds of Static RNM

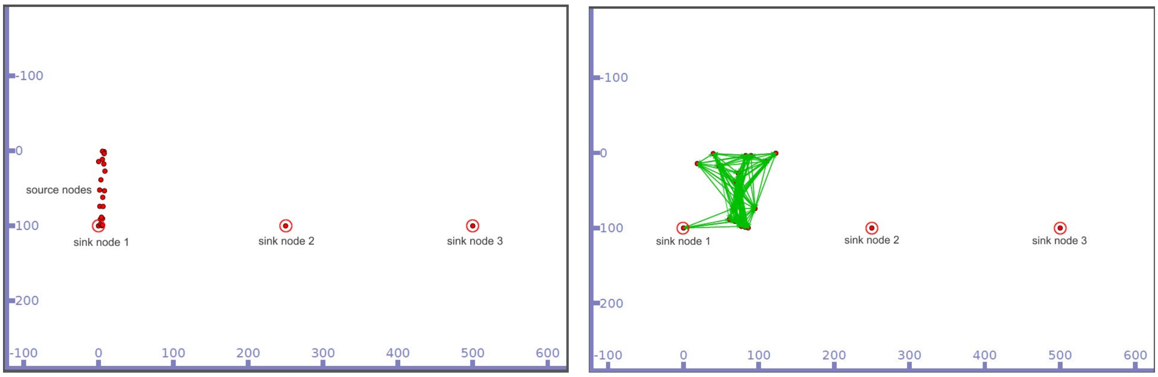
This shortcoming may be offset by deploying several the static WSNs along the course of the river. Static WSNs are ideal for use in stationary water bodies. In a WSN several deployment scenarios may be envisaged; a) static nodes with static sinks as shown in Figure 4.16a and b) static nodes with mobile sinks as shown in Figure 4.16b. In all static (i.e., source nodes and sinks) RNM systems, the source and destination nodes normally use relay nodes that serve as the most energy efficient path for data transmission to conserve energy. In this scenario, the nodes that serve as the relay nodes (i.e., seen as a hotspot and creates energy-hole) deplete their battery power quickly. The distances between the source nodes and the destination nodes are constant and do not change over time. In RNM systems, when mobile nodes are used as sinks, they can move to a new location at a time *t* in the river. In this scenario, the distance between the static nodes (i.e., senders) and the sinks (i.e., receivers) change over time [248].

Node mobility is not always a means to resolving issues in traditional static deployments, especially, in river monitoring network systems, the velocity of the river impacts the sink mobility, which may create an energy-hole. Issues relating to the coverage hole and energy hole problems are like the earlier described systems. To overcome the coverage-hole problem, it may be required to deploy more sensors within the region of interest. Deploying more sensors could also help in overcoming the energy-hole problem.

### 4.6.4. Network Structure/Model

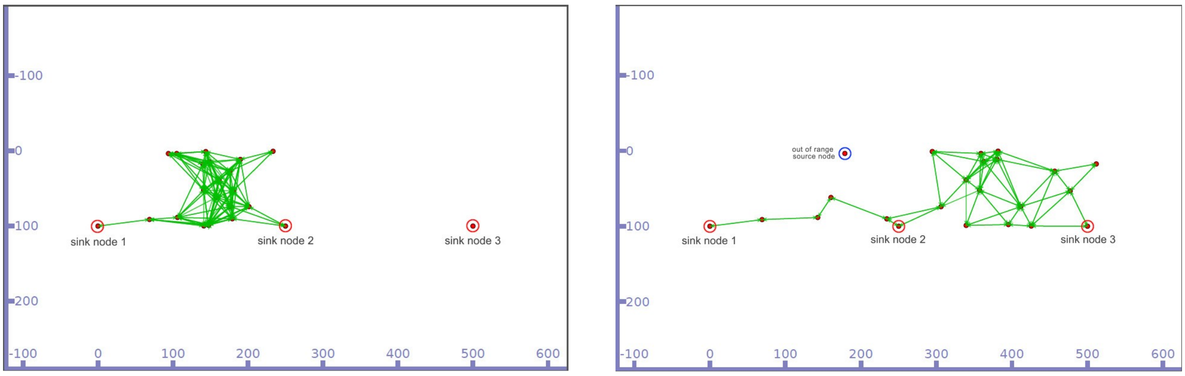
In this section a description is given of the characteristics of the river to be monitored using mobile nodes with stationary sinks. It is assumed that the nodes are left unattended once deployed in the river, and all the sensor nodes are free moving with the current of the river. The sink nodes are stationary, and all the other nodes are mobile. Further, the following assumptions are made:

1. There are a set of sensor nodes $n$, each node is randomly placed within the initial deployment area as shown in Figure 4.11a and Figure 4.11b.
2. Each sensor node has an initial transmission range, $t_x$ to enable the node to reach its immediate neighbours; all distances are in metres.
3. The node adjusts the value of its transmission range $t_x$ value automatically depending on how far or near the node is away from the sink node or hops through the next available node to the sink.
4. The sensor node moves with the current or velocity, $v$ of the river.
5. Sensed data are sent constantly at a rate of *512 (kbps)*.
6. Communication is multi-hop.
7. Nodes have the same cardinality and connectivity constraint. Connectivity constraint has to do with issues related to the communication network and cardinality constraint has to do with issues related to energy balancing and network lifetime maximization.
8. Based on a greedy forwarding algorithm approach, the sensors transmit data packets through a multi-hop approach to the sink.
9. We assume the same power is used by the sensors to transmit data and the maximum transmission range a sensor can operate within and adjust its $t_x$ value is 250m.



(a) Initial deployment (b) At *tx=80m* and at time *t=100 seconds*.

Figure 4. 17 Time evolution of sensors at initial deployment



(a) At tx=80m and at time t=300 seconds (b) At tx=80m and at time t=500 seconds

Figure 4. 18 Time evolution of sensors at end of simulation

Figures 4.17 and 4.18 illustrates a river with the following features: Boundary $B = [0.0, 520] \times [0.0,100]$ meters where 20 source nodes have been deployed randomly with sink nodes at an initial point, the motion of the nodes are represented and it is time-dependent. The motion of the nodes is in the direction of the river current. After the nodes are randomly placed at the initial point (Figure 4.17a), they move with the flow rate. The distribution of the nodes after specified periods of time are shown in Figures 4.17 and 4.18. As can be seen from the diagram, at 100 seconds, some of the nodes have covered over 500m of the river length while others are lagging. This observation is because of the difference in velocity at the different parts of the river body. A node close to the bank of the river will move with smaller velocity than a node at the middle portion of the river where the velocity tends to be high.

Figure 4.17b, shows the distribution of the mobile nodes after time t=100s. The nodes are assumed to all have an initial transmission distance, tx = 80m. At this transmission distance communication is easily established between the source nodes and the first sink node as the distance is within the maximum range. Similarly, we show in Figures 4.18a–4.18b the establishment of communication among the source nodes and the sink node 2 and 3. A special case was observed in Figure 4.18b where one node (i.e., the node with blue circle around it) was out of range to other nodes due to limited amount energy. At a point, it was unable to reach the nodes since it adjusted it is *tx* value a couple of times hence depleted its energy.

### 4.6.5. Coverage and Network Connectivity

The authors in [249], described a network model for a wireless sensor network as a time-varying graph defined as $G = (V(t), E(t))$ as shown in Figure 4.19 which consists of set $V(t)$ of sensor nodes moving within a rectangular boundary over a period of time $t$ where $E(t)$ represents the communication link between two sensor nodes, i.e. $(v_i, v_j) \in E(t)$ where node $v_i$ can send a packet to node $v_j$ since the distances between the nodes will not be a constant value. Set E(t) is time-dependent because of the variability in velocity of the river and the effects of the chosen mobility model. In the RNM system, full coverage is achieved when the nodes are distributed in such a way that all areas within the network are fully covered. In the monitoring area shown in Figure 4.19, we denote an area of interest represented by a subgraph $G_i(V_i, E_i)$.

The number of active nodes in the subgraph guarantees the connectivity of the network and determines the lifetime of the network.

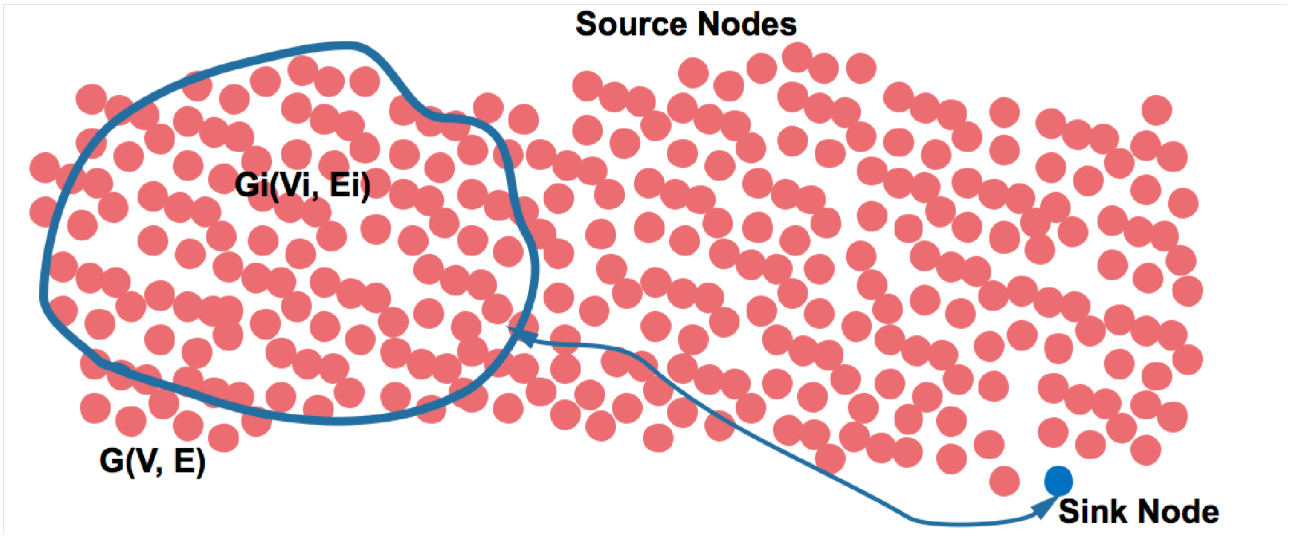
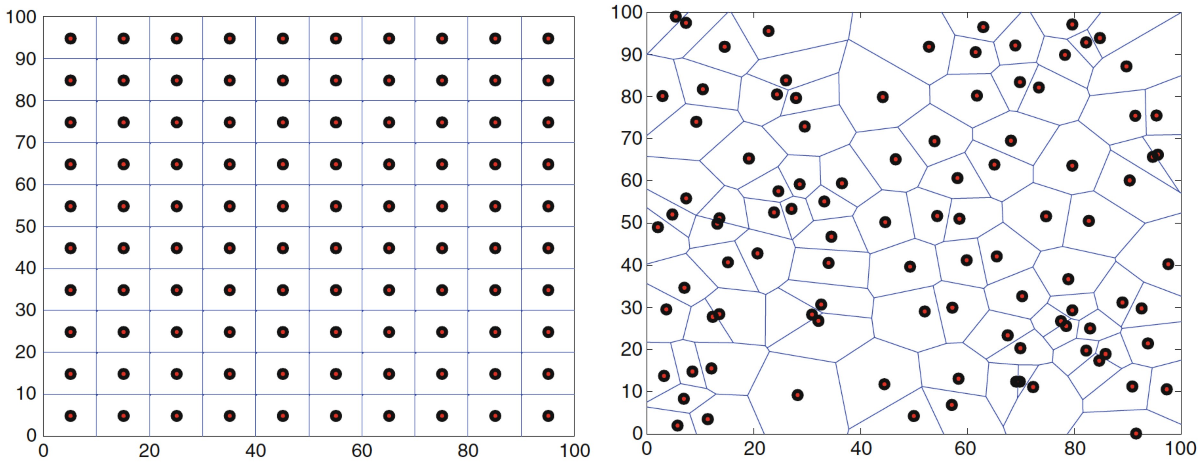


Figure 4. 19 Wireless Sensor Network G (V, E) and subgraph Gi (Vi, Ei)

In RNM applications, the area coverage is a fraction of the full coverage. In other words, the area coverage is the area covered by one sensor at any point in time *t*. Connectivity problems give rise to energy-hole in sensor networks. The nodes closer to the sink nodes receive greater traffic causing them to lose energy quickly.

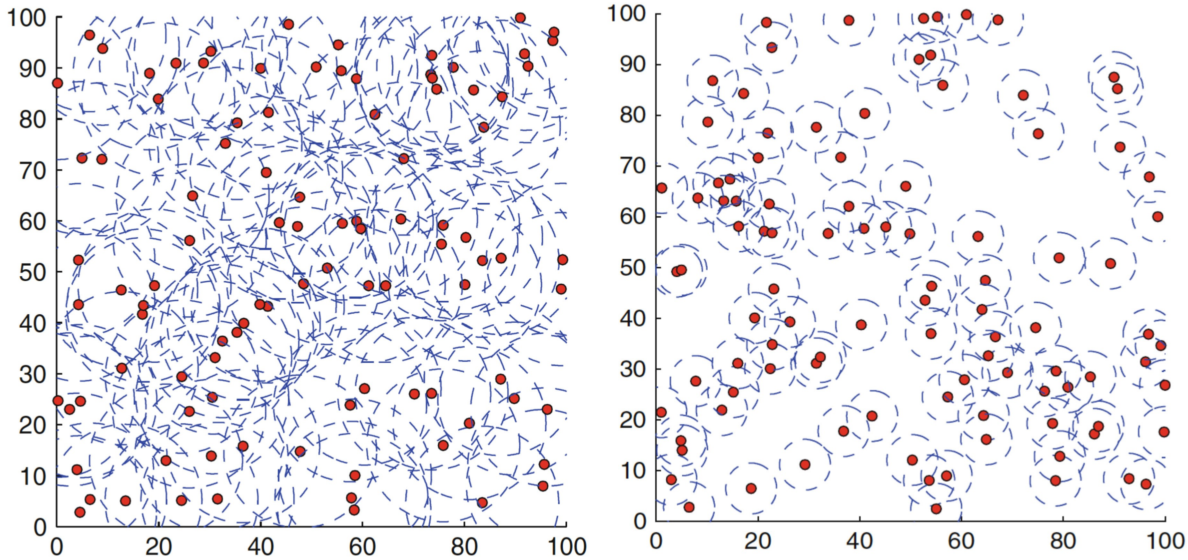


(a) Square Deployment (b) Random Deployment

Figure 4. 20 Types of Node Deployment

In WSNs, to prevent nodes from depleting their energies quickly, the type of deployment must be taken into consideration so that maximum area coverage and connectivity will be maintained. In this regard, nodes may be placed in such a way that they fully or partially cover the monitored zone taking into account the sensing range of the wireless sensor node. For example, nodes may be arranged in a square pattern in the deployment area as shown in Figure 4.20a to detect events within that region. In river network monitoring, a square model of deployment may not be suitable due to the nature of the environment where the pollution spreads over time. Random implementation, shown in Figure 4.20b is another approach for sensor node deployment. It may be uniform or non-uniform [250], [251]. Generally, square, and random deployments may be suitable for stationary freshwater sources such as lakes where there is little movement. RNM requires an optimal sensor node deployment strategy that guarantees full area coverage within the sensing range of the sensor node to ensure that events are detected at any part of the region of interest. Full coverage would also guarantee network connectivity such that the sensed data are transmitted to other nodes in the network and to the sink node.

In WSNs, sensor nodes have a sensing range within which they can detect an event. The sensor node is not capable of detecting events that are out of its sensing range (refer to Figure 4.8a). Sensors deployed in RNM systems sensitivity is reduced when suspended particles in the river settle on the sensor node. Low sensor sensitivity affects the sensed values, and the sensing range also changes. In RNM systems, any location in a monitored region is covered if the euclidian distance calculated between that location and the sensor node is not higher than the node's sensing range, $r_s$ [252], [253]. In full sensing coverage, the coverage problem is overcome since the sensor nodes cover the entire deployable area. For example, Figure 4.21a shows 100 sensor nodes randomly deployed in an RoI with a sensing range of 20 meters (i.e., $n = 100$ and $r_s = 20$). With this kind of deployment, the sensor nodes cover the entire region of interest. In Figure 4.21b, a similar number of nodes are deployed with a sensing range of 5 meters (i.e., $n = 100$ and $r_s = 5$). In this case, most parts of the deployment area are not covered due to the shorter sensing range of the sensor node [251].



(a) Region of interest is nearly fully covered (b) Region of interest not fully covered

Figure 4. 21 Sensing Range Coverage

The sensitivity of each sensor node is also modeled based on model presented in [250]. Node sensitivity decreases as distance increases rendering events beyond the node's circular disk (i.e., sensing range) undetectable.

## 4.7. Automatic Adjustable Transmission Range (AATR)

As may be seen from the preceding discussions, given an initial distribution of sensor nodes in a RNM system, after a time *t*, the nodes will attain different positions due to their mobility. In this section, we consider a wireless sensor network for RNM with *n* mobile nodes and three stationary/static nodes representing the sink nodes. The static nodes are set up in such a way that there is one at the beginning, center and at the end of the Region of Interest (RoI). The rectangular boundary/domain or RoI is dimensioned as follows: Boundary $B = [0.0, 520] \times [0.0, 100]$ meters. When the mobile sensors begin to move with the river current or velocity, routing paths are created by any of the sensor nodes using a standard multi-hop routing protocol. The AATR algorithm proposed here is based on the idea of replacing the initial transmission range value, $tx_{initial}$ during the first deployment and reset it to a new transmission range value, $tx_{adjusted}$ when the node is out of communication range from the next-hop node to create its routing path to the sink. This means that the node is unable to reach its next-hop neighbour with the same $tx_{initial}$ value set during the initial deployment. Hence $tx_{initial} < tx_{current}$ (i.e., the value of the node at its current location after the initial deployment). In such situations, the $tx_{adjusted}$ value is chosen. The goal is to overcome the problem and to reduce the energy wasted by far nodes to reach the sink node or a next-hop node to establish communication for data transmission. In a sensor network, energy is wasted when the node continuously sends broadcast messages several times before reaching nodes out of its communication range. In a similar manner, nodes that are *nearer* to the sink node or its neighbour (s) (i.e., the available next-hop node), requires the same $tx_{initial}$ transmission range or a minimum *tx value* to reach its neighbours or the sink node. Here, $tx_{initial} = tx_{current}$ value or it is adjusted to the $tx_{reduced}$ value which is less than $tx_{initial}$. The goal is to reduce how much energy is required to transmit data to *near-by nodes*.

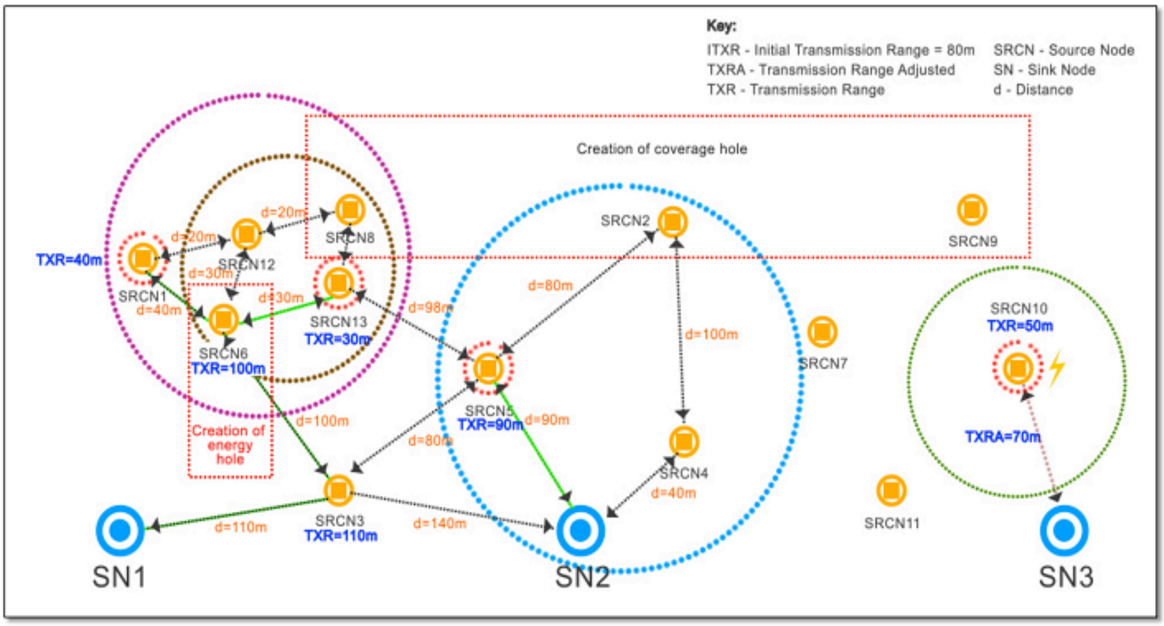


Figure 4. 22 Transmission range adjustment

In Figure 4.22, the transmission range adjustment algorithm is illustrated. For example, source node SRNC1 with transmission range of 40 metres may only reach next-hop neighbours or sink nodes within its range. SRNC1 detects an event and sends a broadcast message to find next-hop neighbours to the sink node. After the broadcast, SRNC1 finds SRNC6, SRNC8, SRNC12, and SRNC13 and calculates the distance to each node using the nodes' position information. There are three transmission choices available to source node SRNC1 after the distance calculation of next-hop neighbours within its range: 1) to transmit the packet to the next-hop neighbour with the minimum distance (i.e., by reducing its transmission power, $tx_{adjusted} < tx_{initial}$ (i.e., the greedy approach); 2) to transmit to the next-hop neighbour with its initial transmission power ($tx_{initial}$ does not change); and 3) to transmit the packets to the next-hop neighbour by increasing its transmission power, $tx_{adjusted} > tx_{initial}$.

To arrive at any of the three decisions described above, the sensor node decides whether to send to the closest neighbour, a random neighbour, or the furthest reachable neighbour. For example, from Figure 4.22 if SRNC1 opts for the greedy method (i.e., case 1), then it will select SRNC12 as its closest next-hop neighbour. Otherwise, SRNC6 will be selected. Depending on the selected next-hop (i.e., either SRNC6 and SRNC12), data packets are forwareded to other neighbours or the sink node. Taking SRNC5, SRNC10, and SRNC13 (with small red circles), after detecting events and broadcasting messages to find next-hop neighbours or the sink node, employs any of the three cases to communicate. SRNC5 with the transmission of 90 metres have neighbours SRNC2, SRNC3, SRNC4, and SRNC2 (i.e., sink node 2). SRNC5 directly communicates with SN2 without adjusting its transmission range. In the case of SRNC13, it communicates with SRNC6 without adjusting its transmission range. Finally, in case of SRNC10, the node has excess energy that makes it capable to adjust its power to reach transmission distance of 70 metres. The proposed transmission range adjustment approach seeks to address energy wastage and coverage problems to improve the network lifetime and to balance the energy in the network for efficient performance.

## 4.8. Energy consumption during transmission and lifetime maximization

Network lifetime maximisation is a critical concern in sensor networks. One major problem area that has not been widely explored is routing and network lifetime maximisation in river sensor networks. The lifetime of the node is the time the node is operational until it dies off. Hence, the power used for packet transmission and reception must be controlled when designing routing protocols for river networks.

### 4.8.1. Problem Formulation

This section presents the proposed model for transmission range adjustment for mobile sensor nodes with stationary sink nodes in WSN and then formulates the problem with mathematical expressions. Considering mobile nodes deployed in a river, the current/velocity of the water determines their positions at any point in time. The first problem is identifying the location of the sensors as they move along the river path to assess their current position in the river (i.e., tracking its path and direction). The second problem is that some of the mobile nodes may move faster than other nodes, causing a break in the communication link. The mobile nodes may be out of communication range at some point in time. The third problem is due to the mobility of the nodes and the break in communication, and regular broadcast is performed by the nodes causing the mobile nodes to deplete their energy and die-off quickly. The situation whereby high energy is consumed by the mobile sensor to perform sensing, transmission, and reception and the link breaking makes the wireless sensor network non-functional. The final problem is how to determine the appropriate route for packet transmission to achieve optimal performance (i.e., lowest energy). The mobile sensors assume constant velocity in the river in one scenario and variable velocity in another in their deployable environment. The nodes may move faster depending on the location in which they find themselves, and if there is no presence of obstacles. This kind of deployment is suitable for river monitoring network systems where detecting events as they occur is essential.

### 4.8.2. System Model

The river network is modelled based on the following assumptions: 1) the sensor network consists of a set of source nodes $N$, where $N = \{n_1, n_2, n_3, ..., n_k\}$. The source node at any time $t$ *(seconds)* may be found at position $P_k (x, y)$. Hence, we represent the set of positions as $P = \{p_1, p_2, p_3, ..., p_k\}$. The sensor nodes are randomly deployed in the RoI, $R$ and based on the relative motion between the source node and its neighbours or the sink, the distance $d$, may be calculated at any time $t$ *(seconds)*. That is $d = vt$, where $v$ is the relative velocity. The distance between source node $i$ and destination $j$ at time $t$ is represented by $d_{i,j}(t)$. The source node's velocity $v_{src}$ can be estimated to have maximum velocity, which is equal to the velocity of the river, $v_{riv}$, i.e., $v_{src} = v_{riv}$.

It is also assumed that the nodes may slow down at the banks/river edges since the river tends to settle at its banks. Our goal is to determine the exact position of the sensor node to calculate $d$, to obtain the minimum distance for data packet transmission and to conserve the amount of energy a node utilizes for transmitting data. Adjusting the transmission range contributes to energy saving in river sensor networks. The Random Walk 2D mobility model is used to describe the mobile nodes' movement pattern. In the mobility model, the following parameters are set to change a) speed, b) direction and bounds. The bounds are the boundaries set for nodes (i.e., the riverbanks in terms of RSNs). These parameters cause each mobile sensor to change its position over time and move in the direction of flow. The Random Walk 2D mobility model is suitable for implementation in a WSN environment. This mobility model is most appropriate, and suites best the behaviour of river network monitoring systems after we modified the direction attribute to pick values (i.e., the minimum and maximum x and y values were set to zero (0)) only in the x-direction.

The nodes are positioned at the beginning of the simulation using the Random Rectangle Position Allocator as shown in Figure 4.23. At the start of the simulation, each node receives information about the positions of each of the sink nodes. Typically, in real life application, the sensor nodes' will be embedded with a GPS to determine their x and y coordinates. 2) The sink nodes may be deployed as static or mobile nodes, depending on the application objectives/requirements. In this work, the sink nodes were immobile. Our primary interest was to monitor the levels of contamination. Hence, our goal was to simulate an environment consisting of mobile source nodes capable of sensing and measuring the levels of contaminants and transferring the measured values to stationary sink nodes placed at different locations at the banks of the river.

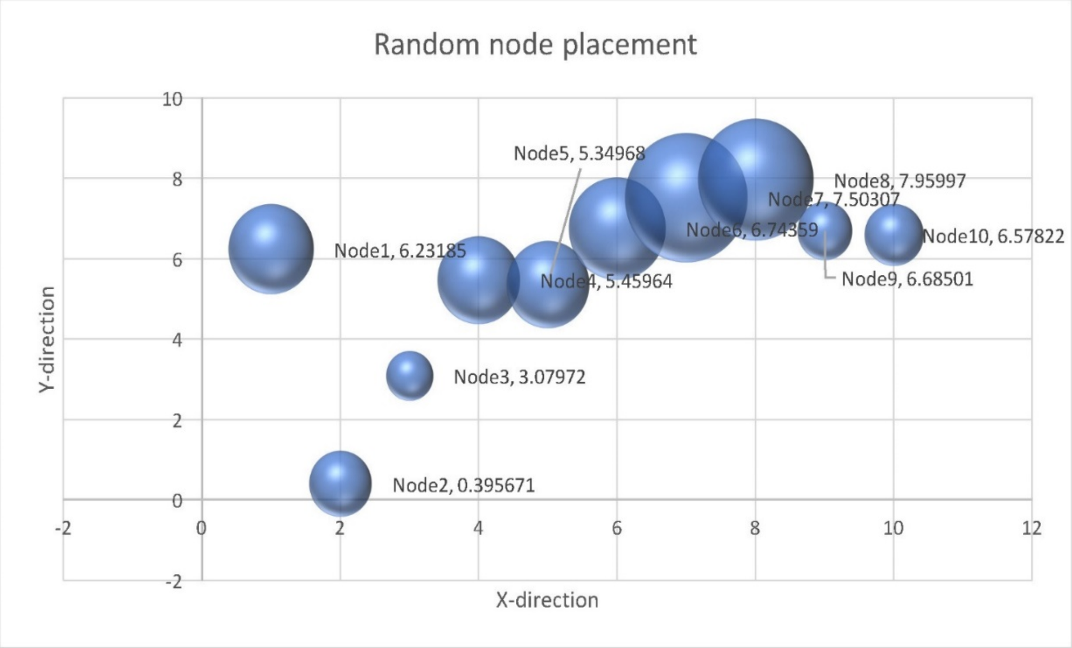


Figure 4. 23 Random placement of mobile sensor nodes

### 4.8.3. Energy Consumption Model

The energy consumption model proposed is based on three key parameters: 1) Energy to sense the pollution, $E_{sp}$, 2) Energy used for data packet transmission, $E_{tx}$, and 3) Energy for data packet reception, $E_{rx}$. The distance between a source node and its neighbour (s) or the sink node is denoted as *d*. Given the distance between a transmitting node and a receiving node the transmission power $P_x$ is adjusted to the known distance *d*, and data packets are transmitted at this adjusted power $P_x (d)$. The source/sink nodes receive intermittent *hello messages* from their immediate next hop neighbors of their current position information. It will be shown that the transmission energy consumed by the node may be significantly reduced using the adjustable transmission range technique. This technique focuses on $E_{tx}$ and $E_{rx}$. In the scenario described in Figure 4.22 the energy utilized in transmission is set to an adjusted $E_{tx} = P_x (d)$. The source node minimizes its energy consumption for packet transmission by selecting the transmission power based on its distance from its next neighbour or the sink node. The amount of energy consumed by the source nodes, *n* in the river network and the packet delivery ratio are calculated by:

$$Src_E = \sum_{i=0}^{n} E_{tx^n} \qquad (4.3)$$

$$PDR = \frac{E_{rx}}{E_{tx}} \qquad (4.4)$$

We also evaluated the transmission power required for a node to send a packet to its destination by calculating the transmission and reception gains between the source *i* and destination *j* as follows:

$$G_{ij} = g_{tx} g_{rx} \left( \frac{\lambda}{4\Pi d_{ij}} \right)^2 \tag{4.5}$$

Since our goal is to limit transmission power to a level which is adequate to sustain good communication quality within the network, we evaluated the desired nominal transmission power based on the gains, $g_{tx}g_{rx}$ and the $d_{ij}$ between the source and the destination nodes using the minimum or initial transmission power, $P_{min}$. The following formula is derived to calculate the desired transmission power:

$$P_{tx} = \frac{P_{min}}{g_{tx} g_{rx}} \left( \frac{\lambda}{4\Pi d_{ij}} \right)^2 \tag{4.6}$$

The $P_{tx}$ parameter is set in a function in the NS-3 propagation loss model and the function is called in the simulation to determine the value of $P_{tx}$. Although, this method for calculating the value of $P_{tx}$ in the simulation works perfectly, the same approach will not be the same for real world deployments.

### 4.9. Chapter Summary

In this chapter, we provide related work/background on location-based routing protocols. A detailed description for river network monitoring is described. Here, the description focused on mobile sensor nodes with stationary sink nodes, mobile sensor nodes with mobile sink nodes, static sensor nodes and static sinks, and static sensor nodes with mobile sinks as approaches for monitoring River Sensor Networks (RSNs). This chapter also focused on sensor node coverage and network connectivity issues in RSNs. Finally, this chapter introduced a background description to the proposed routing protocol which is based on adjustable transmission range as a useful approach to reduce the energy consumption in RSNs thereby maximising the lifetime of the sensor nodes.

# CHAPTER 5

# DISTANCE-BASED ENERGY-AWARE (DBEA) ROUTING PROTOCOL IN WIRELESS SENSOR NETWORK

## 5.1. Introduction

In freshwater sources, such as rivers, contaminants flow along the river path; hence sensor nodes must be deployed to cover a broader area to detect pollutants along the river path or must move along with the pollutant in order to keep track of the level of pollution. In general, sensor networks for freshwater monitoring may be deployed in one of the following three scenarios. These are: 1) pre-installed stationary sensor nodes in the river and along its banks (i.e., stationary sensor nodes), 2) the nodes are allowed to float freely along the river path (i.e., mobile sensor nodes) and 3) a combination of both stationary and mobile sensor nodes. In all cases, fixed or mobile sink nodes may be used to collect the data from the sensor nodes to ensure timely, accurate and reliable contaminant event detection.

In the case of scenarios 2 and 3, the sink node must be activated and be reachable by the mobile nodes. In RSNs, the variability in the speed of the river affects node mobility and the network connectivity. Also, in such networks, locating the mobile sink is challenging since it may be at different points/locations in the river, which gives rise to the far-sink node, near-sink node, and trailing sink-node problems.

The far-sink node problem occurs when a mobile sink node has a velocity higher than the velocity of the other nodes in the mobile sensor network. The near-sink node problem occurs when the mobile sink node finds itself within the source nodes as they move along the river path. In this case, the mobility is seen as a constant. In the trailing sink node problem, the mobile nodes, velocity is slower and therefore lags the source nodes. In the far-sink and trailing-sink problems, there is an increase in the amount of energy consumed by sensor nodes in the network in reaching the sink node. The topology of the network changes frequently depending on the position of the sink node. The near-sink node problem also creates energy hole problems. This arises because the sensor nodes near the sink are likely to use up their energy compared to the sensor nodes far from the sink node.

Under such conditions, attempts by source nodes to reach a mobile sink and transmit data packets will require high transmission power utilisation. In this work, the use of adjustable transmission range is proposed as a method for saving node energy and thereby improving on the network lifetime.

The method proposed requires the dynamic adjustment of the node’s transmission range to ensure optimal energy usage during transmission, thus, maximising the lifetime of the node and the overall network lifetime. When contamination is sensed in a given region of interest, measurements are made, and the data is aggregated and routed towards the sink node. The event-detection node may in each case have to adjust its’ transmission range and use the optimal amount of energy for the transmission. This ensures that the nodes’ lifetime and the network lifetime are extended as much as possible.

In this chapter, a distance-based energy-aware routing protocol is introduced. The chapter focuses on lifetime maximisation in WSNs. The rest of the chapter is organised as follows. Section 5.2 focuses on lifetime maximisation methods in sensor networks based on transmission range adjustment. In Section 5.3, the network model and the problem formulation are described. Section 5.4 presents the algorithms proposed for the study. The simulation results showing the performance of the sensor network modelled in this work is described in Section 5.5. Finally, Section 5.6 provides a summary of the chapter.

## 5.2. Lifetime Maximisation Problem in WSN

Network lifetime is considered as a key characteristic of Wireless Sensor Networks to evaluate the performance of the network. Network lifetime in WSNs depends on the lifetimes of each node in the network. The lifetime of a wireless sensor node depends on the amount of energy the node consumes over time and the amount of energy available for its use. Generally, the wireless sensor node uses much energy to perform activities such as sensing, communication and data processing.

Network lifetime takes metrics such as coverage and connectivity into account when measuring the lifetime of the sensor network. In relation to coverage, lifetime is defined as the time the region of interest is within the sensing range of a sensor node. In relation to connectivity, network lifetime is defined in terms of the number of successful data collection rounds and the total number of data packets that may be transmitted to the sink. In other words, network lifetime in relation to coverage and connectivity is the time interval for the network to perform sensing and transmission functions [13], [45].

The focus of this work is to maximise the sensor node/network lifetime by controlling the amount of energy a node expends on transmitting/receiving data packets in mobile networks with reference to freshwater monitoring applications. In the case of scenario one (1) where pre-installed stationary nodes are fixed in the river and along its banks for monitoring, the lifetime of the network is said to be the time taken for the first node to deplete its energy [254]. So, when the sensor node drains off its power, the node dies and is no longer considered useful in the network. On the other hand, in scenarios (2) and (3), we measure lifetime as the time taken for the source node to deplete its energy.

In WSNs, power is utilised during the following processes: 1) transmission, 2) reception, 3) sensing, and 4) sleep mode. The transmission power (Tx) is the amount of energy/power required to transmit data packets. It is also proportional to the communication distance between the transmitting node and the receiving node (usually called the transmission range). Reception power (Rx) is the amount of energy required to receive data packets in a network. Sensing power (S) is the power needed for a sensor node to sense an event within time $t$ seconds and in sleep mode the power consumed when the sensor node is in the sleep state (where no activity is collected) [50].

Given a network of $n$ nodes, the lifetime of the network may be defined as a point in time $t$ when the death of the $i^{th}$ node (i.e., partitions the network such that it loses its functional purpose) degrades the network to such a point that it can no longer function as a network. For example, taking a network of $n$ nodes that is partitioned into m-subgraph with $k$ anchor nodes that connects this subgraph to the sink as shown in Figure 5.1. Network lifetime is defined as the time that the $i^{th}$ anchor node dies since the nodes of a subgraph is not able to reach other nodes in the network. Anchor nodes are nodes through which all other nodes will gain access to the sink. It is the last node in the route or path to which other nodes could reach the sink.

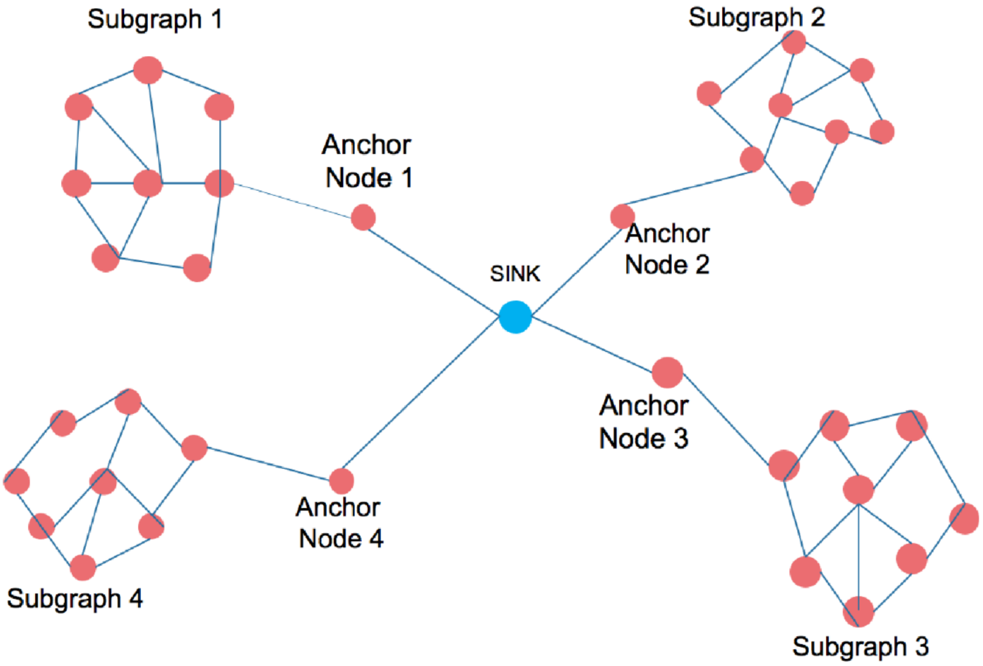


Figure 5. 1 Network Lifetime Illustration

### 5.2.1. Transmission Range Adjustment

In WSNs, reliably transmitting information from the source node to the sink node is vital. It is however important that this is done with minimal energy requirements. In normal networks the transmission range of the nodes is fixed. Independent of how far away they are from each other and the sink node, the same level of power is expended in transmission. To optimize energy usage, it is hereby proposed to adjust the transmission. In a sensor network, the choice of the transmission power between two nodes has a direct impact on the energy consumed by the nodes. Hence, controlling the transmission power and adjusting it to the appropriate distance should be considered to improve upon the lifetime of the network.

### 5.2.2. Effects of Transmission Range Adjustment

Adjusting the transmission range may affect the performance of the network. When a source node changes its transmission range to the highest range, it reduces the number of intermediate nodes (or in some cases may not use an intermediate node) in the path to the sink node. Such an approach will extend the collision domain and hence increase the likelihood of collusion. Choosing a shorter transmission range means using more intermediate nodes to send data packets to the sink. In this case, the collision domain is reduced and, as such, there will be fewer collisions [255]. This technique improves upon the communication in the network and reduces the amount of energy consumed by the nodes at any given time. To this end, the authors in [256] proposed a maximum one-hop transmission distance to minimise the total energy consumed within the network.

### 5.2.3. Effects of Power Consumption

In mobile sensor network applications, the power consumption of nodes depends mainly on the transmission range. Energy consumed during packet transmission and reception depends on the transmitting range of the communicating nodes. The amount of energy required for a packet to be transmitted and received should be minimal to increase the lifetime of the sensor network. In WSN applications where the nodes are mobile, multi-hop communication is the preferred option. Packets may be forwarded from one node to the other using maximum transmitting power to ensure packets are delivered successfully to the receiving node. Although the packet delivery ratio is likely to be high, transmitting at full power may cause a decrease in battery lifetime [257]. In networks for river monitoring applications, the use of a fixed transmission range may not be ideal since nodes are likely to have moved from their original positions due to river current. In such situations, it is expected that communication may be lost since the nodes might have to transmit at maximum capacity to reach the base stations. In other cases, the nodes may be closer to each other thereby transmitting at full power using fixed transmission ranges may only increase the energy wastage. Therefore, in such deployments, how to optimally choose the transmission power is essential. Network lifetime and the packet delivery ratio may be improved by adjusting the transmission ranges of the sensor nodes [258].

### 5.3. Network Model and Problem Formulation

We consider a river sensor network in which mobile sensor nodes detect water quality parameters such as pH, dissolved oxygen, conductivity and many more. Initially, the nodes are assumed to have been deployed uniformly and randomly in a rectangular array. The node forwards the sensed data as packets periodically to static sinks positioned at the various locations along the riverbank. The packets may be sent directly or through a next-hop neighbour to the sink. In each case, the node transmitting the data packet adjusts its transmission range to minimise the amount of energy consumed for the transmission of data packets to prolong the network lifetime.

### 5.3.1. Assumptions

Before providing the details about the transmission range adjustment algorithm, the following assumptions are made:

1. The nodes are randomly placed in the deployment environment to improve network coverage, save energy consumption, and guarantee connectivity. It also limits mobile sensor costs.
2. Sensor nodes with equal transmission range are insufficient to balance energy in the network. Nodes with different transmission range may improve or maximize the lifetime of the sensor network.
3. Automatic adjustment of the transmission range is continuous depending on the position of the nodes in the network. The transmission range is different, although the nodes have the same sensing range. Farthest nodes may require transmissions within the maximum transmission range and nearby nodes may have transmission range lesser than the transmission range *tx.*
4. The network was designed to replicate the movement of a river. Hence, the nodes move in one direction.
5. The system is designed to allow the sensed data to be transmitted at a data rate of 512 kbps.
6. The communication is multi-hop because the NLM techniques used such as routing require such communication.
7. The various constraints affecting energy balancing and network lifetime affect all nodes in the network.
8. Static or mobile sinks are used throughout the simulation.

### 5.3.2. General Notation

In WSNs, the distance between the nodes and the link quality affect the needed transmission power and the nodes' lifetime. In formulating the problem, it is assumed that the sensor network consists of set of sensor nodes $n = \{n_1, n_2, n_3, \ldots, n_j\}$, where $j$ is the number of nodes deployed and $| n | = j$. In modeling the transmission range adjustment problem, the sensor network is represented by a graph $G = (n, c_l)$, where $c_l$ is the communication links with $c_l = \{c_1, c_2, c_3, \ldots, c_n\}$. A source node may directly transmit data packets to sinks or indirectly transmit packets to sinks through its neighbours. The set of sink nodes are represented by $s_k$ with $s_k = s_1, s_2, s_3, \ldots, s_n$ and a neighbour node is denoted by $n_r$.

Communication links are established between the source nodes $n_i$, neighbour nodes, $n_r$ and the sink nodes $s_k$. Nodes $n_1$ *and* $n_2$ are neighbors if they are next hop nodes and the communication path between them belongs to set $c_l$ if they are able to reach each other. The transmission range $R$ is the maximum value set for nodes to communicate, and it is the same for all nodes in the network. In a network, the transmission range of all the sensor nodes may be fixed to a minimum value during packet transmission. In a realistic network, the transmission range depends on the environment. So two nodes that transmit with the same power may reach nodes at different distances in practice depending on the environment (for example, two nodes in line of sight versus two nodes with the same distance away but with a steel wall between them). Typically, we model a fixed transmission range R because it is easier, but this is not realistic.

The Euclidian distance $d$ between nodes $n1$ *and* $n2$ is $d\ (n1, n2)$. Hence, $c_l = \{(x, y) \in E | d\ (n1, n2) \leq R\}$. The position (x, y) of each sensor node in a two-dimensional (2−D) space is represented by $P = \{p_1, p_2, p_3, \ldots, p_t\}$. The positional information is important since that will be required for determining the distance between the nodes.

In this model, the nodes need positional information of their neighbours, the sink, and their position information to decide on which transmission range to use for packet forwarding to conserve energy. Existing location-based routing protocols use GPS information or non-GPS information to determine the positions of other nodes in the network [259]. Our model is based on a non-GPS approach (i.e., a positioning algorithm) to obtain positional information of the sensor nodes in the network. Periodically, each node sends a *hello message* to obtain the positional information of other nodes in the network. In situations where the nodes are not reached by this method, then a broadcast message is sent. The power consumed depends on the distance between the transmitter and the receiver and the energy required for the data to reach the destination.

### 5.3.3. Transmission Range Adjustment Algorithm

To investigate the impact of distance and the location of the sensor nodes on energy consumption, using the ns-3 simulator, $n$ sensor nodes have been randomly deployed in a river of dimension, $A = 100m \times 750m$. The shape of the river may be rectangular or irregular. The randomly deployed nodes obtain the positional information of themselves, their next hop, and the sink nodes.

A source node sends a broadcast message when it detects an event. The source node $n_1$ detects a neighbour node $n_2$ within its transmission range to forward the packets. Then the neighbour node $n_2$ upon detection of sink $s_1$, $n_2$ forwards the packets received from $n_1$ to $s_1$. The goal is to transmit data packets from $n_1$ to $s_1$ with minimum energy consumed by $n_1$, $n_2$, and $s_1$. The main issue of concern tackled here relates to the neighbour node $n_2$ changing its relative position with respect to direction of flow and speed of the river. The sensor node $n_1$ is likely to be within the range of a neighbour node if the following conditions are met: a) sensor node position remains the same; b) the river speed is the same at different sections in the region of interest; c) the *transmit node,* $n_1$ receives constant response from its immediate neighbour when the *hello messages* were sent.

### 5.3.4. Energy and Distance Notation

Network lifetime has been defined earlier as a point in time $t$ when the death of the $i^{th}$ node (i.e., partitions the network such that it loses its functional purpose) degrades the network to such a point that it can no longer function as a network. Ultimately, network lifetime is directly related or proportional to the total amount of energy expended in the network before the network dies. This energy is equal to the sum of energy spent in transmitting from the sensor nodes to the sink node through a neighbour node over some distances. The equations presented in this section consists of variables defined as follows:

$e_{ti}$ = Energy expended by the transmitter

$e_{ri}$ = Energy expended by the receiver

$n_r$ = Neighbour node

$E_{totals-hop}$ = Total energy consumed by nodes through direct communication

$E_{totalm-hop}$ = Total energy consumed by all the nodes in a multi-hop communication

$E_{overall}$ = Total energy expended in the network

$d_{i,j}$ = Distance between node $i$ and node $j$

$r$ = The distance between node positions

$Num_{pktrec}$ = Number of packets received

$e_{sk}$ = the energy expended at the sink to receive and process the data

$\cos\theta$ = The angle subtended between a source node and two neighbours or two sinks

The model proposed in this work calculates the network lifetime as the sum of energy spent to transmit data packets directly to the sink or through a neighbour node to the sink. Hence, the energy consumed for this operation is:

$$E_{total_{m-hop}} = \left( e_{ti} + \sum_{i=1}^{n} e_{ri} + \sum_{i=1}^{n} e_{ti} + e_{s_k} \right) \tag{5.1}$$

Equation 5.1 holds for n > 2 when the number of nodes is equal to 2 (i.e., if n = 2), the total energy expended is given by Equation 5.2.

$$E_{total_{s-hop}} = e_{ti} + e_{s_k} \tag{5.2}$$

The expression in Equation 5.3 is obtained because of the energy required for a source node to transmit packets through a set of neighbour nodes to the sink node over some distance.

$$E_{total_{m-hop}} = \left\{ e_{ti} + \sum_{i=1}^{n} e_{ri} + \left( \sum_{i=1}^{n} e_{ti} * d_{ij} \right) + e_{s_k} \right\} \tag{5.3}$$

To compute the power consumed by the transmitter when a sensor node $n$ sends a packet to sink node $s_k$, the energy consumption between the sensor node and sink node over distance $d_{i,j}$ is:

$$E_{total_{s-hop}} = \left( e_{ti} * d_{ij} \right) + e_{s_k} \tag{5.4}$$

The energy consumed by a source node to communicate through a set of neighbour nodes to the sink is calculated based on the power consumed at the source node, $E_{totalm-hop}$, the next-hop neighbours (i.e., which uses both the transmission power $P_{tx}$ and the received power $P_{rx}$) and the received power at the sink, $e_{sk}$. Also, at the destination (i.e., either a neighbour node or a sink node) the energy consumed by the receiver is calculated.

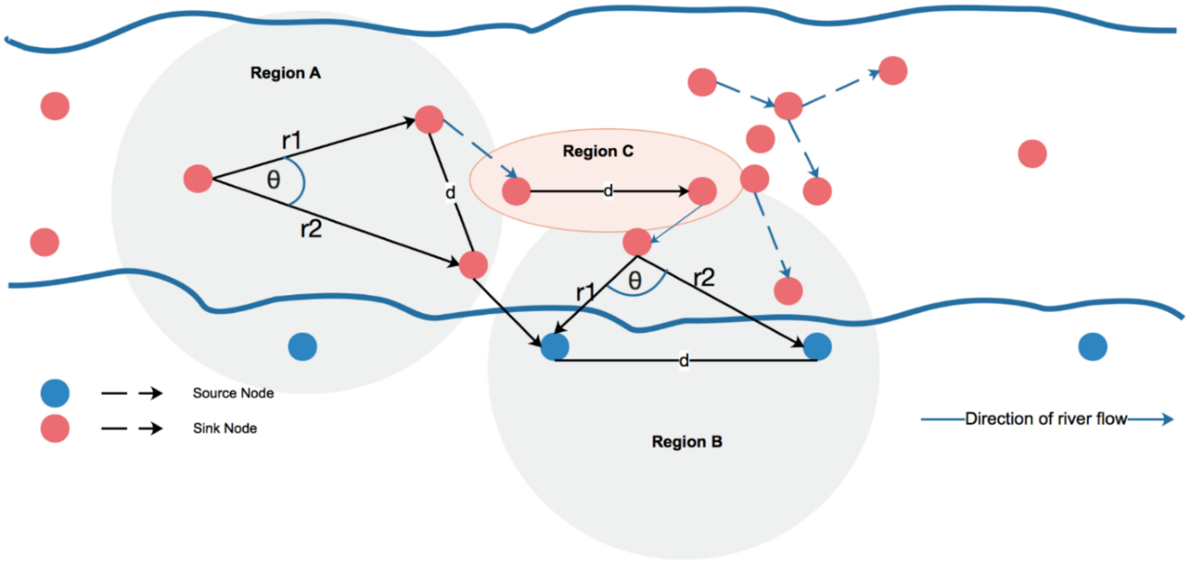


Figure 5. 2 Calculating distance between nodes

A neighbour node receives and transmits packets, therefore the energy used by the neighbour node per packet is the sum of the transmit and receive power.

The sink ($s_k$) uses only the receiving energy to receive packets from source nodes or next-hop nodes. Hence, for a sink to receive packets directly from a source node, it expends the received power energy in Equation 5.5.

$$P_{rx_c} = e_{ri} * Num_{pkt_{rec}} \tag{5.5}$$

In introducing the distance parameter in Equations 5.4 and 5.3, the protocol considers the euclidian distance between the source node and the angle subtended by two neighbours or two sinks taking the source node as reference point.

$$d_{i,j} = \sqrt{r_1^2 + r_2^2 - 2r_1r_2\cos\theta} \qquad (5.6)$$

The distance $d_{i,j}$ holds under three conditions:

Under condition 1, the source node transmits packets to a single neighbour or a sink within its transmission range, as shown in Figure 5.2 Region C. In this case, the angle subtended is 180 and and the formula will reduce to

$$d_{i,j} = \sqrt{r_1^2 + r_2^2 + 2r_1r_2} \qquad (5.7)$$

Under condition 2, we consider a source node within the range of two neighbour nodes, as shown in Figure 5.2 Region A and/or two sinks, as shown in Figure 5.2 Region B. Here, the angle subtended between the two nodes or the two sinks is $\theta$. In this case, where $\theta = 90^{\circ}$, the equation will reduce to

$$d_{i,j} = \sqrt{r_1^2 + r_2^2} \qquad (5.8)$$

Under condition 3, we consider the value of $\theta$ in Equation 5.6 to lie between $0 < \theta < 90^{\circ}$. This is the condition determined in Equation 5.6 for all angles that satisfies the following relation $0 < \theta < 90^{\circ}$. When a source node is in the transmission range of two neighbour nodes or two sinks, the source nodes adjust its transmission distance to the shortest distance between the two nodes within its range. In this case either $r_1 < r_2$ or $r_2 < r_1$ as illustrated in Figure 5.2 Regions A and B.

## 5.4. Algorithm Design

The introduction of a novel non-GPS location-based routing protocol which can adjust the transmission range during data transmission is presented. The proposed AODV with adjustable transmission range protocol (AODV-TP) works as follows: 1) At the initial stage, the sinks broadcast their position for the source nodes to obtain their position and store the location of the receivers; 2) An active source node (i.e., a node that has detected an event) sends a broadcast message and waits for a response. When a response is received, it establishes the position of the neighbour node or the sink and calculates the distance between itself (i.e., the sender) and its immediate neighbours and the destination node.

### 5.4.1. Power Adjustment Algorithm

The proposed algorithm provides strategies to efficiently minimise the energy consumed by the nodes in the sensor network. The network lifetime is prolonged. The mobile sensor nodes transmit the sensed data to a sink node with single-hop or multi-hop communication. The source nodes closer to the sink node die-off fast because they receive much of the traffic load. The energy efficient distance aware algorithm with source nodes and static sinks set up in a rectangular sensor network is used to evaluate the algorithm. From Algorithm 1, if the mobile source node with initial transmission distance *80 meters* senses an event, it broadcasts to find the neighbours and sink/destination nodes within its range. The neighbour nodes within reach of the source node send their position information to the requesting node. Depending on the position information, the sender chooses the node located a minimum distance away and adjusts to it transmit power to be able to communicate with this node. The algorithm is presented in a flowchart shown in Figure 5.3.

**Algorithm 1:** Power-Adjust Algorithm

```
SET srcNODEtxp = Ptxinitial;
for each nextHop in the srcNodes transmission range do
    DETERMINE the position;
    CALCULATE the distance between srcNode position and its NEIGBOURS position;
    SELECT minimum distance (minDIST) from each nextHOP within the range;
    SET Ptxadjusted = assignRANGE (minDIST);
    SEND data packet with Ptxadjusted to the selected node;
end
```

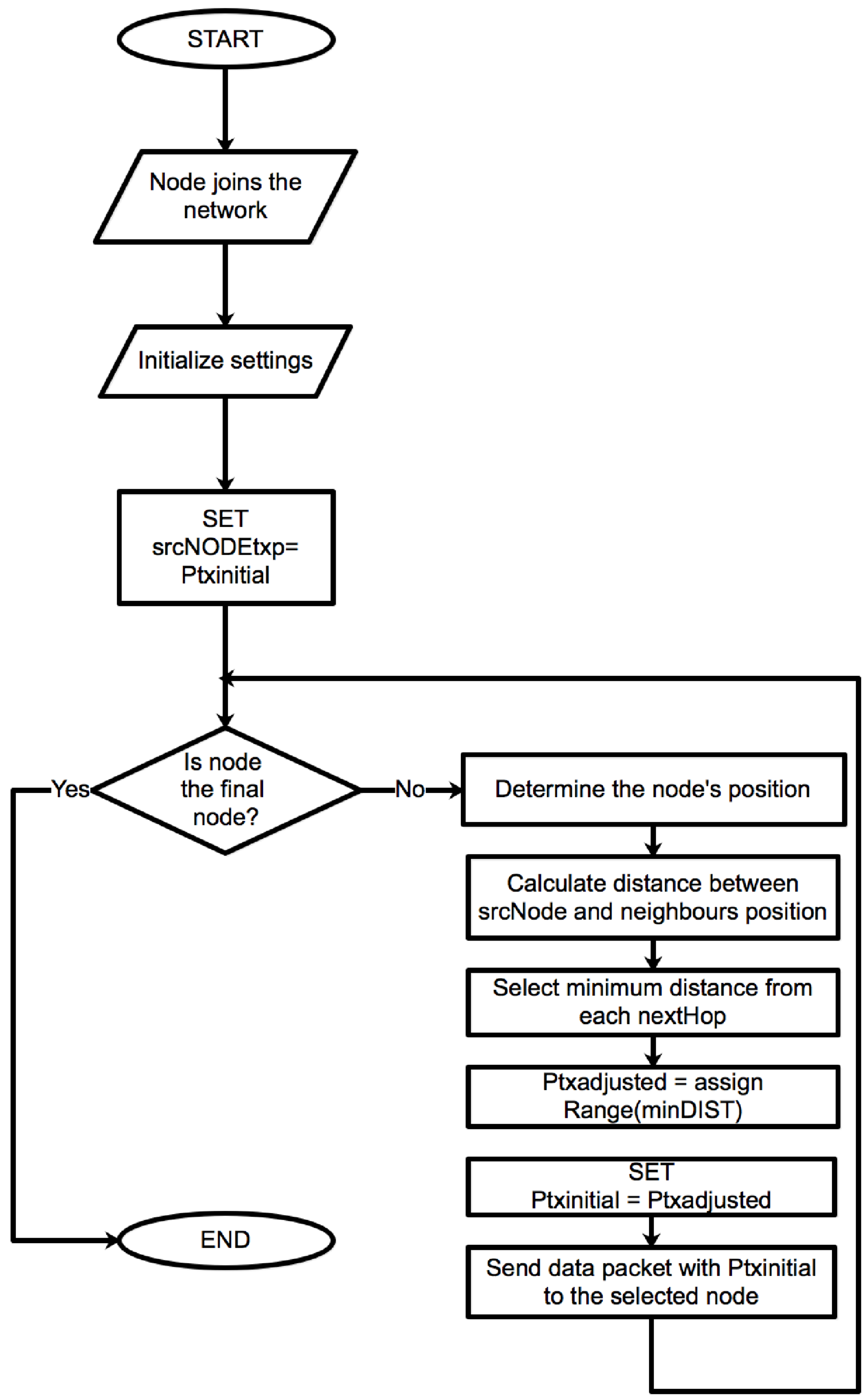


Figure 5. 3 Calculating distance between nodes

### 5.4.2. Direct Transmission to Sink Node (DTS)

In this section, the *DTS Algorithm* is presented as a technique for adjusting the transmission range of nodes communicating directly to the sink node. *DTS Algorithm* as shown in Algorithm 2, is applied in such a way that it automatically adjusts the transmission range by calculating the Euclidian distance between the source node (i.e., the node that has sensed a phenomenon and ready to transmit) and the sink using the Equation 5.8. The Euclidian distance is calculated based on the vector positions of two nodes (the source and the sink). DTS Algorithm uses the distance calculated to determine the appropriate transmission range required to transmit the data packet from one node to the other. The selection of the minimum transmission range is aimed at minimizing the amount of energy consumed for packet transmission. The algorithm is designed for use when the transmitting node has enough energy in its buffer to perform the transmission directly without resorting to neighbour nodes. The approach, as mentioned earlier, guarantees network connectivity. While the source node is still in motion, the source nodes' position information is sent when it also receives a broadcast notification message from its next-hop neighbours. By this approach, energy is reduced to prolong the lifetime of the sensor network. The algorithm is presented in a flowchart shown in Figure 5.4.

---

**Algorithm 2**: Source Node to Sink Communication

---

**Data**: To send data packets directly to the sink node:

**Data**: Source Nodes placed randomly at the region of interest as the node moves at time t and detects/senses a contaminant

**Data**: SrcNode BROADCAST RREQ to send packets to sink at the initial transmission range

```
if srcNode receives RREP from the sink then
    srcNode sends data packet to sink using the PtxInitial;
else
    SET Ptx = PtxMax;
```

```
end
if sink detected then
    CALCULATE the distance to the sink SET Ptx = Ptxadjusted;
    TRANSMIT data packet to sink;
    srcNode receives ACK from sink using RREP;
else
    BUFFER the PACKET and RETRY in t seconds;
end
```

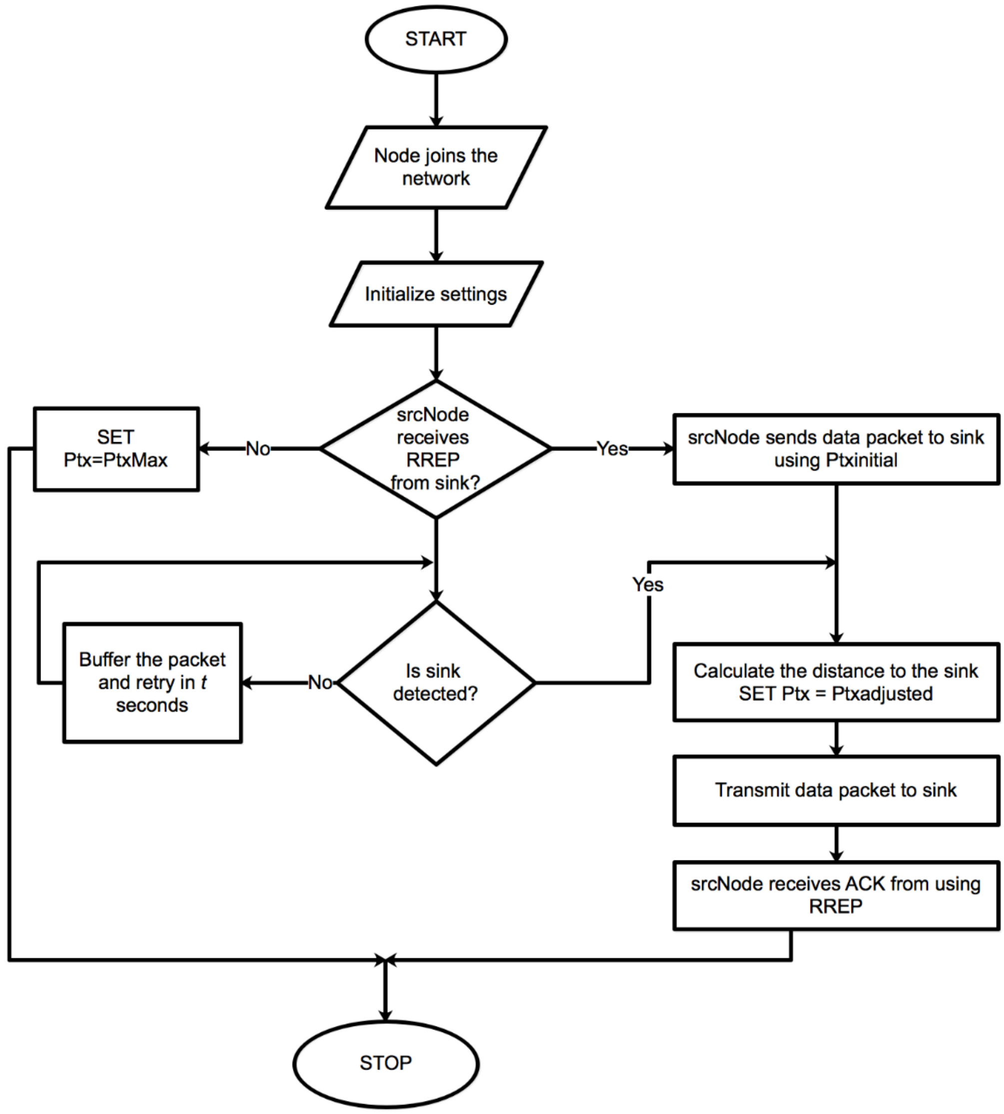


Figure 5. 4 Calculating distance between nodes

### 5.4.3. Neighbor Node to Sink Node Communication

In Algorithm 3, nodes select their next-hop to the sink node by sending broadcasting to the other nodes in the network. When a reply is received from its immediate neighbours, it calculates the distance between each replying node and itself. The broadcasted node then selects the replying node with the shortest distance and the minimum number of hops to the sink. The broadcasted node after choosing the minimum distance transmits packets to the sink using this distance. Figure 5.5 shows a flowchart showing the flow for Algorithm 3.

---

**Algorithm 3**: Neighbor Node to Sink Communication

---

```
Data: To select a nextHop to route to the sink node:
Data: Let the source node (srcNode) broadcast RREQ

if srcNode receives a REPLY then
    Calculate the DISTANCE d, between this NODE (i.e., the node (s) that sent the
    REPLY using the nodes position;
    Source node SELECTS the REPLYING NODE with the shortest DISTANCE
    dshort and the MINIMUM Hops to the SINK NODE;
    ADJUST the TRANSMISSION POWER, Ptx to this DISTANCE dshort value
    calculated
    TRANSMIT data to this receiving NODE at this calculated transmission range
    value, Px(d);
end
Data: Let the source node unicast "Hello" to keep track of the next-hop neighbour
if next-hop is alive then
    Calculate the distance d;
    ADJUST the TRANSMISSION POWER, Ptx to this DISTANCE dshort value
    calculated;
    TRANSMIT data to this receiving NODE at this calculated transmission range
    value, Px (d);
else
    Let the source node (srcNode) broadcast RREQ;
```

```
end
```

---

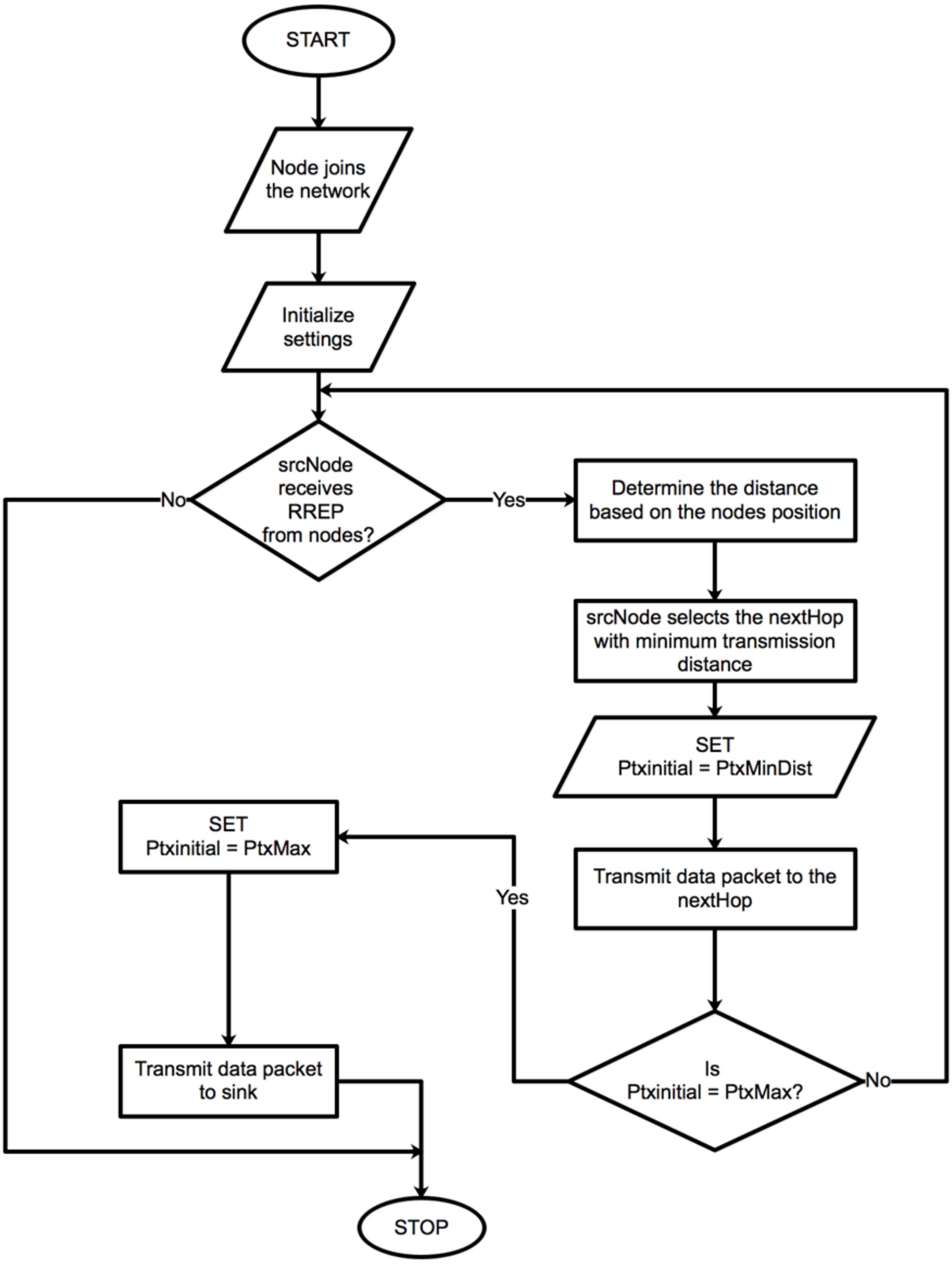


Figure 5. 5 Calculating distance between nodes

### 5.4.4. Greedy-hop Algorithm

---

**Algorithm 4**: Greedy-hop Algorithm

---

**Data**: srcNODE broadcast RREQ to send packets to sink to find all possible routes Receiving nodes (nextHOP) sends their positions

```
if srcNode receives RREP from the nodes within its range position then
  for each RREP do
      DETERMINE the distance d, based on the nodes position/location;
      srcNode SELECTS the next-hop with minimum transmission distance;
      ADJUST Ptxinitial = PtxMinDist (i.e., the calculated distance);
      TRANSMIT dataPacket to the nextHop;
      while PtxInitial! = PtxMax do
      end
end
  ADJUST Ptxinitial = PtxMax (i.e., the calculated distance);
  TRANSMIT dataPacket to sink;
end
```

In the greedy-hop algorithm, as shown in Algorithm 4, each node in an attempt to save energy drops the packet to the next node with the minimum distance without considering the neighbour's energy level and distant to the sink. Figure 5.6 shows a flowchart showing the flow for Algorithm 4.

In our approach, a break in the network connectivity or the transmission link may be due to the movement of a sensor node that had established a connection but moved due to the speed of the node at its current position/location. The break may also be due to insufficient residual energy, which caused the node to die-off.

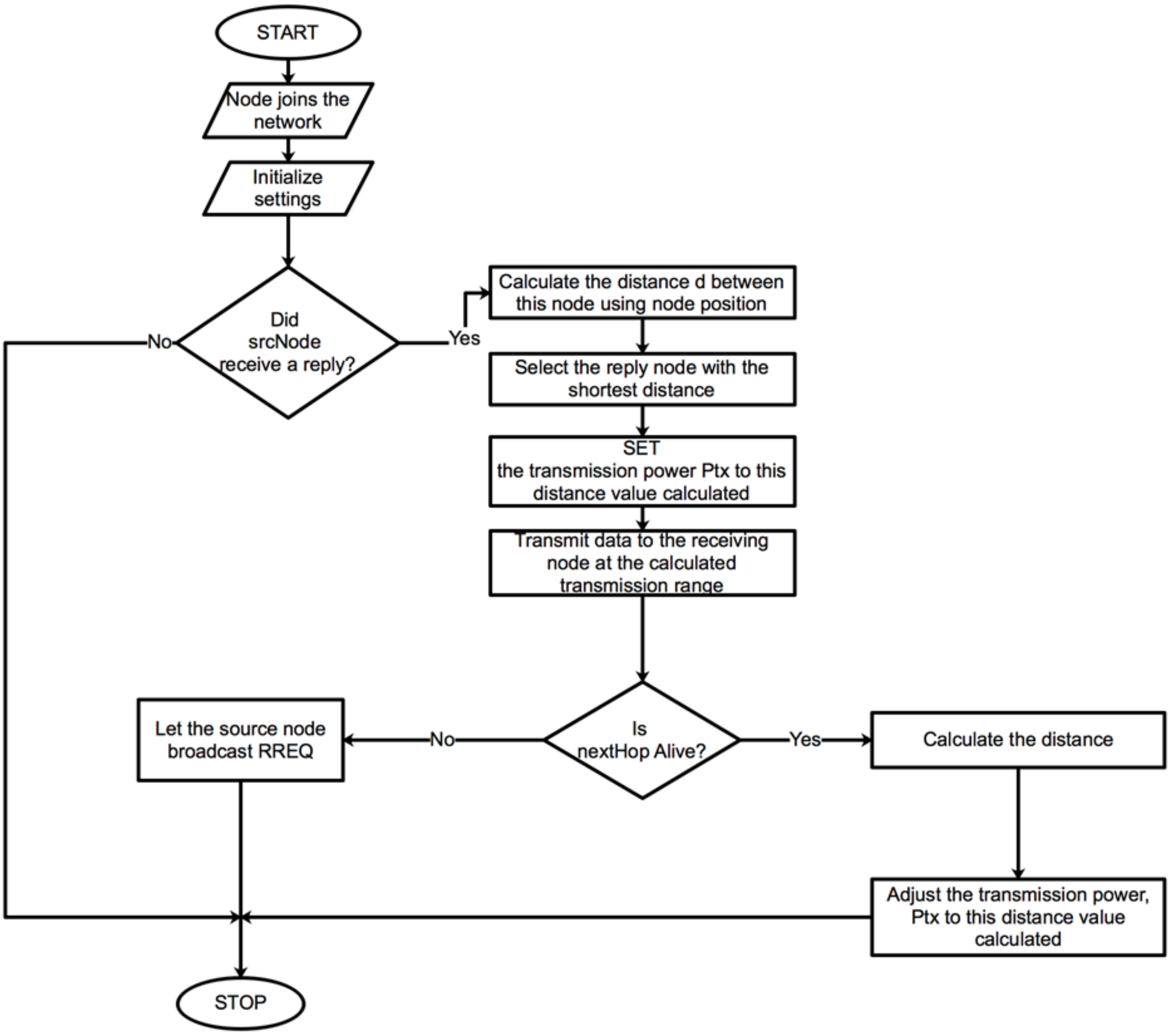


Figure 5. 6 Calculating distance between nodes

## 5.5. Simulation Results

Experiments were run using Network Simulator 3 (NS3). The simulation model is designed to mimic a real water quality monitoring application environment in which frequent water quality data is collected via a network. The network environment simulated in NS3 has a deployment area of 100m by 750m. The initial energy set for each sensor node in the simulation was 20 Joules. Each sensor node generates data at a rate of 7 packets per second. Seven (7) packets per second for packet generation rate was chosen to regulate the amount of energy consumed by the sensor nodes. For the network to ensure a level of connectivity, the transmission range for each mobile sensor node was set to 80m (see Table 5.1).

Table 5. 1 Network Parameters used in Simulation

| **Network Parameter** | **Value** |
|---|---|
| Number of Nodes | 10, 15, 25, 30, 40, 50 nodes |
| Packet Generation Rate | 7 packets per second |
| Type of Traffic | Constant Bit Rate (CBR) |
| Packet Size | 512 Byte |
| Initial Energy | 10 Joules |
| Mobility Model | RandomWalk2D |
| Minimum Speed | 10 m/s to represent low mobility case |
| Maximum Speed | 50 m/s to represent high mobility case |
| Initial Transmission Range (Radio) | 80 meters |
| Propagation Model | Range Propagation |
| Number of mobile sinks | Variable |

### 5.5.1. Analysis on Mobile Sensor Nodes and Static Sinks

Compared with the AODV, AODV with adjustable transmission range protocol (AODV-TP) prolongs the network lifetime of the sensor network thrice that of normal AODV. When the residual energies of both protocols were compared, as shown in Figure 5.7, it was deduced that the energy consumption decreases over time as the number of rounds increases. Comparing traditional AODV and the proposed AODV (i.e., AODV-TP), using AODV, the energy decreases much faster than AODV-TP. In this section, we conclude that when the traditional AODV routing protocol is implemented with our network setup, the node's battery drains more quickly as compared to the proposed algorithm, as shown in Figure 5.7.

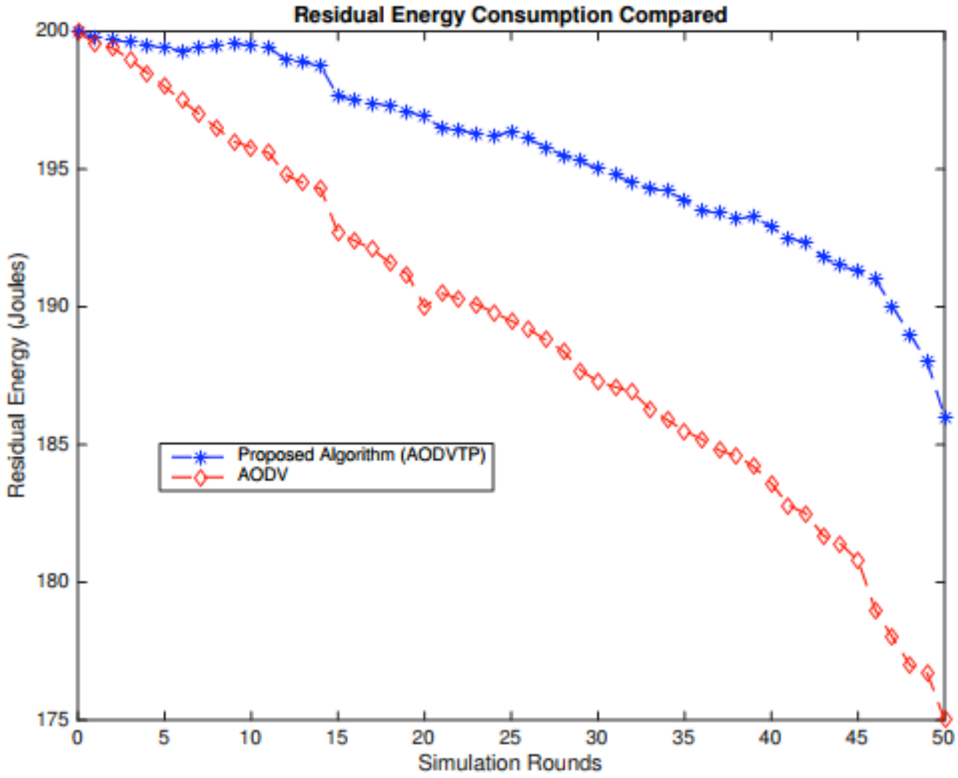


Figure 5. 7 Residual Energy Consumption

To ascertain the performance of the proposed transmission range adjustment algorithm concerning the energy consumption rate by the mobile sensor nodes vis-a-vis the number of packets delivered at the sinks, a scenario of up to 200 nodes was used to compare the performance of the proposed algorithm with AODV. The performance between the two protocols is shown in Figure 5.8. It shows that the proposed algorithm outperforms traditional AODV for the different number of sensor nodes used for the simulation. It may be observed that when the number of sensors was increased to 160 nodes, both algorithms peaked up, but the number of packets dropped sharply when the number of sensor nodes was increased beyond 160.

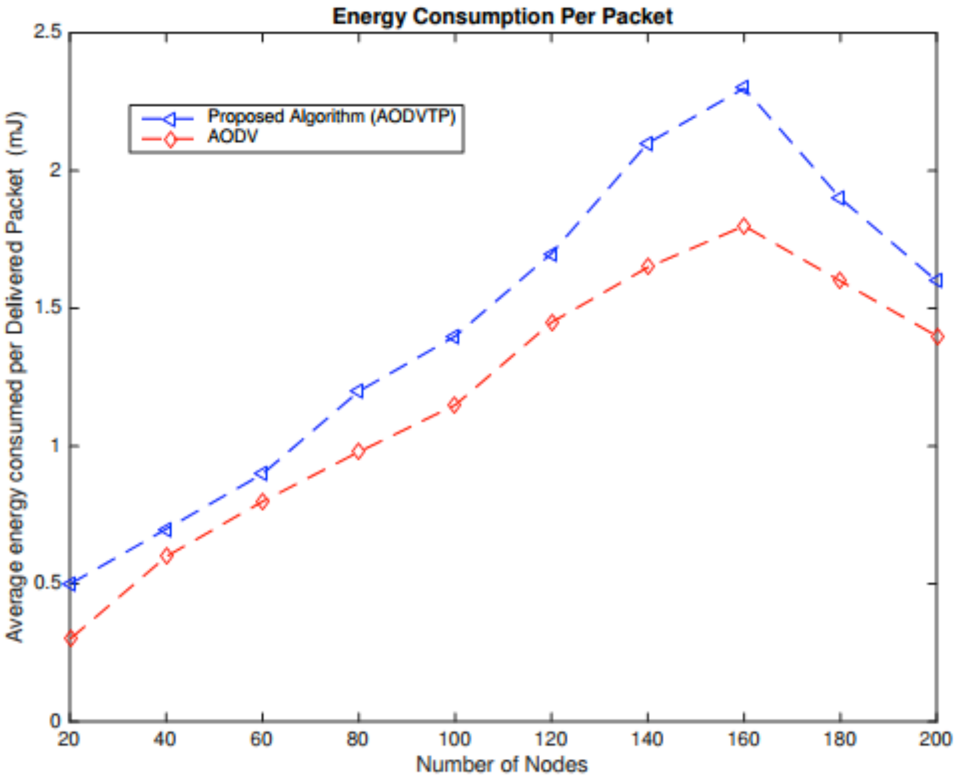


Figure 5. 8 Average Energy Consumption

In other scenarios, the performance of the transmission range adjustment algorithm illustrated in Algorithms 2, 3, and 4 in this work was run to compare their performance, as shown in Figure 5.9. When the greedy approach was adopted, the packet delivery ratio improved to about 95% transmission range at 20 meters but dropped to about 55% at transmission range of 180 meters. The next-hop and the direct-to-sink algorithms yielded a packet delivery ratio of about 82% at 20 meters. The next-hop approach reduced to 30% at about 180 meters. The decrease in PDR is due to the mobility scheme used in the simulation. All three algorithms at transmission range of 80 meters yielded a PDR of about 60 meters. Figure 5.10 shows the end-to-end during data packet delivery. The performance of the proposed system improved because there was less interference in channel. Also, packet transmission errors are minimal in the new approach which improved the number of packets received at the sink. Hence, in the new approach as shown in Figure 5.7 and Figure 5.8, fewer packets are lost.

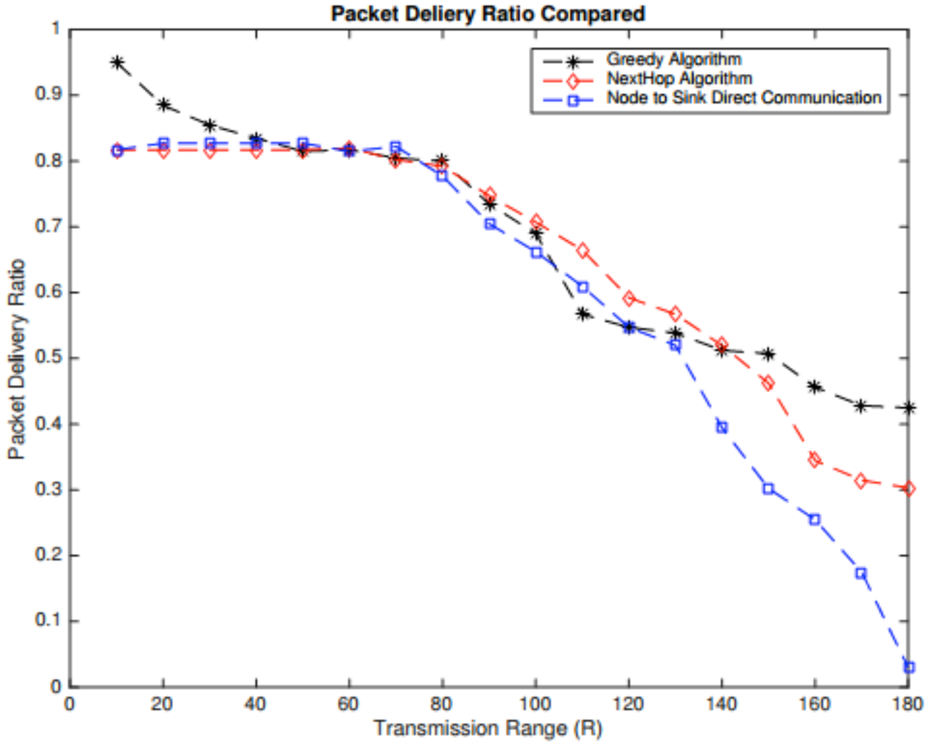


Figure 5. 9 Algorithm performance

Figure 5. 10 End-to-end delay

The performance comparison of the two routing protocols in terms of end-to-end-delay is shown in Figure 5.10. From the graph, the proposed algorithm performs poorly when the speed of the nodes increased over time. The end-to-end delay increased with increasing speed, and it is attributed to mobility. The sensor nodes require position information to take the appropriate decision to adjust its transmission distance before transmitting data packets to the next-hop neighbour at which time the neighbour's position might have changed causing an increase in delay.

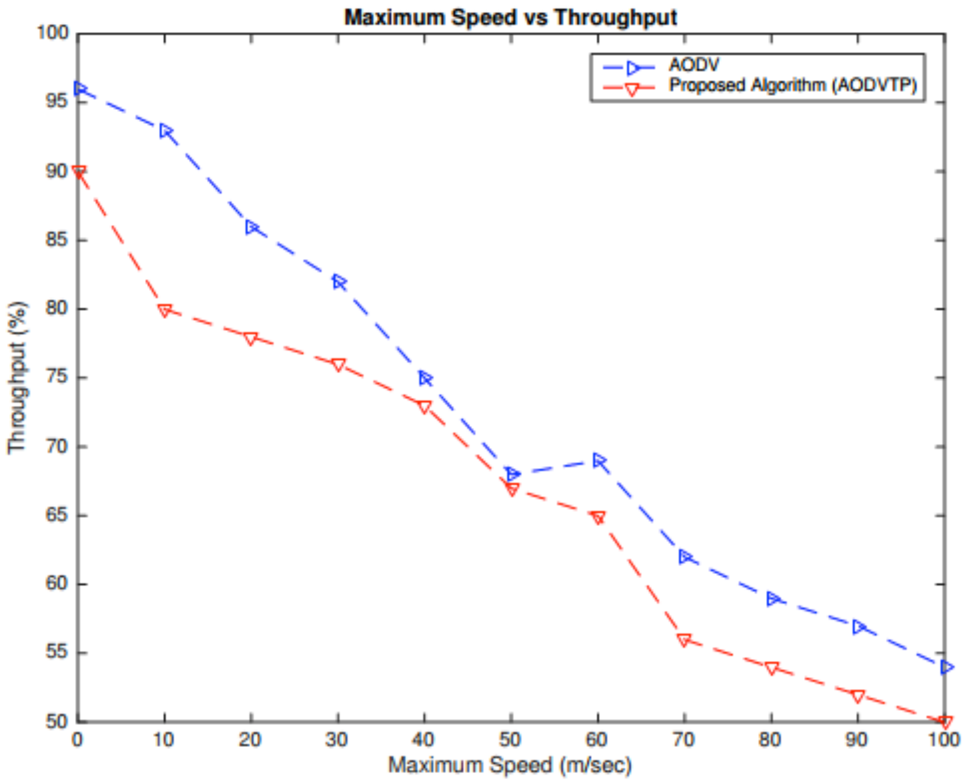


Figure 5. 11 Maximum Speed vs Throughput

As shown in Figure 5.11, AODV experienced low throughput compared to the proposed algorithm. The low performance of AODV is due to the high degree of mobility, which causes the links established between the nodes to break. The proposed algorithm overcomes the link break problem because of its ability to adjust its transmission range.

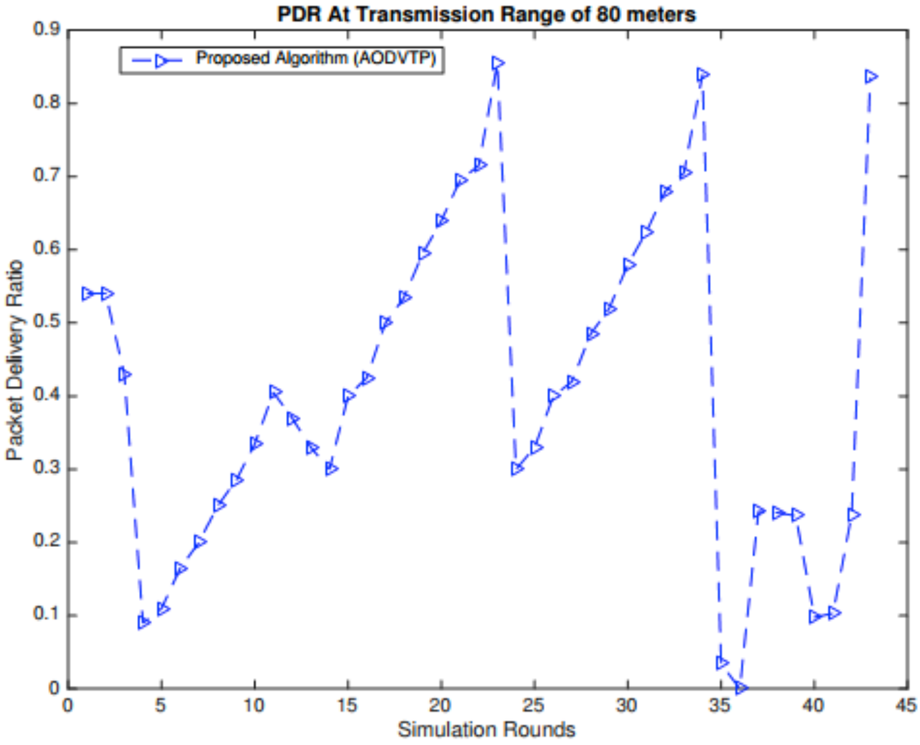


Figure 5. 12 Packet delivery ratio at transmission range of 80 meters

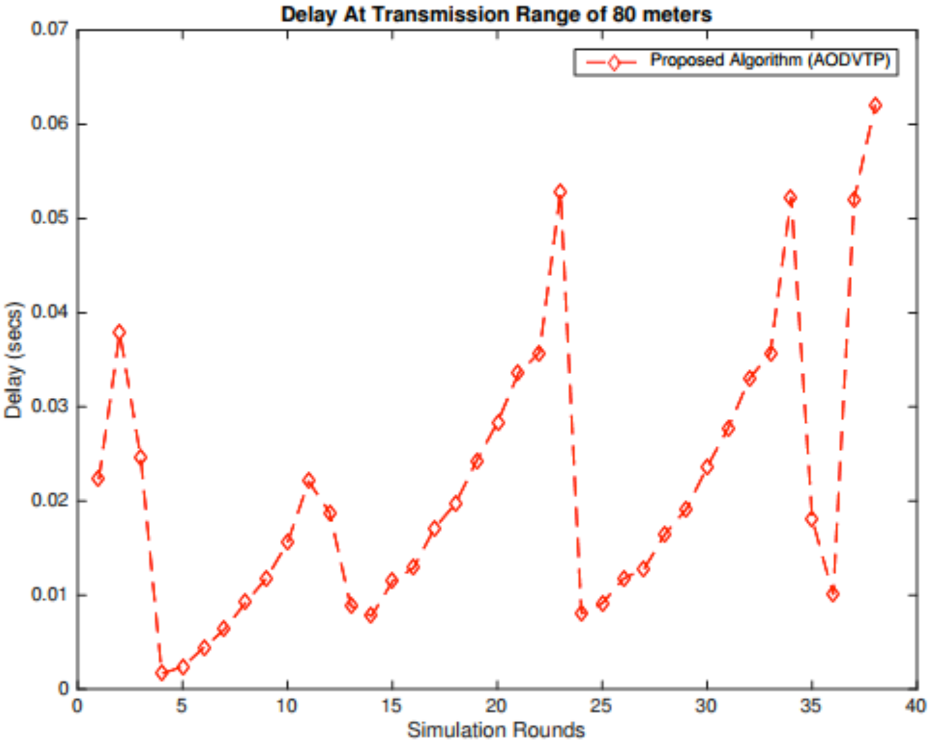


Figure 5. 13 Delay at transmission range of 80 meters

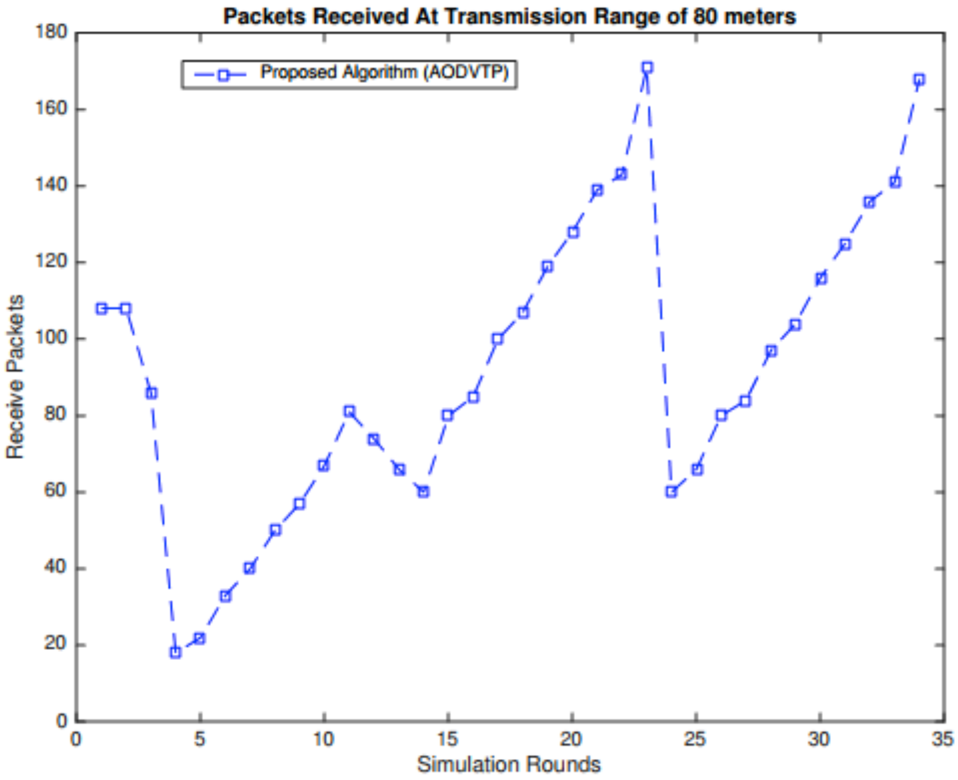


Figure 5. 14 Number of packets received at transmission range of 80 meters

For Figures 5.12 − 5.14, the transmission range was set to 80 meters to evaluate the following performance metrics: end-to-end delay, PDR, and the number of received packets. At the start of the simulation, the performance of the proposed algorithm recorded a PDR of 0.54 (54%). Although the PDR dropped after several simulation rounds (about 20 rounds) the PDR increased to 0.85 (85%) at about 25 simulation rounds (i.e., this happens to be the best performance). PDR again dropped slightly to 0.84 (84%) at 35 simulation rounds and 0.83 (83%) at 43 simulation rounds. The results show high system overheads, which may be due to the relative speed and the direction of the flow, which determines the path of the mobile sensor node. The experimental results show that the movement of the sensor nodes impacts end-to-end delay (see Figure 5.13). An end-to-end for the initial simulation rounds were low. At 25 simulation rounds, delay of 0.05 seconds was recorded, and at 35 rounds, a delay of

0.063 seconds was recorded. It can be deduced from the low delay values that there was less congestion in the system which is the reason for the number of packets received in the sensor network as shown in Figure 5.14. The success rate may be attributed to the minimum number of hops used for packet transmission because of the efficiency of the algorithm. Although a good number of the data packets drop, the experiment shows that several packets sent were also received especially, from the round 15 to 25 the packets received improved to about 175 packets but dropped sharply to about 60 packets per second due to break in links and high mobility. From this time onwards the packets increased steadily to 168 packets. Increasing the number of simulation rounds improved the performance in terms of PDR.

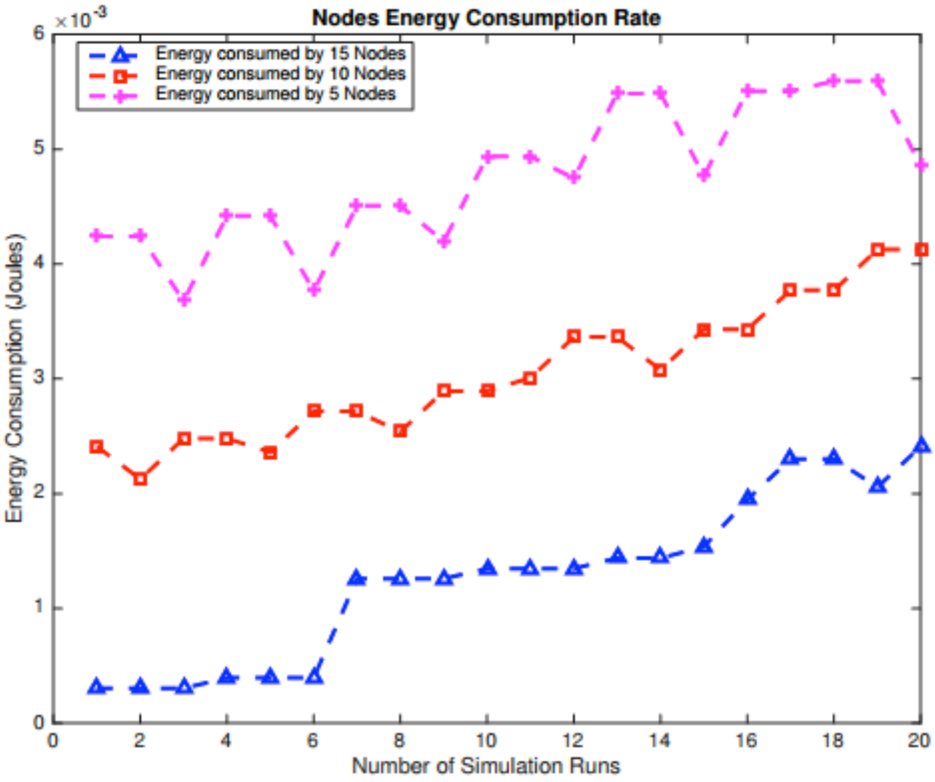


Figure 5. 15 Energy Consumption for Nodes 5, 10, and 15

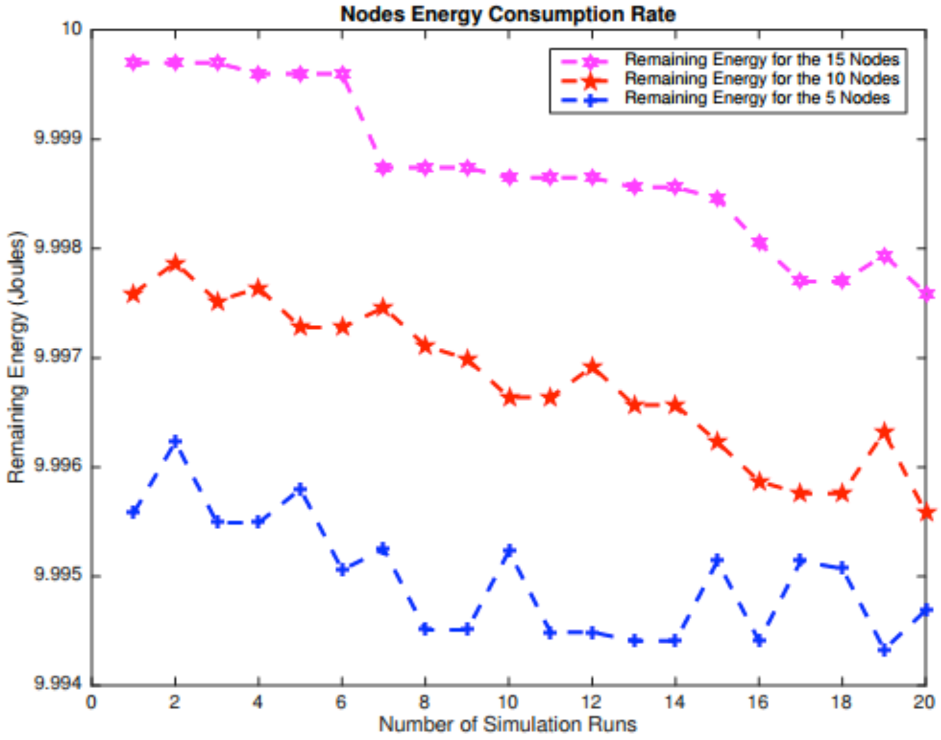


Figure 5. 16 Energy Remaining for Nodes 5, 10, and 15

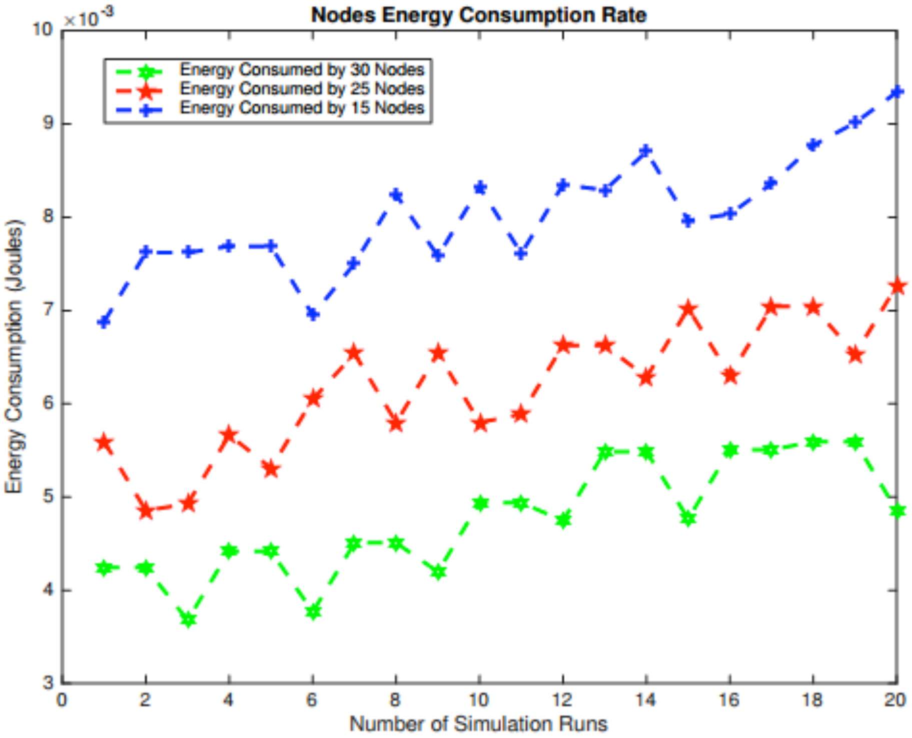


Figure 5. 17 Energy Consumption for Nodes 20, 25, and 30

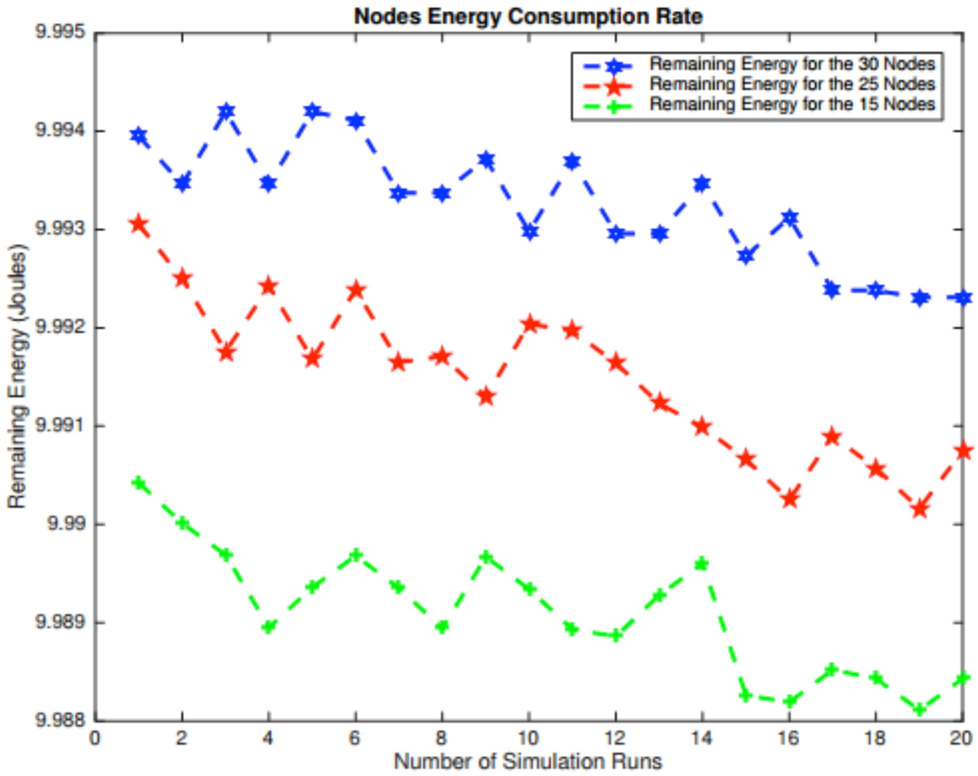


Figure 5. 18 Energy Remaining for Nodes 20, 25, and 30

From Figures 5.15 − 5.18, several nodes between 10 and 30 were used to evaluate the energy consumption pattern using the proposed algorithm. Figures 5.15 and 5.16 show the rate of node depletion in the network. Similarly, Figures 5.17 and 5.18 show the energy consumed and the remaining energy after a transmission and a reception process.

In WSNs, river network monitoring using mobile sensor nodes and static sink (s) improves energy efficiency in the sensor network. In such networks, data packets are forwarded to the sink nodes through single-hop or multiple-hops infrastructure. Routing is used in such sensor networks to minimises the amount of energy utilised by the sensor nodes to perform its operation. Nodes around the sink utlizes their energy quickly and may be the first node to die. Such dead nodes reduce the number of data packets that may reach the sink node (s) and potentially reduces the network lifetime.

### 5.5.2. Analysis on Mobile Sensor Nodes and Mobile Sinks

Wireless Sensor Network (WSN) may be deployed on a large scale for river monitoring network applications. The use of mobile sensor nodes and mobile sinks are to improve data communication and network lifetime. In the chosen scenario and deployment environment, depending on the position of the sink, its speed, and direction may give rise to the three main problems discussed and illustrated earlier in Section 4.6.2. The sink node does not coordinate the movement of mobile sensor nodes because of the nature of the application environment. Both mobile sensors and the sink nodes follow the river path (i.e., direction) and the flow rate of the river (i.e. speed).

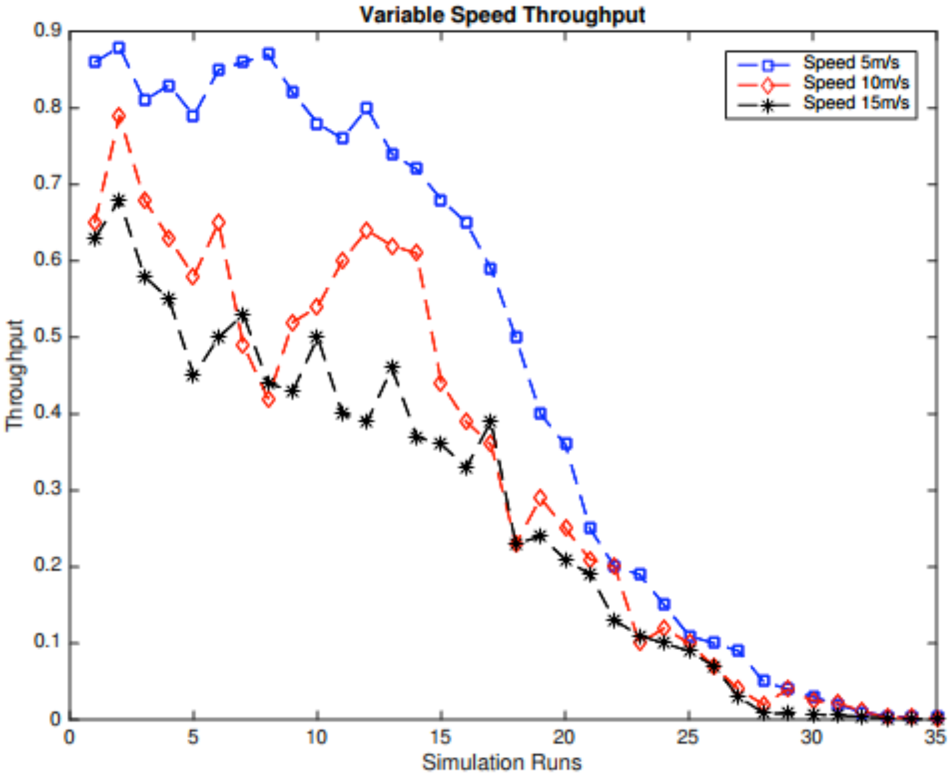


Figure 5. 19 Throughput at different speeds

Figure 5.19 shows the throughput values of the mobile sensor nodes and mobile sinks scenario. The variation in the speed from 5m/s to 10m/s and 15m/s aided in the evaluation of the proposed algorithm. The results showed a huge drop in throughput in all cases after 25 simulation runs. The poor performance of the network may be due to the movement of the sink node, which may be suffering from the sink mobility problems discussed in earlier chapters of this thesis document. The end-to-end delay and the nodes extra energy. Figure 5.19 shows that at 5 m/s, the throughput was better compared to 10m/s and 15m/s.

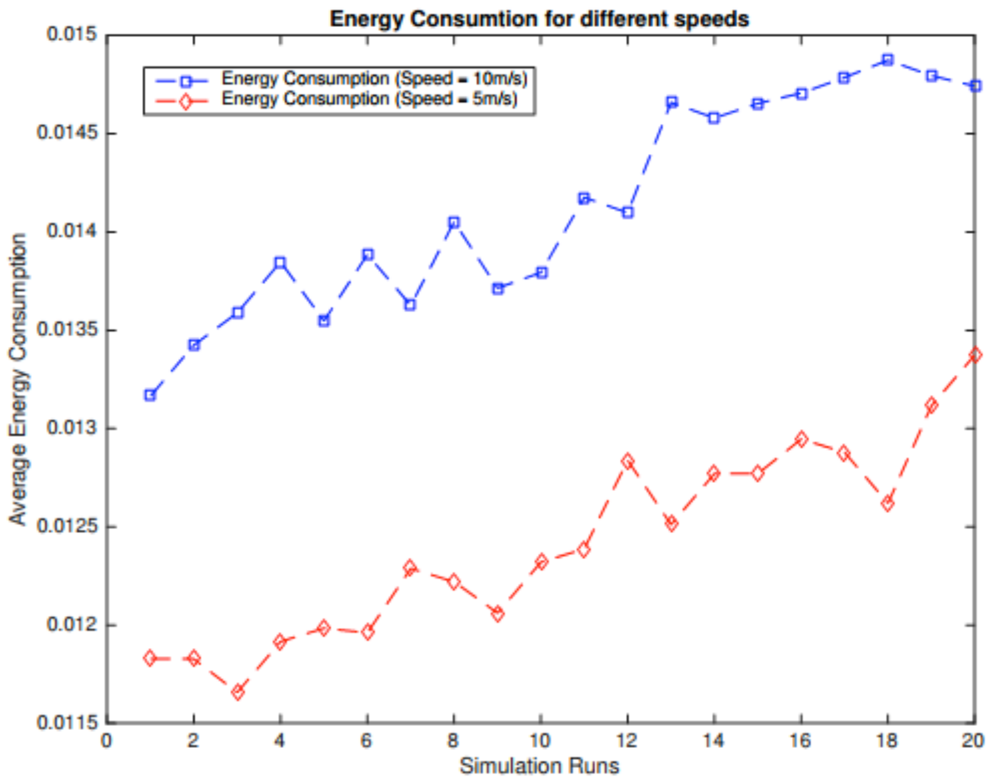


Figure 5. 20 Delay at different speeds

The energy consumed by the mobile sensor nodes and the mobile sinks tends to be higher for higher speeds compared to nodes with lower speeds. Figure 5.20, the energy consumption at 5m/s is lower than when the speed is set at 10m/s. The simulation output (pcap files) was analyzed and validated using Wireshark. Details of each packet were decoded and displayed for evaluation and verification.

### 5.6. Chapter Summary

In this chapter, a distance aware routing protocol was proposed for sensor nodes in a mobile environment. Wireless Sensor Networks for environmental monitoring applications require long battery life and low power consumption to enable them to operate over a prolonged period. A key requirement for such networks is that the energy consumption of the nodes should be kept minimal to increase the lifetime of the wireless sensor network and to improve the performance of the sensor nodes and the wireless network. Ad-hoc On-Demand Distance Vector (AODV) routing protocol designed for routing in mobile ad-hoc networks (MANETs) has been shown to provide efficient routing in Wireless Sensor Networks (WSNs). AODV routes are built and maintained as and when needed by the source node.

In this chapter, we present an improved AODV protocol that takes into consideration the distance from neighboring nodes and adjusts the transmission power accordingly. We calculate the Euclidian distance between the nodes and transmit data using the absolute value of the Euclidian distance as the transmission range between the nodes to minimise energy consumption and maximise the lifetime of the node and the network. NS3 is used to simulate the Packet Delivery Ratio (PDR), energy consumption of the nodes, average delay, and other parameters for performance evaluation of the WSN using the improved AODV. To verify and validate the operation of our algorithm, we showed simulation results from the evaluation.

# CHAPTER 6

# SMART RIVER MONITORING USING WIRELESS SENSOR NETWORKS

## 6.1. Introduction

Monitoring and communicating water quality data in real-time is critical for promoting sustainable development. Rivers are vital resources that support the life of both humans and animals. Hence, their importance cannot be overlooked especially in developing countries where there are several reports of water-borne diseases [260], [261]. Water quality monitoring networks are required to monitor rivers efficiently. The goal is to alert stakeholders and the citizenry about changes in river water quality.

Traditionally in Ghana, trained field officers are sent to the field to collect water samples for analysis in the lab. This approach is challenging, time-consuming and expensive and may not yield the required temporal granularity that is required [5], [54]. To overcome some of the challenges associated with traditional methods, new devices capable of in-situ measurements were developed [54], [262]. Examples of such devices included pH meter HANNA-pH 211, HACH-2100 P turbidity meter, and HACH-Dr 5000 spectrophotometer which are used mostly to measure some of the physio-chemical parameters of the water. These devices could not ensure reliable and timely data collection during the water quality monitoring process. In most cases the samples are taken after the event [263], [264].

A modern approach is to make the devices autonomous by equipping them with wireless transceivers and form them into a wireless sensor network. WSNs thus comprise of autonomous, self-configuring and battery-powered sensor nodes and base station nodes (or sinks). The sensor devices are capable of sensing, performing computations and communicating via different network communication protocols (such as ZigBee, WiFi, WiFiDirect, GSM, WiMax, etc.) [5]. Sensor nodes are small, low-cost devices suitable for a variety of applications ranging from environmental to security applications which do not require any existing infrastructure to operate [265]. These sensors may be fixed at a permanent location or allowed to float to measure the various parameters.

Sensor nodes deployed in freshwater bodies are capable of collecting and analysing data at different sampling locations and transferring the data to a remote central office. Communication is achieved between the sensor node and the remote central office using a low-power radio transmitter to maximise the lifetime of the sensor nodes. The use of wireless sensor networks comes with advantages such as autonomy, reliability, robustness, and flexibility, speed, accuracy, and cost-effectiveness [77]. These advantages make WSN a preferred technology to monitor the presence of pollutants in river bodies and gather a substantial amount of information for policy implementation and managerial planning. In most deployments, the data gathered by the sensor nodes is sent through a gateway to the Cloud or a database using an existing communication network. The sensed data from the sensors are made available on a web-portal in real-time, enabling stakeholders to intervene in the water quality management processes effectively.

In this work, we demonstrate a practical solution to the water quality monitoring challenges in Ghana. Libelium wireless sensors were deployed at the intake to the Weija dam in Ghana to obtain real-time continuous data which is made available to the public via a web portal. The accuracy and precision of the parameters recorded by the smart sensor nodes are compared to the measurements obtained by field personnel in the laboratory.

The choice of using Libelium sensors in this project was influenced by: 1) robust sensor construction (sensor modules are housed in a waterproof case); 2) high accuracy in sensor readings; 3) simple setup process and ease of use; 4) cost of sensors and maintenance warranty policy; 5) low energy consumption; 6) reliablility; 7) online and offline support through webnairs, product training, discussion forum, technical inquiries through email; and 8) software compatibility with other systems such as Arduino sensor board. These meet the criteria set for selecting sensor devices for water quality monitoring [266].

In this chapter, the performance analysis of an experimental testbed deployed at the Weija Dam in Accra is presented. The rest of the chapter is organised as follows. Section 6.1 of the chapter provides detailed information on real-time deployments on smart water quality monitoring in some parts of the world. Section 6.2 provides information on the materials and methods used and provides background information on water quality parameters. Section 6.3 discusses the sensor probes used in the experimentation and provides a description of the sensor calibration procedures and the cloud-based web-portal designed to data analysis. Section 6.4 presents the sensor node architectural design and describes the hardware, software, communication, and energy-related issues that affect the sensor node. Section 6.5 presents issues related to the deployment environment, such as biofouling and sensor cabling. Section 6.6 presents experimental results. Section 6.7 presents discussions and conclusions made from the experimental results. Finally, Section 6.8 provides summary of the chapter.

## 6.2. Related Works

Wireless Sensor Networks have been widely adopted to monitor different phenomena in the environment [63], [97], [267]–[270]. For example, WSNs are used to monitor air quality [271], water quality [5], tracking endangered species [272], monitoring animal habitat [273], and many more. The adoption of WSNs allows the elimination of problems associated with conventional monitoring approaches. One area in the environment that has gained much attention in recent years is using sensor nodes to monitor water quality. Freshwater sources have been subjected to various kinds of pollution globally. Many projects worldwide have been directed at monitoring and improving freshwater sources in areas including, Australia [274], Ireland [275], China [276], Fiji Islands [277], Portugal [278], and Kosovo [37].

In what follows, a brief description of how these projects where implemented, the parameters measured, the communication infrastructure, and data collection rate are provided.

In Australia [274], the authors deployed wireless sensor nodes to monitor coastal underground water resources in the Burdekin area, Queensland, Australia. The sensors were deployed in the field to collect real-time water quality data and the amount of water pumped from the area from April 4, 2007−April 18, 2007. Salinity, water level, flow rate, and flow volume sensors were deployed to collect real-time water quality measurements to improve and sustain irrigation systems in the area. The salinity sensor (Sensorex TC1000) measures up to 100,000 S/cm providing a resolution of 10 S/cm. Similarly, the water level sensor (Tyco PS100) measures up to a depth of 30 meters with a measurement resolution of 5 cm. The flow rate sensor measures up to 100 litres/s with a measurement resolution of 0.5 litres/s. The sensors are based on the Fleck3 platform with a transceiver (NRF905). The distance between two nodes on the average was around 850 meters. The long-range communication causes end-to-end delays. For example, according to the authors, two nodes (i.e., 11 and 2) could not communicate throughout the experiment. The high end-to-end delay is associated with the transmission distance between the nodes (i.e., 600 meters) and the GPRS modems they used which were not robust for outdoor applications. The communication link was not stable due to the distances between nodes and the coverage area and the hostile environment. Hence, the nodes perform retransmission of data packets for about six tries. To overcome this, the authors used a reliable routing protocol to improve the connectivity between nodes.

In River Lee in Ireland [275], the authors provided a water monitoring system called DEPLOY. The DEPLOY project connected five (5) different zones in the city of Cork to monitor water quality using a multi-sensor system in 2009. The parameters measured in the project included pH, dissolved oxygen, temperature, depth, turbidity, chlorophyll-a, and conductivity. GSM was used for data transmission from the wireless sensor network backbone to the central repository. The data collected from all the five zones from the project was presented on a website which was also compatible on mobile phones for easy accessibility by users. The data was transferred through GPRS using the FTP protocol onto an FTP server and stored to a DataLink SQL database. Users are notified through email or SMS when events are detected. The data samples were collected and observed over a 2-month period and the data was sampled once every 10 minutes.

In the Fiji Islands [277], the authors designed a smart WQM system based on Internet of Things (IoT) and remote sensing (RS) techniques to improve the traditional methods for measuring water quality parameters in the Fiji Islands. The parameters measured included pH, oxidation reduction potential (ORP) and temperature. The sensor nodes transmit the sensed parameters via a GSM communication module. Sensed data are read and transferred continuously for an hour and the system is made to sleep for 15 minutes for energy conservation. The authors further extended the lifespan of the batteries used by the sensor devices by setting idle modules to off mode. Experimentation was performed for different marine and freshwater sources and the readings were taken every 1 hour for a day. The water samples used for the experimentation were collected and tested in a safe controlled environment except for tap water that was changed every hour to obtain consistent readings of parameters. The study conducted in the Fiji Islands employed smart water quality sensors; but the water samples were collected and analysed in a lab [277].

In Portugal [278], a WSN project that uses a Libelium Smart Water kit for remote water quality monitoring was implemented. The measured parameters included pH, oxidation-reduction potential (ORP), electrical conductivity (EC) and river temperature. The nodes are designed to use 802.15.4 radios to communicate to the Meshlium (i.e., this device serves as the gateway) via 3G or GPRS communication module. The sensor devices are equipped with 6600mAh battery and a 2W solar panel which improved the lifetime of the sensor devices.

The authors performed both laboratory and field experiment. Sensors were deployed in Southern Portugal Sao Bartolomeu de Messines and the two nodes in Soil Aquifer Treatment (SAT) basins. Sensed data was transmitted every 10 minutes to the cloud.

In the River Sitnica [37], an intelligent water monitoring system is deployed to monitor water quality parameters in Kosovo to provide datasets to policy-makers, water experts, and citizens. Parameters measured in this project include dissolved oxygen (DO), temperature (T), pH, 5-day biochemical oxygen demand (BOD5), nutrients (phosphate and nitrate), conductivity (EC), turbidity, total suspended solids (via turbidity), coliform bacteria and heavy metals. Measurements were taken every 7 or 10 minutes, or on-demand through a gateway node to a central monitoring node through a ZigBee protocol and GPRS. The sensor node senses and transmits data of packet size approximately 100 bytes through the gateway node. The monitoring was done with both static and mobile sensors, and the data was gathered between May 1st and July 12th, 2015. Real measurement data was presented on a Web portal and made available for the public, water quality monitoring experts and wireless sensor network engineers.

Although there are attempts to implement and deploy sensor devices to monitor and measure water quality continuously in some parts of the world, factors such as cost, energy efficiency, hardware/software issues, and communication issues challenge the implementation of such projects in developing countries [279]. This implementation to the best of our knowledge serves as one of the first real-time deployments for monitoring rivers. A critical consideration for monitoring river bodies in real-time is to obtain a large amount of data for trend analysis and scientific research studies. Data on water quality is still inadequate which has affected the number of scientific publications in the application domain. This work, therefore, is one that showcases an application of wireless sensor networks for real-time and continuous monitoring of river bodies in Africa and makes data available for scientific discourse and decision making.

### 6.3. Materials and Methods

The implementation details of the proposed approach for measuring water quality parameters are provided in this section. The background information on water quality parameters monitored in the Weija intake and Web portal designed to present trend analysis of the continuous real-time data are also discussed. Finally, we describe the sensor nodes' architectural design and discuss the evaluation metrics of the infrastructure proposed to solve the water pollution problem in rivers.

Polluted fresh-water sources threaten the existence of aquatic life (both plants and fish), humans, and animals relying on the water bodies. Several factors affect the level of chemical concentrations of physio-chemical parameters in fresh water. In this study, water quality sensor probes capable of measuring pH, calcium ion (Ca2+), conductivity, dissolved oxygen, silver (Ag+), fluoride ion (F-), nitrate ion (NO3-), oxidation-reduction potential, and temperature are used for detecting contaminants in a field experiment. To better understand the choice of the physio-chemical parameters adapted in this experiment, we provide brief descriptions of each chemical element. In Table 6.1, the list of river monitoring parameter characteristics and the units of measurements are provided.

pH is the measure of acidity or alkalinity of a substance. For a river, the pH may vary depending on the geology of the catchment area, the flow, and the amount of wastewater discharged into the river. In river bodies, the pH usually ranges between 6−14 [280].

Table 6. 1 River Monitoring Parameter Characteristics.

| | Water Parameter | Units |
|---|---|---|
| **1** | Temperature | ˚C |
| **2** | pH | pH |
| **3** | Electrical conductivity | Siemens per centimeter (S/cm) |
| **4** | Dissolved Oxygen (DO) | mg/L |
| **5** | Oxidation Reduction Potential (ORP) | mV |
| **6** | Nitrate Ion (NO3-) | mg/L |
| **7** | Fluoride ion (F-) | mg/L or part-per-million (ppm) |
| **8** | Silver (Ag+) | c |
| **9** | Calcium ion (Ca2+) | mg/L |

Rivers are monitored for electrical conductivity (EC) to determine the amount of dissolved ionic salts (that is the presence of dissolved solids such as chloride, nitrate and phosphate) in the river [281], [282]. River bodies with a higher concentration of salinity are likely to record higher electrical conductivity.

EC can be measured using the conductive or inductive method, but in the area of WSNs, it is appropriate to use inductive methods because inductive is based on the attenuation of an electromagnetic field in the river [283]. The EC is measured using the sensor probe shown in Figure 6.6.

Calcium is an alkaline-earth metal [284]. Calcium forms part of the cell wall of aquatic plants and can also be found in the bones and shells of animals in freshwater sources [284]. Calcium Ions (Ca2+) in freshwater sources are obtained from three main sources: 1) Limestone ($CaCO_3$); 2) Dolomite ($CaCO_3 - MgCO_3$); and 3) Gypsum ($CaSO_4 \cdot 2H_2O$) and other rocks and minerals containing calcium. The concentration of Ca2+ in freshwater sources ranges from 0 to 100 mg/L [285]. In freshwater sources, when the level of Ca2+ drops below 5mg/L, then plants and animal life become endangered [285]. In situations where the calcium concentration is high, it usually triggers diseases in fish due to the low level of nutrients affecting the population density of aquatic life [284], [286].

Fluoride is present in freshwater sources. Minerals and rocks in most freshwater bodies contain fluoride. It is an essential element with high health advantages, especially for teeth growth. Fluoride concentrations in seawater measure up to 1.3 mg/L, 1-25 mg/L in freshwater sources such as rivers, lakes, spring and underground and in drinking water fluoride measures at 1.5 mg/L. The levels of concentration are determined with an ion-selective electrode or sensor probe [287]. The probes or ion-selective electrode can detect low fluoride concentrations in freshwater.

Temperature is the measure of the coldness or hotness of a river. Temperature depends on environmental conditions and the time of year [288]. ORP is a measure of electrical potential and measures how much oxidation (i.e., the loss of electrons by atoms, molecules, or ions) or how much reduction (i.e., the net gain of electrons by atoms, molecules, or ions) take place in rivers [288].

### 6.4. Sensor Probes

The real-time monitoring of rivers in this project was undertaken with the use of the following wireless sensor probes: pH sensor, calcium ion (Ca2+) sensor, electrical conductivity sensor, dissolved oxygen sensor, silver (Ag+) sensor, fluoride ion (F-) sensor, nitrate ion (NO3-) sensor, oxidation-reduction potential sensor, and temperature sensors. These sensor probes measure the levels of concentration of contaminants and offers several advantages. These include: 1) Real-time information on concentrations will provide an adequate solution to the ongoing questions to the management of freshwater sources in Ghana especially at a time that the various freshwater sources are being contaminated with mining activities; 2) Reporting of higher or lower concentrations will inform decision makers about treatment levels to obtain good quality drinking water; 3) Continuous and accurate information will be provided on hourly, daily, monthly and yearly bases about the concentration loads of the freshwater sources; 4) Trend analysis; 5) Development of statistical models to support realistic estimation of concentrations over a period of time using discrete time-series information; 6) Provision of new insights for scientific studies and analysis about the ecosystem health; and 7) Early warning signal [289].

In the Sections that follow, we provide a detailed description of the sensors employed for measuring the level of concentration of physical and chemical properties at the Weija intake in Ghana.

### 6.4.1. Temperature Sensor

Many of the water quality parameters, dissolved oxygen, oxidation-reduction potential (ORP), electrical conductivity and salinity, and pH are temperature dependent. Several factors affect the temperatures of streams or freshwater sources in general. Typical among these factors are warm or cold air, the presence of trees or grass at the banks of the river, the climate season (dry or raining), and the presence of human settlements around the river [38], [290]. The temperature sensor measures temperatures ranging from 0 to 100°C with resistance of 1000Ω. For outdoor deployment, the temperature sensor cable extends approximately 150cm when attached to the smart water sensor board [291]. Figure 6.1 illustrate the temperature sensor purchased from Libelium for our field deployment.


Figure 6. 1 Temperature Sensor


Figure 6. 2 pH Sensor Probe

### 6.4.2. pH Sensor Probe

The pH sensor probe illustrated in Figure 6.2 comes with measuring and a reference electrode. [269] suggests that the pH of freshwater sources can be measured using a glass electrode and a reference electrode or Ion-Selective-Field- Effect-Transistor (ISFET). Since the former is much more affordable and reliable to use and its the most preferred for environmental monitoring applications [292]. The type of pH sensor adopted in this study is a combination electrode which is capable of measuring pH values within the range of 0−14 pH and operates at temperatures 0~80◦C. Also, the zero-electric potential for the sensor devices is 7±0.25p with response time less than 1 minute. The pH electrode comes with a cable length of ~ 500cm [291]. The pH sensor probe is immersed in the river such that the electrode is fully inside the river to measure the acidity or alkalinity level in freshwater sources. pH measurement electrode measures the changes in hydrogen ion concentration of a solution and the reference electrode does not change in hydrogen ion concentration.

### 6.4.3. Electrical Conductivity Sensor Probe

The electrical conductivity sensor is designed to measure two (2) or four (4) electrodes with a conductivity cell constant which typically ranges from $0.1 S/cm^{-1}$ to $10 S/cm^{-1}$ [292], [293]. In this study, the conductivity sensor employed is a two-electrode sensor made from platinum. The conductivity cell constant used ranges from $1 \pm 0.2 \text{S}/cm^{-1}$. For our field experiment, we purchase an electrical conductivity with a fixed cable length of ~500 cm [291]. Figure 6.3 shows the electrical conductivity sensor used in our field deployment in the river network monitoring process.

Figure 6. 3 Electrical Conductivity Probe

Figure 6. 4 Calcium Ion (Ca2+) Sensor

### 6.4.4. Calcium Ion (Ca2+) Sensor Probe

Calcium ion is one of the principal cations (i.e., apart from Na+, K+, Mg2+) found in freshwater sources [294]. Calcium Ion (Ca2+) Sensor Probe shown in Figure 6.4 was employed to measure the concentration of calcium in freshwater sources. The sensor probe works only when the single junction reference probe is attached to the sensor device. The probe measures calcium and transmits the data every 30 minutes.

### 6.4.5. Nitrate Ion (NO3-) Probe

Nitrate Ion (NO3-) sensor probe is used to measure the concentration of nitrate in freshwater sources. For example, the use of fertiliser in agriculture is a contributing factor for nitrates to penetrate freshwater sources. The nitrate sensor probe requires a single junction reference probe to read the ions accurately with its measurement probe (see Figure 6.5).

Figure 6. 5 Nitrate Ion Sensor Probe Probe

Figure 6. 6 Fluoride Ion (F-) Sensor Probe

### 6.4.6. Fluoride Ion (F-) Sensor Probe

Fluoride Ion (F-) sensor probe requires the use of the single junction reference probe to obtain accurate readings of the levels of fluoride concentrations in freshwater sources. Fluoride are ionic compounds (i.e., salt) that are found in most freshwater bodies normally generating from rocks and the surrounding soils [295]. Fluoride in freshwater such as rivers and lakes, the fluoride concentrations are generally less than 0.5 $mgl^{-1}$. The effects of low or high concentrations of fluoride in water is presented in [296].

### 6.4.7. Oxidation-Reduction Potential Probe (ORP)

The ORP sensor probe measures the oxidizing potential in freshwater sources. OPR sensor probe measures the presence of contaminants, dead plants and animals in a river [297]. ORP may also be described as a solution's potential to santize itself [277]. It is measured in millivolts. The oxidation reduction potential sensor electrodes are made up of a reference electrode and ORP electrode. The ORP electrode works by using an inert metal electrode. The ORP electrode give up electrons and accepts electrons from an oxidant and reductant respectively until a potential is developed. The charge built up due to the exchange of electrons is equivalent to the ORP solution. On the other hand, the reference electrode, works using a silver chloride electrode similar to the one used for pH measurements [298].

### 6.4.8. Dissolved Oxygen Probe

Dissolved oxygen measured in (mg/L) is the amount of gaseous oxygen dissolved in water [288]. Dissolve oxygen content in freshwater sources is seasonal depending on the time of the year. In freshwater sources, the dissolve oxygen value obtained during the harmattan or dry season ranges between 4-7mg/L and in rainy season DO typically ranges from 12-13mg/L [296].

Figure 6. 7 Silver Sensor Probe

Figure 6. 8 Oxidation Reduction Potential Sensor

### 6.4.9. Sensor Calibration

In WSN for WQM-based applications, data obtained from the sensor nodes affect data analysis and reporting. Therefore, the sensor nodes must be handled with much care from calibration to the deployment environment. Sensor calibration is performed to reduce errors, maintain consistency and accuracy in measurements and to improve sensor performance [299]. Manufacturers calibrate industrial sensors for environmental applications, but for real-time monitoring applications, it is recommended that sensors were recalibrated before deployment to remove the errors in data readings. Sensors become faulty or erroneous due to the following factors: 1) subjection to heat; 2) cold; 3) humidity, and 4) shock during assembling, packaging, shipment, and storage. Wireless sensor devices also are likely to lose their sensitivity over time and hence, require regular recalibration to maintain its accuracy [300]. The sensor probes are calibrated with a standard reference solution for stable sediment concentrations (see Figures 6.10 to 6.12).

Figure 6. 9 Dissolved Oxygen Sensor Probe

Figure 6. 10 EC Caibration

Each of the probes was immersed in distilled or de-ionized water to clean any impurities before placing the probe in the reference solution to obtain precise value of the cell constant [291]. A well calibrated sensor, will given a particular input, produce the same output independent of how many times the measurement is taken (i.e., precision). The sensor node's precision is affected by noise and hysteresis. Wireless sensor nodes deployed in freshwater sources are affected by environmental conditions and interferences during communication which leads to noise. Interference or noise from signals affects accuracy and precision in measurements.

Figure 6. 11 DO Calibration

Figure 6. 12 pH Calibration

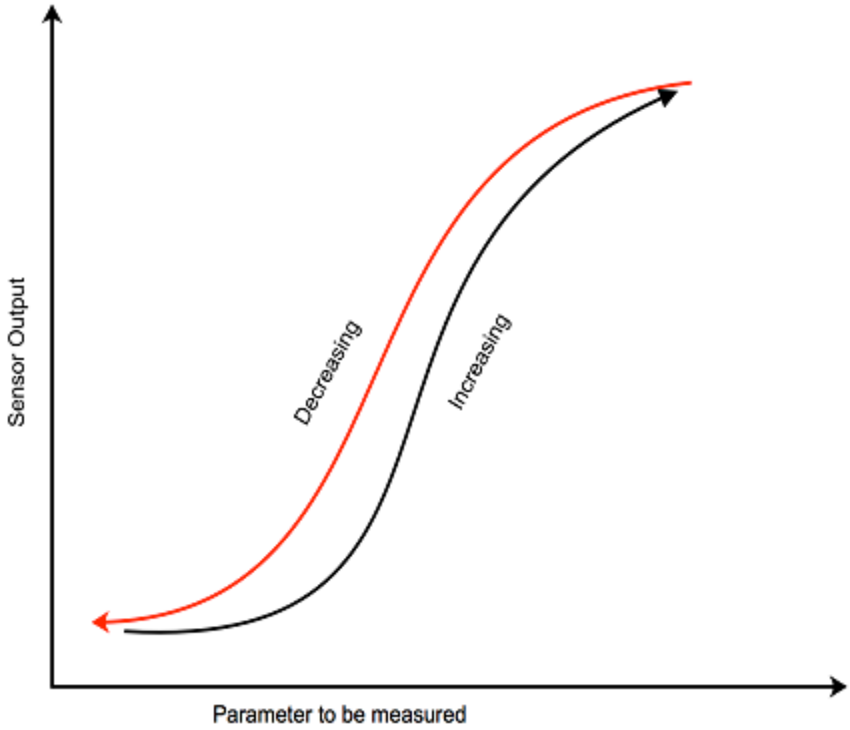


Figure 6. 13 Sensor exhibiting hysteresis

From Figure 6.13, hysteresis as shown in may lead to data measurement delays which may significantly affect data accuracy and precision. Hysteresis in temperature sensors for example, may arise in an event where moisture penetrates inside the sensor node. Hysteresis may also arise if an amount of strain is applied to the sensor in freshwater monitoring [301]. It is important for the sensors to also have a high resolution, i.e. they must be capable of detecting small variations in the measurements. For real-time water quality monitoring, wireless sensors perform continuous sensing and transfer the measured values to a storage location for analysis and reporting. Sensors with low signal-to-noise-ratio (SNR) do not support continuous water quality monitoring, because such sensors have problems taking repeatable measurements. Figure 6.14 shows the correlation between the output of the sensor and the calibrated measure for a node with low SNR. As can be seen, even though there appears to be a relatively high correlation, it is not strong enough as the points do not lie on the ideal response line. Figure 6.15 shows the output response from a sensor node with a high SNR. In this case, there is a strong correlation between the output and the calibrated measure.

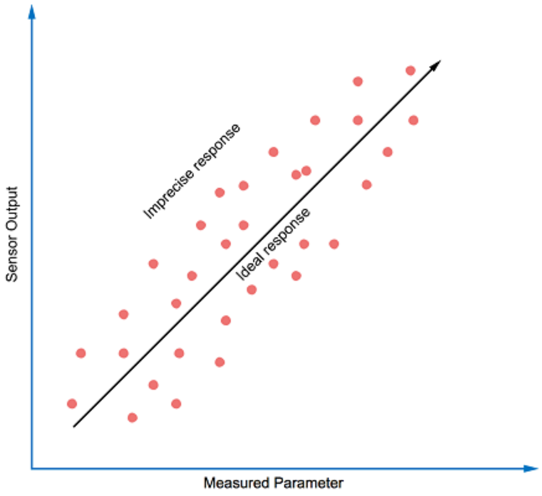


Figure 6. 14 Imprecise precision[300]

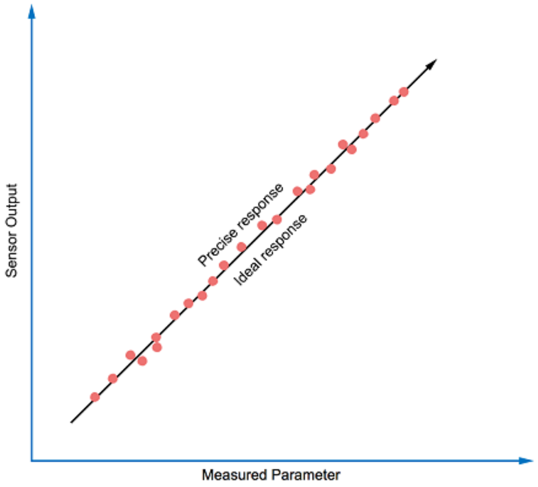


Figure 6. 15 Precise precision[300]

Also, when the sensor values estimated lags behind the changes in the river, it affects precision [300]. In [300] the authors demonstrated the various kinds of error that can occur in the calibration process. Figure 6.16 shows the ideal case whilst Figure 6.17 depicts the case where there is an offset in the measurements. Figure 6.18 illustrates the situation where the sensor node has a gain. Finally, Figure 6.19 shows the situation where the sensor node displays a non-linear response.

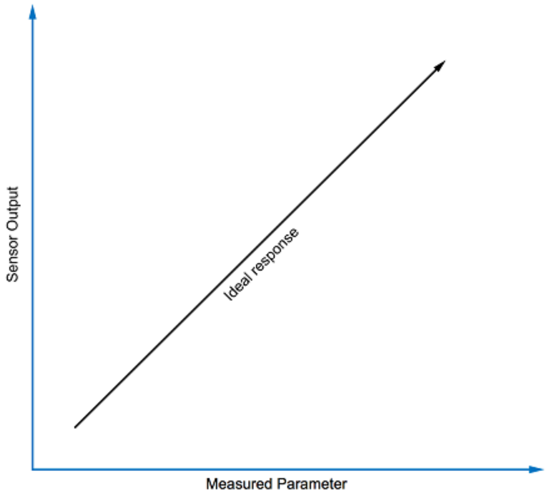


Figure 6. 16 Ideal Response

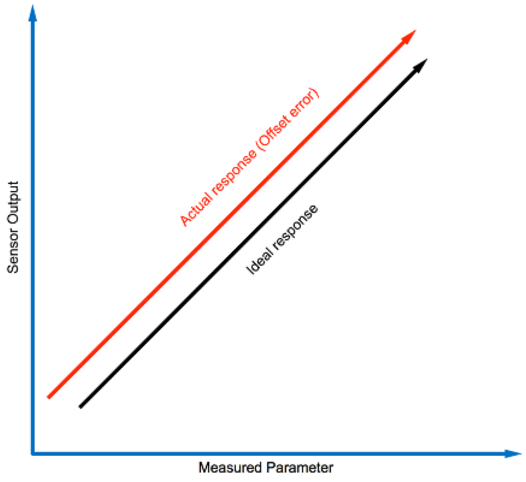


Figure 6. 17 Offset Error

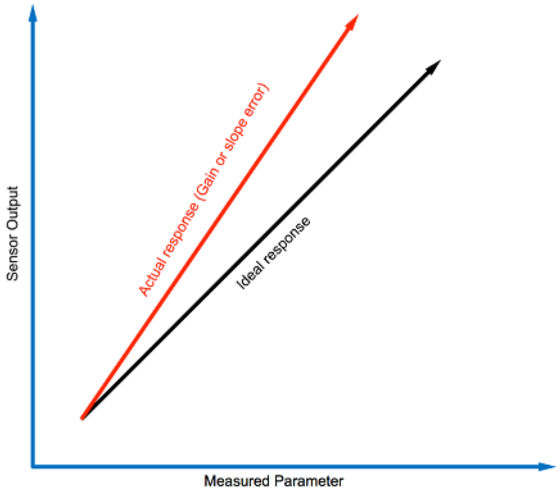


Figure 6. 18 Gain or Slope Error

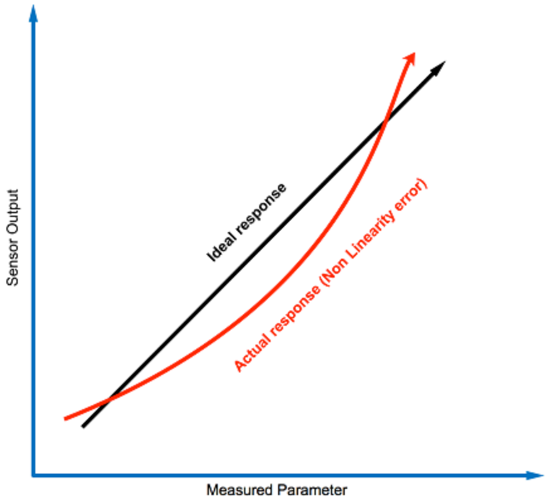


Figure 6. 19 Non Linearity Error

To calibrate the sensor probes in this work, we adopted one-point, two-point calibration and three-point calibrating methods. In the one-point calibration, only one measurement point is used. One-point method of calibration is linear and produces the expected measurement value. The sensor probe is used to take measurements to compare to the standard reference point. The new measured value is subtracted from the reference point to obtain the offset. In two-point calibration, re-scaling the sensors make them capable of correcting offset errors. In two-point calibration, two measurements are taken to produce accurate measurements. The sensor probe's value after the calibration process is provided. The pH sensor was calibrated to give accurate and precise pH readings. The pH sensor probe was calibrated using a three-point calibration method in a standard buffer solution. The buffer solutions were pH 4.0, 7.0, and 10.0. The pH calibration was performed at 25°C. The accuracy and precision of the probe were determined after some time to obtain the standard pH calibrated values shown in Table 6.2.

Table 6. 2 pH Calibration Points

| | **Initial value** | **Calibrated value** |
|---|---|---|
| **pH10** | 1.985 | 1.998 |
| **pH7** | 2.070 | 2.099 |
| **pH4** | 2.227 | 2.244 |
| **Temperature°** | 23.7 | 25 |

A similar calibration process was undertaken to immerse all the other probes into their respective buffer solutions for some time to obtain the new standard values to run on the sensor nodes. The resulting calibrated points are shown in Tables 6.3 to 6.7.

Table 6. 3 Conductivity Calibration Points

| **Data before calibration** | | |
|---|---|---|
| | **Initial value** | **Calibrated value** |
| Concentration 10500 S/cm | 197.0 | - |
| Concentration 40000 S/cm | 150 | - |
| **Data after calibration** | | |
| Concentration 12880 S/cm | - | 124.00 |

| | | |
|---|---|---|
| Concentration 80000 S/cm | - | 176.00 |

Table 6. 4 Calcium Calibration Points

| | **Initial value** | **Calibrated value** |
|---|---|---|
| Concentration 10 (ppm) | 2.163 | 2.409 |
| Concentration 100 (ppm) | 2.296 | 2.430 |
| Concentration 1000 (ppm) | 2.425 | 3.981 |

Table 6. 5 Fluoride Calibration Points

| | **Initial value** | **Calibrated value** |
|---|---|---|
| Concentration 10 (ppm) | 3.115 | 3.0771 |
| Concentration 100 (ppm) | 2.834 | 2.990 |
| Concentration 1000 (ppm) | 2.557 | 2.688 |

Table 6. 6 DO Calibration Points

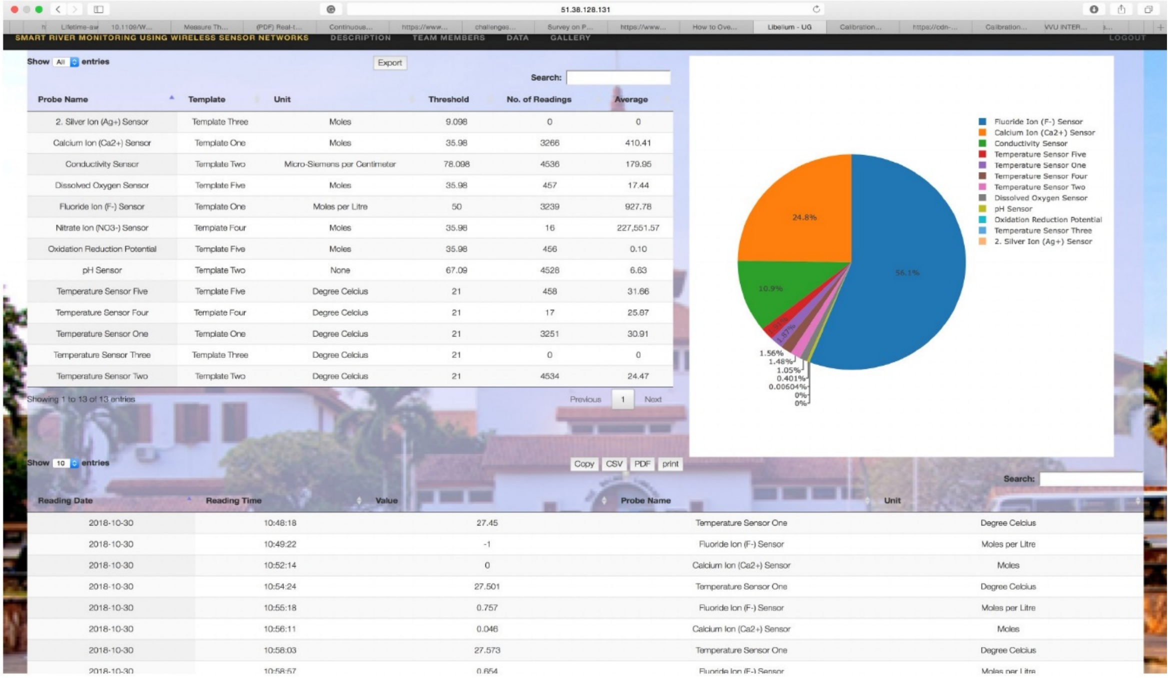
| | **Initial value** | **Calibrated value** |
|---|---|---|
| Calibration in Normal Air | 2.65 | 2.796 |
| Calibration under 0% condition | 0.0 | 0.0 |

Table 6. 7 ORP Calibration Points

| | **Initial value** | **Calibrated value** |
|---|---|---|
| Calibration in Normal Air | 2.65 | 2.796 |
| Calibration under 0% condition | 0.0 | 0.0 |

### 6.4.10. Cloud-based Web Portal Design

The relevance of wireless sensor networks for water quality monitoring lie in their ability to provide up to the minute information to stakeholders. One effective way in which this can be achieved is using web portals and sms alerts. Using a web-portal, the information is made readily available to the public, water quality experts and wireless sensor network engineers through alert systems. In this section, an intelligent web-portal designed to collect, model, store, retrieve, manipulate, analyse, visualise and share data and information obtained from the sensor devices, sensing and measuring water quality parameters in real-time is described. The cloud-based web portal shown in Figure 6.20 is used to track the positions of the wireless sensor nodes. In smart river monitoring projects, massive amounts of data are generated from the sensing nodes.



| Probe Name | Template | Unit | Threshold | No. of Readings | Average |
|---|---|---|---|---|---|
| 2. Silver Ion (Ag+) Sensor | Template Three | Moles | 9.098 | 0 | 0 |
| Calcium Ion (Ca2+) Sensor | Template One | Moles | 35.98 | 3266 | 410.41 |
| Conductivity Sensor | Template Two | Micro-Siemens per Centimeter | 78.098 | 4536 | 179.95 |
| Dissolved Oxygen Sensor | Template Five | Moles | 35.98 | 457 | 17.44 |
| Fluoride Ion (F-) Sensor | Template One | Moles per Litre | 50 | 3239 | 927.78 |
| Nitrate Ion (NO3-) Sensor | Template Four | Moles | 35.98 | 16 | 227,551.57 |
| Oxidation Reduction Potential | Template Five | Moles | 35.98 | 456 | 0.10 |
| pH Sensor | Template Two | None | 67.09 | 4528 | 6.63 |
| Temperature Sensor Five | Template Five | Degree Celcius | 21 | 458 | 31.66 |
| Temperature Sensor Four | Template Four | Degree Celcius | 21 | 17 | 25.87 |
| Temperature Sensor One | Template One | Degree Celcius | 21 | 3251 | 30.91 |
| Temperature Sensor Three | Template Three | Degree Celcius | 21 | 0 | 0 |
| Temperature Sensor Two | Template Two | Degree Celcius | 21 | 4534 | 24.47 |

Showing 1 to 13 of 13 entries

| Reading Date | Reading Time | Value | Probe Name | Unit |
|---|---|---|---|---|
| 2018-10-30 | 10:48:18 | 27.45 | Temperature Sensor One | Degree Celcius |
| 2018-10-30 | 10:49:22 | -1 | Fluoride Ion (F-) Sensor | Moles per Litre |
| 2018-10-30 | 10:52:14 | 0 | Calcium Ion (Ca2+) Sensor | Moles |
| 2018-10-30 | 10:54:24 | 27.501 | Temperature Sensor One | Degree Celcius |
| 2018-10-30 | 10:55:18 | 0.757 | Fluoride Ion (F-) Sensor | Moles per Litre |
| 2018-10-30 | 10:56:11 | 0.046 | Calcium Ion (Ca2+) Sensor | Moles |
| 2018-10-30 | 10:58:03 | 27.573 | Temperature Sensor One | Degree Celcius |
| 2018-10-30 | 10:58:57 | 0.654 | Fluoride Ion (F-) Sensor | Moles per Litre |

Figure 6. 20 Web portal showing data received from the deployment site

The general architecture for the deployment is shown in Figure 6.21. Wireless sensor nodes transmit data through a GSM/GPRS to the cloud.

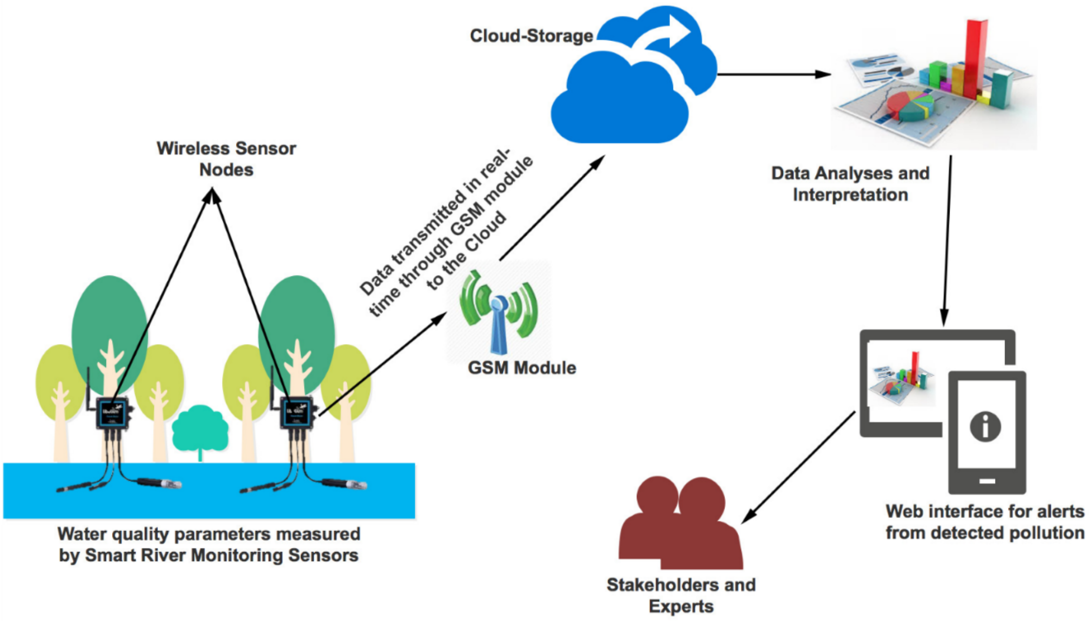


Figure 6. 21 The Monitoring Process

The Waspmote data frame is designed with a specified structure as shown in Figures 6.22 and 6.23. The frame type is a 1-byte field that determines whether the frame is binary, or ASCII and it also defines frames based on the activity the frame performs (i.e., event or alarm).

| HEADER | | | | | | | | | PAYLOAD | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <=> | Frame Type | Num of bytes | # | Serial ID | # | Waspmote ID | # | Sequence | # | Sensor_1 | # | Sensor_2 | … | Sensor_n | # |

*Figure 6. 22 Libelium ASCII Data Format*

In the ASCII frame structure (Figure 6.22), the *start delimiter,* <=> is a 3-byte field that identifies the each starting frame, the *number of fields* is 1-byte and it is used to determine the number of sensor fields sent in the frame. The *serial ID* is a 16-byte field that uniquely identifies a Waspmote device. This field is read-only. The frame *sequence* field is 1 to 3-byte field used to indicate the sequence of the frame and to detect missing frames. The *sensor field* consist of sensorID, value, and a separator. The value may be one, two or three values depending on the type of data (i.e., simple, or complex). Finally, a *separator* field denoted by # is a 1-byte field placed before and after each field in the frame [302]. In the binary frame structure (Figure 6.23), all the other fields are similar to the fields in the ASCII frame structure except the *number of bytes'* field and the size of the *serial ID* field (i.e., 8-bytes). The number of bytes' field is a 1-byte field that specifies the number of bytes after the number of bytes' field until the end of the payload is found [302].

| HEADER | | | | | PAYLOAD | | | | |
|---|---|---|---|---|---|---|---|---|---|
| <=> | Frame Type | Num of bytes | Serial ID | Waspmote ID | Sequence | Sensor_1 | Sensor_2 | … | Sensor_n |

Figure 6. 23 Libelium Binary Data Format

In this work, the sensor data to be transmitted is as shown in Figure 6.24. In the frame structure, each sensor has a unique identification number, the *device ID* which is 8-byte in length.

| HEADER | | | | | PAYLOAD | | |
|---|---|---|---|---|---|---|---|
| Device ID | Parameter Name | Location | Sensor Type | # | Measured Value | Packet Rx Date/Time | Threshold Value |

Figure 6. 24 Data Format

The name of the parameter is stored in the field labelled *parameter name* which is 16-byte in size. The *sensor type* field is a 3-byte field that describes the two kinds of sensor devices used: smart sensor unit and smart water ion. A 4-byte field is assigned to the *measured value* from the sensor node. The data is measured in real-time, hence we keep track of the date and time the measured value was received. The size of this field is between 3 to 10 bytes. The location information (i.e., the sensor device has GPS sensor onboard to measure the latitude and longitude information) is stored in the *location field* which is 4-byte.

The wireless sensor nodes were deployed in September 2018 and have been transmitting data to date. Notwithstanding the continuous data transmission, the data reported in this dissertation covers five-months period, September 2018 to January 2019. The wireless sensor deployment coincided with the latter part of the rainy season which is usually from March to mid-November in the southern parts of Ghana and also fell within a window of the dry season generally from December to March.

## 6.5. Sensor Architectural design

The Libelium Waspmote Plug and Sense unit consist of the Waspmote device, communication modules, sensor board, and sensor probes. The sensor probes are able to measure single and multiple parameters.

### 6.5.1. Hardware Architecture

Hardware Architecture: In this work, the Libelium smart water unit and smart ion unit were used for sensing and measuring some water quality parameters. The parameters that were measured are listed in Table 6.1. Each sensor node can measure multiple parameters. Waspmote is waterproof, hence suitable for deployment in the application domain. The hardware is composed of the sensing subsystem, the processing subsystem, power subsystem and communication subsystem. The sensing subsystem depends on the sensor probes to sense parameters from the region of interest.

The processing subsystem consist of data acquisition of raw data, data processing, and data analysis. The power subsystem monitors the power consumption of the sensor node. The main power source of the Waspmote Smart Water Sensor is rechargeable battery. To be able to compensate the energy budget of the sensor node, a solar panel to the power subsystem is added to the set up. Each component on the sensor board consumes an amount of power when the device is in use. The communication subsystem is varied. The common types used by the smart water device include Wifi, etc. The Libelium Waspmote sensor uses cellular communication modules such as 3G/4G, General Packet Radio Service (GPRS), long-range 802.15.4/ZigBee (868/900MHz) and Wideband Code Division Multiple Access (WCDMA) connectivity to transmit data/information to the Cloud. The 4G communication model features a GPS that enable researches to perform real-time monitoring and allows the use of a SIM card for GSM network communication.

### 6.5.2. Software Design

The wireless sensor devices were programmed to meet the design requirements for the project. The goals for the project include minimising the amount of energy consumed by the transmitter and detecting pollutants in real-time. The variables shown in Table 6.8 were defined at the programming level. The GSM module was activated anytime a pollutant was detected. The data acquisition system has been designed to transmit water quality data to a monitoring center via 4G communication infrastructure. The data values received from the sensor devices are processed and analyzed directly online.

Table 6. 8 Sensor Attributes

| **Attribute** | **Data Type** | **Description** |
|---|---|---|
| **Device_ID** | Number | Identification of the sensor device |
| **Location_coordinate** | Varchar | Current location of the sensor node/probe |
| **Sensor_type** | Varchar | Type of sensor |
| **Date** | Date/Time | Date of the received frame |
| **Time** | Date/Time | Time of the received frame |
| **Sensor_per_device** | Integer | Number of sensors attached to each Waspmote |

| | | |
|---|---|---|
| **Sensor_value** | Integer | Sensor values received |
| **Threshold_value** | Integer | The standard value of each parameter |

The connectivity status contains the codes for the 4G connectivity attempts. The system checks for the host, the port and resource (i.e., the location of the sensor node, the probe ID, and the reading) availability. To establish connection, it verifies the name of the access point (i.e., the APN used is Vodafone Internet), the login credentials (user name and password), the host (i.e., the server IP to which the HTTP request is sent with the probe readings), the port number, the connectivity status and the HTTP status. When these verifications are completed and a connection is available, readings are sent to the Cloud, otherwise the 4G communication module is put to DEEP SLEEP to save energy. When a sensor node is ready to send readings and it loses the connection, the process is repeated until a 4G connectivity is established for data to be transferred successfully (see Figures 6.25 to 6.27).

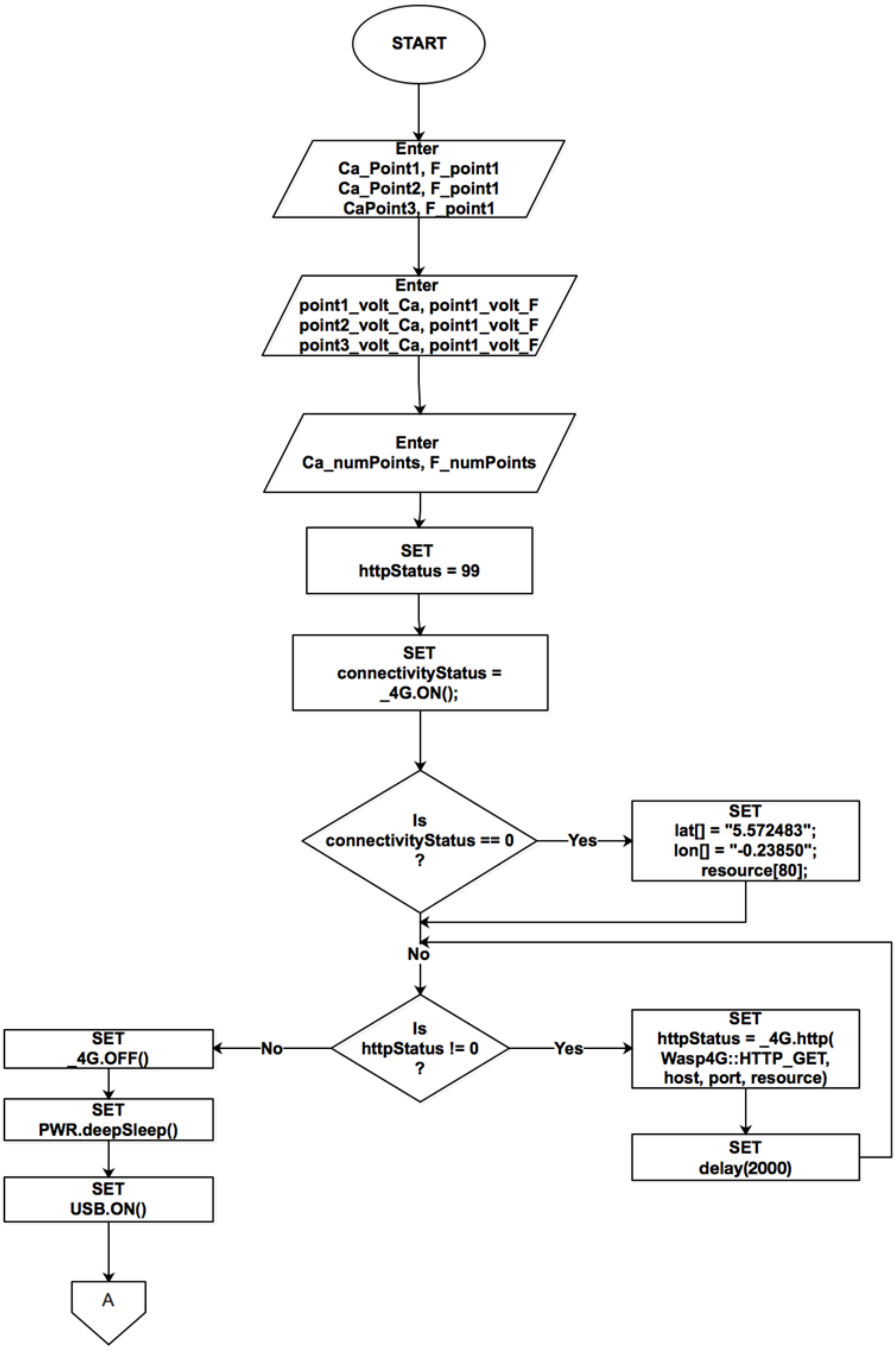


Figure 6. 25 Implementation process-4G Connectivity

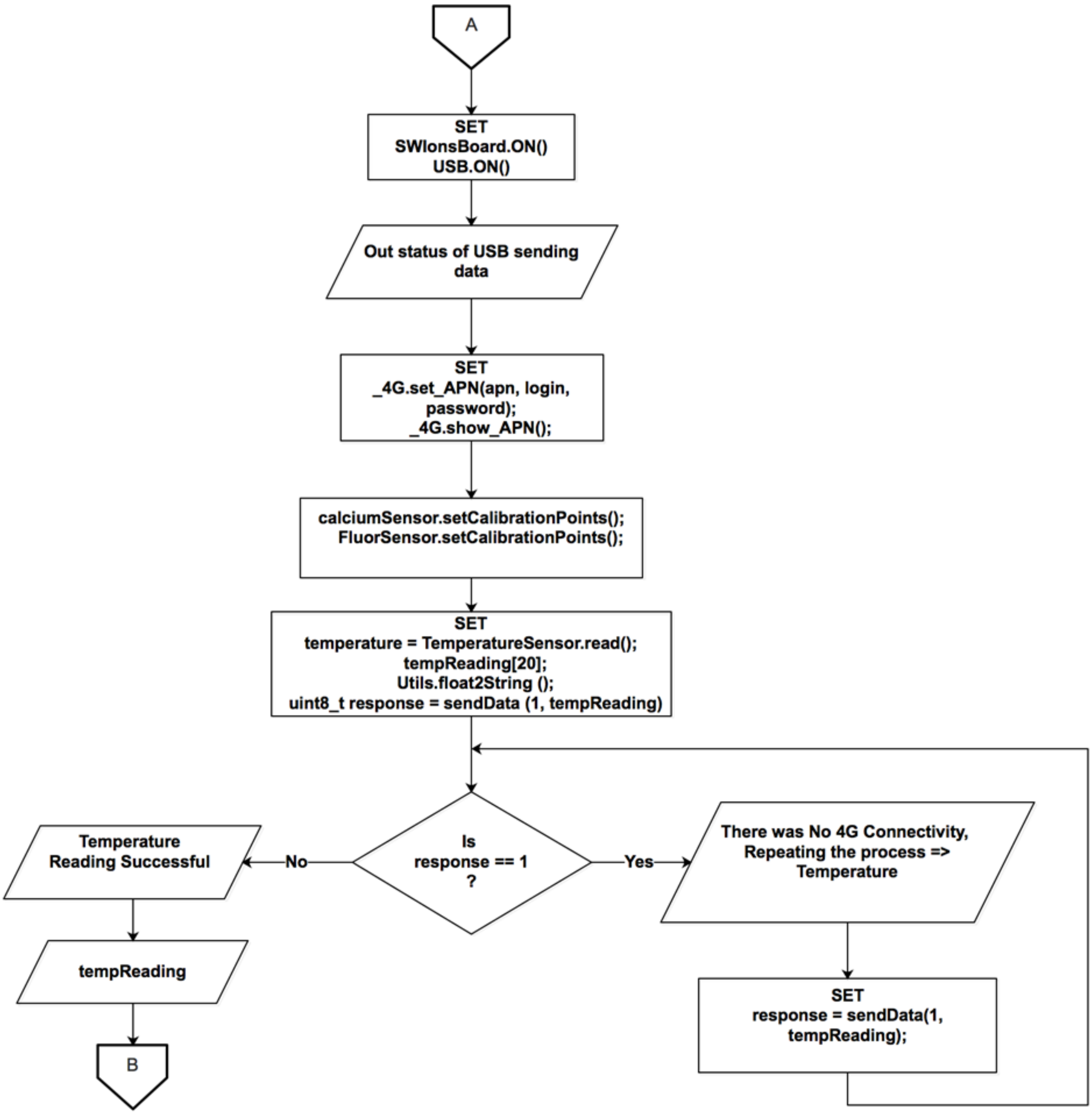


Figure 6. 26 Implementation Process-Reading Temperature

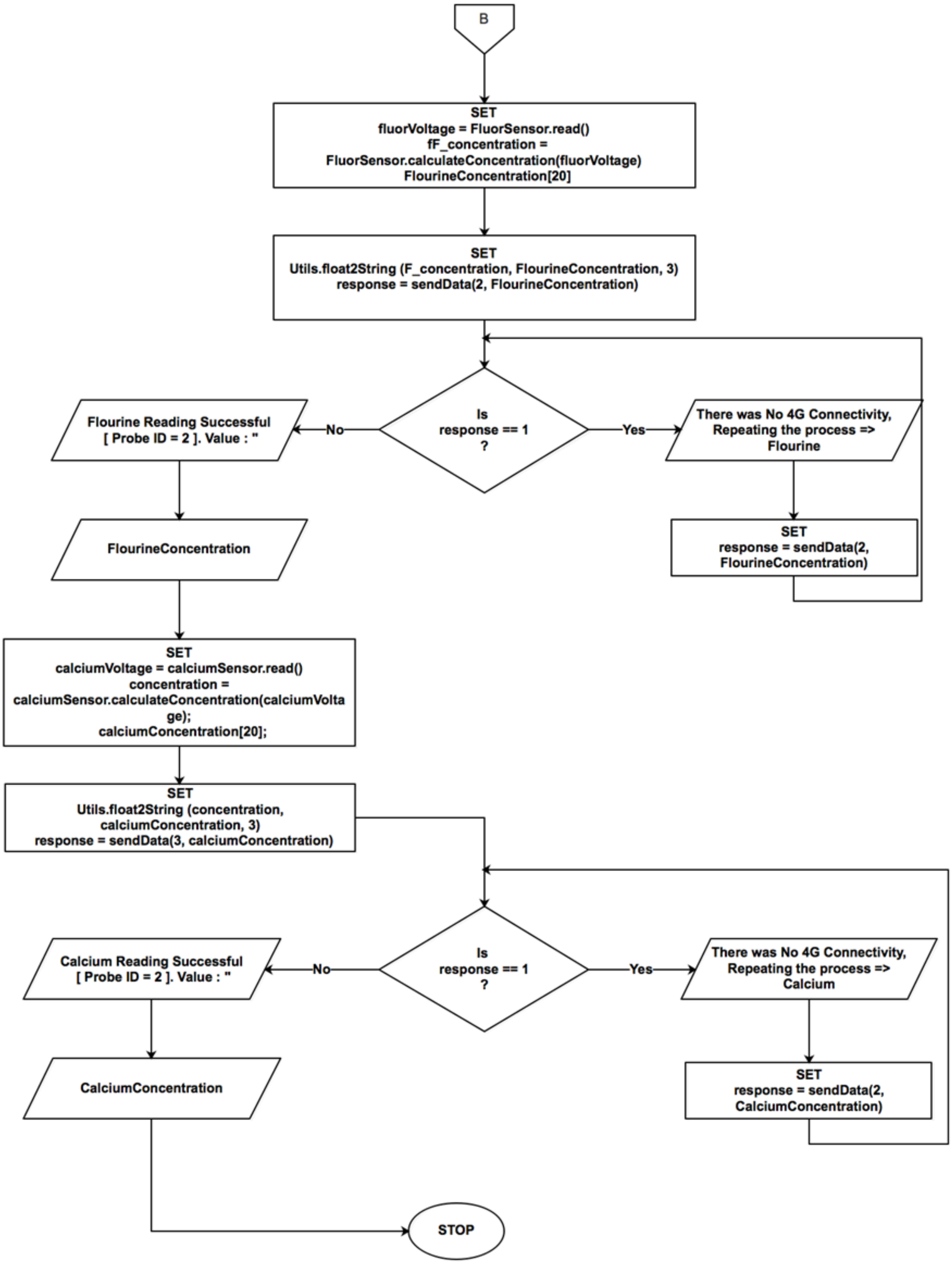


Figure 6. 27 Implementation Process-Reading calcium and fluoride

### 6.5.3. Data Communication

The smart water sensor board and the smart water ion sensors are low-powered devices designed to communicate through different radio modules (i.e., XBee-PRO, XBee, XBee-PRO, LoRaWAN, Sigfox, WiFi PRO, and 4G (GSM/GPRS, GPS)) to transmit water quality data to a secured database server or the Cloud in real-time. In such application domain, selecting the right type of network communication is essential and in most cases the range, radio power consumption, network speed, security of data, reliability of data transmission, and network usage cost are attributes that must be closely considered. 4G network transmits data based on the mobile phone network. This makes 4G attractive since its less expensive, easy to setup, and easy maintain. Because 4G communication presents several advantages over other communication standards, it serves a better choice for a real-time WSN-based WQM application. Also, 4G works better over long-distances and covers large geographical area in Ghana. Despite the advantages 4G presents, it is greatly affected by poor weather conditions, rendering the network unreliable at times [5], [266].

Some factors that affect the reliability of the data is the type of scheduling employed at the MAC layer. Some MAC protocols include Aloha, Slotted Aloha, CSMA/CS, CSMA/CA, e.t.c. Aloha and Slotted Aloha are Random Access Protocols implemented on the MAC layer of the Data Link Layer of the OSI Model. The Aloha works by determing which node will be transmitting data when the multi-channel is free. The node is permitted to send data frames whenever it has data hence the time is continuous but not synchronized between all nodes in the network. Pure Aloha permits all nodes in a network the opportunity to transmit data when they have data to send. This introduces collision in the network. An acknowledgment frame is received when transmission is successful, or else the node considers the transmission as unsuccessful hence more data frames are sent. The successful transmission of data frame or throughput of Aloha is $T = G * e^{-}2G$, where $T$ is the throughput and $G$ is the mean of the

Poisson distribution over transmission-attempt. The maximum throughput of Pure Aloha is 0.18 (18%) when $G$ is 1/2 is equal of the total transmitted frames. To mitigate the challenges of Pure Aloha, the Slotted Aloha was introduced. Unlike the Pure Aloha where time is continuous, the time is divided into discrete time slots which corresponds to the length of a data frame. Nodes are permitted to transmit data in the next time slot. The throughput $T = G*e^{-}G$ with a maximum throughput when G=1, which corresponds to 37% of the total transmitted packets with 26% collision.

In the Libelium waspmote used in the application developed, the slotted Aloha MAC protocol is implemented with time slot of 30 minutes for each node placed in the Weija river. The nodes implemented Zigbee protocol and therefore each node in the network knows the location of its neighbours, but communication is not permitted between them. All communication from the de-ployed sensor node is made with a central base station situated about 1500 meters from the nodes, and then forwarded to the cloud where remote processing and monitoring is done.

The original slotted Aloha is presented as below.

1. The working cycle $T$ which is the time for each node to receive a data packet is divided into time slots. Each node can send a packet in each time slot.
2. If a node has packet to send, an attempt is made to send at the next time slot.
3. If new packet is successfully transmitted i.e. transmitted with received acknowledgement, then the node can transmit in the next time slot.
4. If collision is detected by a transmitting node, i.e. when acknowledgement is not received within a specified time window, the old packet is re-transmitted in each subsequent time slot with a certain probability until the packet is transmitted successfully.

In [303], a generalized approach was implemented that allowed a node to vary the probability of transmission. In the duty cycle implemented, we consider connected stationary network of 5 nodes with a single sink. In the initialization stage all nodes are assumed to be are awake at deployment time. In the next working cycle, all nodes operate with a duty cycle of 0.5, which periodically turns on the radio to transmit or receive packets based on a wakeup schedule. The network assumes a star topology where all nodes transmit to the single sink. A specific sleep/wake up schedule is not assumed as nodes transmit to the sink in their scheduled time slots in a one-hop data communication. A sleeping node is switched to the active state when it has data to send in its time slot.

Duty cycled WSN can be loosely categorized as either random duty cycle or coordinated duty cycle. In random duty cycle, each node switches off or on generating random working schedules [304]. Random variables known as independent and identical distributed (i.i.d) define the state of a node at each time slot. Partial randomized schemes exchange their random working schedule with their neighbours to reduce latency. Latency could also be reduced by having shorter time slots. Shorter time slots mean nodes switch between sleep and wake is very frequent. This could increase the number of collisions or packets dropped if the receiving nodes switches to sleep before packets reach their destination or acknowledge do not return to transmitting hence the communication is considered a failure. The time slot has an impact on the time and energy efficiency of the duty cycle. Shorter time slot means the frequent switches, and that affects the overhead in the operations such as for opening or closing the radio connections. Longer time slot also means there will be longer times to connect with neighboring nodes and connection duration also lasts longer. Following [305], the delay in packet delivery may be described as follows

1. Send Time: It is the time needed to assemble the data packet and issue a send request to the MAC layer. The send time is dependent on the overhead of the Operating

system used and the processor load. It is highly non-deterministic and could be as high as hundreds or milliseconds.

2. Access Time: It is the delay incurred waiting for access to the transmitting channel to the time transmission begins. It is the least deterministic parameter in the MAC layer
3. Transmission Time: It is the time taken for the sender to transmit messages. It is dependant on the length of the message frame and the speed of the radio. It is usually in tens of milliseconds.
4. Propagation time: It is the time for a transmitted message to reach the receiver once it leaves the sender station. It is dependent on the distance between sender and receiver and is less than than one millisecond for distances less than 300meters.
5. Reception Time: It is the time for the receiver to receive a message.
6. Receive time: It is the time to process the incoming message and to notify the receiver application.

The data obtained from the Weija were observed to have an average delay of 3.22 minutes. This delay may be attributed to the distance between the sensor nodes and the base station which is approximately 1500 meters. Other factors that may contribute to the delay include the send time, access time, and transmission time. Based on the results obtained, the average delay may be attributed to the send time which is nondeterministic and the propagation time which is dependent on distance. A typical example is of delay found in data received is shown in Tables 6.9 and 6.10.

Table 6. 9 Daily Sensor Readings from pH and Calcium

| pH Sensor | | |
|---|---|---|
| **Reading Date** | **Reading Time** | **Value** |
| 2018-11-01 | 00:22:31 | 9.736 |
| 2018-11-01 | 00:54:27 | 9.648 |
| 2018-11-01 | 01:27:04 | 9.555 |
| 2018-11-01 | 01:59:38 | 9.599 |
| 2018-11-01 | 02:31:28 | 10.026 |
| 2018-11-01 | 03:04:205 | 9.968 |
| 2018-11-01 | 03:36:59 | 9.937 |
| 2018-11-01 | 04:09:10 | 9.862 |
| 2018-11-01 | 04:41:53 | 9.775 |
| 2018-11-01 | 05:14:29 | 9.778 |
| 2018-11-01 | 05:46:45 | 9.755 |
| 2018-11-01 | 06:18:53 | 9.712 |
| 2018-11-01 | 06:51:05 | 9.654 |
| 2018-11-01 | 07:23:40 | 9.517 |
| 2018-11-01 | 07:56:15 | 9.487 |
| 2018-11-01 | 08:28:42 | 9.256 |
| 2018-11-01 | 09:01:14 | 9.392 |
| 2018-11-01 | 09:33:45 | 9.696 |
| 2018-11-01 | 10:06:40 | 10.101 |
| 2018-11-01 | 10:39:38 | 10.222 |
| 2018-11-01 | 11:12:03 | 10.476 |
| 2018-11-01 | 11:44:50 | 10.394 |

| Calcium Sensor | | |
|---|---|---|
| **Reading Date** | **Reading Time** | **Value** |
| 2018-11-05 | 00:12:38 | 1.903 |
| 2018-11-05 | 00:45:05 | 1.954 |
| 2018-11-05 | 01:17:41 | 1.939 |
| 2018-11-05 | 01:50:09 | 1.916 |
| 2018-11-05 | 02:22:41 | 1.863 |
| 2018-11-05 | 02:55:27 | 1.986 |
| 2018-11-05 | 03:28:33 | 1.992 |
| 2018-11-05 | 04:01:29 | 2.02 |
| 2018-11-05 | 04:34:16 | 1.774 |
| 2018-11-05 | 05:06:46 | 2.115 |
| 2018-11-05 | 05:39:13 | 2.056 |
| 2018-11-05 | 06:11:48 | 2.102 |
| 2018-11-05 | 06:44:14 | 2.074 |
| 2018-11-05 | 07:16:58 | 2.113 |
| 2018-11-05 | 07:49:32 | 2.009 |
| 2018-11-05 | 08:21:59 | 1.788 |
| 2018-11-05 | 08:54:34 | 1.899 |
| 2018-11-05 | 09:27:14 | 1.635 |
| 2018-11-05 | 09:59:25 | 1.391 |
| 2018-11-05 | 10:31:49 | 1.382 |
| 2018-11-05 | 11:04:04 | 1.132 |
| 2018-11-05 | 11:36:31 | 1.255 |

| | | |
|---|---|---|
| 2018-11-01 | 12:17:28 | 10.609 |
| 2018-11-01 | 12:49:51 | 10.578 |
| 2018-11-01 | 13:33:56 | 10.919 |
| 2018-11-01 | 14:06:11 | 10.914 |
| 2018-11-01 | 14:38:27 | 10.038 |
| 2018-11-01 | 15:10:50 | 11.054 |
| 2018-11-01 | 15:43:21 | 10.886 |
| 2018-11-01 | 16:16:19 | 10.947 |
| 2018-11-01 | 16:48:56 | 10.414 |
| 2018-11-01 | 17:21:26 | 9.856 |
| 2018-11-01 | 17:53:50 | 9.629 |
| 2018-11-01 | 18:26:13 | 9.808 |
| 2018-11-01 | 18:58:32 | 9.897 |
| 2018-11-01 | 19:30:55 | 9.905 |
| 2018-11-01 | 20:03:18 | 9.741 |
| 2018-11-01 | 20:35:44 | 10.412 |
| 2018-11-01 | 21:08:12 | 9.812 |
| 2018-11-01 | 21:40:40 | 10.126 |
| 2018-11-01 | 22:13:03 | 10.263 |
| 2018-11-01 | 22:45:20 | 10.175 |
| 2018-11-01 | 23:17:43 | 10.068 |
| 2018-11-01 | 23:50:02 | 10.055 |

| | | |
|---|---|---|
| 2018-11-05 | 12:08:58 | 1.239 |
| 2018-11-05 | 12:41:25 | 1.347 |
| 2018-11-05 | 13:13:53 | 1.448 |
| 2018-11-05 | 13:46:13 | 1.497 |
| 2018-11-05 | 14:18:37 | 1.579 |
| 2018-11-05 | 14:50:45 | 1.569 |
| 2018-11-05 | 15:23:23 | 1.675 |
| 2018-11-05 | 15:55:56 | 1.862 |
| 2018-11-05 | 16:28:38 | 1.998 |
| 2018-11-05 | 17:01:25 | 2.199 |
| 2018-11-05 | 17:33:36 | 2.286 |
| 2018-11-05 | 18:05:30 | 2.18 |
| 2018-11-05 | 18:37:53 | 2.151 |
| 2018-11-05 | 19:10:49 | 2.381 |
| 2018-11-05 | 19:43:26 | 2.292 |
| 2018-11-05 | 20:16:01 | 2.222 |
| 2018-11-05 | 20:48:21 | 2.469 |
| 2018-11-05 | 21:20:27 | 2.521 |
| 2018-11-05 | 21:52:56 | 2.317 |
| 2018-11-05 | 22:25:29 | 2.085 |
| 2018-11-05 | 22:57:54 | 2.266 |
| 2018-11-05 | 23:30:32 | 2.268 |

Table 6. 10 Daily Sensor Readings from Conductivity and Fluoride

| Conductivity Sensor | | |
|---|---|---|
| **Reading Date** | **Reading Time** | **Value** |
| 2018-11-01 | 00:23:26 | 138.685 |
| 2018-11-01 | 00:55:15 | 137.456 |
| 2018-11-01 | 01:27:53 | 137.9 |
| 2018-11-01 | 02:00:08 | 137.554 |
| 2018-11-01 | 02:32:42 | 135.042 |
| 2018-11-01 | 03:05:32 | 125.454 |
| 2018-11-01 | 03:37:47 | 162.083 |
| 2018-11-01 | 04:10:33 | 158.954 |
| 2018-11-01 | 04:42:43 | 155.646 |
| 2018-11-01 | 06:19:41 | 155.86 |
| 2018-11-01 | 06:52:02 | 156.142 |
| 2018-11-01 | 07:24:27 | 155.523 |
| 2018-11-01 | 07:56:46 | 155.45 |
| 2018-11-01 | 08:29:45 | 156.008 |
| 2018-11-01 | 09:02:09 | 165.416 |
| 2018-11-01 | 09:35:13 | 162.295 |
| 2018-11-01 | 10:07:37 | 157.414 |
| 2018-11-01 | 10:40:10 | 170.381 |
| 2018-11-01 | 11:12:57 | 150.475 |
| 2018-11-01 | 11:45:43 | 161.256 |
| 2018-11-01 | 12:18:19 | 143.815 |

| Flouride Sensor | | |
|---|---|---|
| **Reading Date** | **Reading Time** | **Value** |
| 2018-11-01 | 00:14:47 | 0.11 |
| 2018-11-01 | 00:47:23 | 0.111 |
| 2018-11-01 | 01:19:52 | 0.109 |
| 2018-11-01 | 01:52:23 | 0.116 |
| 2018-11-01 | 02:24:46 | 0.121 |
| 2018-11-01 | 02:57:12 | 0.122 |
| 2018-11-01 | 03:29:41 | 0.126 |
| 2018-11-01 | 04:02:14 | 0.128 |
| 2018-11-01 | 04:34:28 | 0.122 |
| 2018-11-01 | 05:06:57 | 0.12 |
| 2018-11-01 | 05:39:31 | 0.115 |
| 2018-11-01 | 06:12:31 | 0.116 |
| 2018-11-01 | 06:44:37 | 0.116 |
| 2018-11-01 | 07:16:52 | 0.122 |
| 2018-11-01 | 07:49:40 | 0.133 |
| 2018-11-01 | 08:22:32 | 0.128 |
| 2018-11-01 | 08:54:41 | 0.132 |
| 2018-11-01 | 09:27:13 | 0.217 |
| 2018-11-01 | 09:59:38 | 0.168 |
| 2018-11-01 | 10:31:48 | 0.162 |
| 2018-11-01 | 11:04:46 | 0.161 |

| | | |
|---|---|---|
| 2018-11-01 | 12:50:21 | 165.877 |
| 2018-11-01 | 13:34:28 | 167.42 |
| 2018-11-01 | 14:06:56 | 168.423 |
| 2018-11-01 | 14:39:10 | 167.831 |
| 2018-11-01 | 15:11:40 | 149.452 |
| 2018-11-01 | 15:44:20 | 143.743 |
| 2018-11-01 | 16:17:10 | 157.998 |
| 2018-11-01 | 16:49:49 | 152.901 |
| 2018-11-01 | 17:22:12 | 158.549 |
| 2018-11-01 | 17:54:37 | 160.371 |
| 2018-11-01 | 18:27:01 | 159.725 |
| 2018-11-01 | 18:59:17 | 159.617 |
| 2018-11-01 | 19:31:45 | 159.894 |
| 2018-11-01 | 20:04:07 | 160.21 |
| 2018-11-01 | 20:36:35 | 161.003 |
| 2018-11-01 | 21:09:06 | 160.726 |
| 2018-11-01 | 21:41:24 | 160.577 |
| 2018-11-01 | 22:13:49 | 159.368 |
| 2018-11-01 | 22:46:10 | 157.831 |
| 2018-11-01 | 23:18:29 | 157.399 |
| 2018-11-01 | 23:50:54 | 157.101 |

| | | |
|---|---|---|
| 2018-11-01 | 11:37:11 | 0.177 |
| 2018-11-01 | 12:09:43 | 0.192 |
| 2018-11-01 | 12:42:11 | 0.208 |
| 2018-11-01 | 13:14:03 | 0.193 |
| 2018-11-01 | 13:46:15 | 0.193 |
| 2018-11-01 | 14:18:21 | 0.169 |
| 2018-11-01 | 14:50:24 | 0.129 |
| 2018-11-01 | 15:22:35 | 0.129 |
| 2018-11-01 | 15:55:06 | 0.117 |
| 2018-11-01 | 16:27:37 | 0.119 |
| 2018-11-01 | 16:59:34 | 0.115 |
| 2018-11-01 | 17:32:02 | 0.109 |
| 2018-11-01 | 18:04:43 | 0.114 |
| 2018-11-01 | 19:09:28 | 0.107 |
| 2018-11-01 | 20:36:35 | 0.102 |
| 2018-11-01 | 19:41:53 | 0.107 |
| 2018-11-01 | 20:14:15 | 0.105 |
| 2018-11-01 | 20:46:54 | 0.095 |
| 2018-11-01 | 21:19:05 | 0.074 |
| 2018-11-01 | 21:51:32 | 0.087 |
| 2018-11-01 | 22:23:34 | 0.099 |
| 2018-11-01 | 22:55:55 | 0.098 |
| 2018-11-01 | 23:28:21 | 0.09 |

Table 6. 11 Readings with anomalies - Conductivity

| Reading Date | Reception Time | Value | Delay |
|---|---|---|---|
| 2018-11-27 | 14:19:51 | 208.801 | N/A |
| 2018-11-27 | 14:19:59 | 208.801 | 00:00:08 |
| 2018-11-27 | 14:52:31 | 203.216 | 00:32:32 |
| 2018-11-14 | 15:48:25 | 188.359 | N/A |
| 2018-11-14 | 16:21:06 | 180.853 | 00:32:41 |
| 2018-11-14 | 16:21:24 | 180.853 | 00:00:18 |
| 2018-11-14 | 16:21:33 | 180.853 | 00:00:09 |
| 2018-11-14 | 16:54:09 | 177.836 | 0:32:36 |
| 2019-01-01 | 00:41:17 | 222.754 | N/A |
| 2019-01-01 | 00:41:26 | 222.754 | 00:00:09 |
| 2019-01-01 | 01:13:52 | 222.553 | 00:32:26 |
| 2019-01-01 | 01:46:06 | 222.495 | 00:32:14 |

In some sections of the data collected, due to the MAC protocol implementation, delays were observed. In Table 6.11, the data obtained from the conductivity sensor on some of the days in November 2018 and the month of January 2019 are recorded indicating the delay time. In some instances, over some seconds, the same data were sent either two or three times since the transmitter did not receive ACK from the base station, it forwarded the data value again after some seconds. For example, from Table 6.11, 180.853 was sent after 18 seconds and 9 seconds respectively due to the propagation delay. In Table 6.12, the packets arrival time of pH values received between 17:53:50 and 23:50:02 is indicated. Packets were received approximately 3 minutes after it was sent.

Table 6. 12 Readings with anomalies - pH

| Reading Date | Reception Time | Value |
|---|---|---|
| 2018-11-01 | 17:53:50 | 9.629 |
| 2018-11-01 | 18:26:13 | 9.808 |
| 2018-11-01 | 18:58:32 | 9.897 |
| 2018-11-01 | 19:30:55 | 9.905 |
| 2018-11-01 | 20:03:18 | 9.741 |
| 2018-11-01 | 20:35:44 | 10.412 |
| 2018-11-01 | 21:08:12 | 9.812 |
| 2018-11-01 | 21:40:40 | 10.126 |
| 2018-11-01 | 22:13:03 | 10.263 |
| 2018-11-01 | 22:45:20 | 10.175 |
| 2018-11-01 | 23:17:43 | 10.068 |
| 2018-11-01 | 23:50:02 | 10.055 |

In [303], a generalized approach was implemented that allowed a node to vary the probability of transmission. Frequent data transmissions are likely to increase the amount of power consumed by each wireless sensor node, therefore, we reduced the number of transmissions to achieve minimum energy consumption by the nodes during the transmission (Tx) and reception (Rx) of data packets. The 4G module selected also supported the sending of SMS and email messages in the form of alerts to stakeholders and allows users to perform HTTP and FTP requests. The 4G module can perform multi-socket connections to TCP/IP and UDP/IP clients which serves as an advantage in the deployment country.

### 6.5.4. Energy

In WSN, a node's communication system consumes more energy compared to sensing and local data processing [279]. Replacing the sensor nodes batteries in the deployment in the river is a difficult task, expensive, and inconvenient. Depleted batteries affect the project's goal of achieving continuous monitoring for months and even years. The internal battery in most cases are unable to meet the energy budget hence, in WSN for environmental applications such as WQM; the energy budget may be improved by designing algorithms and protocols that are capable of regulating and reducing the amount of energy consumed and the frequency of data transmission when the measured parameter is transmitted to the cloud. Also, the energy budget may be compensated by harvesting energy from ambient sources to extend the lifetime of the battery during its operation. In the application domain, the possible ways to harvest energy to recharge the sensor nodes include harvesting energy from the flowing river (i.e., kinetic energy), radio frequency (RF) sources (i.e., from sun flares, lightning, stars in space, electromagnetic waves), and harvesting energy from the sun using either internal or external solar panels. Apart from solar energy, all the other forms of energy harvesting are challenging to implement.

To efficiently maximise the use of energy in the sensor node, it is important to consider the energy costs per the different modules of the sensor nodes and the different algorithms and protocols that run on the nodes. Some of the sources of energy consumption include sensor node sleep/wake up scheduling, data sensing, signal-to-electrical conversion, signal conditioning e.t.c.

Duty cycle which is the scheduling of the sleep/wake up modes of the sensor node also contributes to energy consumption. In the sleep mode, all operations of the sensor node are shut down and resume when the node is awake. The power consumption of the nodes increases when there is a frequent switch between the sleep and wake up states. In the event of collisions or subsequent failed attempt to transmit which results in no acknowledgement received, the traffic control signals transmitted increases thereby increasing the energy consumed.

Energy harvesting provides a means of replenishing the energy supply in Energy Harvesting sensor networks. The energy harvested could either be used directly by the sensor nodes or stored in rechargeable batteries [5]. Sources of energy harvesting in sensor networks include solar, vibration, thermal, wind, the current of water waves, e.t.c [5]. The amount of energy harvested in solar powered wireless sensor networks is proportional to the size of the solar panels and their conversion power. Due to the minute sizes of sensor nodes, and to keep the overall size of the sensor unit within limits, appropriately sized panels are used resulting in small amounts of energy harvested. The transfer of energy from one medium to another results in large energy losses and hence the rate of discharge of energy in a node is usually faster than the rate of charging through harvesting. For efficient use of the energy in these networks, prediction models have been employed to forecast the energy consumption and rate of replenishing in these sensor nodes [306].

Prediction models have been proposed in WSN to forecast the data values of nodes. The predicted values have augmented some WSN operations in conserving energy. In [307], time series prediction model was used to reduce data transmission in WSN and to predict future values of time series data. When predicted values are within some predefined error threshold, nodes do not transmit their data. This reduces data transmission and hence, conserves energy in the network. Other applications of prediction models in WSN for energy conservation are included in [308], [309].

In WSN, the amount of energy depleted during communication could either be energy loss during Transmission (*Tx*) or energy loss for Reception (*Rx*). In a duty cycle, the energy lost in transmitting $l$-bits of data over a distance $d$ is expressed as for example, in [5], the authors pointed out that, energy can be harvested from river flow, but the flow should come with higher pressure (i.e., turbulent) to generate power to charge the sensor nodes. Kinetic energy harvesting in rivers also requires that the sensor nodes be designed to use small turbines that move to generate electricity to charge the batteries directly. Energy harvesting based on temperature gradient becomes a challenging technique to adopt because of variations in weather conditions in the sub-region. Also, at the current deployment site, there are limited sources of RF signals which do not make it an attractive option in the present study. Solar energy has proven to be the most dominant form of energy available and easy to implement at the deployment site. The current smart water sensor nodes designed by Libelium allows users to harvest energy to augment the power stored in the batteries. Hence, we harvest solar energy to compliment to prolong the lifetime of the wireless sensor nodes and the lifetime of the overall sensor network (Figure 6.28).

Figure 6. 28 Externally mounted solar panel for energy harvesting in freshwater

The highest power density a photovoltaic cell can provide on a bright sunny day is $15\text{mW}/cm^2$ [306]. The hardware architecture followed the harvest-store-use energy harvesting architecture presented in [306]. To harvest energy, we mounted the solar panel on the protective case housing the sensor device as shown in Figure 6.28. The Libelium wireless sensor node's energy consumption is compared to other available commercial sensors and as indicated in Table 6.13. Libelium sensors consumes 30mA of energy to transmit and receive data packet compared to IMote2 and SunSpot that require 44mA and 40mA respectively for packet transmission and reception.

Table 6. 13 Commercial Sensor Nodes Energy Consumption Characteristics. [310]

| | **Libelium** | **IMote2** | **SunSpot** | **MicaZ** |
|---|---|---|---|---|
| **Radio Standard** | 4G (GSM)/802.15.4/ZigBee | 802.15.4 | 802.15.4 | 802.15.4/ZigBee |
| **Microcontroller** | Atmel ATmega 1281 | Marvell PXA271 | ARM 920 T | ATMEGA 128 |
| **Sleep** | 30 µA (Sleep)<br>33 µA (Deep sleep)<br>7 µA (Hibernate) | 390 µA | 33 µA | 15 µA |
| **Processing** | 15 mA | 31−53 mA | 104 mA | 8 mA |
| **Transmission** | 30 mA | 44 mA | 40 mA | 19.7 mA |
| **Reception** | 30 mA | 44 mA | 40 mA | 17.4 mA |
| **Idle** | - | - | 24 mA | - |
| **Supply** | 6 − 12 V | 3.2 V | 4.5 − 5.5 V | 2.8mW |

The sources of energy depletion in duty cycling could be attributed to the frequent switches between sleep and wake up states. The frequent switches could introduce more collisions and also the traffic control signals. This happens because when no acknowledgment is received or there are failed attempts to transmit, more packets are resent. The energy consumed when *l*-bits of data is sent over a distance *d* is transmitted is obtained from the Equation 6.1.

$$E_{T_x}{=}E_{T_{x-elec(1)}} + E_{T_{x-amp}(l,d)}$$

$$= l * E_{elec} + l * \varepsilon_f s * d^2 if d < d_0 \tag{6.1}$$

$$= l * E_{elec} + l * \varepsilon_m p * d^4 if d \geq d_0$$

where $E_{elec}$ is the energy dissipated per every bit of data to transmit or receive. while $\varepsilon_f s$ and $\varepsilon_m p$ are the characteristics of the transmitter amplifier, $\varepsilon_{fs}$ for free space and $\varepsilon_{mp}$ is for multipath.

The energy consumed to receive *l*-bits of data is shown in Equation 6.2.

$$E_{R_{x(l)}}{=}E_{Elec} + l \tag{6.2}$$

and the energy threshold value is shown in Equation 6.3

$$d0 = \sqrt{\varepsilon_f s / \varepsilon_m p} \tag{6.3}$$

## 6.6. Deployment Environment

Sensor devices deployed for environmental monitoring are normally deployed in open unsecured areas, it is therefore important to consider a number of factors when deploying these sensors. The deployment site was selected based on the following factors: 1) security of the sensor devices at the deployment area (i.e., away from residents to prevent the devices from tampering or sabotage); 2) river structure (such as spillways, intakes, outlets, reservoirs etc); 3) vegetation in the river (such as plants, shrubs and trees, etc); and 4) activities within the area (such as mining, farming and fishing) [266]. The Weija intake is a restricted zone with security presence to take care site to prevent unauthorised persons from entering the site. Their presence at the intake also prevents illegal activities such as fishing and farming from taking place in and around the intake. The deployment site, therefore, is appropriate for experiments such as this because the safety of the sensor nodes is guaranteed, and the monitoring process is not interrupted throughout the deployment. The Weija intake serves as a significant water source to the Weija treatment plant of the Ghana Water Company Limited (GWCL) which supplies treated water to the people of Greater Accra and parts of Central regions of Ghana. This makes it convenient to install the sensor nodes to monitor the river water quality. Additional sensor nodes may be added when the project is extended. The Weija intake being a restricted zone prevents the operation of fishing and farming activities. Mountains and a large forest zone bound the river feeding into the Weija dam. Figure 6.29 shows the Weija intake showing the positions the sensor devices were placed and Figure 6.30 shows the map of the area of deployment.

Figure 6. 29 Weija Intake

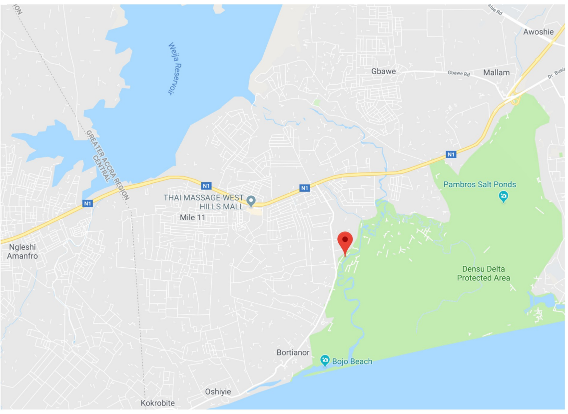


Figure 6. 30 Area Map

From September 30, 2018 till date (experimentation ongoing), smart water sensors and ion sensors have been deployed at the intake to monitor physical and chemical parameter composition in the river body. The pH, electrical conductivity, calcium, fluoride probes and temperature of the sensor devices were programmed to transmit data packets every 30 minutes and the dissolved oxygen and the oxidation reduction potential transmitted data packets every hour. The time interval was set to overcome communication delays and energy consumption issues. The data presented here is for a period of five (5) months from September. When the sensor probes senses and measures a parameter, then the data was transferred to the monitoring center for evaluation. We observed the data in real-time from a web portal. As shown in Table 6.11, there were some anomalies observed in the communication of the data. The research team visited the project site weekly to check and clean fouling and inspect the sensor cables.

### 6.6.1. Bio-fouling

In water quality monitoring applications, the sensors are deployed in the freshwater source for several months and sometimes years due to the application requirements. The length of time the sensors stay immersed in the freshwater sources causes biofouling of the sensors which affects the accuracy and data consistency, analysis, and reporting. Biofouling is the accumulation of unwanted plants, algae, microorganisms and animals exposed on the surface which forms around the sensor node [143]. After some months of deployment of the various sensors, there was data degrading owing to fouling of the wireless sensors (Figures 6.31 and 6.32). The sensor nodes operating lifetime is decreased due to biofouling. Biofouling of the sensor devices generally introduces errors into the measured data values. Conventional methods for removing biofouling as such as wiper mechanisms, copper corrosion mechanisms, and chlorine evolution mechanisms are not suitable for removing fouling of sensors in this environment [5]. These existing techniques are costly and does not easily work for the type of sensors adopted for the monitoring process. From the initial deployment date, trends were observed in the river for variations. We observed the high levels of algae bloom and freshwater weeds which contributed to the fouling of the wireless sensor nodes. The sensors were cleaned using a white *kalico cloth* and freshwater monthly in the absence of antifouling guards and housing to prevent biofouling to prevent further degradation in the measured data quality and data accuracy.

Figure 6. 31Biofouling (fuoride and calcium sensors)

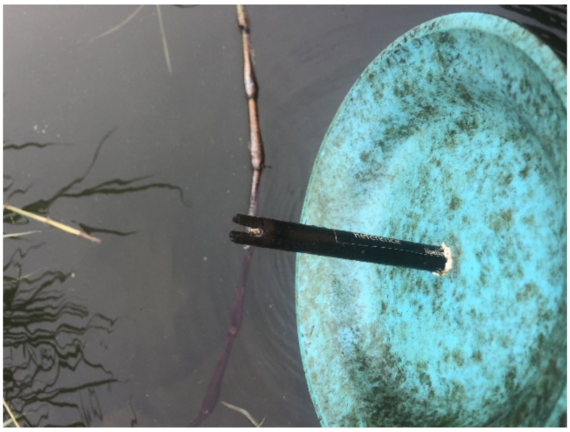


Figure 6. 32 Biofouled of DO Sensor

### 6.6.2. Sensor Cable Damage

In the experiment, the cable themselves were left unprotected whilst the sensor devices were placed in a protective case. The sensor probes were placed directly into the river. An unusual data was received from the second temperature sensor on January 04, 2019. The readings received on that day was 11.765°C at 04:05:07. Then on January 07, 2019 at 16:45:08 GMT, the data read from the pH sensor was 5.525 and that same day at 17:17:28 GMT a pH value of -1.993 was received. A site visits the following day showed that the sensor cables had been damaged (snipped, possibly by a wild fish or an alligator as shown in Figures 6.33 and 6.34

Figure 6. 33 Sensor Cables Damage

Figure 6. 34 Snipped Cable

## 6.7. Experimental Results

Water quality assessment is important in every nation; hence, it is one area of the environment that government spends much resources to get proper assessment and evaluation performed. Typically, water quality assessment is performed to address water quality needs that comes with potential risk to citizens. Also, water quality monitoring is performed to collect huge amount of water quality data for scientific analysis by the research community so that efficient models can be developed for trend analysis. Water quality assessment or monitoring is also performed to ascertain the impact of the water characteristics on animal and plant health. The types of data collected in water management system include but not limited to geographical and space-oriented data (e.g., location information using geographical information systems (GIS) or global positioning system (GPS)), time-oriented and historic data (e.g., water quality data), and relation-oriented data (i.e., information for trend analysis and reporting) [266].

During the period of deployment, the data collected were observed over time. We noticed several challenges during the data collection and transfer phase: 1) equipment malfunctioning; 2) damage of water quality sensor probes; 3) untimely recharge of internet data by service provider; interruptions in data transmission and 4) data-value out-of-range. The challenges encountered in the data collection and transfer phase required researchers to perform data validation and reliability analysis. Data validation was performed to ascertain the quality and reliability of the data since errors will affects stakeholders' decision and planning. Gaps and inconsistencies were observed in some of the values reported by some of the sensor probes.

Table 6. 14 Summary of Data Collection from September 30, 2018 to February 13, 2019

| Sensor Probe | Template Number | Number of Readings | Average Reading | Standard Deviation |
|---|---|---|---|---|
| **Calcium Ion (Ca2+) Sensor** | 1 | 3266 | 3.13 | 0.455 |
| **Fluoride Ion (F-) Sensor** | 1 | 3239 | 0.12 | 0.0093 |
| **Conductivity Sensor** | 2 | 4302 | 186.11 | 70.106 |
| **pH Sensor** | 2 | 4294 | 9.86 | 5.19 |
| **Oxidation Reduction Potential** | 5 | 431 | 0.098 | 0.035 |
| **Dissolved Oxygen Sensor** | 5 | 432 | 17.36 | 30.439 |
| **Temperature Sensor One** | 1 | 3251 | 30.91 | 1.258 |
| **Temperature Sensor Two** | 4 | 17 | 25.87 | 10.124 |
| **Temperature Sensor Five** | 5 | 433 | 31.65 | 1.549 |

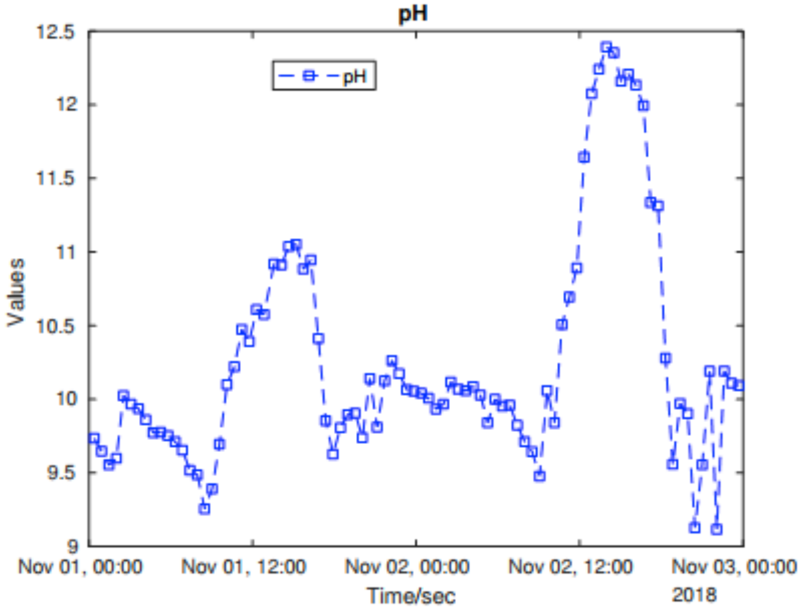


Figure 6. 35 pH from Nov. 1-3, 2018

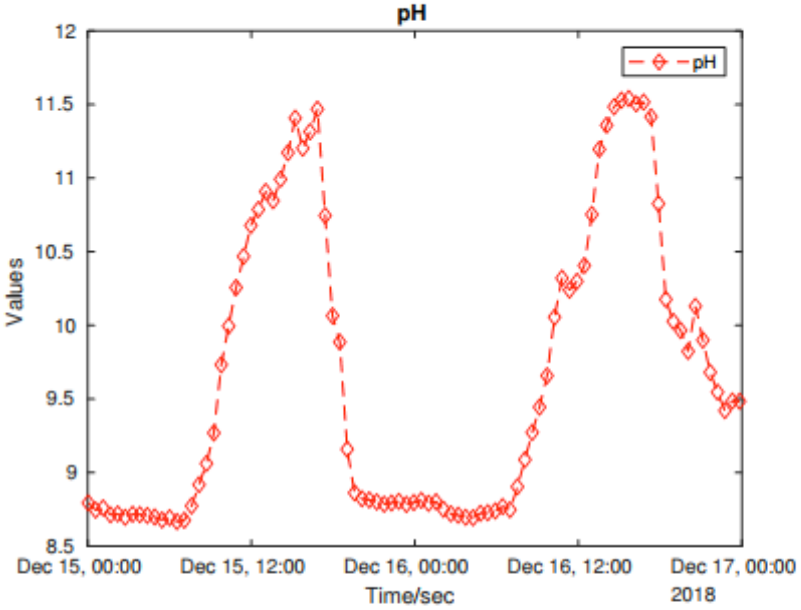


Figure 6. 36 pH from Dec. 15-17, 2018

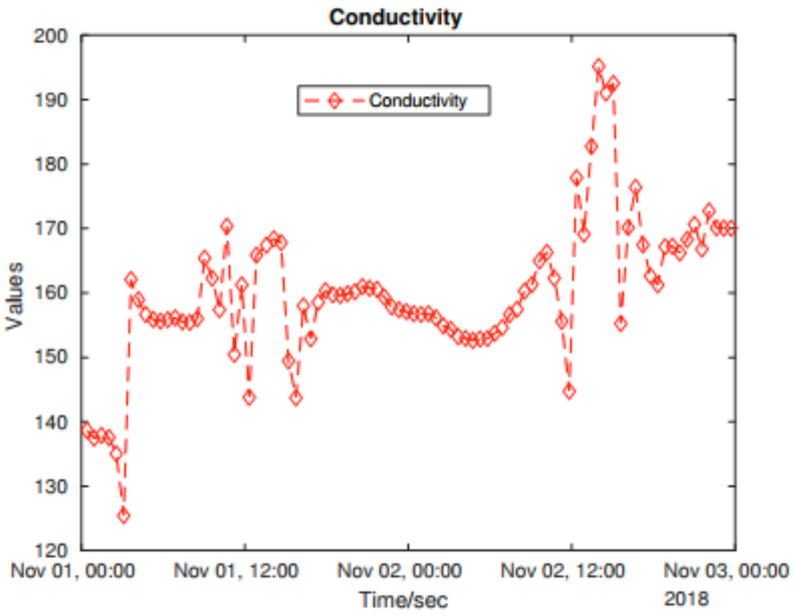


Figure 6. 37 Conductivity from Nov. 1-3, 2018

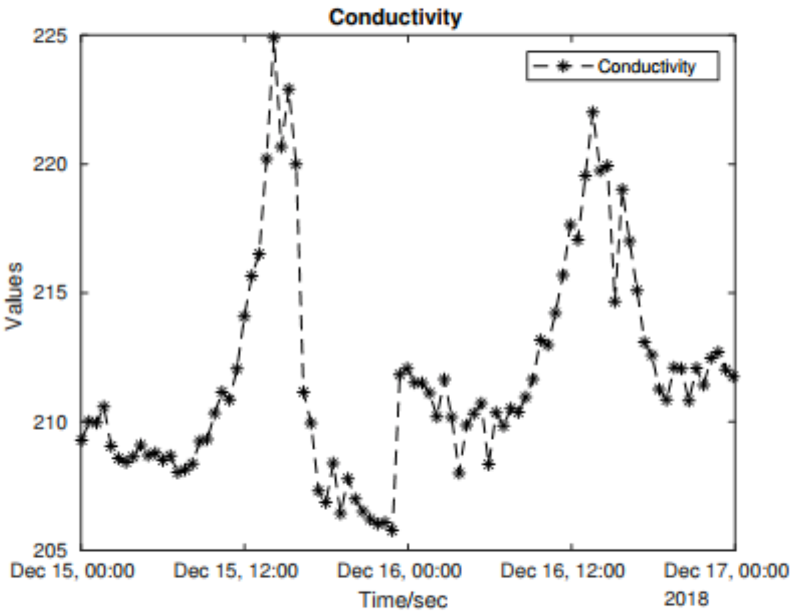


Figure 6. 38 Conductivity from Dec. 15-17, 2018

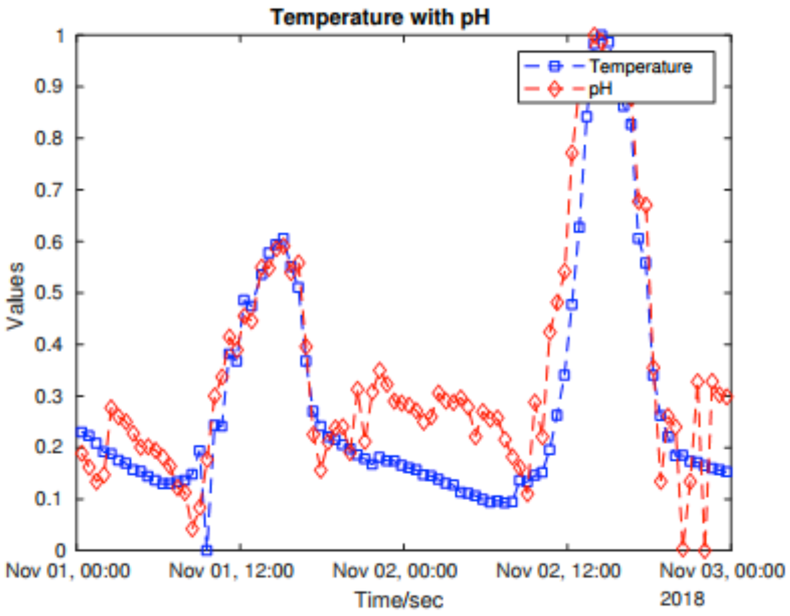


Figure 6. 39 Temp. vs pH (Nov. 1-3, 2018)

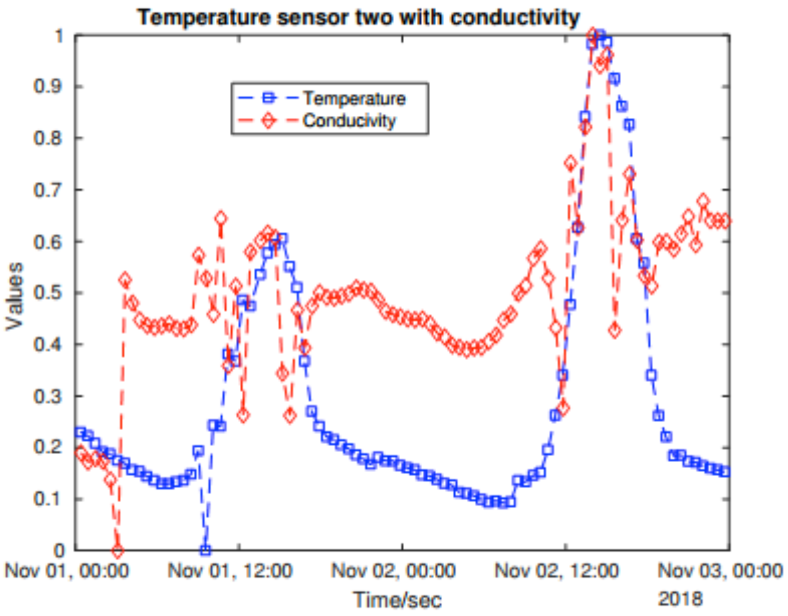


Figure 6. 40 Temp. vs EC (Nov. 1-3, 2018)

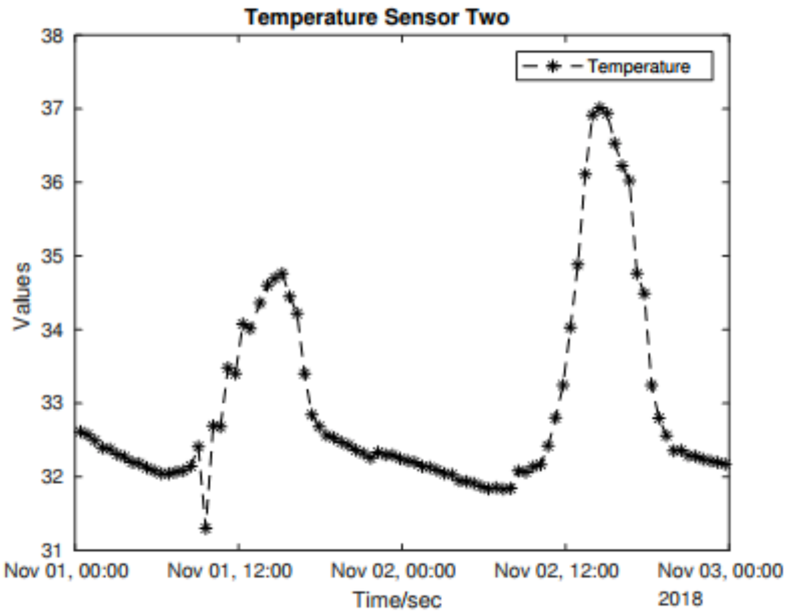


Figure 6. 41 Temperature from Nov. 06-08, 2018

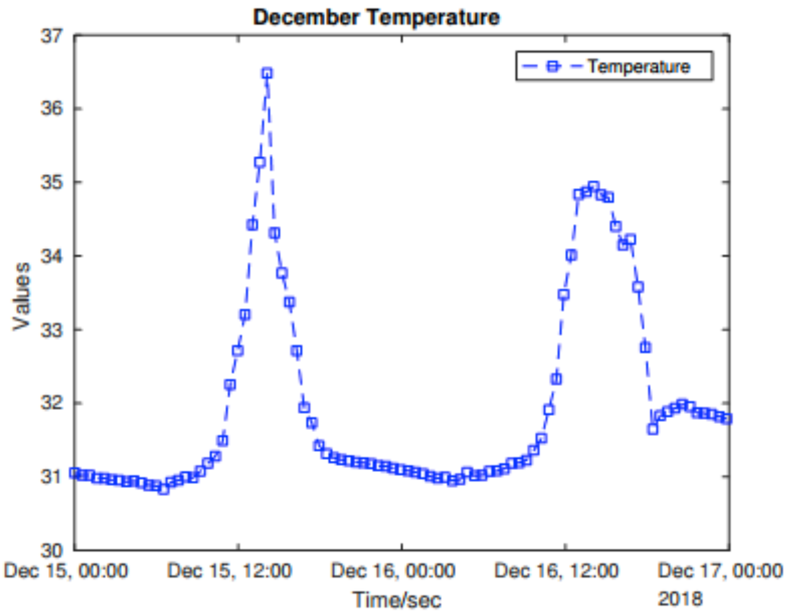


Figure 6. 42 Temperature from Dec. 15-17, 2018

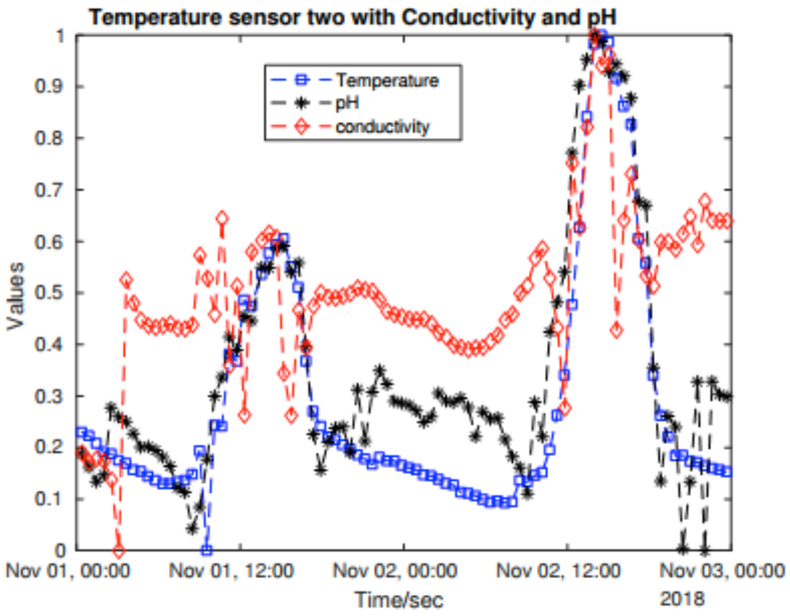


Figure 6. 43 Temp. vs pH and EC (Nov. 1-3, 2018)

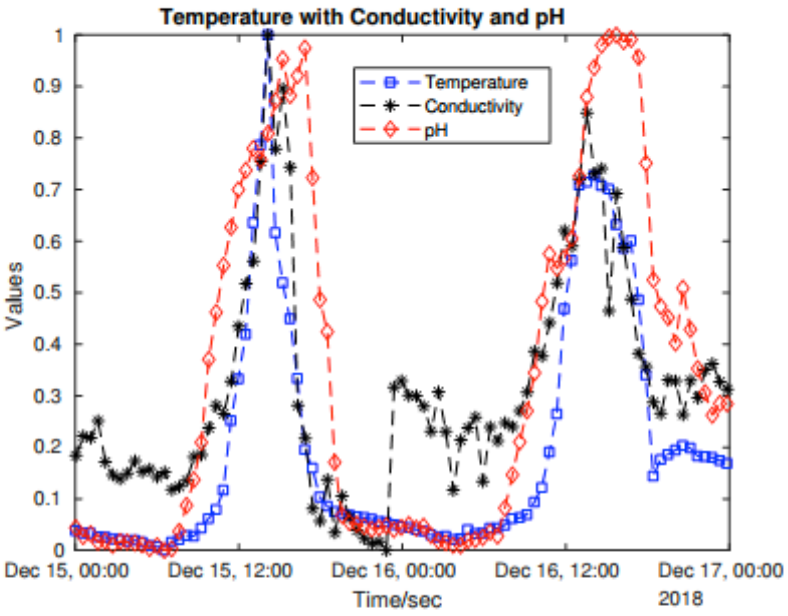


Figure 6. 44 Temp. vs pH and EC (Dec. 6-8, 2018)

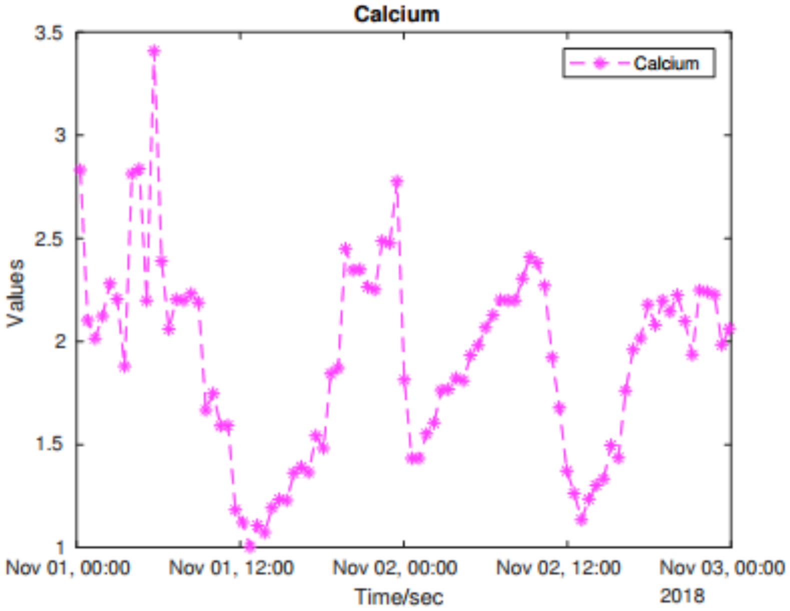


Figure 6. 45 Calcium, (Nov. 1-3, 2018)

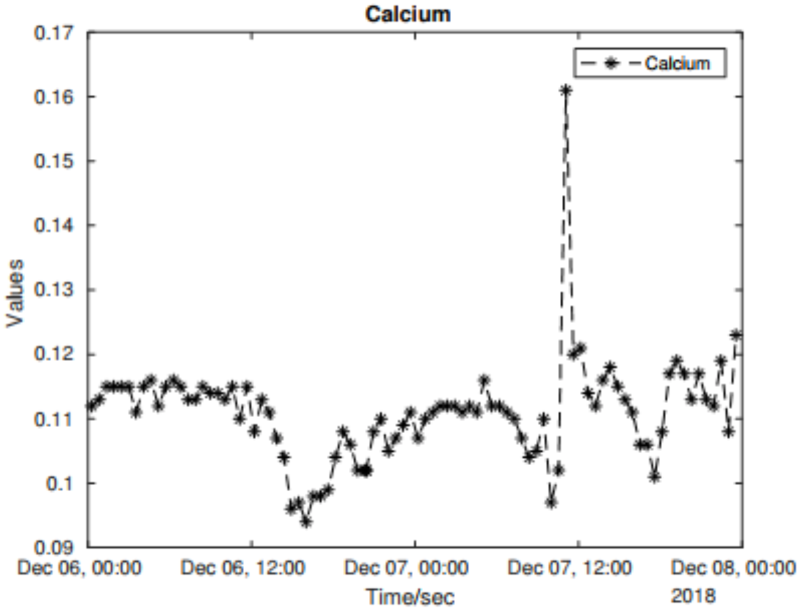
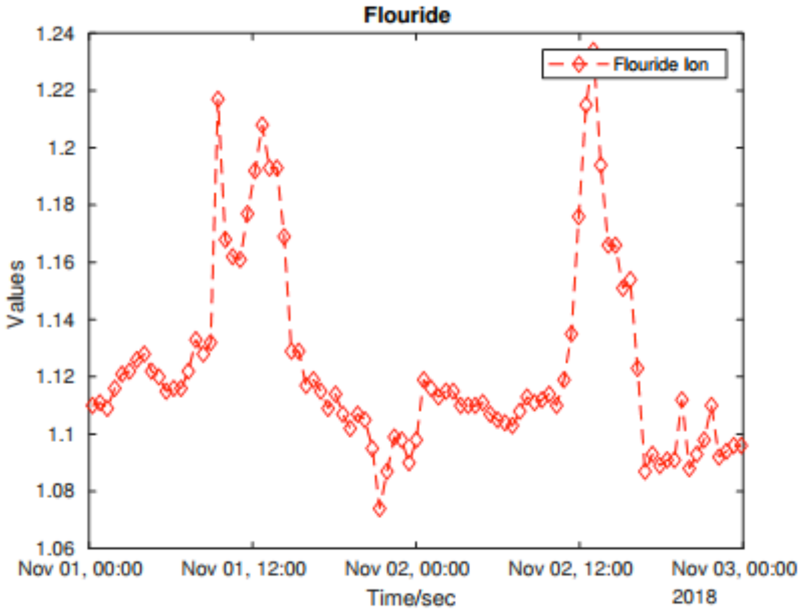


Figure 6. 46 Calcium, Dec. 6-8, 2018



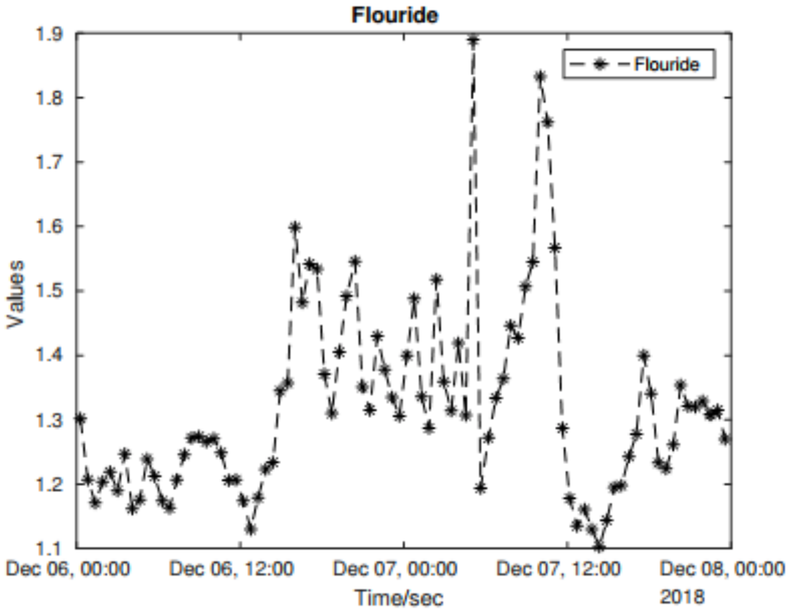


Figure 6. 47 Flouride, Nov. 1-3, 2018

Figure 6. 48 Flouride, Dec. 6-8, 2018

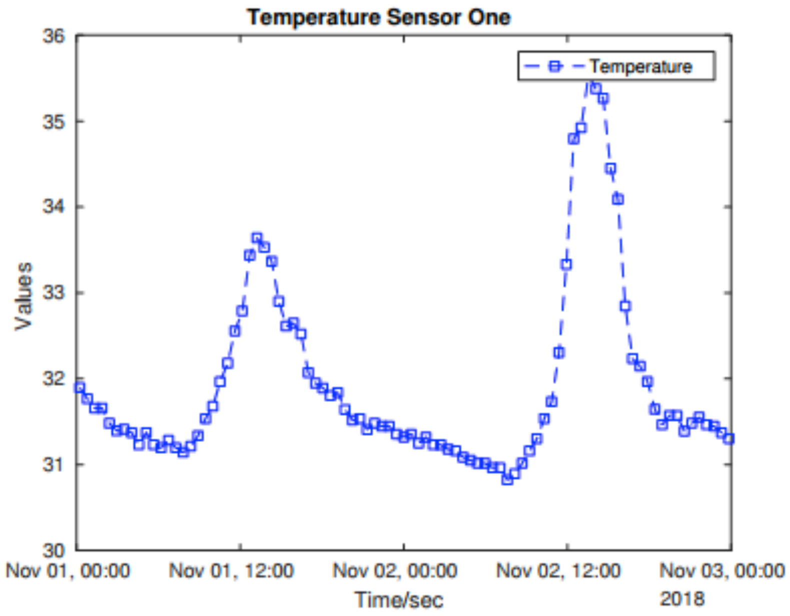


Figure 6. 49 Temp. Nov.1-3, 2018

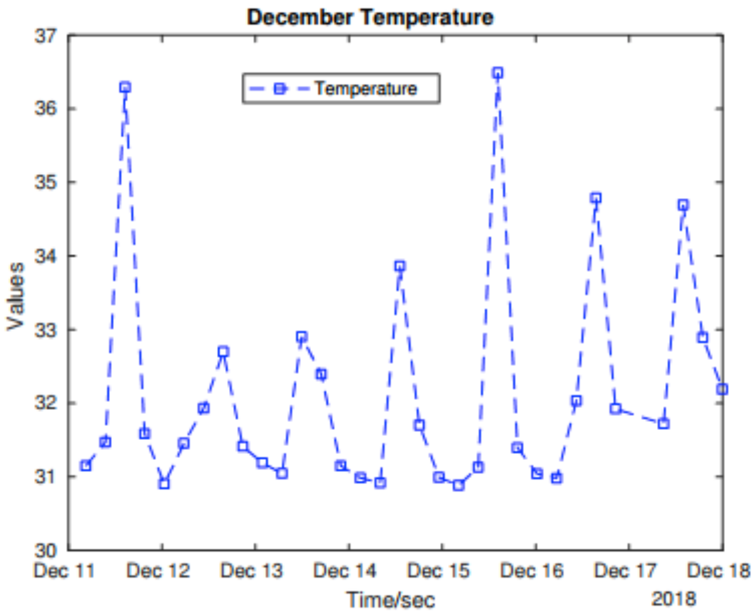


Figure 6. 50 Temp. Dec. 11-18, 2018

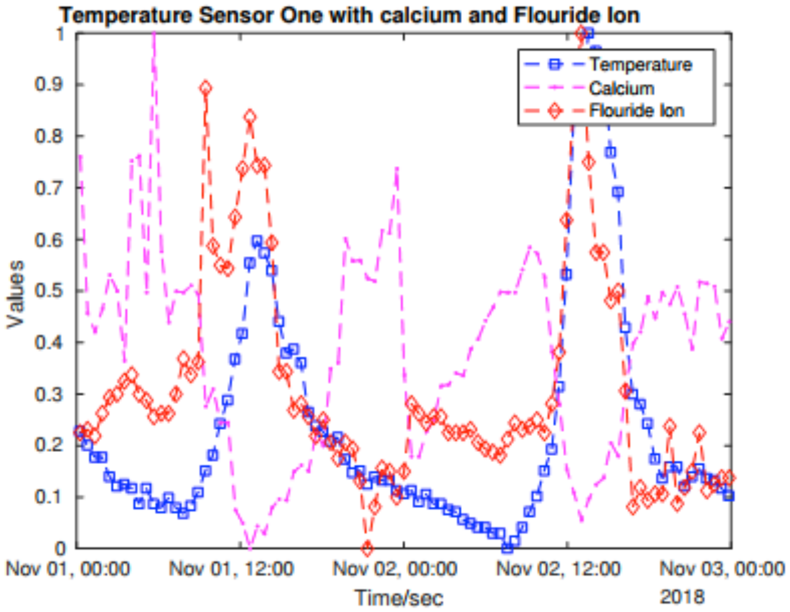


Figure 6. 51 Temp. vs Cal. and Flouride, Nov. 1-3

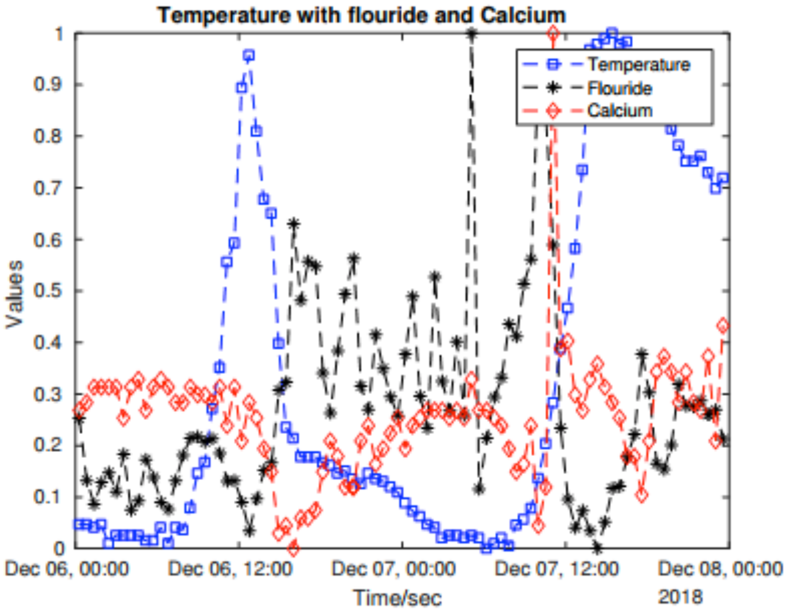


Figure 6. 52 Temp. vs Cal. and Flouride, Dec. 6-8

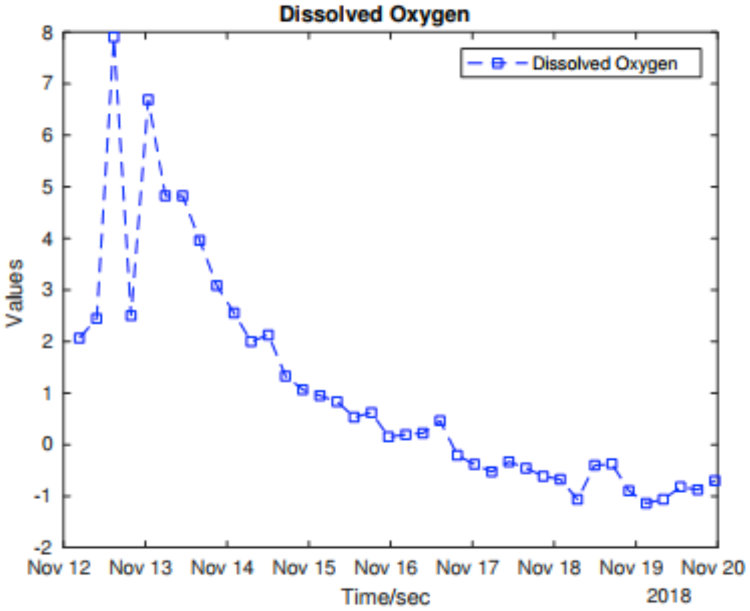


Figure 6. 53 DO, Nov. 12-20

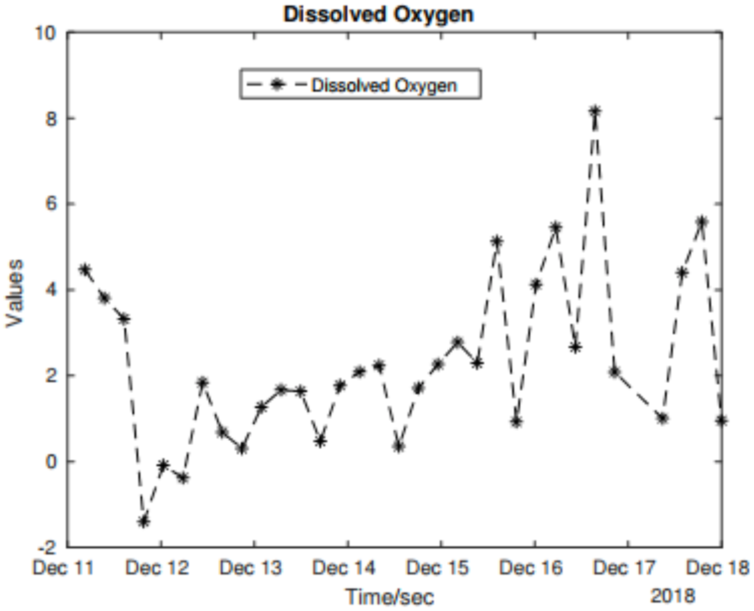


Figure 6. 54 DO, Dec. 11-18

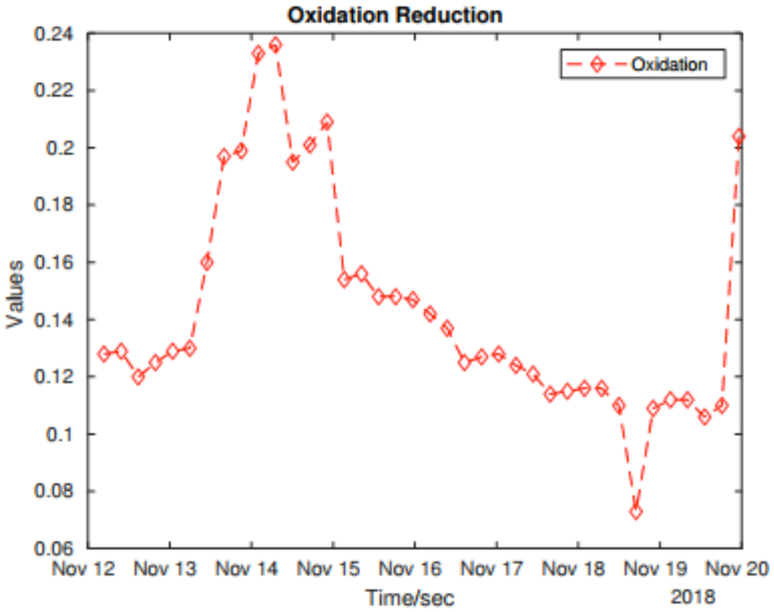


Figure 6. 55 ORP, Nov. 12-20

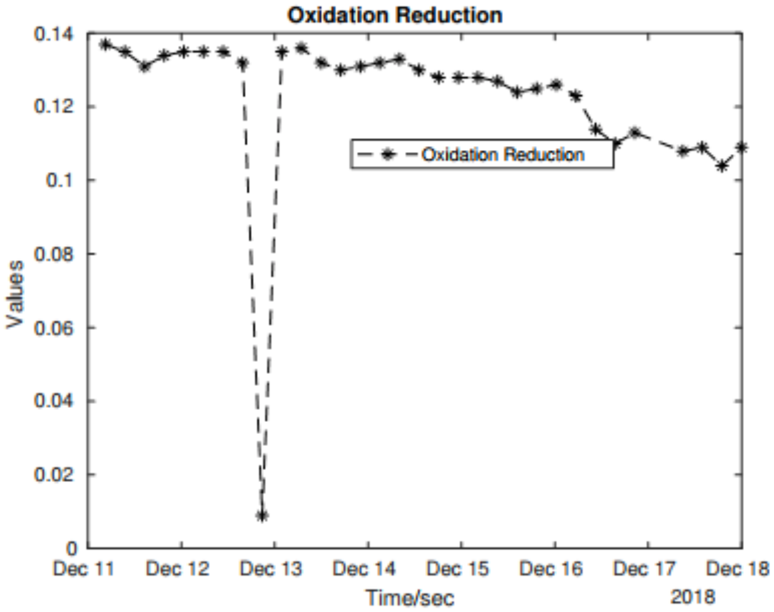


Figure 6. 56 ORP, Dec. 11-18

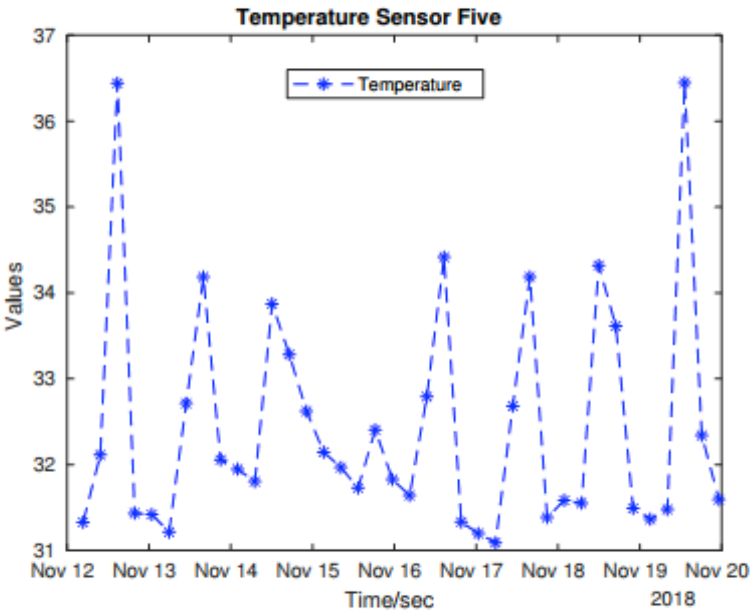


Figure 6. 57 Temp5, Nov. 12-20

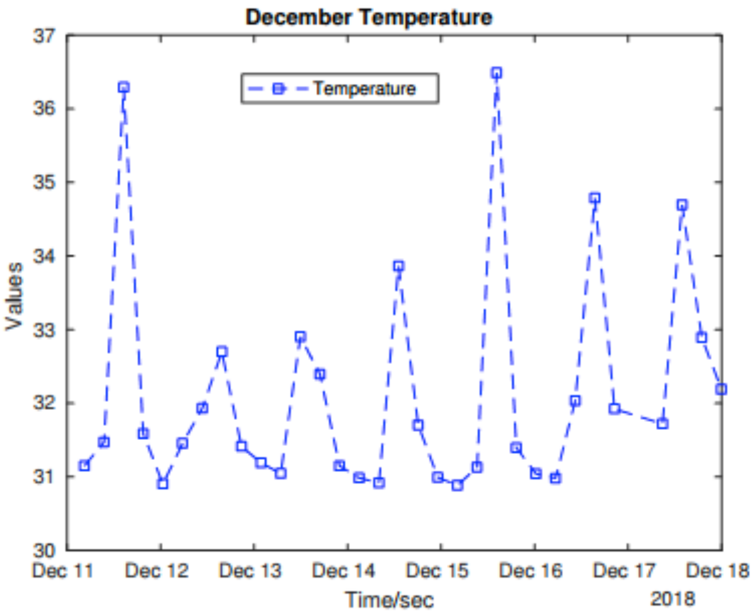


Figure 6. 58 Temp5, Dec. 11-18

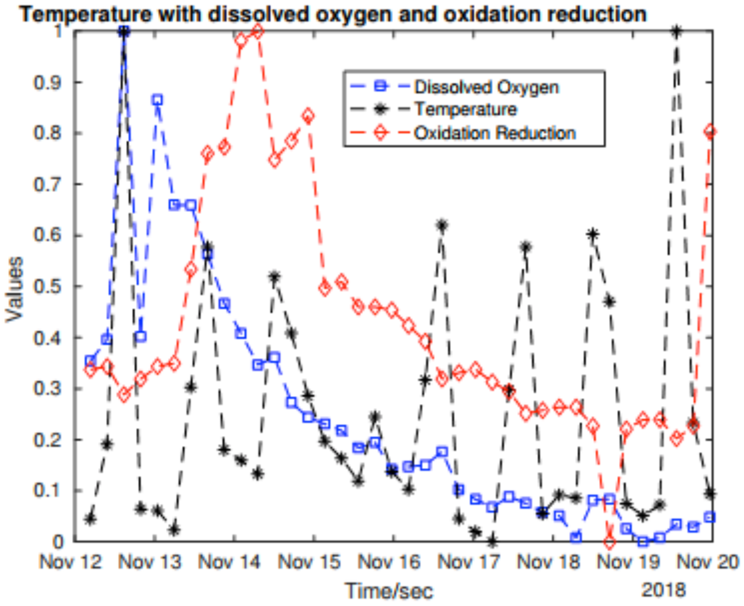


Figure 6. 59 Temp, DO, ORP Nov. 12-20

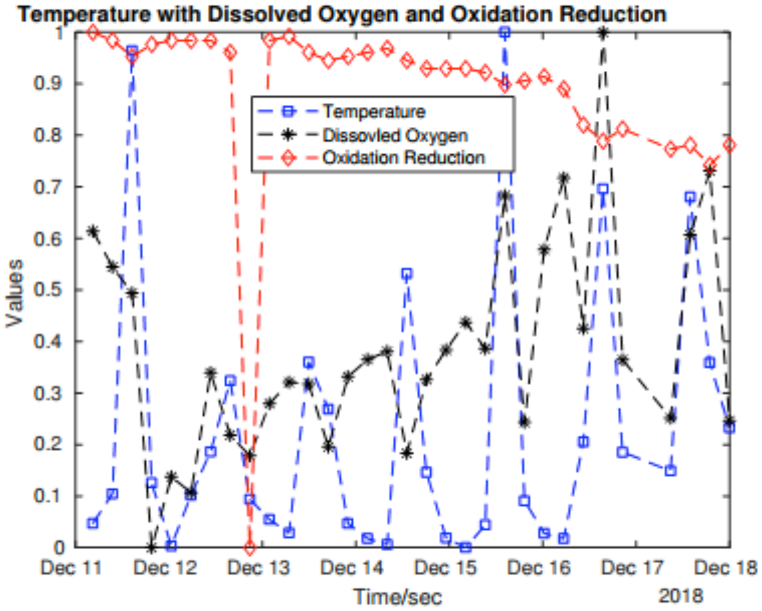


Figure 6. 60 Temp, DO, ORP, Dec. 11-18

## 6.8. Discussions

In this section, discussions and conclusions are provided. Figures 6.35 to 6.36 show the graphs obtained from the sensor readings for some of the days within the period of deployment. Although the deployment area is a reserved area and activities such as fishing and farming were restricted, some fishing activities were illegally seen at certain times on the river. These fishermen used the freshwater weeds to trap fishes and after their operation, they leave the weeds to float down stream (see Figure 6.61) and this causes an increase in algae bloom (see Figure 6.62).

Figure 6. 61 Weeds cover sections of river

Figure 6. 62 HABs in river

The weeds cover sections of the river resulting in habitat alteration and depletion of oxygen in the river as noted in [311] and results shown in Figure 6.53 seem to confirm this. Apart from freshwater weeds, the presence of harmful algal blooms (HABs) was detected after a month of deployed especially when the dry season period was ushering in from 16th November 2018 to 28th January 2019 (Figure 6.64). Between the two-months period, we observed that the oxygen content was low due to the presence of HABs and freshwater weeds.

This had a serious effect on aquatic life (see Figures 6.63 and 6.64). HABs domination over a long period of time was also due to the activities happening upstream. Farming activities along the river stretch also saw the presence of pesticides and other harmful chemicals detrimental to aquatic life flow gradually into the river. The results obtained from this study indicate how WSNs may be used to predict activities happening upstream enabling stakeholders to use these data to develop and design strategies and come out with environmental management programs and other interventions for the community, region, and the nation as a whole for individuals to exert positive attitudes towards our freshwater resources.

Figure 6. 63 Dead fishes in river

Figure 6. 64 Dead fish in river

The results presented are based on data obtained from three Waspmote sensor devices attached to template 1, template 2, and template 5 as shown in Table 6.5. The probes remained in the river body till date. Live data values are presented at the following web portal: (51.38.128.131/libelium/public/index.php/login).

pH may be defined as the logarithmic concentration of hydrogen (H+) and hydroxide (OH-) ions of a substance constituting H+ + OH- = H20. The pH values obtained ranged between 6.75 to 14 as can be observed from the graphs shown in Figure 6.36. It shows the variations in pH in the river at different times of the day. The pH values recorded above the pH value of 7 indicates that the Weija intake is more basic or alkaline in nature and therefore supports aquatic animals much better.

The level of alkalinity of a river may be attributed to the location of the river as well as activities happening upstream. Other atmospheric factors contributed to the increase of pH over time especially in the month of November 2018. Electrical conductivity is the ability of a medium to carry electrical energy. The electrical conductivity of water is directly proportional to the amount of salt ions in the water. The temperature of the river, the geology of the area, climatic changes (e.g., from rainy to sunny seasons) and pollution from human waste or some industrial activities affects the conductivity levels in freshwater bodies.

Conductivity values ranging from 0 to 200µS/cm is considered as low conductivity. Conductivity values ranging from 200 to 1000µS/cm is considered within the mid-range of conductivity levels and values ranging between 1000 to 10000µS/cm is considered as high conductivity values. The higher the river's temperature, the higher the conductivity value. The conductivity sensors were calibrated at a room temperature of $30^{\circ}$C. Aquatic animals who live in freshwater sources do not require high levels of conductivity. High levels of conductivity indicated in Figure 6.37 in November and December may also have led to the death of some aquatic animal such as fishes as shown in Figure 6.63. Figure 6.57 shows that the temperature of the river rose up to $37^{\circ}$C. These rises in temperatures was a result of the high levels of algae bloom in the river around that period and that may be the possible cause of conductivity levels rising to 225µS/cm in the month of December 2018 as shown in Figure 6.38. In Figures 6.43 and 6.44, show normalised temperature, pH and EC readings during the months of November and December 2018. Although, several factors affect the increasing and decreasing levels of electrical conductivity levels in river bodies.

A study conducted by [312], revealed that rivers undergo self-purification which may result in the reduction of pollutants in the river during certain times of the day. Therefore, we observed that some points in the month of December 2018, especially 16th December 2018, conductivity levels dropped to 205 S/cm which may be attributed to the self-purification process probably around that time.

The geological structure (such as the type of soil, plantation, weather conditions) at the Weija intake contributed to the presence of calcium in the river [313]. The study showed that calcium levels rose to about 3.5 mg/L in the month of November 2018 and dropped to about 0.16 mg/L in December 2018 as shown Figure 6.46. The temperature sensor connected to this Waspmote sensor unit measured temperature of the river up to about 35°C in the month of November 2018 and in December 2018 temperatures rose to about 36°C as shown in Figures 6.49 and 6.50. Fluoride levels measured in November 20118 rose to about 1.24 mg/L and in December 2018 the amount of fluoride in the river rose to about 1.9 mg/L as shown in Figures 6.47 and 6.48. In Figures 6.51 and 6.52, the calcium, fluoride, and temperature readings from November to December 2018 is shown.

The amount of DO in a river determines the number and type of organisms that live in the river [314]. Fish for example depends on the amount of dissolve oxygen in river body. The study revealed high levels of DO content in the river from October to November 13, 2018 (Figure 6.53). These DO levels significantly dropped from November 13 to negative DO values. This was because of the high levels of algae bloom and other grasses that covered the surface of the river rendering less oxygen penetration into the river. This it is believed might have attributed to the death of aquatic species in the river. However, in the month of December, the oxygen content rose up from the negative DO to reach 8 mg/L. Temperatures recorded by the sensor connected to this Waspmote unit indicated that most of the time in the months of November and December 2018, the river was warm recording temperatures between 32 to 37°C (see Figures 6.57 and 6.58). Warmer temperatures decrease the oxygen content in the river. This also affects aquatic life [315]. Figures 6.59 and 6.60 show the ORP graph. The ORP value declined due to the lower amount of oxygen content in the that time of day.

## 6.9. Chapter Summary

In this chapter, a real-time deployment of a wireless sensor network application for collecting water quality measurements was proposed. As a real-time deployment, the project was undertaken for a five-month period, September 2018 up to January 2019. The project used smart sensor nodes from Libleium for measuring the water quality parameters. The implementation provides a sustainable approach that monitors freshwater sources to support citizens in a particular locality where there is no access to clean potable water but rely on lakes, streams, rivers, and boreholes, enabling them to know the characteristics of the water they are drinking. The measured data value is transferred to cloud storage for analysis. We designed a web portal using a set of protocols to process the captured data. Compared to other real-time deployed systems across the world, the solution presented here is secured, uses efficient MAC layer protocol which enhances the transmission and reception time and implements a network layer protocol that takes care of the delay factor in the transmission process. At the network level, we design the setup in such a way that when a parameter is measured, and the communication channel is not available, we perform retransmission until the communication channel is made available. Each of the parameters measured: calcium ion (Ca2+), electrical conductivity, pH, dissolved oxygen, silver (Ag+), fluoride ion (F), nitrate ion (NO3-), oxidation-reduction potential (ORP), and temperature indicated significant fluctuations over time. These changes may be attributed to pollution from upstream which are time varying. We plan to increase the number of sensor nodes taking into account sensor probes such as the turbidity sensor probe since its one of the parameters the stakeholders requested, we measure for them.

# CHAPTER 7

# CONCLUSIONS AND FUTURE DIRECTIONS

## 7.1. Conclusions

In this dissertation, an introduction of a novel routing algorithm based on adjustable transmission range was proposed as a useful approach to reduce the energy consumption in river sensor networks thereby maximising the lifetime of the sensor nodes. Our results showed an improvement in the adjustable transmission range algorithm considering energy consumption during data packet transmission.

The dissertation focused on a real-time deployment of a wireless sensor network application for collecting water quality measurements for a five-month period, September 2018 up to January 2019. The project used smart sensor nodes from Libleium for measuring the water quality parameters. The implementation provides a sustainable approach that monitors freshwater sources to support citizens in a particular locality where there is no access to clean potable water but rely on lakes, streams, rivers, and boreholes, enabling them to know the characteristics of the water they are drinking. The measured data value is transferred to cloud storage for analysis. We designed a web portal using a set of protocols to process the captured data. Compared to other real-time deployed systems across the world, the solution presented here is secured, uses efficient MAC layer protocol which enhances the transmission and reception time and implements a network layer protocol that takes care of the delay factor in the transmission process. At the network level, we design the setup in such a way that when a parameter is measured, and the communication channel is not available, we perform retransmission until the communication channel is made available. Each of the parameters measured: calcium ion (Ca2+), electrical conductivity, pH, dissolved oxygen, silver (Ag+), fluoride ion (F), nitrate ion (NO3-), oxidation-reduction potential (ORP), and temperature indicated significant fluctuations over time. These changes may be attributed to pollution from upstream which are time varying. We plan to increase the number of sensor nodes taking into account sensor probes such as the turbidity sensor probe since its one of the parameters the stakeholders requested, we measure for them.

## 7.2. Future Directions

This work provides several vital opportunities to explore deeper into significant issues related to sensorbased water quality monitoring. For example, to conserve energy of the sensor nodes, researchers in the future should be looking into designing models that can predict water quality data based on historical data to regulate the sensor's energy consumption. Researchers in the future should also be interested in investigating the design of persuasive technology models (i.e., applying physiological principles to persuade people), data analysis models, and sensors that are capable of measuring both physical and chemical parameters. Monitoring water quality in real-time in developing countries is vital, and this work provides the initial steps.

### 7.2.1. Security, Privacy and Data Confidentiality

Sensor nodes are exposed to external threat in the environment they are deployed. Hence, the security of the sensor nodes is essential. Apart from the sensor node hardware that requires protection from humans (i.e., tampering with devices or stealing devices), aquatic animals may also tamper with the cables. Wireless sensor network security in WQM remains an open issue. WQM applications utilising WSNs require data security, both at the local network and during data transmission over a wide-area network to the remote monitoring centre. WSNs security in WQM system and researchers must ensure that high-quality data is provided to stakeholders and consumers. Security is one of the areas that has not been given sufficient attention in the literature [5], [316]. Security mechanisms in water quality monitoring must be implemented from the freshwater source to the point where the consumer utilises the water.

Several issues affect the physical security of the local monitoring station, the wireless sensor nodes themselves and the sensor network in general. Researchers must ensure system and data integrity; it is essential to review the threats that may harm the WQM process and system. Implementing and deploying a WSN architecture needs a high level of physical and logical security [5], [316], which ensures the integrity of water distribution departments and prevents acts of tampering, theft and destruction of the wireless sensor nodes and the local monitoring centre.

Recent research has not paid considerable attention to security concerns within water quality monitoring systems as, traditionally, the data was physically acquired from the water quality monitoring systems and was then, most of the time, accessed only by a small number of stakeholders. However, in current WQM systems employing wireless sensor networks, data retrieval is automated. The system does not require user interaction, and there has been a shift toward unlimited web-based data access. The entire water quality monitoring architecture is now tracked online using different network technologies, shared databases, servers, and software systems [5], [317]. At the network level, the node and data security issues are considered. The sensor nodes may be tampered with or damaged by invaders at the deployment location.

When security is compromised in WSN, the sensor nodes can lure other sensor nodes to transmit data to them (typically referred to as a sinkhole or wormhole attacks). Once received by the compromised sensor node(s), the data can be altered, making the data stale and invalid. The compromised sensor node (s) could also affect sensor node activities and data or network traffic analysis. The attackers can also set up other sensor devices nearby the base station and eavesdrop all transmissions from the sensor network. One main issue in WSNs is extending the lifetime. Any security violation may consume the batteries of the sensor nodes, rendering the system inoperable [5], [318], [319].

Data integrity and data confidentiality are eminent because hackers or intruders can intercept the wireless network and change or modify the data. When this happens, the analysis and the results are consequently affected. Furthermore, intruders can attack route the data transferred and redirect the data for their gain. When illegal users gain access into the database, they may attempt to alter its contents. Hence, setting up authentications and permissions will increase sensor node security. Additionally, malicious code injection affects the analysed data in the system. Malicious code injected into the database may result in data losses and inconsistencies [5], [318], [319]. From the above discussion, research is needed to combine existing security mechanisms within wireless sensor network based water quality monitoring systems or, if required, develop new security mechanisms to protect the overall system against all forms of attacks [5].

### 7.2.2. Underwater Propagation

Communication among nodes in underwater WSNs is a challenging task due to limited availability of bandwidth, signal fading, node failure, and propagation delay [5], [320], [321]. Underwater communication in marine water sources is challenging because GPS signals and other communication technologies such as ZigBee do not propagate well through water; hence, an alternative communication such as acoustic communication is needed for such environments [5], [321]. In WQM, most of the deployed systems use terrestrial communication technologies (e.g., GSM, GPRS, ZigBee, WiFi, and WiMax) since the sensor nodes normally are incorporated with a radio module for wireless communication. In monitoring underground water, two or more communication technologies could be adapted for real-time monitoring. Combining underwater acoustic communication and any of the terrestrial communication standards (i.e., GPRS or GSM) will be a better choice when monitoring fresh water sources that require the sensors to be placed underwater. In considering the combination of both underwater and terrestrial communication standards in WQM applications (especially for underground water quality monitoring), researchers should look into issues related to the channel, the protocol (e.g., MAC) and also issues that have to do with the node mobility [5].

### 7.2.3. Data Analysis and Computation Techniques

This section explains the essential computational, analytic, and reporting facets of the WQM process. The calculated data values allow stakeholders to make informed decisions. Data reporting involves communicating the analysed data values as information to aid decision-makers to take the appropriate action. In WSNs, different water sensor probes can be used to sense different water quality parameters and compute these data values in real-time. Currently, existing guidelines provided for water monitoring activities do not provide information about data computation at the water sample site. In the traditional monitoring approaches for WQM, water samples collected from a location is analysed at the laboratory, which is not different from other lab-based in-situ methods. In these existing methodologies, basic statistical techniques are used to perform the data analysis [5].

In future, researchers should focus on designing specialised algorithms to perform trend analysis due to huge data collected with the use of WSNs. Another area of research considered as future work is at the data processing phase. Researchers should look into collaborative task processing (CTP) among the sensor nodes. In CTP, individual nodes are expected to offload some of their tasks to nearby nodes that have fewer data to compute and more energy to process the data. When collaborative task processing is explored to its full potential, it could augment existing energy management schemes. It is expected that for the sensor network to become more energy-efficient, data processing shared among the wireless sensor nodes in the network will be a more efficient (this is also known as distributed task processing (DTP)) [5].

### 7.2.4. Data Communication and Transmission

The focus for the data communication infrastructure is to enable the reliable transfer of data gathered from the deployment site. These systems communicate with other devices within the network through a single hop routing technique, whereas others employed multi-hop routing or did not provide the methods used in their implementation [5].

Most of the existing systems use ZigBee as the wireless communication protocol to communicate among the sensors and between the sensors and a local base station. Also, the access technologies used to connect the local base station to a remote monitoring station are mainly CDMA, GPRS and GSM cellular networks, WiMax (IEEE 802.16) and IEEE 802.15.4 [5].

In WQM projects, to connect local WSN with the remote monitoring centre, additional investigations are needed to identify the functionalities and number of wireless sensor gateway nodes to be used. To this end, increasing the number of gateway sensor nodes reduces the single point of failure. It is thus improving network reliability and fault tolerance of the system. It will also increase the overall implementation and maintenance costs. Furthermore, increasing the functionalities of the gateway node requires efficient management of the wireless sensor node's energy consumption to allow for continuous operation. Researchers in this area can also look into different WSN protocols that may be adaptable for WQM applications [5]. For example, the use of cluster-based hierarchical protocols can be adapted for WQM applications. Routing algorithms can be proposed to improve the quality of data delivered at the base station and enhance the network lifetime and uptime.

### 7.2.5. Designing Prediction Models

Due to the energy consumption of nodes during data communication and the necessity to have continuous data during water quality monitoring, predictive models have been suggested. Predictive models reduce the data communication while still producing highly accurate data. Water parameters that are monitored could produce either linear or non-linear data. Linear data could be predicted using time series models while non-linear data could be predicted using neural networks or support vector machines.

Water quality data are usually a combination of both linear and non-linear. Predicting combined linear data is easier to implement with low complexities but are limited in predicting the nonlinear variations in the data. Examples of linear models include Autoregressive (AR), Autoregressive Moving Average (ARMA), Autoregressive Integrated Moving Average (ARIMA), Grey Series Models, etc. ARMA models are for predicting slow changing data while MA models are for data with sudden and sharp changes. Non-linear models are rather difficult to implement but give better accuracy, examples include neural networks, decision trees and rule learners, genetic algorithms, etc. The limitation of neural networks in WSNs is that while the data sets are mostly centralized, making them not suitable for distributed adhoc deployments, they also require longer time to train the models. Several WQM approaches use a combination of some linear and non-linear models [307], [322]. Much work must be done to efficiently use time series models for near accurate predictions that could be used effectively in solving problems related to adhoc wireless networks such as mobility and topology changes, energy limitations, routing and adhoc deployment.

### 7.2.6. Designing of Persuasive Technology Models

Water quality monitoring could be an effective tool in influencing the behavior of people living at the banks of river bodies who use the water directly without further treatment. Persuasive technologies are a general class of technologies with the intention of applying physiological principles of persuasion such as credibility, trust, reciprocity and authority to change intended users' attitudes and behaviors [323]. Persuasion is with the intended effort to change attitudes and behaviors using technologies from abstracted ideas such as water quality monitoring. It would be very important if applications were developed that inform an intended audience about the water quality parameters and give alerts that suggest the changes in these qualities especially when they go beyond the acceptable thresholds. Such an application will not only change people's attitudes to the devices, but also provide them with a sense of ownership and how they relate towards the water and the environment at large.

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# APPENDIX

Performance Comparison of Adjustable Transmission range (using the distance-based energy aware routing protocol (DBEA)) in terms of Energy Comsuption with AODV.

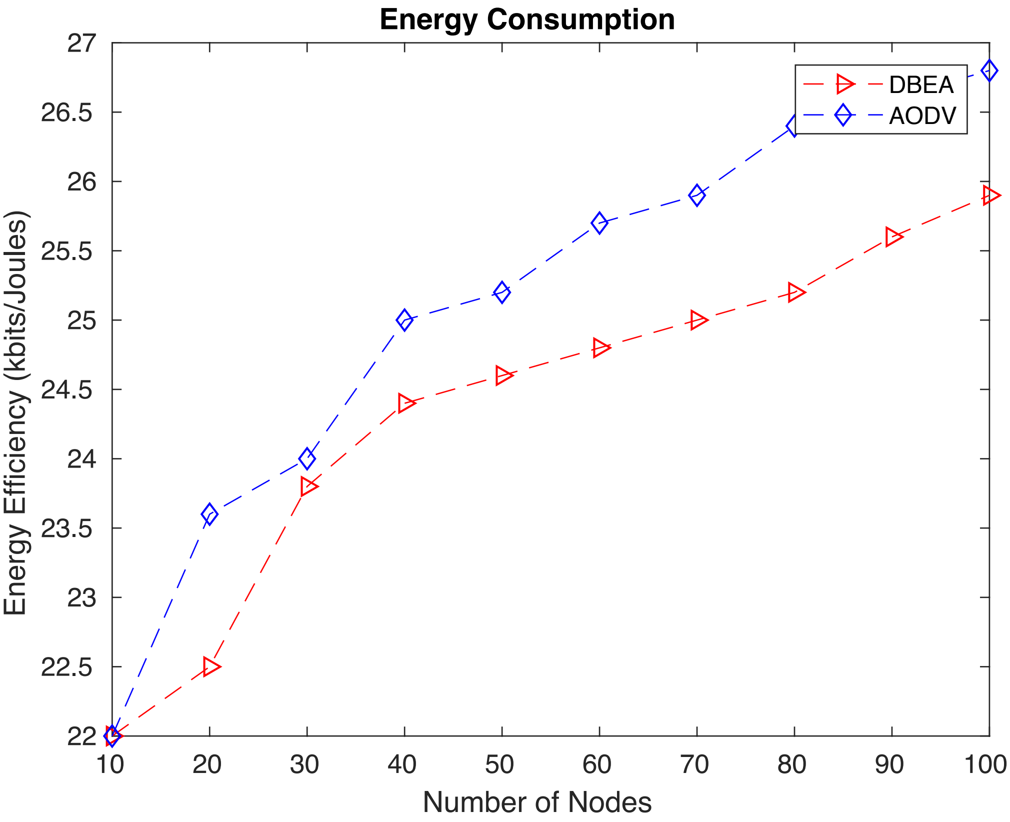

Figure 1A: Energy efficiency vs Number of Nodes

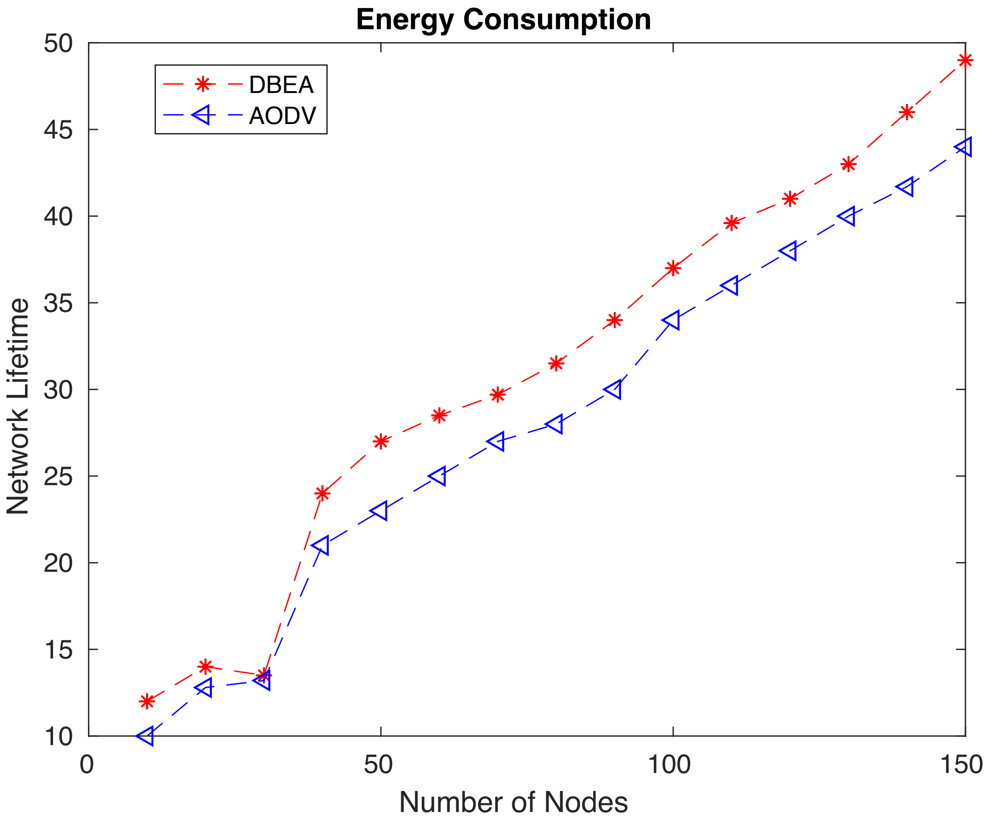

Figure 2A: Network Lifetime vs Number of Nodes

Figure 3A: Normalised PDR vs Number of Nodes

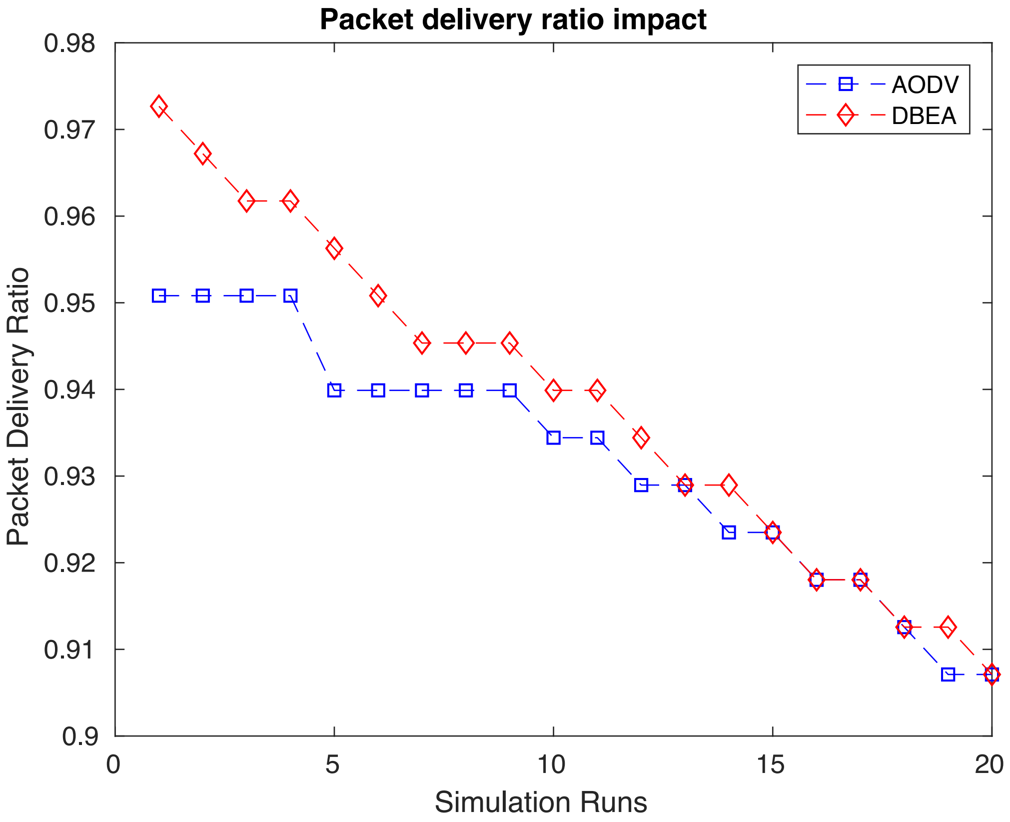

Figure 4A: PDR at 20 simulation rounds