An Optimized Cross-Layer Protocol for Wireless Sensor Networks

By Ahlam Saud Althobaiti

A thesis submitted for the requirements of the degree of
Master of Computer Science

Faculty of Computing and Information Technology
King Abdulaziz University - Jeddah
Jumada Al-Akhirah 1437H – March 2016G

بسم الله الرحمن الرحيم

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Dedication

In the beginning, I would like to thank Allah for giving me the strength and the power to be able to finish my degree. Without his generosity and mercy, none of this would have been possible.

I dedicate this modest work to all those who contributed to my education, I particularly appreciate and thank: Dr.Manal Abdullah. I want to give a glad tiding of Prophet Mohammed "peace be upon him" saying:"The fish in the sea, and birds in the sky, pray for who teaches people well", they assisted and guided us in this research.

I would also like to record my sincere thanks to the invaluable and able help and guidance of my mother Ms. Rabiah, my father Mr. Saud, my husband Mr.Mansour and my family, as well as my baby Battal. Their support played an important role in helping me during my studies.

Acknowledgment

I would like to take this opportunity to express our deep sense of gratitude and profound feeling of admiration to my supervisor. Many thanks to all those who helped me in this work.

An Optimized Cross-Layer Protocol for Wireless Sensor Networks

Ahlam Saud Althobaiti

Abstract

In modern networks, a Wireless Sensor Network (WSN) is distributed widely to monitor physical or environmental conditions, such as temperature, sound, etc. WSNs are considered emerging technologies that are used in a wide spectrum of applications over open networks. WSN is built from thousands of nodes; each node is connected wirelessly to one or several sensors. The most considerable challenge facing WSNs is the requirement of significant reductions in energy consumption of the sensor nodes.

The cross-layered approach in WSN is proven to be more effective and energy efficient than traditional layered approaches. Despite the fact that traditional layered approach endures more transfer overhead, these overheads are minimized by cross-layered approach where it has data shared among layers. In cross-layered approach, the protocol stack is treated as a system not individually and independent of each other.

In WSNs, the energy consumption of sensor nodes is greatly affected by the Medium Access Control (MAC) protocol which controls the node radio functionalities. There are many MAC protocols that have been successfully designed towards the prime objective of energy efficiency. However, the vast majority of the existing protocols are based on classical layered protocols approach that leads to significant overhead.

This study contributes towards the design of cross-layer protocol that joins optimal design of MAC and network layer. This protocol: OXLP (An Optimized Cross-Layers Protocol) considers, beside energy consumption, delay, packet delivery, traffic adaptability, scalability, etc.

While OXLP protocol improves energy consumption over well-known protocols in same filed, also both of the packet delivery ratio and packet delay reached a good level compared to other protocols in literatures. It is proven its efficiencies for traffic adaptability and scalability.

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LIST OF SYMBOLS AND TERMINOLOGY

AEA: Adaptive Election Algorithm

AILMAC: Adaptive Information-Centric LMAC

ALOHA: Additive Link On-Line Hawaii System

AP: Adaptive Protocol

BER: Bit Error Rate

BMAC: Berkeley MAC

BS: Base Station

CDMA: Code Division Multiple Access

CH: Cluster Head

CN: Collector Node

CSMA: Carrier Sense Multiple Access

CSP: Cluster Status Protocol

DFS: Depth First Search

DoS: Denial of Service

DSR: Dynamic Source Routing

ESP: Schedule Exchange Protocol

FDM: Frequency Division Multiplexing

FLAMA: Flow-Aware Medium Access

GCF: Green Conflict Free

GW-node: Gateway Node

LAN: Local Area Networks

LMAC: lightweight medium access protocol

LP: Linear Programming

LPL: Low Power Listening

MAC: Media Access Control

MANET: Mobile Ad Hoc Networks

MCU: Micro-Controller Unit

M-GCF: Multicolor-GCF

NP: Neighbor Protocol

OSI: Open Systems Interconnection

OXLP: An Optimized Cross-Layers Protocol

PER: Packet Error Rate

QoS: Quality of Service

RF: Radio Frequency

SCP-MAC: Scheduled Channel Polling MAC

SMAC: Sensor-MAC

SP: Schedule Protocol

TDM: Time Division Multiplexing

TRAMA: Traffic-Adaptive Medium Access Protocol

WSN: Wireless Sensor Network

XLM: Cross-Layer Module

Z-MAC: Zebra MAC

Chapter 1: Introduction

Chapter 1

Introduction

1.1. Introduction

In fact, the computing and communication technologies have been highly developed specifically in the last decades. Respectively, this development had been started in the first generation of computing in 1940s from the vacuum tube technology, then the invention of transistors in 1950s, continuously until micro-processors and large scale integration technologies in 1970s. However, Moore's and Bell's Laws have always been consistently sensed, since that the number of transistors incorporated in a chip will approximately double every two years according to Intel co-founder Gordon Moore in 1965 prediction. Based on this prediction- in 1972, Gordon Bell expected that after every decade the world would has new generation of computing technology. This improvement during the current fifth generation in the integration scale has mostly earned everything for the computing and communication technologies; such as reducing the cost, shrinking the size, reducing the switching power consumption, increasing the speed and efficiency, and providing the mobility and portability features.

Wireless networks and sensors integration developed this technology domain by making data movement, network distance, and network monitoring seamless.

Wireless networks are flexible by allowing users to get connection anywhere with no more restriction of cables cost. The invisibility feature in the embedded systems can be integrated into the environment by assisting users in performing their tasks. Therefore, the compatibility between these advancements has improved small devices to re-organize them, and also it has introduced the domain of Wireless Sensor Networks (WSNs). A new perspective has been added to the wireless technologies depending on the pervasiveness and self-organization of low-cost, low-power, long-lived, and small-sized sensor node.

Coupled with sensing, computation, and communication into a single tiny device, WSNs are emerging as an ideal candidate for several applications. Particularly, this emerging technology is highlighting in monitoring and controlling domains. In general, the networks demands for improvement are exponentially expanding with the increase in networks dimensions. Whereby, continuous development on the technologies is always pushing this domain even further [1].

Unlike traditional networks, WSNs have their own design and resource constraints. The design constraints are application dependent and are based on monitored environment [2]. Whatever the design approach, it is essential that WSNs are subject to a rigorous analysis to provide long- term survivability of the architecture. The OSI (Open Systems Interconnection) layer model is generally used to specify the protocol architecture. However, due to the lack of memory and energy, it becomes difficult to use the traditional layer model in WSN. Cross-layer design is proposed to achieve gains in overall system performance in wireless networks [3].

Cross-layer techniques improve energy conservation in WSN. Hence, most cross-layer protocols have been proposed to reduce energy consumption in WSN [2]. These protocols are efficient solutions for energy conservation. They use MAC

(Media Access Control) layer information such as joint scheduling, power control, and sleep state of sensor nodes, to control energy consumption. Furthermore, a common mechanism to reduce energy consumption is to turn the transceiver of sensor nodes into a low power sleep state when it is not being used.

This research mainly contributes towards the design of a cross-layer protocol OXLP (An Optimized Cross-Layers Protocol). Our approach is characterized by a synergy between mainly MAC layer and network layer with a view towards inclusion of higher layers as well. The proposed protocol includes features from both MAC and network layers whereas it significantly reduces energy consumption of nodes through increase the sleep periods as much as possible, dealing with collisions and control overhead. At the same time, it substantially aims to reduce packet delay by enabling the receiving node to respond early and adaptively to the sending node. As well as, proposed protocol focuses on improving the scalability and adaptability and avoids the hidden and exposed terminal problems.

The research methodology is based on developing and evaluating schedule algorithm for MAC layer that establishes and maintains traffic-based information. The MAC protocol is compared its performance against both contention-based and scheduling-based protocols. Then this protocol is extended using cross-layer concepts which allow to integrate MAC protocol and routing protocol for improvement overall performance for WSN. The proposed cross-layer protocol (OXLP) compares against both cross-layer based protocols and also against routing protocols.

The performance of the proposed OXLP protocol was evaluated through simulations. The protocols are designed and implemented in MATLAB [4]. Simulation results demonstrate the effectiveness of proposal OXLP in terms of packet delivery ratio, network lifetime, delivery delay to the BS and consumed energy for various traffic loads in the network.

1.2. Research Aims and Objectives

The research aims are to develop and validate a cross-layer approach protocol. The developed protocol is evaluated against many performance criteria.

This study is performed based on the idea of cross-layer protocol for WSNs. Moreover, the life time and performance of proposed protocol are part of objectives of this research. Thus, the methodology used to fulfill the above aim is as follows:

- Literature review on energy challenges in WSNs.
- Related work on cross-layer protocol in WSNs.
- Optimized MAC protocol.
- An efficient cross-layer protocol for WSNs will be proposed.
- A comparison study between our proposed protocol and some existing protocols.
- Highlighting results of the performance of the proposed protocol.

1.3. Contribution

Severe energy constraints of battery-powered sensor nodes necessitate energy-efficient communication in WSNs. However, the vast majority of the existing solutions are based on classical layered protocols approach, which leads to significant overhead. It is much more efficient to have a unified scheme which blends common protocol layer functionalities into a cross-layer module.

This thesis develops two main contributions as shown in Figure 1.1. As first contribution, we propose schedule protocol, which is designed to control medium access in WSNs. This protocol is aimed to reduce overhead, reduce overhearing, and avoid the hidden and exposed terminal problems. It also prevents inter-node interference and increasing network lifetime.

As a second and main contribution, cross-layer interactions are added to enhance the performance of proposed schedule protocol, as OXLP protocol. According to the properties of this protocol, applications where lifetime is critical, OXLP protocol is most suitable. However, both of these protocols can be configured depending on the application.

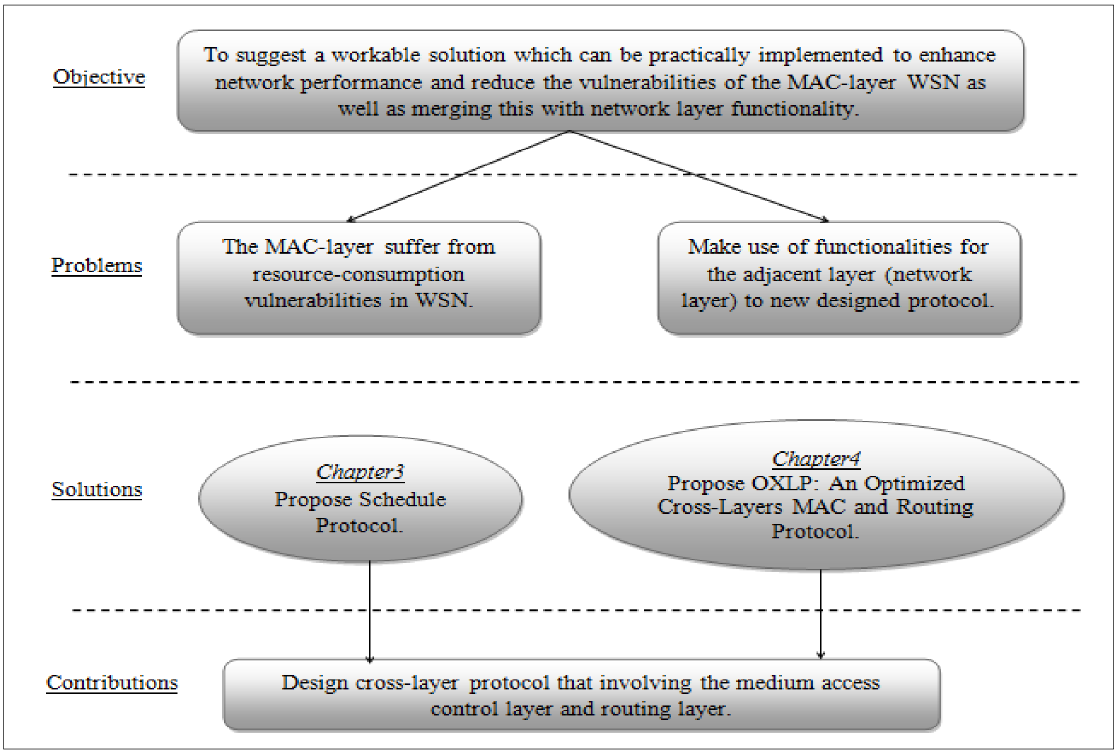


Figure 1.1: Research Contribution.

1.4. Problem Statement

From the extensive background study that we have conducted, it is note that considerable researches are being done in the area of energy saving techniques for WSNs – with specific focus on energy awareness at different network layers in WSNs. Moreover these existing systems suffer from several limitations related to overhead and the congestion of traffic. Specifically in this thesis, we focus on optimizing the systems performance by suggesting a cross-layer protocol at the network/data-link layer for sensor networks. We have developed a scheme for better and improved energy efficiency, packet delivery ratio, network lifetime and delivery delay to the BS in WSNs by combining the ideas of energy-efficient cluster formation, routing and medium access together. The scheme is based on a collaborative approach supported by proposed MAC scheme and integrated it with an efficient routing protocol.

1.5. Thesis Outlines

The chapters organization of this thesis is as follows.

- Chapter 2 explains the background of the research by introducing the fundamental concepts of WSNs, its application classes and the basics for MAC and network layers followed by an overview of related work.
- Chapter 3 shows the schedule-based MAC protocol that is proposed in this thesis in details.
- Chapter 4 shows the extension of proposed protocol by explaining the OXLP protocol.

- Chapter 5 is the simulation experiment design for evaluating the schedule-based MAC protocol and OXLP protocol. This chapter describes the metrics to be used as an evaluation criterion and followed by evaluating the performance of the proposed approaches.
- Chapter 6 concludes the thesis by presenting conclusion and directions for future research.

Chapter 2: Background Material

Chapter 2

Background Material

2.1. Introduction

Information and communication are two of the most important strategic issues right now. Recent advances in networking technology are driving the ubiquitous deployment of wireless sensor networks (WSNs). This chapter provides fundamental information on WSNs. This chapter introduces background information that is necessary for this research.

2.2. Wireless Networks

Wireless networks are widely used by many different applications. This type of networks is spreading rapidly due to its flexibility and freedom.

Any system of wireless communication contains of the following elements:

- Transmitter that sends signals.
- Receiver that receives the signals sent by transmitter and then processes it. Sometimes transmitter and receiver are on same device such as cellular phone, this device is called transceiver.

- Antenna which used to emit the electromagnetic energy in the air. Antennas have different shapes [5] as shown in Figure 2.1.

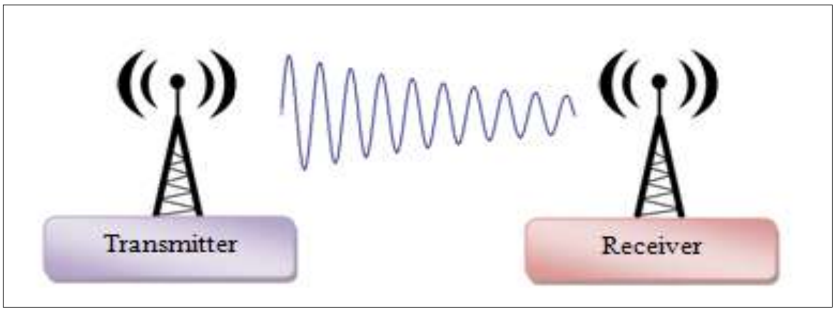


Figure 2.1: Elements of Wireless Communication System.

Wireless networks have unique features such as:

- The channel of communication between sender and receiver is affected frequently by fluctuation of weather and noises.
- The sender and receiver are not connected physically with a network. Therefore, the location of sender and receiver are important to start the communication. Topology can be dynamic due to mobility.
- The channel bandwidth is limited. Government organizations only permit narrow ranges of frequency to achieve wireless communications.

In wireless networks, information is intangibly carried through the air by radio frequency (RF). The key standards of the wireless networks are IEEE 802.16 (i.e. WMAN) and IEEE 802.11 (i.e. WIMAX) [6]. These networks can be in different topologies, for example, mobile ad hoc networks (MANETs), mesh networks and cellular networks. They also can be domain specific networks, for example, wireless sensor networks (WSNs) referring to Figure 2.2.

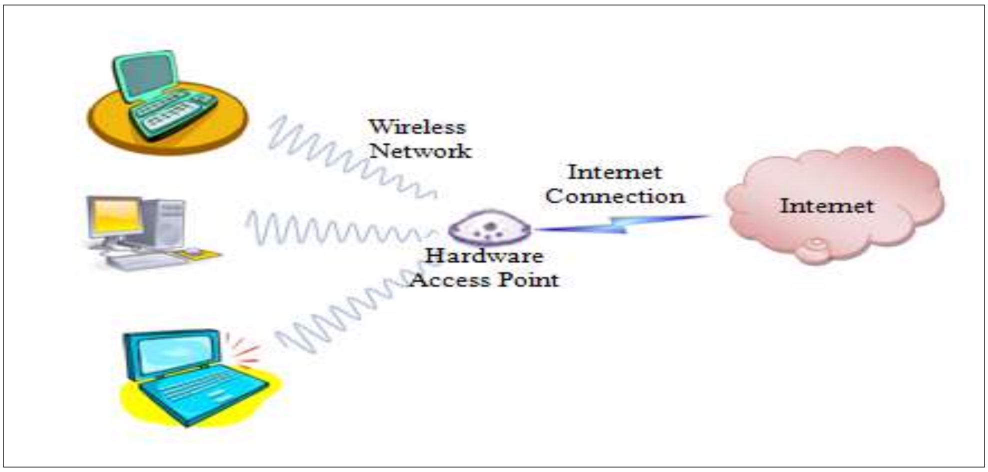


Figure 2.2: Wireless Connected Computers via an Access Point.

2.3. Wireless Sensor Network

In wireless sensor network (WSN), ad hoc network has been simply designed as a WSN without any prepositioning for the sensor nodes. However, sensor network protocols must have self-organizing abilities to cover the unreachable areas by its random distribution. As well, sensor network has unique feature which is known as the "sensor node cooperative effort". This feature allows sensor nodes to send briefly the required computed information to the responsible nodes, rather than transmitting the raw data with much detail.

As shown in Figure 2.3, hundreds of nodes are heavily deployed in the field since the two neighbored nodes distance is limited to few meters. However, the more capable node in the sensor field is defined as a collector node (CN), which is normally located inside the sensor field. As well as, CNs are also known as "sinks" or "base stations" which collect data from nodes to be forwarded to users. Moreover, the CNs distribute the tasks to many different applications. The CN is supposed to be as an interface between sensor networks and users since the data is transmitted through sensor and gathered in collector nodes by multiple ad hoc hops.

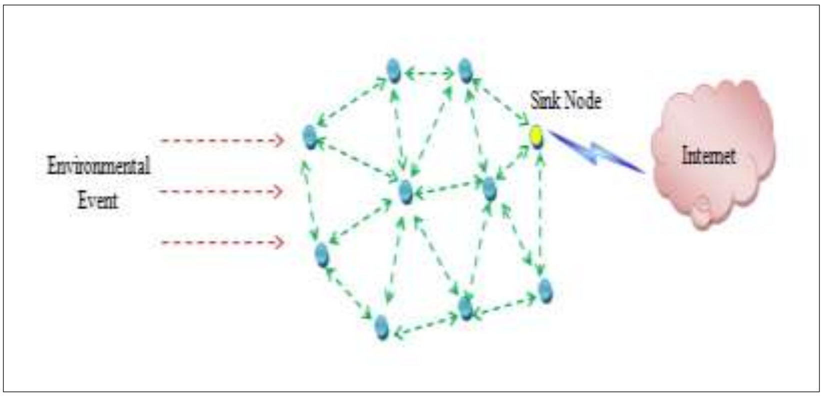


Figure 2.3: Wireless Sensor Networks.

2.3.1. Application Examples of WSNs

There are many WSN applications that can be categorized such as; security, control, complex systems actuation/maintenance and monitoring of outdoor/indoor environment applications. Among these are Military applications, Environmental applications, and Commercial applications:

- **Military Application**: is a special WSN application used to guarantee some military services such; command, control, intelligence, etc. Basically, this application can be configured successfully with high deployment performance based on nodes heavy deployment and the low-cost sensor nodes. Typically, some military applications are considered friendly for:
    - Strengthen tracking
    - Battlefield monitoring
    - Reconnaissance
    - Evaluating for target damages

- **Environmental application:** is used to monitor local environment entities, irrigation environmental situations (livestock and crops), and macro instrument for earth and chemical- biological detection, and earth-planetary exploration.
- **Commercial application:** there are many commercial application categories including:
  - Managing organization inventory, monitoring product quality, creating smart offices, monitoring and controlling offices.
  - Monitoring patient and elderly.
  - Applications for medical implant communication services; that are used for many purposes. For example, paralyzed muscle stimulation, artificial immune system creation and continuous monitoring. Whereby, this application can be operated by embedding special medical sensors in the human body.

2.3.2. WSNs Architecture

A WSN usually consists of several sensor nodes distributed either inside or very close to a geographical region of interest with a view to sense, collect, and disseminate data relating to one or more parameters. The architecture of the WSN can reasonably be divided into the node architecture and network architecture. Energy efficiency can be achieved at both node and network levels [7]. At the node level, radio management, modulation, computation, packet forwarding, and interaction among layers can be made energy efficient. At the network level, energy aware topology and traffic management, better collaboration and communication among sensor nodes, and the reduced overhead can greatly help in the energy efficient objective of the WSN. Both of these architectures are detailed below.

2.3.2.1. Node Architecture

A sensor node mainly consists of five basic components; a Micro-Controller Unit (MCU), a radio unit, a memory unit, an I/O interface unit, and a power unit.

The low-power MCU usually consists of a microcontroller or a microprocessor, which provides intelligence to the node by performing tasks, processing data, and controlling the functionality of other components. The sensor node usually comes with the self-sufficient and cost-effective microcontroller and integrated memory unit. For better power management purposes, the MCU may support different operating modes such as an active, idle, and sleep mode.

The radio transceiver contains an antenna, frequency synthesizer, oscillator, demodulator, amplifier, and other circuitry needed to communicate with other sensor nodes over the radio channel. The radio is an important component, especially for the energy efficient operations of the sensor node. It helps in deciding several factors such as power consumption, carrier frequency, data rate, modulation, coding schemes, transmission power, error blocking, and many more [8].

The power unit supplies battery power to drive all other components of the sensor node. Due to its limited capacity, energy aware operations by each component are required. The I/O interface unit integrates several application-specific sensors, which observe a physical phenomenon and generate traffic based on the observed phenomenon.

In addition to these basic components and as per requirements of the application, the sensor node can also be equipped with some additional components. For some localization applications, needing the knowledge of the physical location, the node can have a GPS component attached to it. For mobile and mechanical related applications, a motor or a mobilize may be attached to move sensor nodes. To have an increased power supply, nodes can carry an additional power generator with them, which may utilize solar, thermal, kinetic, or vibration energy to generate extra power. However, such components usually require too much power or are too heavy to be practicable for low-power and light-weight matchbox-sized sensor nodes.

2.3.2.2. Network Architecture

Several scattered nodes in a sensor field communicate and collaborate with each other in an ad hoc fashion to form a WSN. Each of these sensor nodes has dual responsibilities of generating and routing data back to the sink node, usually via multi-hop paths. Figure 2.4 shows typical network architecture of a WSN. The sink node may communicate with the end-user via a gateway by using the Internet or any other communication network, so that the disseminated data can be stored, treated, and analyzed. The sensor field can have more than one sink node depending on the terrain, size, and traffic load of the field. The gateway can also be connected to more than one WSNs, where sensor nodes may perform totally different tasks.

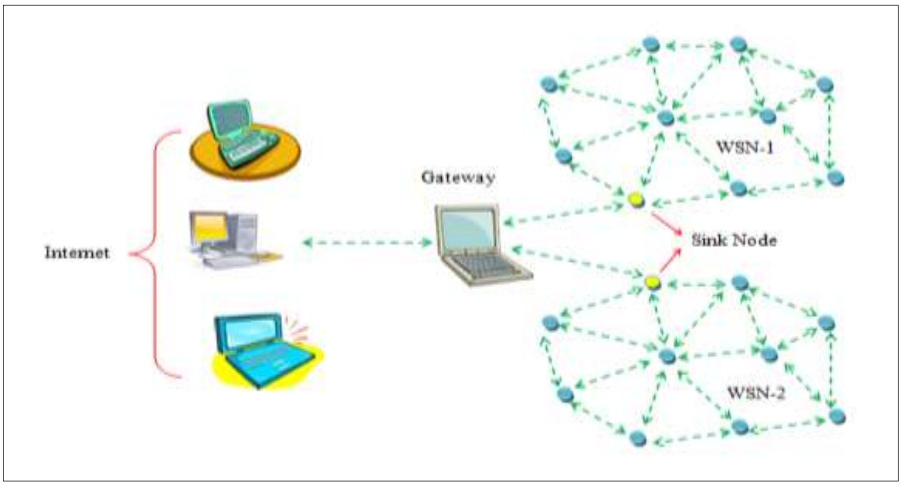


Figure 2.4: Architecture of a Typical WSN. The capabilities of sensor nodes in the WSN may vary widely. Some nodes may perform simple tasks of monitoring a single phenomenon, whereas the other may perform complex and multiple sensing or aggregating tasks.

The network architecture of WSNs, depending on how sensor nodes communicate with each other, can be further divided into flat architecture and hierarchical architecture [9]. In flat architecture, each sensor node is a peer and has the same capabilities in performing a sensing task. Sensor nodes form multi-path routes to the sink node in a distributed fashion by relaying data to other peers. In hierarchical networks, nodes are organized into clusters; each one is supervised by a cluster head. The cluster members send their data to the head, which then relays it to the sink node in a single or multi-hop manner. The cluster head may have different capabilities than other nodes. Both of these sub-architectures have their own advantages as well as disadvantages.

2.3.3. WSNs Communication Architecture

Basically, WSNs communication architecture is considered the most important fundamental in the wireless sensor network. Since, the standard network protocol stack [10] has Physical layer, Data Link layer, Network layer, Transport layer, and Application layer. The sensor network protocol stack is also similar to the standard protocol stack [10] (as shown in given Figure 2.5).

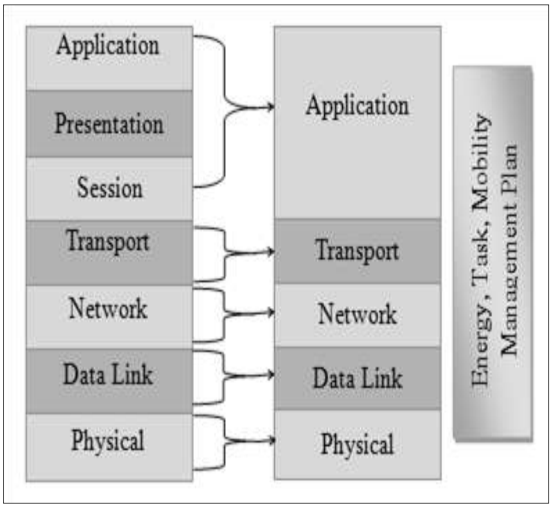


Figure 2.5: Protocol Stack for Wireless Sensor Networks.

The Physical layer has leading task the in communications; it determines major characteristics such as; modulation type, data coding, operating frequency, and the interfacing between the system's hardware and software. While, Data link layer is the second network layer in the stack and its task is for controlling the communication tasks on the MAC layer protocols between the adjacent network nodes over the wide area network (WAN). In addition, power control and error control strategies are also under Data link layer responsibilities. In the Network layer, the protocols are applied to insure packet forwarding that include routing packet from the source node to the destination node according to the quality of service (QoS) such as; latency or packet delivery ratio and energy consumption. In the fourth layer, the Transport layer provides some services for reliability, maintaining data flow and connection-oriented to guarantee the connection between WSNs and the outside network. The application layer is the higher network layer; it is for connecting end user's applications or interfaces [10], [11]. However, this study is mainly focusing on the energy efficient scheduling on the MAC layer, as well the optimizing of the energy efficient by using other layers.

2.3.4. Challenges and Research Issues in WSNs

WSN has different characteristics compared to the traditional wired or wireless networks, hence it has the following unique characteristics:

1. WSN has no fixed infrastructure, and sensors will be self-organized via collaboration between them.
2. Sensors are constrained in terms of their resources limitation such as; processing, energy, bandwidth, and memory.
3. Normally, the network topology is changed quickly and dynamically depending on the sensors status. Since some sensors may fail due to reasons like energy waste, interference, movement or obstacles.

Therefore, WSNs have different challenges and research issues to be studied as follows:

- **Energy conservation:** in WSNs, sensors have lifetime of working that is ranged as several months to years, since sensors are normally powered by limited batteries. Therefore, the researchers are interested to prolong the network lifetime, whereby this problem is highlighted as the primary challenge in WSNs. However, there are several key factors which can affect the energy consumption in WSNs. Moreover, energy consumption can correspondingly be divided into two parts: hardware components can be installed on the sensor board to reduce the energy consumption during sensing phase, and protocols on various layers can impact the energy consumption greatly. For example, the node sleeping and wakeup mechanism [12] can be introduced in the MAC layer to reduce energy consumption.

On other hand, routing protocol is strongly applied on WSN lifetime. Routing protocol induces an initial waste of energy, since it require the flooding of control packets to determine the routes [13]. In addition, network topology is changed especially when nodes leave the network due to energy depletion in WSNs. Furthermore, constant control messages exchange is then required to keep information about routes, adding transmission overhead and consuming sensors energy. Thus, WSNs' routing protocols must be energy-aware and energy-efficient. In addition, the least overhead is possible by using routing protocol to avoid reducing the network lifetime which occurred by unacceptable thresholds.

To achieve energy efficiency, we can also combine the design protocols during the two above network layers. Thus, in order to tackle the layers problems, a cross-layer protocol is needed. Clearly, the proposals based cross-layer is more complex than the non-cross-layer proposals. Since, energy consumption based on cross-layer must be reduced at all costs in these networks; otherwise, nodes will not operate for the extended periods that they are supposed to. The ideal of cross-layer solution is also complex because it should involve parameters from all layers of the stack, since it affects energy consumption to some degree. Hence, the increasing in the sensors design complexity is inevitable and inversely proportional to the sensors energy capacity.

- **Topology design:** energy consumption, reliability, and connectivity are actually effected according to the topology design and network coverage of WSNs. Therefore, topology design is critical importance in WSNs. Moreover, the sensor nodes can be arranged with specific pattern (like disk or grid) or promptly in a random distribution. However, balancing the energy workload with the aid of topology design is a practical challenge to the successful application of WSNs.
- **Architecture design:** energy, processing and memory are dynamically changed in WSNs. Therefore, the system should operate autonomously, and each application requires changing its configurations individually.
- **Collaborative signal processing:** in WSNs, nodes need to collaborate with each other to generate useful information which is then sent to the remote the sink node. Meanwhile, collaborative signal processing in WSNs is now considered as a new research field in WSNs. Currently, there are several studies that present the importance of the information sharing between nodes and show how nodes fuse information from other nodes [14]. More communication resources are required for better performance during processing data from more sensors. Thus, the WSNs considers the trade-off between performance and the resource utilization in the collaborative signal processing.
- **Security:** Security is a critical problem in WSNs. It includes research topics such as key management, authentication, security infrastructure, robustness to Denial of Service (DoS) attacks, secure routing, cryptography, and privacy. However, to achieve a secure system, security must be integrated and applied

into each component, since components that are designed without security tool can easily become a point of attack in WSNs.

2.3.5. Design Objectives and Requirements

While WSNs share the wireless medium among sensor nodes, they are subject to a variety of unique objectives, requirements, and constraints, which considerably distinguish them from their counterparts. Some of the main design objectives of sensor networks are concisely outlined below. Note that the application-specific nature of the WSN does not need to implement all of the objectives at one instance.

- Small node size to allow dense deployment in harsh and hostile environments.
- Low node cost to reduce overall cost of a dense network.
- Low power consumption to prolong network lifetime.
- Application diversity to make WSNs suitable for several applications.
- Self-configurability among sensor nodes to autonomously organize themselves, even under varying traffic and topology situations and un-engineered deployment.
- Scalability to support different network sizes under different applications and conditions.
- QoS oriented to behave in terms of delay and reliability according the requirements of the application.
- Simplicity to run uncomplicated yet efficient algorithms.
- Adaptability to face varying traffic and post-deployed topology situations.

- Reliability to deliver data efficiently under harsh and varying topological conditions.
- Fault tolerance to enable sensor nodes for the automatic repair and recovery process in an unattended environment, if the faint hardware gets failed or blocked for a while.
- Converge cast ability to support flowing of data in many-to-one pattern, i.e., from nodes towards the sink node.

2.4. MAC Layer Basics for WSNs

The MAC sub-layer is a part of the data link layer specified in the communication protocol stack and is shown in Figure 2.6.

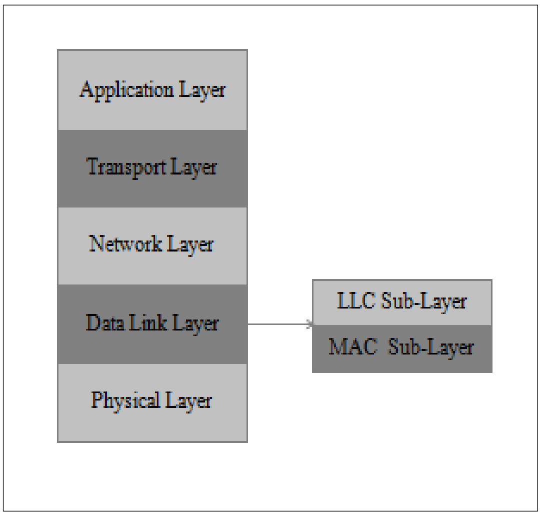


Figure 2.6: The Communication Protocol Stack. This five-layered simplified model is commonly applied to network research as apposite to the seven-layered OSI model. An end-user can use application specific software/algorithms at the application layer. The transport layer helps maintaining the sensor data flow. The network layer routes data on an appropriate path. The LLC sub-layer of the data link layer provides framing, flow control, error control, and link management facilities, whereas the MAC sub-layer manages collisions and helps in energy aware operations of sensor nodes. The physical layer takes care of the radio, channel, modulation, transmission, and reception of bits on a physical medium.

It provides the channel access mechanism to several medium sharing devices. On a wireless medium, which is shared by multiple devices and is broadcast in nature, when one device transmits, every other device in the transmission range receives its transmission. This could lead to an interference and collision of the frames when a transmission from two or more devices arrives at one point simultaneously. Sensor nodes usually communicate via multi-hop paths over the wireless medium in a scattered, dense, and rough sensor field. A MAC protocol manages the communication traffic on a shared medium and creates a basic network infrastructure for sensor nodes to communicate with each other. Thus it provides a self-organizing capability to nodes and tries to enforce the singularity in the network by letting the sender and receiver communicate with each other in a collision and error-free fashion.

Moreover, the typical requirement to increase lifetime of a WSN without the need of any power replacement and/or human interaction has prompted the development of novel protocols in all layers of the communication stack. However, prime gains can be achieved at the data link layer, where the MAC protocol directly controls the activities of the radio, which is the most power consuming component of resource-scarce sensor nodes. Efficient MAC protocols utilize the radio judiciously to conserve its energy. Thus the MAC protocol helps fulfilling important design objectives of WSNs by specifying how nodes employ the radio, share the channel, avoid collision in correlated and broadcasting environments, response the inquirer timely, and survive for a longer period. Hence, designing novel solutions for MAC protocols for WSNs has been and will remain a focal point for many researchers.

2.4.1. MAC Services

In general, the fundamental task of any MAC protocol is to regulate the fair access of sensor nodes to the shared medium in order to achieve good individual throughput and better channel utilization [15]. However, constrained resources, redundant deployment, and collaboration rather than competition among nodes considerably change the responsibilities of the MAC protocol for WSNs. On one hand, some relaxations may be granted to such MAC protocol. For example, nodes in WSNs usually send very small frames and use the channel occasionally, either periodically or whenever an important event occurs. Fairness in WSNs is not as important as in other networks, since nodes cooperate to achieve a common purpose. They remain idle or in sleep mode most of the time and rarely compete for the channel. Achieving good channel utilization is usually not considered as an important metric for WSNs. The data flow in WSNs is usually unidirectional, i.e., from nodes to the sink node, and end-users generally focus on the collective information rather than the individual throughput.

On the other hand, the MAC protocol for WSNs has some extra responsibilities to deal with as well. First and foremost is the issue of energy conservation. Since a distributed network of several nodes demands for long-time and maintenance-free operations, a MAC protocol irrespective to the scheme and work space it uses-certainly must have built-in power-saving mechanism. Along with energy efficiency and as per application requirements, provision of timeliness, adaptability to traffic and topology conditions, scalability, support for non-synchronized operations, and interaction with other layers via cross-layering may also play an important role in designing the MAC protocol for WSNs. Additionally, the ideal MAC protocol ensures self-stabilization, graceful adaptation, an acceptable delivery ratio, low overhead and low error rates for a WSN.

2.4.2. MAC Challenges

The design of MAC protocol for WSNs is a complex task due to the energy constraints, low transmission ranges, and compact hardware design of sensor nodes. Along with these factors, the event- or task-based network behaviour and application diversity of WSNs also demand for peculiar MAC schemes, which are not common with traditional wireless networks. Additionally, by virtue of the wireless broadcast medium, WSNs inherit all the well-known problems of wireless communication and radio propagation in the shape of interference, fading, path loss, attenuations, noise, and high error-rates [16].

The communication power of the node depends on several factors that include the type of modulation scheme used, data rate, transmit power, operational modes of the radio, and the switching frequency between these modes. At the same time, a MAC protocol can be made accountable for the following sources of energy waste, which mainly relate to the communication.

- **Idle listening:** Since a node in a WSN usually does not know when it will be a receiver of a message, it keeps its radio in ready-to-receive mode, which consumes almost as much energy as in receive mode. In low traffic applications, this is considered one of the major sources of energy waste.
- **Collisions:** A collision is a wasted effort when two frames collide with each other and are discarded because the receiver has to drop the overlapped information. A collision usually results in retransmission and drains more

energy in transmitting and receiving extra packets. The half duplex nature of the wireless medium precludes collision detection, thereby increasing the responsibilities of the MAC protocol. The high density of the deployed nodes, on one hand, helps improving network connectivity without compromising the transmission power. However, on the other hand, it increases collision probability for the MAC protocol by increasing the number of nodes contending for the channel.

- **Overhearing:** An overhearing occurs on the wireless broadcast medium when the node receives and processes a gratuitous packet that is not addressed to it. In the dense network and under heavy traffic situations, this could lead to a serious problem.
- **Control packet overhead:** An increase in the number and size of control packets results in overhead and unnecessary energy waste, especially when only a few bytes of real data are transmitted in each message. Such control signals also decrease the channel capacity. A balanced approach is required so that the required number of control packets can be kept at minimal.
- **Over-emitting:** An over-emitting or deafness occurs due to the transmission of the message when the destination node is not ready to receive it.
- **Complexity**: Computationally expensive algorithms might decrease the time the node spends in the sleep mode. They might limit the processing time available for the application and other functionalities of the protocol. An overly simple MAC algorithm can save higher energy than a complex one, but it may not be able to provide the complex functions such as adaptation to traffic and topology conditions, clustering, or data aggregation.

MAC protocols are vulnerable to other problems such as Hidden and Exposed Terminal Problem [17]. In Figure 2.7, the hidden terminal problem is illustrated as; node A sends to node B, while node C cannot receive from A. Node C wants to send to B, C senses a "free" medium. This will make collision at B, which means that node A is "hidden" for C.

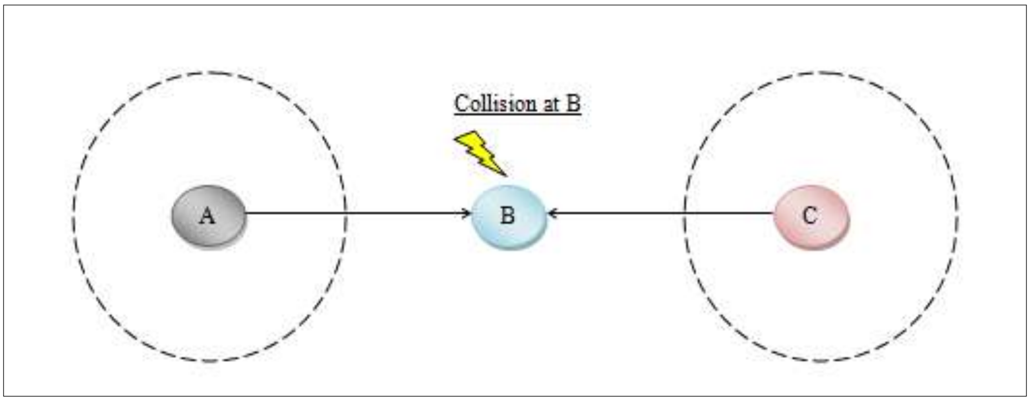


Figure 2.7: Hidden Terminal Problem.

Figure 2.8 shows the exposed terminal problem. In the meantime, node B sends to node A, and node C wants to send to node D. In this case, node C has to wait (medium in use). Since A is outside the radio range of C and the waiting is not necessary which mean that node C is "exposed" to node B.

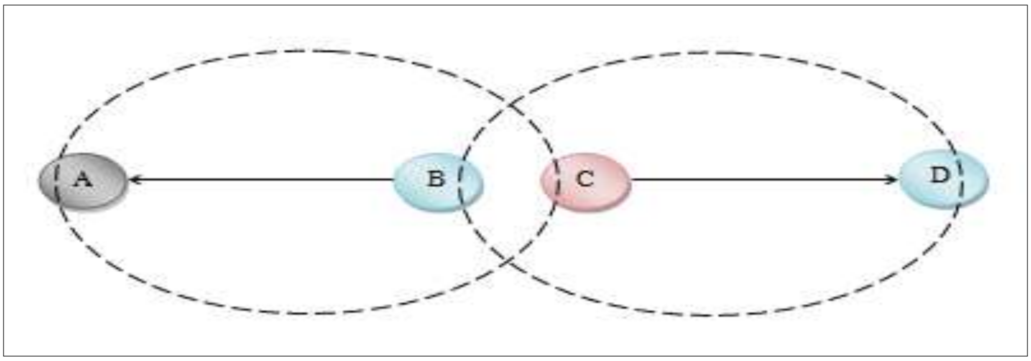


Figure 2.8: Exposed Terminal Problem.

2.5. Routing in WSNs

Routing is the process of selecting paths in a network, which is to determine a best path between the source and the destination upon the request of data transmission. As mentioned earlier, network layer is used to implement the routing process of the incoming data. Whereby, in multi-hop networks based WSNs, the source node couldn't directly reach the sink. Therefore, intermediate sensor nodes should relay the source packets to next step until reaching the sink. However, the implementation of routing tables might be given the solution. Routing table is defined as the task of the routing algorithm along with the help of construction / maintenance routing protocol. Routing table covers the lists of node option for any given packet destination.

2.5.1. Routing Challenges

Regarding to the consideration of sensor networks such as: different architectures, application, and design goals, the performance of a routing protocol are closely related to the architectural model [18].

- **Network dynamics:** in fact, there are very few setups to utilize sensors, for this reason, network architectures assume that sensor nodes are mostly stationary. Though, supporting the mobility of sinks or cluster-heads (gateways) is necessary. Moreover, the routing stability, energy, routing messages and bandwidth are considered the most important optimization factors in WSNs.
- **Node deployment:** The routing protocol performance has been affected by applying node deployment application. Besides, the deployment can be

categorised into two categories as: First, deterministic situation where the sensors are manually placed, and also data is routed through pre-determined paths. Second, self-organizing system where the sensor nodes are distributed randomly, as well as, the infrastructure is created in an ad hoc manner. Somehow, the cluster-head or the position of the sink is also crucial regarding to the terms of performance and energy efficiency.

- **Energy considerations**: The process of routes setting up is greatly influenced during the creation of an infrastructure. Typically, multi-hop routing is consuming less energy than direct communication, since the transmission power consumption of a wireless radio in the presence of obstacles is directly proportional to distance. However, if all the nodes are very close to the sink, then direct routing is applied with well enough performance. Multi-hop routing introduces significant overhead for topology management and medium access control. Over an area of interest, sensors are mostly scattered randomly and multi-hop routing becomes inevitable.
- **Data delivery models:** Data delivery model to the sink can be classified depending on the application of the sensor network into: continuous, event-driven, query-driven and hybrid. In the continuous delivery model, sensor must send data periodically. Whereby, the transmission of data is triggered when the sink generates a query or an event occurs in event-driven and query-driven models. Hybrid model is a combination of continuous, event-driven and query-driven data delivery models. However, the routing protocol is highly influenced by the data delivery model, especially to minimize the energy consumption and route stability.

- **Data aggregation fusion**: in data transmission, similar packets from multiple nodes can be gathered to reduce the transmission flow, since; these sensor nodes sometime generate significant redundant data. Data aggregation is the combination of data from different sources, and it has been done by using some functions such as: suppression (eliminating duplicates), min, max and average.

2.6. Cross Layer Design and Optimization

Cross layer design with respect to the particular layered architecture is known as a protocol design by the violation of reference layered communication architecture [20]. Generally, the protocols relying on interaction between various layers of the protocol stack can be also called as cross layer design. On other hand, it is defined as the breaking of OSI hierarchical layers in communication networks [19]. In general, cross layer design is concluded as the interaction between various layers or the violation of reference architecture include merging of layers, the breaking of OSI hierarchical layers, creation of new interfaces, or providing additional interdependencies between any two layers.

However, developed robust and scalable protocols for the Internet has been simply designed by combining the design of a layered protocol stack with static interfaces between independent layers, whereby this combination performs poorly for wireless ad-hoc networks [21]. Statistically, the optimal performance for different network parameters like energy efficiency or delay can be utilized by the inter-dependencies between different layers.

2.7. Related Works

Medium Access Control (MAC) protocol has a frame format which is used to provide the data link layer of the Ethernet LAN system to control access over the communication channel. In general, well-known MAC protocols include Ethernet [22] and MAC is used in the IEEE 802.11 (Wi-Fi) family [23]. However, there are several various types of MACs have been developed for WSNs. This section discusses the various types of MAC protocols by categorizing them in different channel accessing classes and then cross-layer protocols, but before that we would explicate brief history about channel accessing schemes, as follows:

2.7.1. Channel Accessing Chronology

The nature collision in wireless broadcast medium requires an efficient channel accessing method to control access to the shard medium. Therefore, this collision can offer free communication among nodes. Specifically, accessing the channel is classified into two major categorizations; contention based networks and contention free networks. In contention based networks, devices are contending each other to gain access of the channel. Whereby, contention free networks uses time or frequency to schedule the channel. In this category, devices can only access their allocated channel slots, and these devices communicate with the central node in a collision free method.

On the other hand, accessing channel scenarios have been already proposed to find the answer of who is allowed to access and how can access. However, the Additive Link On-Line Hawaii System (ALOHA) protocol [24] is proposed in 1970s and also defined as pure ALOHA. This protocol is considered as one of the pioneer protocols in this category. It allows devices' data to be transmitted immediately when they have data to send. ALOHA is a simple and decentralized MAC protocol works seamlessly under low loads [24]. In ALOHA, the slotted ALOHA is used to double ALOHA utilization by subdividing the time into slots. In this case, collisions can occur only at the beginning of the slot, since the node is allowed to start a transmission only at the beginning of a slot. However, slotted-ALOHA reduces the collisions probability by doing synchronization among nodes.

Commonly, the Carrier Sense Multiple Access (CSMA) scheme is used in wired and wireless Local Area Networks (LANs). CSMA can sense the transmission of other nodes before starting a node its transmission. Therefore, CSMA is considered as a contention based access protocol, as well as it is simple, flexible and robust especially for the dynamic networks topology. However, this scheme is still suffering from serious energy waste, high overhead and throughput degradation which are caused by the additional collisions [25]. The distributed interfering sensor scheduling (DSS) algorithm proposed in [26] is based on CSMA. This algorithm requires frequently negotiation between the sensor nodes to decide the node tasks and the results in high energy consumption.

In CSMA-CA scheme, Collision Avoidance, it is introduced among other approaches to minimize the impact of the hidden and exposed terminal problems. However, CSMA-CA introduces four-way handshake mechanism to achieve successful communication between sender and receiver. On the other hand, IEEE 802.11 is also considered as a conventional MAC protocol [23].

2.7.2. Classification of WSN MAC Protocols

Several MAC protocols have been successfully proposed to meet the stringent design requirements of WSNs. Actually; these protocols depend on how protocol allows nodes to access the channel. We have classified WSN based MAC protocol as depicted in Figure 2.9 into four categories. These categories are contention based, scheduling based, channel polling based, and hybrid protocols.

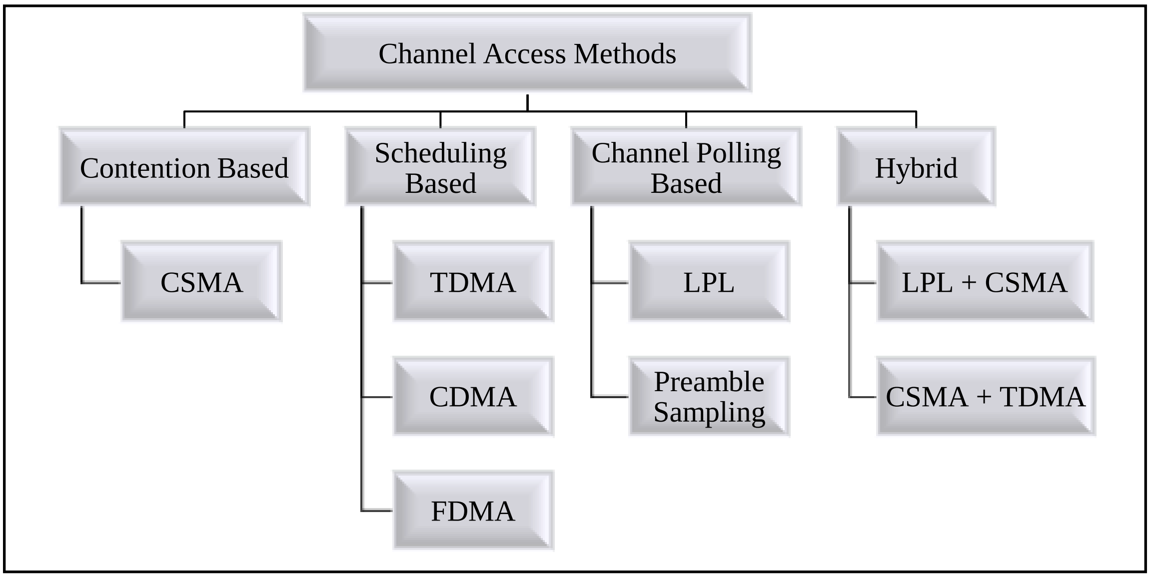


Figure 2.9: Channel Accessing Taxonomy in WSNs.

2.7.2.1. Contention Based MAC Protocols

As mentioned earlier, nodes using contention based schemes are working on acquiring the channel. Hence, the network node competes with its neighbors to get the channel. This process will be done when the node senses the carrier before getting started with data transmission. If the carrier is set up as idle, then node will start its transmission, otherwise node will defer the transmission for some time randomly. This deferring is usually determined by a back-off algorithm. Event-driven WSN applications use contention based MAC protocols to reduce the processing resources consumption. However, contention based MAC protocols are flexible and dynamics to network scales. Since, clustering and/or topology information are not required for their works. Hereby, each node in the network can independently decide for contention without controlling the frame exchanges. In this case, the transmission is purely handled by sender, as well as the problems of hidden and exposed terminals may occur causing collisions, overhearing, idle listening, and less throughput in the result.

There are several MAC protocols consider the contention times as synchronized according to a schedule, i.e., at each periodic interval, all neighboring nodes wake up simultaneously to exchange packet. Some representative protocols are showen in [27], [28], [29], and [30].

2.7.2.2. Channel Polling Based MAC Protocols

Channel polling scheme is known as a preamble sampling and Low Power Listening (LPL). Moreover, sending prefixes data packets with extra bytes are called a preamble. Specifically, node sends the preamble over the channel to ensure that the destination node detects the radio activity and wakes up before arriving the actual payload from the sender. On a wake-up, if a radio activity is detected by receiver, it will turn on its radio to receive data packets. Otherwise, the node (receiver) goes back to the sleep mode until the next polling interval [26]. On other hand, since the common active/sleep schedules are not performed in channel polling based protocols, then the synchronization, scheduling, or clustering among nodes are not needed.

As proposed in [31], the combination of ALOHA with the preamble sampling is considered as pioneer and typical example of the extended preamble based channel polling scheme. Also, the channel polling scheme has been renamed as the LPL in the Berkeley MAC (BMAC) protocol [32].

2.7.2.3. Hybrid MAC Protocols

In order to achieve a joint improvement, hybrid MAC protocols combine the strengths of two or more different MAC schemes. Usually, hybrid MAC protocols combine a synchronized scheme with an asynchronous scheme. Though hybrid protocols cumulative the advantages of multiple schemes, they can also carry, scaling and complexity problems in maintaining two or more different working modes. Zebra MAC (Z-MAC) [33] protocol is one of the most important example in hybrid scheme, which combines the strengths of TDMA and CSMA while offsetting their weaknesses. As well as, the Scheduled Channel Polling MAC (SCP-MAC) [34] and Funneling-MAC protocol [35] are also two important examples on this scheme.

2.7.2.4. Scheduling Based MAC Protocols

During the initialization phase, scheduling based schemes assign collision-free links between neighboring nodes. However, links may be allocated as frequency division multiplexing (FDM) bands, time division multiplexing (TDM) slots, or code division multiple access (CDMA) based spread spectrum codes. Due to the complexities that incurred with FDMA and CDMA schemes, therefore, WSNs prefer TDMA schemes as scheduling methods to reduce the incurred complexity [25]. In TDMA schemes, the system time is divided into slots. These slots are then assigned to all the neighboring nodes. The schedule controls the participant authorization on the resources with regular time. The schedule is typically regulated by a central authority; as well it can be fixed or computed on demand (or a hybrid). On other hand, a node does not need any contention with its neighbors, since it can only access its allocated time slot.

Likewise, the minimum collisions, the less overhearing, and the implicitly avoidance of idle listening are all grouped as the main advantages of scheduling based schemes. Scheduling based schemes also provide a bounded and predictable end-to-end delay. The average queuing delay is normally high, since the node should wait for its allocated time slot before accessing the channel. However, there are other major concerns with these schemes such as; overhead and extra traffic, lacking of adaptability, reduced scalability, and low throughput. In scheduling based schemes, allocating conflict-free TDMA schedules is really difficult task. TDMA- based MAC protocols has attracted attentions of sensor network researchers [36]. This study depicts some of the representative protocols of this category.

As proposed in [3] some numerous design of wireless MAC protocols based on time division multiplexing have been suggested, while some of them need global topology information that may not be scalable for very large-size networks [37] [38]. However, many distributed slot assignment schemes have been proposed, such as; DRAND [39], PACT [40], and TRAMA [41] to overcome the difficulty of obtaining global topology information in the large networks. Additionally, the depth first search (DFS) scheme [37], the green conflict free (GCF), and the multicolor-GCF (M-GCF) algorithms [12] obtain local topology and interference information at each node. These approaches compose schedules by exchanging messages between local nodes within a certain range (i.e., the interference range). However, comparing the distributed scheduling with the approaches demanding global topology information is highlighting that the distributed scheduling is more flexible, but the cost is increased according to the schedule length [3].

Flow-Aware Medium Access (FLAMA) [42] is a TDMA - MAC protocol derived from TRAMA, and optimized for periodic monitoring applications. The main idea in FLAMA is to avoid the overhead that associated to the exchange of traffic information. Meanwhile, classical slot reservation algorithms tend to be complex and not flexible. Therefore, some researchers have been proposed successfully to investigate simpler schemes which simultaneously aim to achieve good energy efficiency. For example, a low-complexity slot selection mechanism is adopted in [43], whereby a lightweight medium access protocol (LMAC) is proposed [43]. Mainly, LMAC aims to reduce the radio state transitions and the protocol overhead. To achieve this aim, data is not acknowledged in LMAC; as well the actual slot assignment is based on a binary mask of occupied slot and a random selection among free ones. However, the main drawback of LMAC is based on the fixed length of the frame, which has to be specified prior to deployment, and may be problematic. To this end, article [44] proposed an Adaptive Information-centric LMAC (AILMAC), so the slot assignment can be more tailored to the actual traffic needs.

2.7.3. Cross-layer Protocols

As proposed in [37], [38], [39], [40], [41], [42], [43], and [44], these studies are basically focused on MAC layer. However, working with single layer may lead us to inefficient utilization for network resources. Recently, camping between cross-layer design approach and TDMA scheduling is to obtain prolonged network lifetime. In

[45], joint routing, link scheduling, and power control are strongly considered to support high data rate for broadband wireless multi-hop networks. A framework for cross-layer design toward energy-efficient communication is presented in [46]. In [47], authors address the joint link scheduling and the power control with the objective of energy efficiency subject to QoS guarantees in terms of bandwidth and bit error rate (BER).

Interference-free TDMA schedules are calculated in [47] for a small-scale network by joining the optimization of the physical, MAC, and the network layers. Also authors use convex optimization to solve the cross-layer-based network lifetime optimization problem, in addition to employ the interior point method [48]. On the other hand, a single frame without slot reuse for the whole network is to guarantee of non-interference. This also leads to significant end-to-end delay, which makes this approach unsuitable for large-size WSNs. In [49], authors consider both joint layer optimization and the slot reuse to derive energy-efficient schedules. A convex cross-layer optimization model is proposed and solved iteratively to maximize the network lifetime. The link schedules evolve at each iteration until reaching the specific energy consumption goal or the iteration is performed with no more optimal solution.

Unifying sensor-net protocol in [50] proposed a unified SP to provide shared neighbor management and a message pool. This protocol runs on a single link layer technology over a broad range of devices, it supports a variety of network protocols while not losing efficiency. The unified SP allows network level protocols to choose their neighbors wisely based on the available information that in the link layer. This protocol can be professionally used in some experiments were carried out using two types of radio technology, such as; IEEE 802.15.4 on Telos and B-MAC on micas.

The use of on-off schedules in a cross-layer routing and MAC framework is also investigated in [51]. In [52] work, a TDMA-based MAC scheme is devised, where nodes select their appropriate time slots based on local topology information. The routing protocol also exploits the local topology information for routing establishment. In terms of energy and network lifetime, EYES MAC protocol was compared against the sensor-MAC (SMAC) [52], as EYES MAC protocol was also compared against the dynamic source routing (DSR) [53]. However, EYES MAC protocol outperforms SMAC and DSR when nodes are network based mobile system. In a mobile network, there may be regular updates on routing system due to route breakage. EYES MAC protocol minimizes the overhead in routing and re-establishment the route by utilizing the information from the MAC protocol. Whereby, SMAC and DSR perform better when nodes are static as well when the routes are established only once.

In article [54], the researchers present the objectives of MAC/Physical layer integration and Routing/MAC/Physical layer integration. They propose a variable length TDMA scheme where the slot length is assigned to some optimum energy consumption criteria in the network. The researchers [54] formulate a Linear Programming (LP) problem where the decision variables are normalized time slot lengths between nodes. In general, it is really hard to have the node distance information and the traffic generated by the nodes themselves. LP solver could only be run on a powerful node. However, online decisions are required for the dynamic behaviors of sensor networks, whereby, these decisions are very costly in terms of calculation and hard to be adapted in an existing system.

The unified cross-layer protocol [55] combines the functionalities of the transport, network and medium access protocols into a single module. Although, the unified cross-layer module (XLM) achieves energy efficiency and reliable event communication.

Article [56] addresses three main titles which are: a cross-layer optimization problem of joint design of routing, medium access control (MAC), and physical layer protocols with cooperative communication. As the aim of article [56] is majored to achieve the minimum power cost under a specified per-hop packet error rate (PER) objective in wireless sensor networks.

However, The TDMA MAC protocol is based upon cross-layer optimization, Physical layers and MAC [3]. The main goal in TDMA MAC protocol is to reduce the energy consumption. It proposes an algorithm for driving the TDMA schedules by utilizing the slot reuse concept to achieve the minimum TDMA frame length.

CL-MAC protocol [57] is a novel cross-layer MAC protocol. Significantly, it is different from other MAC protocols since it is supporting construction of multi-hop flows. Moreover, all pending packets in the routing layer buffer and all flow setup requests from neighbors are in the CL-MAC considerations, which will be occurred when setting up a flow in CL-MAC. These considerations allow CL-MAC to make more informed scheduling decisions, reflecting the current network status, and optimizing its scheduling mechanism dynamically.

In [58], a cross- layer routing protocol (PLOSA) is designed to offer a high delivery rate, a low end-to-end delay and low energy consumption. To achieve these goals, the transmission channel is divided into different slots and a sensor has access to a slot related to its distance from the collector. The transmissions are then ordered within the frame from the farthest nodes to the closest ones which is a key point in order to ease forwarding and to conserve energy.

Authors in [59] proposed a cross-layer optimized geographic node-disjoint multipath routing algorithm, that is, two phase geographic greedy forwarding plus. To optimize the system as a whole, their algorithm is designed on the basis of multiple layers' interactions, taking into account the following physical layer; sleep scheduling layer and routing layer.

In this context authors proposed cross layers protocol in [60], based on the combined use of a duty-cycling protocol and a new kind of active wake-up circuit, based on a very-low-consumption radio frequency (RF).

In [61], authors investigate the problem of transmission power minimization and network lifetime maximization using cooperative diversity for wireless sensor networks, under the constraint of a target end-to-end transmission reliability and a given transmission rate. By utilizing a cross-layer optimization scheme, distributive algorithms which jointly consider routing, relay selection, and power allocation strategies are proposed for the reliability constraint wireless sensor networks.

Although various MAC protocols have been proposed, there is a possible future work for system performance optimization such as; Cross-layer optimization, Cross-layer interaction, etc. Hence, Cross-layer optimization is a MAC protocol area that should be explored more extensively. Cross-layer interaction can reduce packet overhead on each of the layers, thereby can reduce the energy consumption. Many existing MAC protocols have been successfully addressed to present the performance studies of the static sensor nodes, but still there is a lack of literature for comparing these protocols with mobile network. However, enhancing the MAC protocol can significantly improve communication reliability and energy efficiency.

Chapter 3: Schedule-Based MAC Protocol

Chapter 3

Schedule-Based MAC Protocol

3.1. Introduction

Medium Access Control (MAC) protocols for WSNs greatly influence the energy consumption of sensor nodes by controlling the functionalities of radio, which is the most power consuming component of a sensor node [30]. Each sensor node can be in active (for receiving and transmission activities), idle or sleep mode. In active mode, nodes consume energy when receiving or transmitting data. In idle mode, the nodes consume almost the same amount of energy as in active mode, while in sleep mode, the nodes shut down the radio to save energy. A node's main waste of energy is due to the following factors collision, ideal listing, control packet overhead and overhearing [62].These factors were detailed in sub-section 2.4.2. The first cause is collision that occurs when different nodes transmit at the same time which causes the failure of data and need retransmission. The second major cause for energy wastage is idling listening, i.e., listening to receive possible traffic that is not sent. This is especially true in many sensor network applications. If nothing is sensed, nodes are in idle mode for most of the time. The third cause is control packet overhead where sending and receiving control packets consume energy too, and less useful data packets can be transmitted. The last cause is overhearing, meaning that a node picks up packets that are destined to other nodes.

Furthermore, a common mechanism to reduce energy consumption is to turn the transceiver of sensor nodes into a low power sleep state when it is not being used. In order to exploit the desired cross-layer approach and to reduce the WSN power consumption, an efficient schedule algorithm should be designed. In this section, a MAC schedule protocol is proposed.

3.2. Schedule-Based MAC Protocol

This part of research mainly contributes towards the design of an efficient schedule algorithm. Our proposed MAC method focuses on increasing the sleep periods as much as possible, reducing overhead, reducing overhearing, avoiding collision, and avoiding the hidden and exposed terminal problems, as shown in Figure 3.1. The proposed MAC method employs a distributed scheme by selecting temporary admin node to schedule the transmissions between the nodes based on their high level layer status, and then the admin node will distribute the shift schedule (shift table) to nodes in its cluster. However, admin node is able to distribute the shift schedule over its cluster by specifying which nodes are actually should send and to which destinations during each time slot. This hierarchical algorithm has advantages in improving network's robustness and flexibility, and it is more appropriate for large scale of networks [63]. The proposed method consists of three sub-protocols: the Cluster Status Protocol (CSP), the Schedule Protocol (SP), and the Adaptive Protocol (AP). Moreover, the proposed method assumes a single, time-slotted channel for both data and signaling transmissions. Since, this method specify special ID for each node in the cluster, the node can directly communicate with other node by sending dynamic wake-up packet that carrying the specific ID for the intended node (destination).

The operation of proposed MAC method is divided into rounds. Each round begins with a CSP sub-protocol when the clusters are organized, followed by SP sub-protocol and AP sub-protocol.

The functional architecture of the proposed schedule algorithm and the basic operation is illustrated in Figure 3.2.

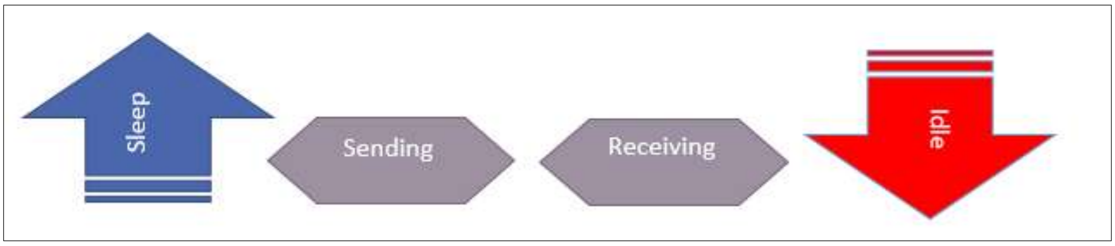


Figure 3.1: The Main Objectives of the Proposed MAC Method with Respect to Power Consumption.

3.2.1. Cluster Status Protocol (CSP)

Hierarchical algorithm is one of the most popular researches in WSNs. In this type of algorithm, sensor nodes would be divided into several parts according to some rules, and every part means a cluster. This kind of algorithm has the advantages as the energy consumption of sensor node is more balanced, and the robustness of WSNs is strong [63]. In WSNs, nodes may die (power drained) or new nodes may be added (additional sensors deployed). To accommodate topology dynamics, the proposed method alternates between random- and scheduled access. This method starts in random access mode where each node transmits its information by selecting a slot randomly. Nodes can only join the network during random access periods. As well as, nodes have to define themselves and give more details about schedule interval, communication, and data packets according to their activities. Since, is assumed to be dynamic WSN, random access periods should occur more often. However, each node in the cluster is identified by unique ID that is obtained from the base station. During random access periods, all nodes must be in either transmit or receive state, so they can send out their updates and receive the schedule from its admin node.

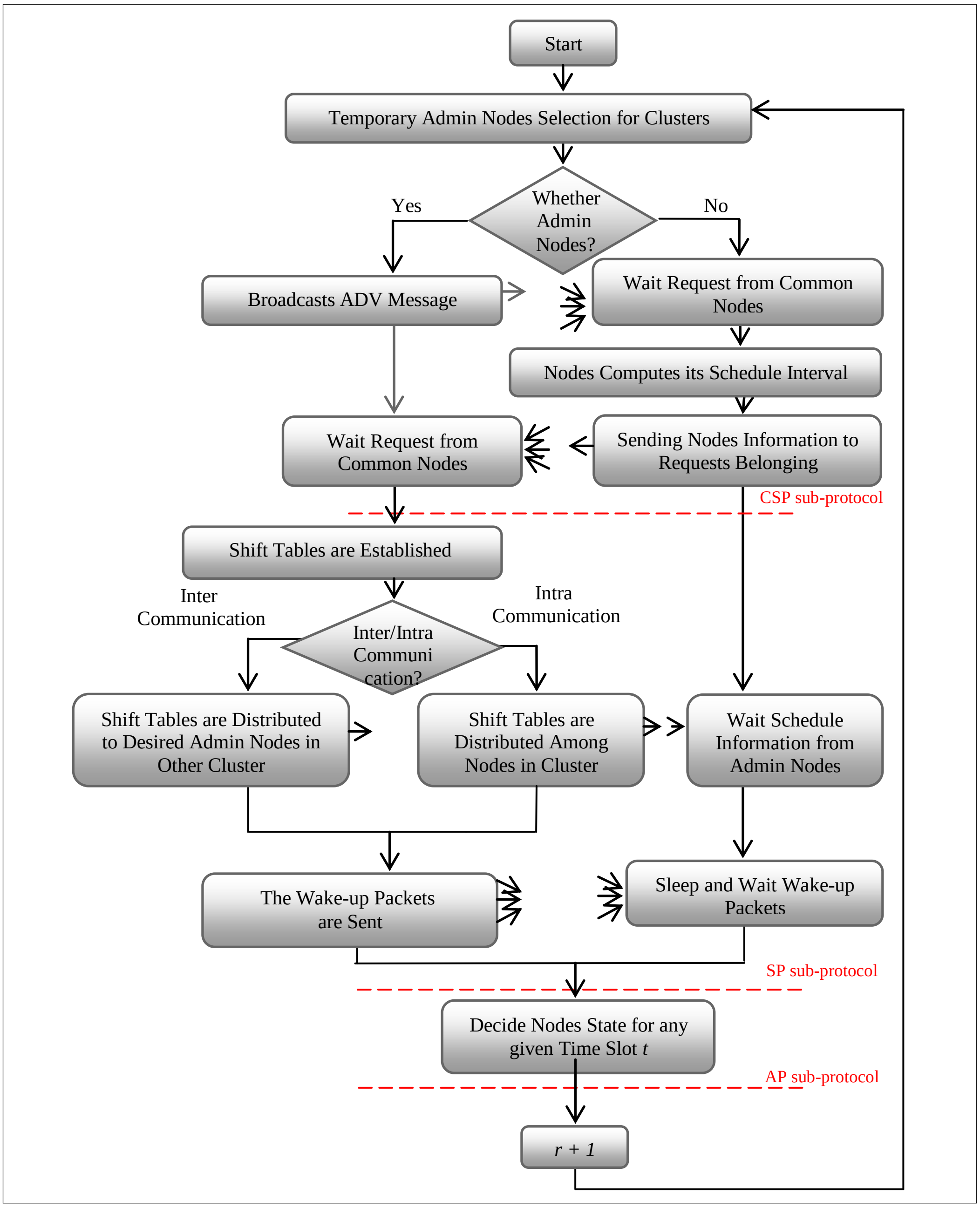


Figure 3.2: The Functional Architecture.

CSP forms clusters by using a distributed algorithm, where nodes make autonomous decisions without centralized control and elect the temporary admin node. This admin node is then produces shift table to organize data transmissions between nodes based on nodes' loads and priorities during time slots. Figure 3.3 shows an example of one cluster where it consists of five nodes A, B, C, D and E; node C is the temporary admin node for the current random access period.

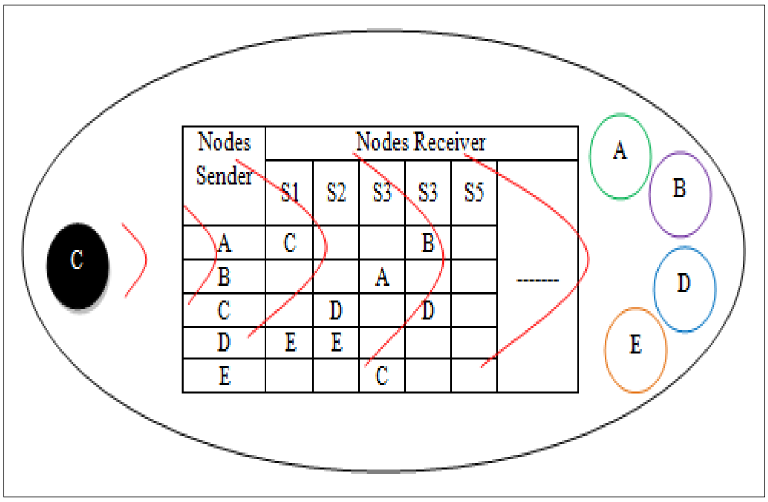


Figure 3.3: The Temporary Admin Node "C" Distributes the Shift Schedule for Nodes in its Cluster.

The CSP employs a cluster formation algorithm such that there are a certain number of clusters in the communication during each round. However, if nodes begin with equal energy, the main aim attempts to distribute the energy load equally among all the nodes in the communication. Furthermore, this process respects that there are no overly-utilized nodes that will run out of energy before the others. In the clustered network, admin nodes in each cluster are being as much more energy intensive than non-admin nodes, this requires that each node takes its turn as admin node. Given round *r*, at the beginning of round $r + 1$, each sensor node *i* elects itself to be an admin node that starts at time *t* with probability $P_i(t)$. As shown by Equation 3.1,

$P_i(t)$ is chosen such that the expected number of cluster admin nodes for the round r is k in a network with N nodes

$$E[\#Admn] = \sum_{i=1}^{N} P_i(t) = k \qquad (3.1)$$

Where $E[\#Admn]$ is the expected number of cluster admin nodes for the round $r+1$. In general, ensuring that all nodes are admin nodes the same number of times requires each node to be an admin nodes once in N/k rounds on average. As shown by Equation 3.2, $C_i(t)$ is an indicator function determining whether the node is an admin node or not in the most recent r mod N/k rounds. In Equation 3.2, $C_i(t)=0$ means that node i has been an admin node, while $C_i(t)=1$ if the node wasn't admin node recently, as well each node should be chosen to become admin node at round r.

$$P_i(t) = \begin{cases} \dfrac{k}{N - k * \left(r \bmod \dfrac{N}{k}\right)} & : \ C_i(t) = 1 \\ 0 & : C_i(t) = 0 \end{cases} \qquad (3.2)$$

Therefore, admin nodes may be designed at round $r+1$ such that nodes have not been admin nodes before and probably have more energy power than other nodes. However, the expected number of nodes that have not already employed as admin nodes in the first r rounds is formulated as $N-k*r$. After N/k rounds, all nodes are expected to be as admin node, since all nodes are eligible to perform this task in the next sequence of rounds. In Equation 3.2, $C_i(t)$ is initialized to 1, if node is eligible to be an admin node at time t. otherwise, $C_i(t)$ is valued as 0. Whereby, the term

$\sum_{i=1}^{N} C_i(t)$ computes the total number of nodes in the network that are eligible to be employed as admin node at time *t* and

$$E\left[\sum_{i=1}^{N} C_i(t)\right] = N - k * \left(r \bmod \frac{N}{k}\right) \qquad (3.3)$$

Actually, this process ensures that the energy at all nodes is approximately equal to each other after every round. Moreover by using (3.2) and (3.3) the Equation 3.4 computes the expected number of admin nods per round.

$$E[\#Admn] = \sum_{i=1}^{N} P_i(t)$$

$$= \left(N - k * \left(r \bmod \frac{N}{k}\right)\right) * \frac{k}{N-k*\left(r \bmod \frac{N}{k}\right)}$$

$$= k \qquad (3.4)$$

As mentioned earlier, the probability choice of selecting admin node is based on the assumption that all nodes start with an equal amount of energy, as well as all nodes are also have data packet to be sent over the communication. On the other hand, the assumption of selecting admin node between different amounts of nodes' energy can be successfully designed by selecting the highest energy nodes as admin nodes, to ensure that all nodes die at approximately the same time. Furthermore, this assumption can be achieved by setting Equation 3.5 as the probability of becoming an admin node as a function of a node's energy level relative to the aggregate energy remaining in the network, rather than the purely process that is based on the function of computing the number of times the node has been admin node (refer to Equations 3.5 and 3.6). Whereby, $E_i(t)$ is illustrated as the current energy of node i and using these probabilities.

$$P_i(t) = \min\left\{\frac{E_i(t)}{E_{total}(t)}k, 1\right\} \quad (3.5)$$

Where $E_{total}(t) = \sum_{i=1}^{N} E_i(t)$ (3.6)

Referring to Equation 3.7, more likely to select admin nodes from the higher nodes energy than nodes with less energy. Hence, the expected number of admin nodes is presented by Equation 3.7.

$$E[\#Admn] = \sum_{i=1}^{N} P_i(t) = \left(\frac{E_1(t)}{E_{total}(t)} + \ldots + \frac{E_N(t)}{E_{total}(t)}\right) k = k \quad (3.7)$$

Once the nodes have elected themselves to be admin nodes using the probabilities in Equation 3.2 or 3.5, each admin node must announce itself to all other nodes in the network. However, each admin node broadcasts an advertisement message (ADV) using a non-persistent carrier-sense multiple access (CSMA) MAC protocol [64] during the random access period. This message is actually small message contains the node's ID and header which clarifies this message as an announcement message.

On the other hand, each non-cluster admin node determines its cluster for this round by choosing the admin node. Though, this process requires the minimum communication energy, based on the received signal strength of the advertisement from each admin node. Commonly, assuming symmetric propagation channels for pure signal strength, the admin node advertisement heard with the largest signal strength, since the admin node requires the minimum amount of transmit energy to apply the communication. Typically, the admin node closest to the sensor, unless there is an obstacle impeding the communication, in the case of this kind of communication, a random admin node is chosen.

After that, each node has decided to which cluster it belongs, it must inform the cluster admin node that it will be a member of the cluster by exchanging small signaling packets during the random access period using a non-persistent CSMA MAC protocol. These packets are again short packets, consisting of the admin node's ID and the nodes information such the node's ID, destination's ID and schedule interval as shown by Figure 3.4. In CSP sub-protocol, each node computes a schedule interval based on the rate at which packets are produced by the higher layer application.

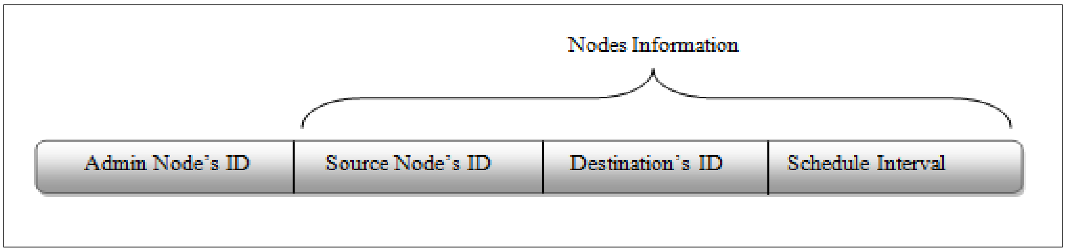


Figure 3.4: Signalling Packet Format.

Clustering scheme for proposed MAC method organizes the nodes of the sensor network into two virtual domains, such as intra-cluster and inter-cluster domain. In the intra-cluster domain, the admin node schedule the communication between the nodes within the cluster directly (single hop) or through other nodes (multi hop). Since the radio channel has high contention in the intra-cluster domain, the proposed

MAC method is utilized for achieving high energy efficiency. In the inter-cluster domain, the communication is between separated clusters. The admin nodes should exchange their shift tables before distributing them to the nodes in the cluster.

3.2.2. Schedule Protocol (SP)

In SP, admin node establishes and maintains traffic-based schedule information required by the transmitter and receiver. A node's schedule is distributed by the temporary admin to the nodes in the cluster in intra-cluster domain or other admin nodes in inter-cluster domain, since the admin schedules the transmission traffic between the nodes in the network based on time slots. In the proposed method, this schedule is defined as shift table or shift schedule refered to by Figure 3.5, for the example shown by Figure 3.3 by admin node to avoid the collision between nodes in the network during their transmissions. However, the proposed method reduces the wasteful power consumption by increasing the sleep periods as much as possible and, avoiding overhead, reduce overhearing, collision problem. As well as, sending and receiving data packets are defined as useful power consumption.

Hence the proposed method supposes that all nodes should sleep by default while the nodes are not scheduled to be active for sending or receiving data by referring to the shift table. The proposed MAC enables nodes to communicate parallel in the cluster refer to Figure 3.6, since each node has its special ID and the transmission is presented by the shift table to avoid collision, exposed and hidden problems. This method improves the energy efficiency while the node calls its destination (or receiving) node by sending short and dynamic wake-up packet which carrying the ID for the intended node.

Node Sender	Node Receiver					
	S1	S2	S3	S4	S5	
A	C			B		
B			A			....
C		D		D		
D	E	E				
E			C			

Figure 3.5: An Example for Shift table – Transmission Status.

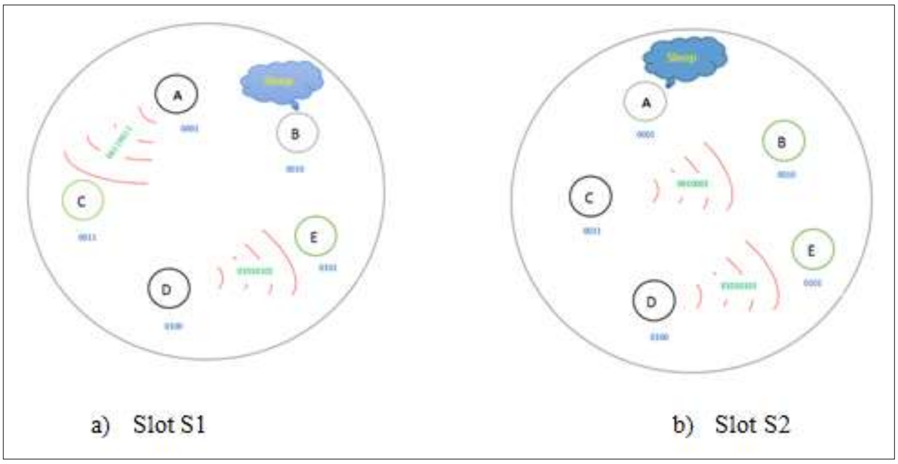


Figure 3.6: Transmission Status.

For the wireless network cluster with *N* nodes, the first step in intra-cluster proposed protocol is to count the number of nodes for current transmission N_c. Two nodes can directly establish their communication based on their shift table schedule. This is started by sending wake-up packet from the sender node to the destination node in t_w time process. Since the sending wake-up packet carries the ID for intended destination. Meanwhile, the destination node is already scheduled to receive from the sender (by the distributed shift table), but it must be sleep until receiving the wake-up packet that includes its specific ID (refer to Figures 3.7 and 3.8). Directly, the sender will then transmit the data packet to the wake-up node during t_a.

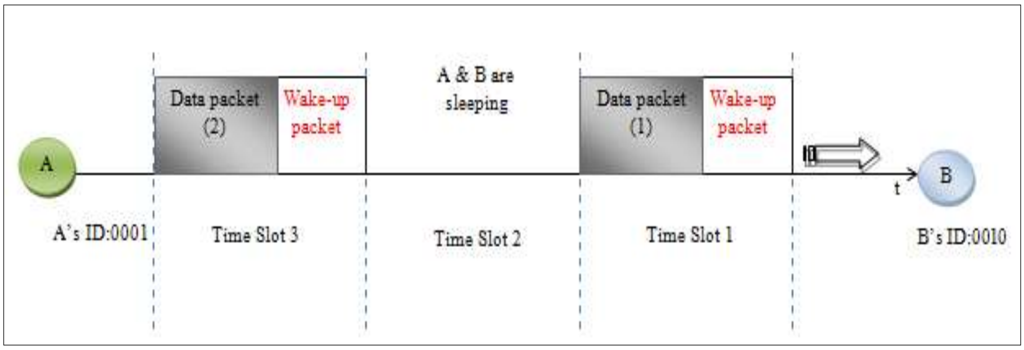


Figure 3.7: Node A is Waking-up and Sending to Node B at two Different Slots.

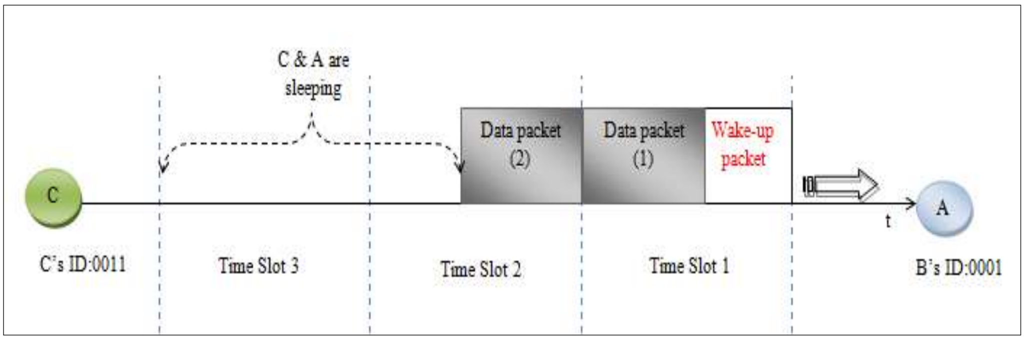


Figure 3.8: Node C is waking-up and Sending to Node A at "S1" and Sub of Slot "S2".

Based on the presented shift table, the schedule information of the node is updated periodically. The transmitter node can wake-up the receiver only by sending wake-up packet that involves the ID for the receiver node. We assume that the wake-up packet is 8 binary bits, it duplicates the destination node ID as a signal for the destination as (refer to Figure 3.7). Figure 3.9 shows the format of the wake-up packet. Nodes A and B should be sleeping at time slot 2 as shown by Figure 3.7.

Referring to Figure 3.8, it is possible for a node to get some extra sub-slots for transmissions as a winning sub-slots time, since data packet 2 will be sent to node A without wake-up packets. This process actually increases the network performance in terms of avoiding the overhead, and overhearing cost.

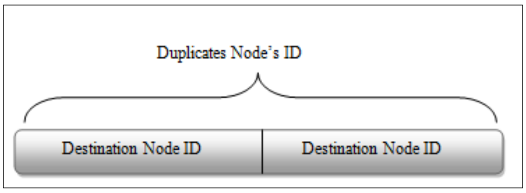


Figure 3.9: Wake-up Packet Format.

The transmission time for sending single data packet between two nodes is computed by Equation 3.8, whereby Equation 3.9 is generalized to compute the transmission time for the N_c nodes at the same time.

$$t_x = (t_a + t_w) \qquad (3.8)$$

$$t_c = \sum_{i=0}^{N_c} t_{a(i)} + t_{w(i)} \qquad (3.9)$$

Where t_x is the transmission time for sending single data packet between two nodes, t_a is the time to access node, t_w is the wake-up time, $t_c$is the transmission time for the N_c nodes at the same time and N_c: # of nodes that transmit their data packets at the same time.

3.2.2.1. An example for shift table of transmission status in intra-cluster domain:

As the window of traffic (shift table) shown by Figure 3.5, node A is scheduled to send node C at slot "S1" and node B at slot "S4". While node D is scheduled to send node E at slot "S1" parallel to node A at the same time slot "S1" in this example. This process is actually proposed to avoid the exposed and hidden problem (refer to Figure 3.6). Furthermore, Figure 3.5 shows that the proposed method can avoid overhead problem, since node D sends two packets continually to node E at slot time "S1" and slot "S2". This process is actually can be successfully done in the proposed MAC by using single wake-up packet to node E (refer to Figure 3.8).

On the other hand, if a node does not have enough packets to transmit, it announces that it gives up the corresponding slot (S). This situation occurs when the data transmission is stopped as a result of a technical fault in the network or in the transmitted nodes. Other nodes that have data to transmit can make use of these “available” slots after the admin node re-organizing process. However, this process is called winning case, since some parts of the time slots can be saved for another transmission.

As the distributed shift table based on t transmission time between N nodes, the transmission consumption time for N nodes are calculated depending on Equation 3.10.

Whereby, the switching process is also concerned to change the transmission situation between the scheduled nodes. The switching time is defined as t_s, and reserved for each transmission situation when the current transmitted nodes are changed.

$$t_N = \sum_{i=1}^{N}((t_{a(i)} + t_{w(i)}) + t_s) \rightarrow t_N$$

$$= \sum_{i=1}^{N}(t_c + t_{s(i)}) \qquad (3.10)$$

Where t_N is the total time to transmit *N* nodes at *t* time, $t_{a(i)}$ is the access time to transmit node *i*, $t_{w(i)}$ is the wake-up time node *i* and t_s is the switching time.

However, Figure 3.8 presents the possibility of sending series of data packets continuously between two nodes depending on the shift table (refer to Equation 3.11). In this case the sender node has to send only one single wake-up packet to the receiver node, then series of data packets will be flowed to the receiver respectively. Furthermore, this case is defined as the best situation since the power consumption is reduced by decreasing over heading problem (refer to Equation 3.12). However this situation is also being as winning case as the communication can win time slots for data transmissions instead of sending wake-up packets.

$$t_b = t_w + \sum_{i=1}^{j}(t_{a(i)} + t_{s(i)}) || j\text{: \# of packets} \qquad (3.11)$$

Where

$$t_{win} = (j - 1) \times t_w || j\text{: \# of packets} \qquad (3.12)$$

Figure 3.10 is timeline diagram for data exchange between two nodes A and B, at the receiver node, when receiving data packet, it is be sent acknowledgement (*ACK*) value (*true* or *false*) to confirm the receipt of data packet. At the transmitter node, the timer is begun to receive the *ACK* value from receiver node. If the transmitter node does not receive the *ACK* value within a timeout interval t_{ACK} (7 ms), the data packet will send again 3 times if there is no response again, this receiver node considered as dead node and removes it from next schedule tables.

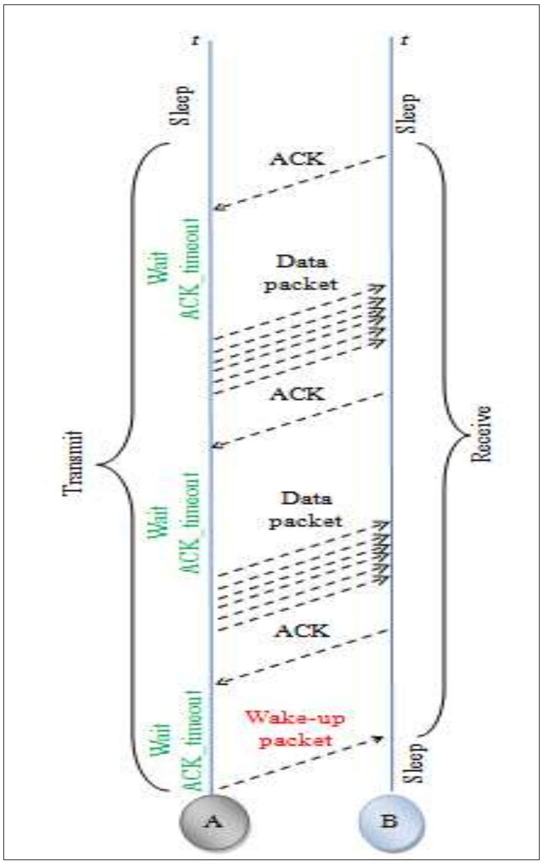


Figure 3.10: A Basic Data Exchange. Node A send wake-up packet and data packet to node B. Node B must be sending *ACK* after each data packet.

Finally, the power consumption for *n* communicated and scheduled nodes in the proposed MAC system is performed by Equation 3.13. Equation 3.13 presents the overall time consumption for *N* nodes with *Q* winning cases, where *j* is the number of series data packets as mentioned in the winning case. However, this performance evaluation shows that the presented MAC method keeps the power consumption for the useful cases (transmission cases) as much as possible, since the power consumption is presented only for the actual data packet transmission as shown by Equation 3.13.

$$T_{overall} = \sum_{i=1}^{n-[sum(js)]based\ Q} [(t_{a(i)} + t_{w(i)}) + t_{s(i)}]$$
$$+ \sum_{k=1}^{Q} \left[t_{w(k)} + \sum_{i=1}^{j} (t_{a(k)(i)} + t_{s(k)(i)}) \right]$$
$$+ \sum_{i=1}^{n} t_{ACK(i)} \qquad (3.13)$$

Where: *n*: #of the scheduled packets; *Q*: # of the winning cases; the variable j: # of packets for the current best case and t_{ACK} is the time needed for receiving *ACK*.

In other cases, inter-cluster communication between separated clusters, each cluster has to choose its admin node during the CSP. However, the admin nodes should exchange their shift tables before distributing them to the nodes in the cluster. This process actually enables nodes to be communicated between separated clusters without collision problem. Since, the next cluster schedule should be care about the nodes status in case at nodes might be busy with another node in another cluster.

3.2.2.2. An example for shift table of transmission status in inter-cluster domain:

Figure 3.11 shows two communicated clusters (cluster 1and 2). Cluster 1 has five nodes; A, B, C, D, and E. Cluster 2 has four nodes; V, W, X, Y, and Z.

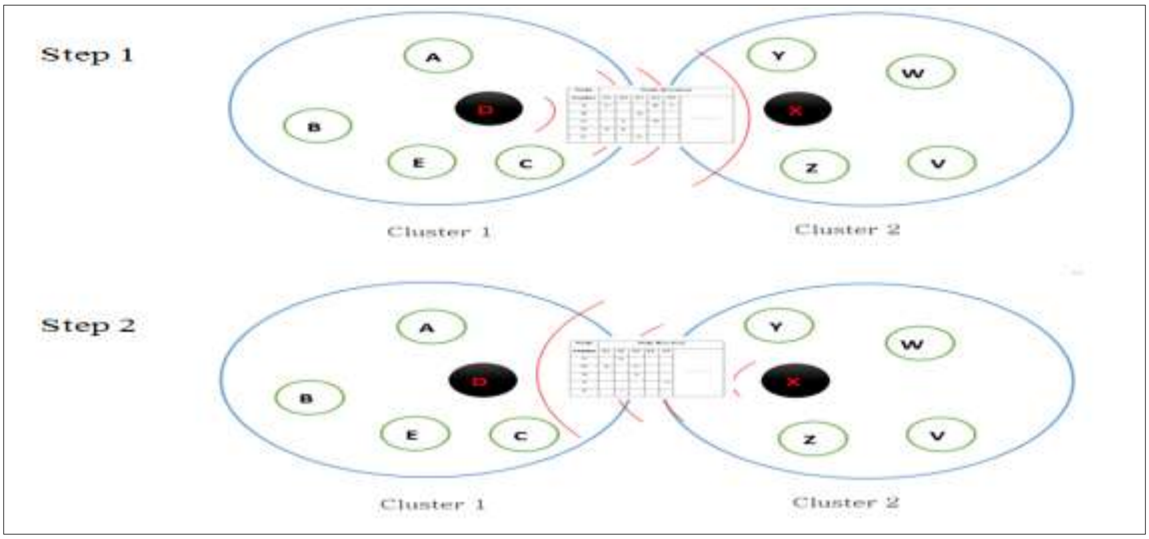


Figure 3.11: The Proposed MAC Processing with Multi-hop Connection.

As shown in Figure 3.12, nodes A and C in cluster 1 should be busy with nodes Y and Z in cluster 2. Since node A will be busy with node Y at time slot "S5" and node C will also be busy with node Z at time slot "S2". Therefore, the admin node D in cluster 1 should exchange the shift tables with the admin node X in cluster 2 before broadcasting the shift tables to the nodes its clusters. However, we suppose in Figure 3.11 that cluster 1 generate its schedule firstly by the admin node D, then node D should pass its schedule directly to the admin node X in cluster 2 (refer to Figure 3.11-Step 1). Figure 3.11-Step 2 shows that the admin node X will also generate its shift table in cluster 2 and send the shift table back to the admin node D in cluster 1.

As shown by Figure 3.13, the admin node in cluster 2 avoids employing nodes Y at "S5" and Z at "S2" according to the received shift table by cluster 1 admin node. Finally, each cluster admin node will distribute the schedule to nodes in its clusters to establish the communications.

Node Sender	Node Receiver					
	S1	S2	S3	S4	S5	
A	C			B	Y	
B			A			
C		Z		D		....
D	E	E				
E			C			

Figure 3.12: Clusters 1 Transmission Status-shift Table.

Node Sender	Node Receiver					
	S1	S2	S3	S4	S5	
V		W				
W	X		V			
X			Y			....
Y					A	
Z		C				

Figure 3.13: Clusters 2 Transmission Status-shift Table.

3.2.3. Adaptive Protocol (AP)

In this subsection, proposed method is presented to develop the energy efficiency for the MAC protocol. This method switches nodes to sleep state whenever it is possible, and attempts to re-use unused time slots by the selected transmitter for bandwidth efficiency. Time slots might be shifted to other nodes when the selected node has not packets to send, then it may give its transmission slot for another transmission by contacting the admin node; this slot could then be used by another node depending on admin schedule. However, admin node exchange current traffic information with nodes in its cluster to make effective use of low-power and accomplish slot re-use.

Moreover, proposed method has three possible states as: transmit (*Tx*), receive (*Rx*), and sleep (*SL*). At any given slot *t*, node A is in the *Tx* state if: (1) A has the highest priority in the schedule, and (2) A has data to send. While, A node is in the *Rx* state if A is the intended receiver to receive the current transmission. Otherwise, the node A is in *SL* state, meanwhile node A is switched off to the sleep *SL* state, because it is not sharing in any data exchange. However, AP protocol should be executed by each node to decide its current state (*Tx*, *Rx*, or *SL*) based on current node priorities and also on the announced schedules.

However, the proposed MAC keeps track of nodes that could use extra slots to send their data based on the communication with the admin node. Admin node first computes the set of nodes that can possibly transmit at the current time slot. A node can transmit without collisions only if it follows its shift table.

Chapter 4: OXLP : An Optimized Cross-Layers Protocol

Chapter 4

OXLP: An Optimized Cross-Layers Protocol

4.1. Introduction

The main research objective in WSN domain is the development of algorithms and protocols ensuring the best performance whether they are minimum energy consumption or longest network lifetime. Most proposed solutions are based on one-layer stack model approach. Recently, some works tend to exploit together many layers in order to optimize the network performance. In this chapter, we propose Optimized Cross-Layers Protocol (OXLP). It is using two adjacent layers (MAC and Network layers) to improvement overall performance for WSN. OXLP protocol will extend proposed MAC protocol introduced in chapter 3.

4.2. System Model

4.2.1. Assumptions

For the sake of clarity, we first present some assumptions that hold in OXLP protocol. These assumptions are necessary to ensure network integrity and consistency. The following assumptions are made about the sensor nodes and the network model:

- Wireless data collection network model has a large number of sensors and one base station (BS). As the BS is generally connected to the mains power source, it is not a restrictive power assumption.
- The transmission power of BS is assumed to be high enough to reach all sensors in the network.
- In OXLP, network is grouped into different clusters. Each cluster is composed of one cluster head (CH) and cluster member nodes.
- The respective CH gets the sensed data from cluster member nodes, and forwards it to BS by using of a multi-hop forwarding if necessary.
- A linear model is used with the distance between nodes as variable *s*, as shown in Figure 4.1.
- Each sensor has a unique identifier that is appended to the information field in the packet to identify the source of data.

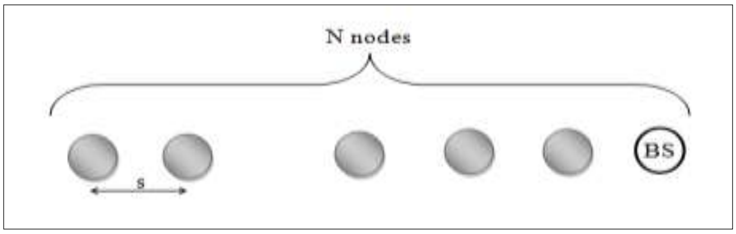


Figure 4.1: Simple Linear Sensor Network.

4.2.2. Energy Model

A simple model for the radio hardware energy dissipation is assumed where the transmitter consumes the energy to run the radio electronics and the power amplifier, and the receiver consumes the energy to run the radio electronics, as shown in Figure 4.2.

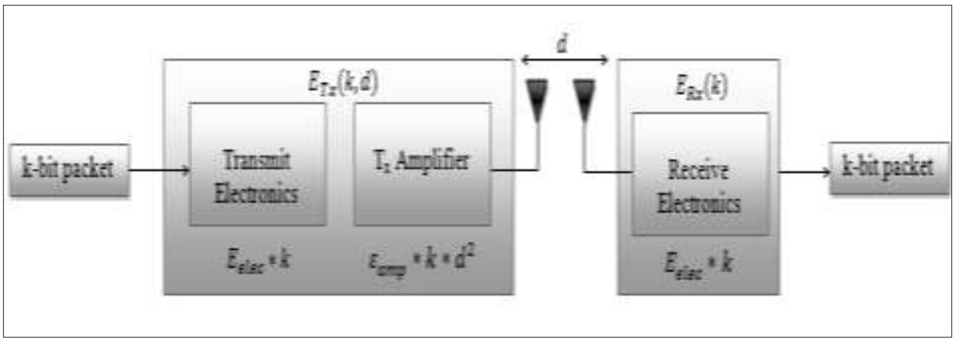


Figure 4.2: Radio Energy Consumption Model.

From the Figure 4.2, let *k (bits)* be the packet size, and E_{elec} *(Joule/bit)* represents the energy dissipated by the electronics for transmitting or receiving a *k-bit* of data. Let ε_{amp} *(Joule /bit/m^2)* denotes the energy expended by the power amplifier at the transmitter for achieving acceptable bit energy to noise power spectral at the receiver. Then, if source node *x* which is *d* far from its destination transmits a *k-bit* packet, the radio dissipates as in the following Equations 4.1 and 4.2:

$$E_{Tx}(k,d) = E_{Tx\_elec}(k) + E_{Tx\_amp}(k,d) \quad (4.1)$$

$$E_{Tx}(k,d) = E_{elec} * k + \varepsilon_{amp} * k * d^2 \quad (4.2)$$

And to receive *k-bit* packet, the radio consumes

$$E_{Rx}(k) = E_{Rx\_elec}(k) \quad (4.3)$$

$$E_{Rx}(k) = kE_{elec} \quad (4.4)$$

We express the energy dissipated by the radio during each idle listening period as

$$E_I(k) = \alpha E_{Rx}(k) \qquad (4.5)$$

Where α is the ratio of the energy dissipated in receiving mode to the energy dissipated in idle listening mode.

4.3. Overview

OXLP protocol is cross-layer optimized algorithm based on joint consideration of different underlying layers. Proposed protocol is a Cross-Layer protocol which allows integrating MAC protocol and routing protocol for energy efficient data delivery to the sink node. The network layer uses information of data link layer when the routes establishment to access the medium efficiently, as shown in Figure 4.3. The forwarding process is composed of two phases: the MAC window and transmission window.

When the network diameter is increased beyond certain level, distance between cluster-head and cluster member nodes is increased enormously. This case consumes a large transmission power and quickly drains the battery of the nodes which reduces the system lifetime. To address this problem multi-hop routing is proposed in OXLP protocol. Thus nodes act as routers for other nodes' data in addition to sensing the environment.

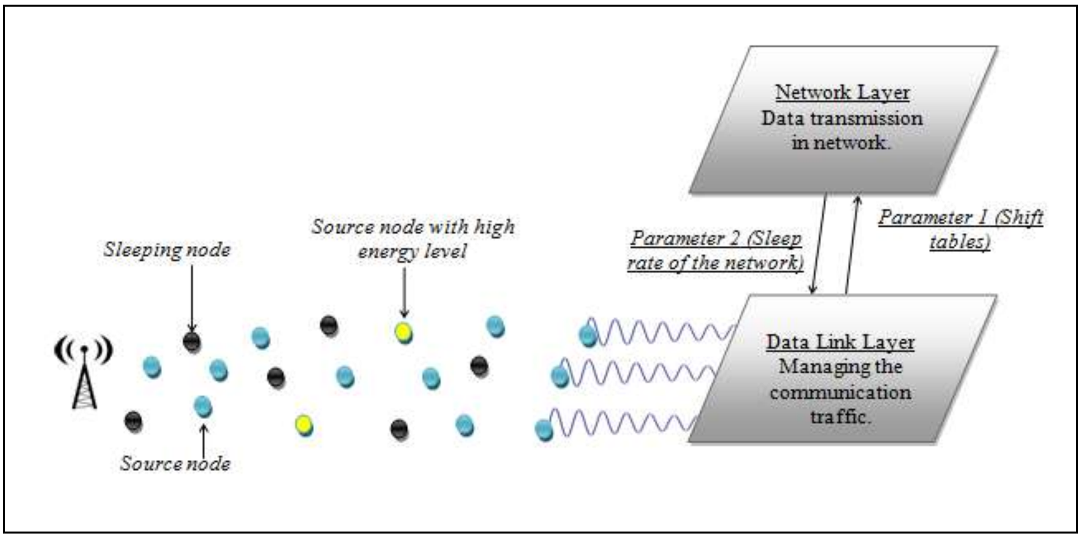


Figure 4.3: The Cross-layer Optimized Framework.

The OXLP protocol allows two types of communication operations. These are inter-cluster communication and intra-cluster communication. In inter-cluster communication, the whole network is divided into clusters. Each cluster has one cluster-head (CH). Cluster-head is responsible for communication for all nodes in the cluster. Cluster-head receives data from all nodes at multi-hop and transmits this data to sink by using of a multi-hop if necessary. On the other hand, in intra-cluster communication the nodes send their data directly to the cluster-head or through intermediate nodes during their allocated transmission slot.

To illustrate energy efficiency for OXLP, consider the linear network shown in Figure 4.1, where the average of distance between nodes is *s*. If we consider the energy expended transmitting a single *k-bit* message from a node located a distance *hs* from the base station using the direct communication approach. From Equations 4.2 and 4.4, we have:

$$E_{Tx}(k, d = hs) = E_{elec} * k + \varepsilon_{amp} * k * (hs)^2 \qquad (4.6)$$

$$= k\left(E_{elec} + \varepsilon_{amp} h^2 s^2\right) \qquad (4.7)$$

Where *h* is hops number and *s* is average of distance between the nodes.

In OXLP protocol, each node sends a message to the other nodes on the way to its CH. Also, CHs send to other CHs on the way to base station. Thus the nodes or CHs located a distance *hs* from its destination would require *h* transmits a distance *s* and *h-1* receives.

$$E_{Tx}(k, d = hs) = hE_{Tx}(k, d = s) + (h - 1) * \ E_{Rx}(k) \qquad (4.8)$$

$$= h\left(E_{elec} * k + \varepsilon_{amp} * k * s^2\right) + (h - 1)kE_{elec} \qquad (4.9)$$

$$= k\left((2h - 1)E_{elec} + \varepsilon_{amp} * hs^2\right) \qquad (4.10)$$

Where *h* is hops number and *s* is average of distance between the nodes.

4.4. OXLP Protocol

The functional architecture of the OXLP protocol and the basic operation is illustrated in Figure 4.4. The operation of OXLP is divided into rounds. Each round begins with MAC window when the clusters are organized and the routing paths are determined, followed by a transition window when data are transferred from the nodes to the cluster head then to the BS.

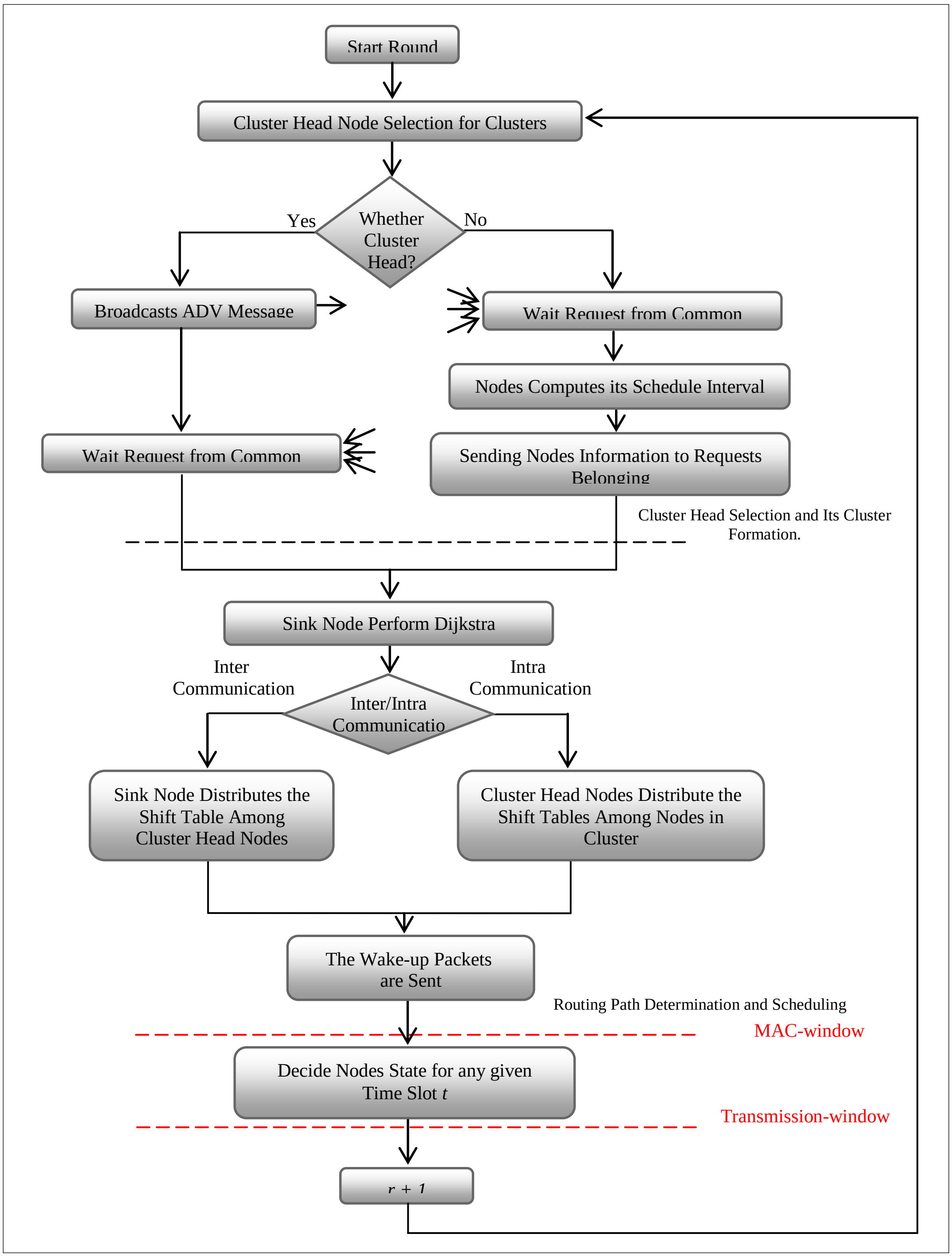


Figure 4.4: The Functional Architecture.

4.4.1. MAC Window

MAC window introduces the core of OXLP protocol. The basic idea behind MAC window is to integrate both MAC and routing mechanisms. This solution allows planning proactive routing table and medium access simultaneously. Each cluster head maintains a routing table, in which each entry contains destination ID, sender ID and allocated time slot.

This way affords three strong principles that are:

1. Allocate the time slots in efficient manner in order to avoid data collision from different nodes. At the same time, it is fairly and efficiently shares the bandwidth resources among multiple sensor nodes for entire network.
2. Select the route of each message destined to the base station in the network in a way really crucial in terms of network lifetime.
3. Focus on increasing the sleep periods as much as possible, ensuring efficient awakening and avoid hidden and exposed terminal problems as proposed in chapter 3.

Among responsibilities of MAC window are to determine shortest path routes from all sensor nodes to corresponding CH in intra-cluster communication and meanwhile between CHs to the sink node in inter-cluster communication.

In-depth detail of MAC window, it has two phases as follows:

1. Cluster formation and Cluster head selection.
2. Routing path determination and scheduling.

The MAC window in OXLP protocol depends heavily on MAC model which have proposed in chapter 3. In next sub-sections, we will address MAC window phase in detail.

4.4.1.1. Cluster Head Selection and Its Cluster Formation.

In OXLP protocol, cluster head selection phase apply same mechanism that is used in CSP sub-protocol in admin nodes selection sub-section (3.2.1), which we introduced in detail in chapter 3.

In MAC window, when clusters are being created, each node decides whether or not to become a cluster-head for the current round. This decision is based on the suggested percentage of cluster heads for the network (determined a priori) and the number of times the node has been a cluster-head so far.

Each node that has elected itself a cluster-head for the current round broadcasts an advertisement message to the rest of the nodes. All other nodes other than the CH keep their receiver on and decide to which CH they will join. Every node selects a cluster head which is close to it. All nodes send its information to their respective CH. The CH creates a proper schedule for all the nodes in its cluster. Only during their respective schedules, nodes interact with neighbor nodes and the CH, else the nodes go to sleep mode. The cluster heads obtain data from all nodes in its cluster, further aggregates the data and finally send it to the BS.

4.4.1.2. Routing Path Determination and Scheduling.

In this phase the routing path determination for intra-cluster as shown in Figure 4.5 and inter-cluster shown in Figure 4.6 communications. The MAC window is able to determine shortest path routes from all sensor nodes to corresponding CH and from all CHs to sink nodes, using Dijkstra's algorithm [Appendix A].

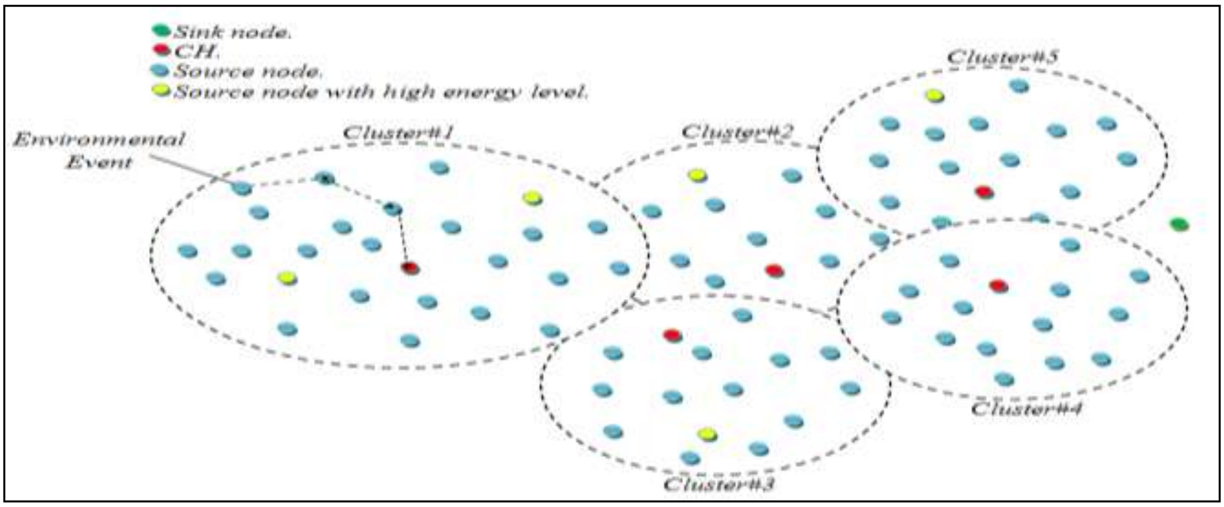


Figure 4.5: The Intra-cluster Routing.

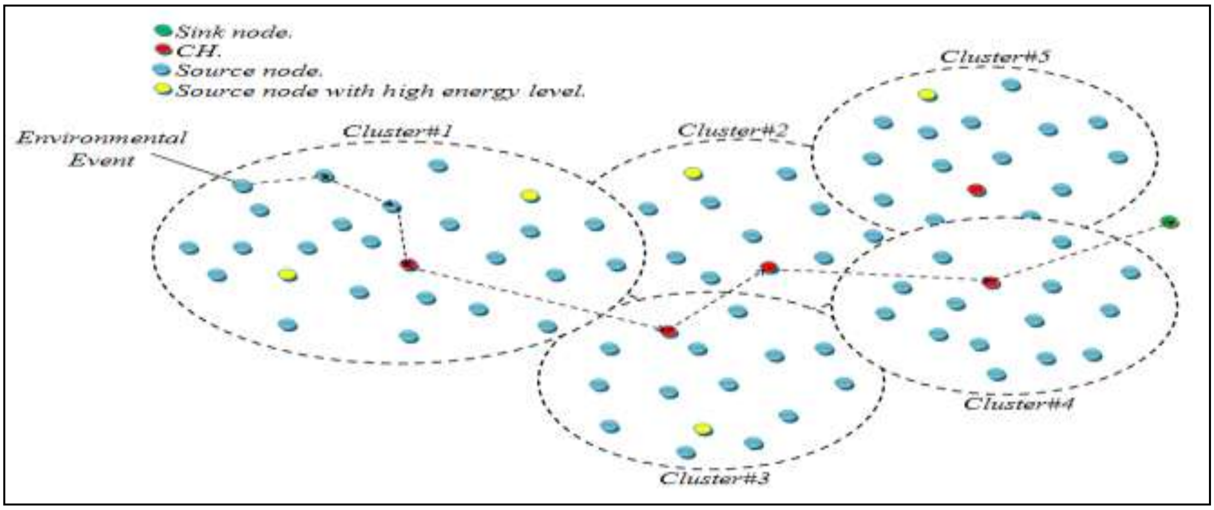


Figure 4.6: The Inter-cluster Routing.

Each CH establishes and maintains traffic-based schedule information required by the transmitter and receiver selection for intra-cluster communications. BS is responsible for scheduling the inter-cluster communications between all CHs in the network. This schedule is defined as shift table in same way that in Schedule Protocol (SP) in MAC model which is introduced early.

These tables can be used to determine appropriate transmission, reception and sleep schedules for all nodes, such that information can be efficiently transferred from source to sink in a collision free manner. The shift tables themselves then serve to inherently form the routes through the network, eliminating the need for a routing protocol.

4.4.2. Transmission Window

In transmission window phase, CH collects data from all nodes in its cluster and transmits data directly or through other cluster-head to BS.

The states allowed for nodes in transmission window are: transmit (*TX*), receive (*RX*), and sleep (*SL*). Each node decide its current state (*TX*, *RX*, or *SL*) based on current node priorities and also on the announced schedules by MAC window. The total power consumption at sensor node *x*, denoted by $E_{overall}$, is shown by Equation 4.11

$$E_{overall} = \sum_{i=1}^{n} E_{Tx(i)}(k,d) + \sum_{i=1}^{n} E_{Rx(i)}(k) + \sum_{i=1}^{n} E_{w(i)}(k) + \sum_{i=1}^{n} E_{ACK(i)}(k) + \sum_{i=1}^{n} E_{I(i)}(k) \quad (4.11)$$

Where *n*: number of the scheduled packets, $E_{Tx}(k,d)$ is the energy consumed when source node x which is d far from its destination transmits a *k-bit* for *n* packet, $E_{Rx}(k)$ is the energy consumed to receive a *n* packet that has *k-bit*, $E_w(k)$ is the energy consumed in wake-up packets, $E_{ACK}(k)$ is the energy consumed for wait to receive the *ACK* value for data packets, and $E_I(k)$ is energy dissipated by the radio during each idle listening period.

4.5. Cross-Layer Optimization Model

Based on information provided in section 4.4 a cross-layer optimization model is formulated by the object function that is minimizing power consumed of Equation 4.11 as given by Equation 4.12:

$$minimize\ (E_{overall}) = minimize\left(\sum_{i=1}^{n} E_{Tx(i)}(k,d) + \sum_{i=1}^{n} E_{Rx(i)}(k) + \sum_{i=1}^{n} E_{w(i)}(k) + \sum_{i=1}^{n} E_{ACK(i)}(k) + \sum_{i=1}^{n} E_{I(i)}(k)\right) \qquad (4.12)$$

Now, as noted in chapter 3, for a given WSN applications (i.e., given monitoring environment), $E_{I(i)}(k)$ is constant. At any given time slot *t*, the value of $E_{I(i)}(k) = 0$ because proposed MAC algorithm in OXLP protocol does not contain the idle state for any given *t* slots. From these preceding statements, we can consider the last summation term in Equation 4.12 as zero. Based on the foregoing, along with the fact that the energy optimization is being done with respect to the backbone network nodes, Equation 4.11 then reduces to

$$E_{overall} = \sum_{i=1}^{n} E_{Tx(i)}(k,d) \ + \sum_{i=1}^{n} E_{Rx(i)}(k)$$

$$+ \sum_{i=1}^{n} E_{w(i)}(k) + \sum_{i=1}^{n} E_{ACK(i)}(k) \qquad (4.13)$$

Furthermore, in case of best situation the power consumption is reduced by decreasing over hearing problem. This situation is also known as wining case as the communication can win time slots for data transmissions instead of sending wake-up packets. Based on what stated in previously, $E_{w(i)}(k)$ in Equation 4.13 is reduced and then this can leads to achieve the optimum model for OXLP protocol.

4.5.1. Proclamation 1.

For the optimal energy consumption model proposed in Equation (4.12) on any link *(x, y)* $\in$ *L (L* is a set of links between nodes), the model must use the optimal transmission power of this link $E_{opt\_Tx}(k,d)$ to achieve networkwide optimal energy consumption.

Proof. Assume that the network-wide per *k-bit* optimal relay energy consumption is

$$E_{opt-total}(k,d) = X + \ E(k,d) \qquad (4.14)$$

Where $E(k,d)$ is the per *k-bit* relay energy consumption on link *x, y* where *d* is the distance between *x*,*y* and *X* is the per *k-bit* relay energy consumed by the other links in the network.

Suppose the transmission power at link *(x,y)*, $E_{Tx}(k,d)$, is not equal to the optimal transmission power $E_{opt\_Tx}(k,d)$ of this link, we then have

$$E(k,d) > E_{opt}(k,d) \qquad (4.15)$$

Thus,

$$\left(E_{opt\_total}(k,d) = X + E(k,d)\right) > \left(E`_{opt\_total}(k,d) = X + E_{opt}(k,d)\right) \quad (4.16)$$

Which contradicts with the statement that $E_{opt\_total}(k,d)$ is the network-wide per *k-bit* optimal relay energy consumption.

Chapter 5: Simulation-based Performance Evaluation

Chapter 5

Simulation-based Performance Evaluation

5.1. Introduction

In this chapter, we evaluate the performance of the proposed approaches through simulation. The experiments of the suggested protocols are designed and implemented using MATLAB [4] software application in order to investigate the efficiency of the protocols. In 5.2 sub-sections, the research presents the performance metrics and simulation parameters. Through simulation, at 5.3 sub-sections, proposed MAC method is evaluated and compared its performance against both contention-based and scheduling-based protocols. While considering SMAC [29] as example of contention-based protocols and WiseMAC [30] as example of preamble based protocol, TRAMA protocol [41] is used as example of scheduling-based protocol. In 5.4 sub-sections, the research evaluates the performance of OXLP protocol and compares it against both cross-layer based protocols which are found in the literature such EYES [51] and PLOSA [2] and also against routing protocols for instance an application-specific protocol architecture for wireless micro-sensor networks LEACH [65].

5.2. Performance Metrics and Simulation Parameters

The proposed mechanisms are analyzed in terms of the following metrics

- **Packet Delivery Ratio (expressed in Percentage):** It is the ratio of total number of delivered packets successfully received by the BS to the number of packets sent by all sensor nodes in the network.
- **Percentage Sleep Time (expressed in Percentage):** It is the ratio of the number of sleeping slots to the total number of slots averaged over the entire network.
- **Average End-to-End Delay (expressed in Milliseconds):** It is the time taken by a data packet to be transmitted across a network from source to destination.
- **Energy Consumed (measured in Joule):** It is a measure of rate at which energy is dissipated by sensor nodes in a WSN within a specific time period.
- **Network Lifetime (measured in Seconds):** The lifetime of a WSN can be defined as the time elapsed until the last node dies, or a fraction of nodes dies.
- **Control Packet Ratio (expressed in Percentage):** It is the ratio of number of routing control packets sent by the protocol to the total packets sent.

Also, the research assumes that the same amount of energy is needed to send *k*-bits from A to B and vice versa. The parameters used in MATLAB simulator are summarized in Table 5.1. The reason for choosing these parameters is twofold: firstly, their higher impact on the metrics compared to others (e.g., the SMAC). It means to be able to compare the proposed methods with other protocols presented in literature. Secondly and more importantly, all of the chosen ones are common parameters in WSNs evaluations.

Table 5.1: The Parameters Used in Simulation.

Parameter	Value
Number of sensor nodes	n= From 20 to 100
Packet size	k = 4000 *bits*
Network Area	A= M×M = 100×100
GW-node Location	Center BS (50,50) Corner BS (10,10)
Communication model	Bi-directional
Transmitter/Receiver Electronics	E_{elec} = 50 *J/bit*
Initial energy for normal node	E_o = 0.5 *J*
Data aggregation energy	E_{DA} = 5 *nJ/bit/message*
Transmit amplifier	ε_{amp} = 10 $J/bit/m^2$
Number of runs	25

The proposed protocols are analyzed in terms of packet delivery ratio, network lifetime, delivery delay to the BS, consumed energy and percentage sleep time in case of MAC mechanism for various traffic loads. The load is expressed as the average number of new packets per slot. It can be easily expressed as a function of λ, inter-arrival period of messages for a node. The research changes the traffic load by varying λ (inter-arrival period of messages). If λ = 5s, a message is generated every 5s by each source node. In this experiment, λ are varies from 1s to 5s. For the highest rate with a 1s inter-arrival time, the wireless channel is nearly fully utilized due to its low bandwidth.

5.3. MAC Algorithm Performance Evaluation

The research tests MAC algorithm performance when driven by data gathering applications, which are typical sensor networks application. The simulated network is composed of 20 nodes. Although this network size is not typical for WSN, but the research uses same parameters used in several previous studies to make the results comparable to those reported in other work including [29] and [30].

5.3.1. Data-Gathering Application

In this study, BS is assumed for collecting data from all sensors. The BS sends out a broadcast query to gather data from all sensors in the network. Periodically, the sensors respond back with the requested data. However, the research implemented a simple reverse path routing to forward the data from the sensors to the BS. Figure 5.1 shows two different scenarios considered for this study. The base station node or sink is placed in the corner at the first case and in the centre at the second case.

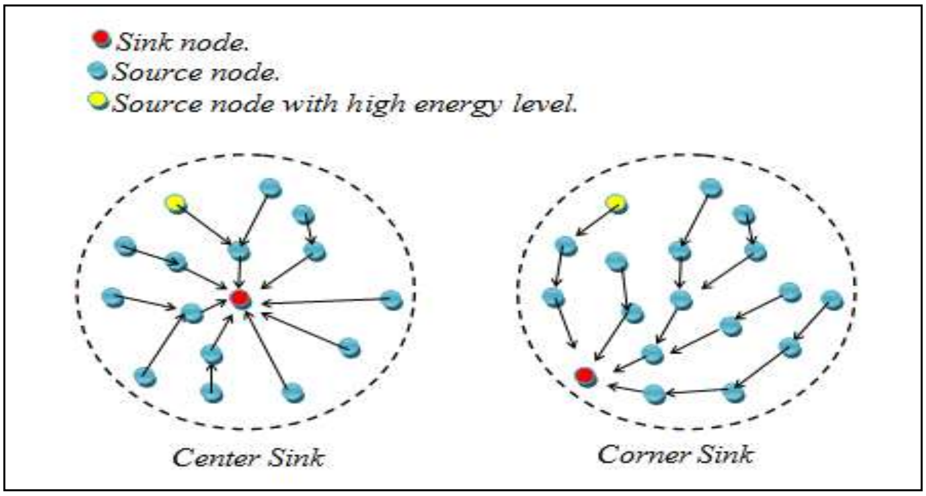
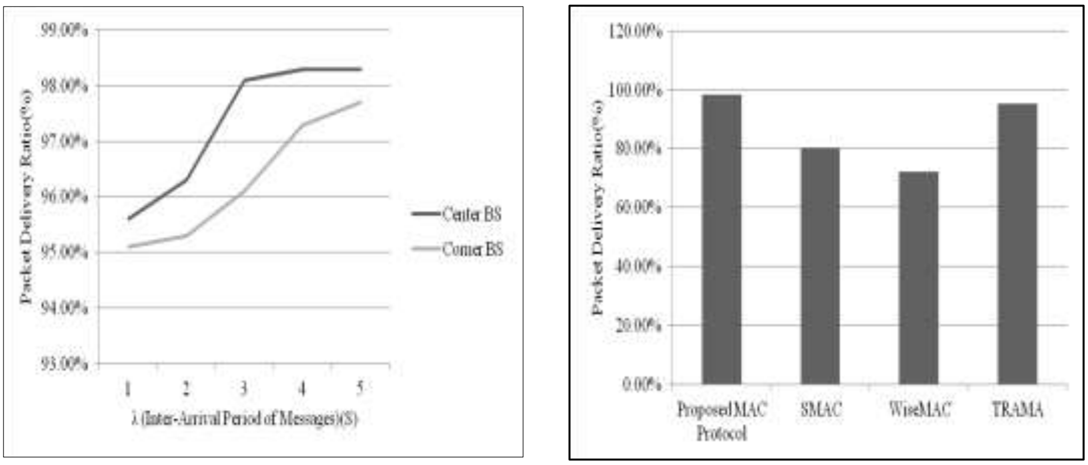


Figure 5.1: Data Gathering Application.

5.3.2. Simulation Results

The proposed protocol is tested using a sensor network data gathering application. The BS starts sending a broadcast query. All nodes receiving a non-duplicate query add the sender of the query as the next hop for data forwarding, establishing a reverse-shortest path tree with the BS node as the root. Figure 5.2(a) shows the packet delivery ratio for the corner BS and centre BS scenarios. The delivery is higher for the scenario in which BS is in the centre because the packets need to go through fewer number of hops to reach the BS



(a) (b)

Figure 5.2: Packets Delivery Ratio. (a) Delivery ratio for centre BS and corner BS. (b) Delivery ratio for different MAC protocols.

Figure 5.2(b) shows that schedule-based MAC protocols [Proposed MAC protocol and TRAMA] outperform the contention-based MAC protocols [SMAC and WiseMAC] in all cases. This is because the overall load in the network is low and performs well within the capacity of the protocols. Also it is noted a slight difference between proposed MAC method over the TRAMA protocol, that is because the collision in data traffic for TRAMA protocol. Figures 5.3(a) and 5.3(b) show the average end to end delay for all the protocols for the sensor scenarios. When compared to the corner BS scenario, the delay is higher for the scenario in which BS is in the centre because increased the traffic load. In center BS, the queries are sent and received from all direction while in corner BS the load of queries would be specific directions.

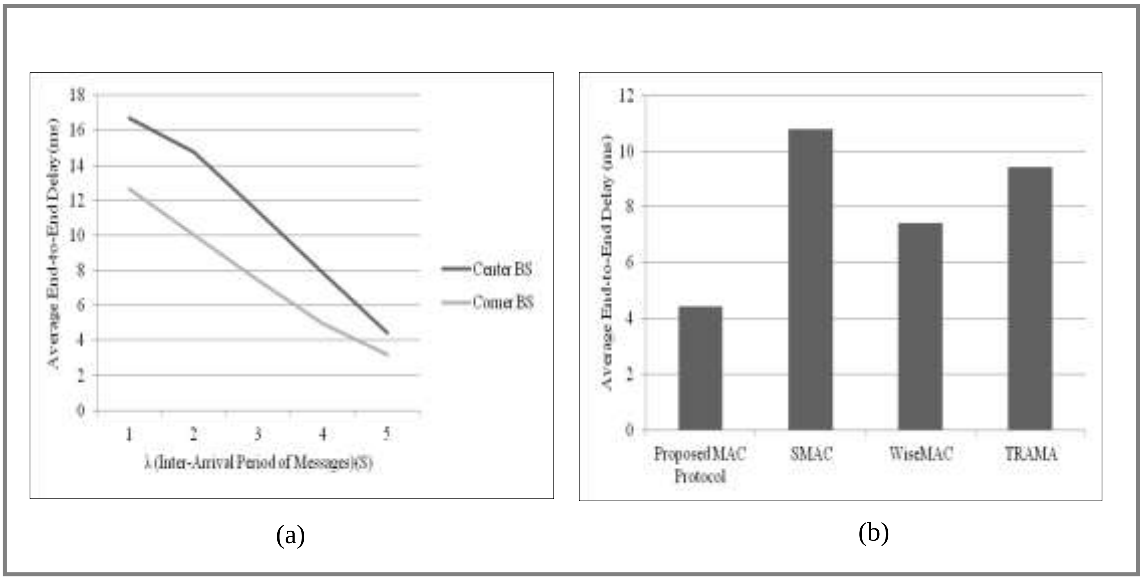


Figure 5.3: The Average End to End Delay. (a) The average end to end delay for centre BS and corner BS. (b) The average end to end delay for MAC protocols.

Figure 5.3(b) shows the proposed MAC protocol outperform scheduling-based protocols in terms of delay. This is due to the latency introduced by scheduling.

Figure 5.4 shows the percentage sleep time achieved by protocols. The percentage of time nodes can be put to sleep increases with the decrease in traffic load. When compared to the corner BS scenario, the percentage sleep time is less for the centre scenario due to the increased load. In the corner BS case, data forwarded by the nodes which are closer to the BS is heavier than data forwarded by nodes farther away. This reduces sleep time for these nodes and hence the overall percentage sleep time is lesser than the case where the BS is in the centre.

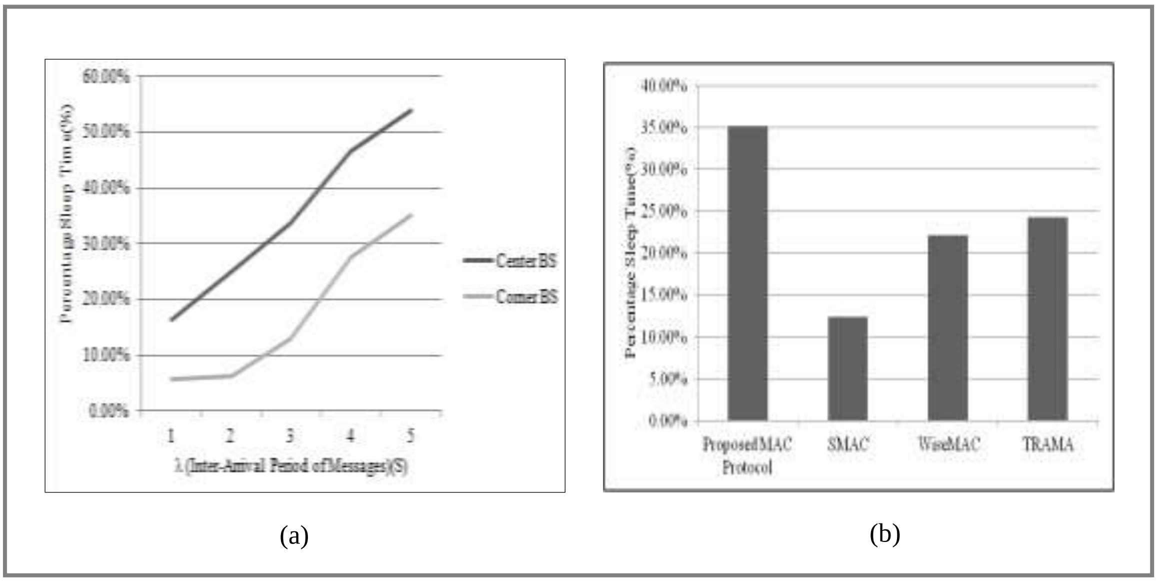


Figure 5.4: The Percentage Sleep Time. (a) The percentage sleep time for centre BS and corner BS. (b) The percentage sleep time for MAC protocols.

The percentage sleep time is quite high (as high as 20%) for the centre BS scenario which has the lowest load. Again, the average length of the sleep interval is also the highest for this case. This clearly shows the benefit of proposed MAC algorithm traffic adaptability when compared to TRAMA and S-MAC protocols. The average sleep interval of proposed MAC scheme is significantly higher than that of TRAMA and S-MAC protocols.

Figure 5.5(a) shows the energy consumed for the corner BS and centre BS scenarios. The energy consumption is roughly equal to the scenario in which the corner nodes are generating traffic with slight increase in centre BS in case of the higher load.

Figure 5.5(b) shows that the proposed MAC scheme outperforms the schedule-based MAC protocols and contention-based MAC protocols. Mainly, this is because the sleep interval for proposed MAC scheme is longer than other protocols.

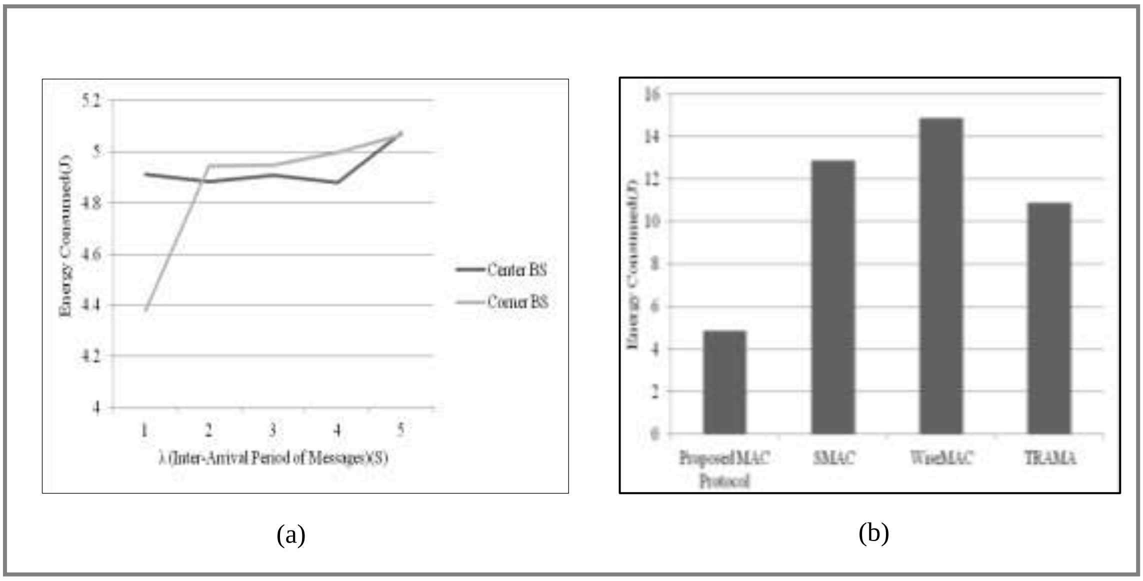


Figure 5.5: The Energy Consumed. (a) The energy consumed for centre BS and corner BS. (b) The energy consumed for MAC protocols.

Figure 5.6 shows the network lifetime achieved by all protocols. As seen clearly the proposed MAC algorithm has the longest lifetime among all other protocols principally in the case where the BS is in the centre.

Finally, the control packet ratio is below 13% in both scenarios. Where the location of BS does not have an observable effect on the ratio.

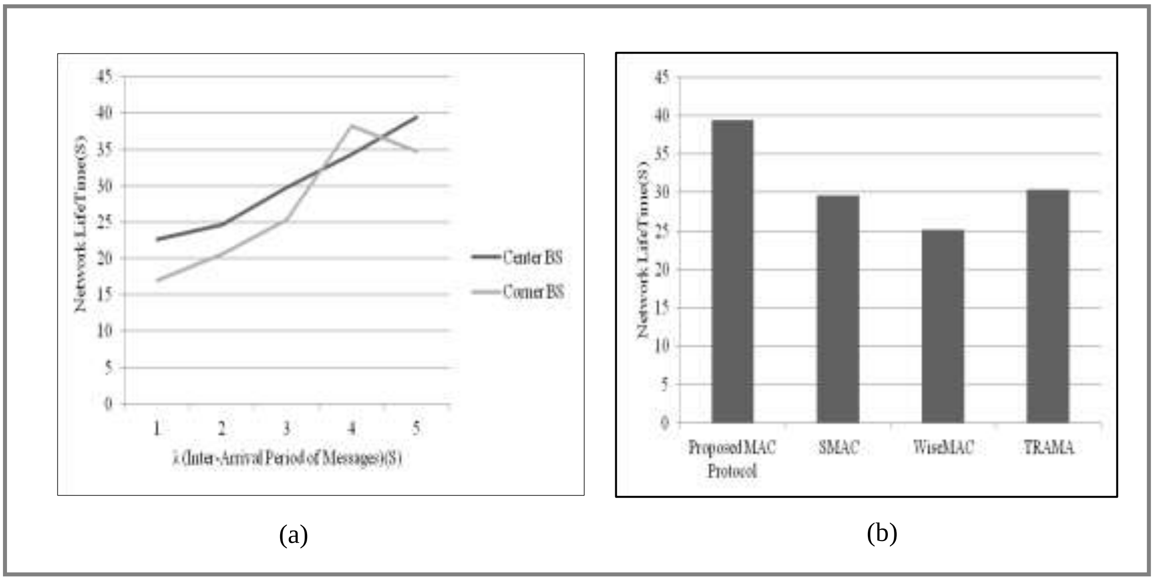


Figure 5.6: The Network Lifetime. (a) The network lifetime for centre BS and corner BS. (b) The network lifetime for MAC protocols.

5.3.3. Comparison of MAC Protocols.

Table 5.2 is a comparison of three protocols with the proposed MAC protocol. From the table, it is shown that the WiseMac and TRAMA have been optimized and perform high percentage of sleep and adaptively compared to other protocols. Since WiseMac has dynamic preamble length adjustment results in better performance under variable traffic conditions. As well as, TRAMA has higher percentage of sleep time and less collision probability. Whereby, TRAMA and WiseMac protocols have some wasteful power consumption, since TRAMA is limited with the hidden and exposed terminal problem. WiseMAc is also limited with control packet overhead problem compared to the proposed MAC method. However, TRAMA complexity refers to the energy expended as a result of having to run computationally expensive algorithms and protocols. Meanwhile the SMAC has adaptive listening that causes overhearing or idle listening resulting in inefficient battery usage. Since sleep and listen periods are fixed variables, traffic load makes the algorithm efficient. Therefore, the performance of the proposed MAC will be also compared against the well-known MAC protocols. Hence, the proposed MAC is based on TDMA and uses short/dynamic wake-up packets instead of the long preambles as presented in WiseMac protocol, these packets are carrying the ID for the intended node. The proposed MAC method assumes that all nodes sleep while the nodes is not scheduled to be active for sending or receiving data according to the presented shift table. Hence, this table provides data routing table that enable nodes in same cluster to communicate based on its scheduled time slot without collision problem. Furthermore, increasing the sleep periods, avoiding overhead, reducing overhearing, and solving collision problem are emphasized in this system. Actually, Table 5.2 shows the improvements in the overall time calculation for communication cases.

Snapshots reports of some experiments are shown in Appendix B.

Table 5.2: Comparison of MAC Protocols.

MAC Protocol	**Time Sync Needed**	**Type**	**Advantages**	**Disadvantages**
SMAC	No	CSMA, Contention -based	• Energy waste caused by idle listening is reduced by sleep schedules. • Simplicity.	• Sleep and listen periods are predefined and constant, which decreases the efficiency of the algorithm under variable traffic load.
WiseMAC	No	CSMA, Preamble based	• Dynamic preamble length adjustment results in better performance under variable traffic conditions.	• Decentralized sleep-listen scheduling results in different sleep and wake-up times for each neighbor of a node. • Hidden terminal problem
TRAMA	Yes	TDMA/CSMA	• Higher percentage of sleep time and less collision probability is achieved compared to CSMA based protocols.	• Without considering the transmissions and receptions, the duty cycle is at least 12.5%, which is a considerably high value.
The Proposed MAC	Yes	TDMA Wake-up Packet	• Increases sleep stats. • Reduces overhearing. • Reduces overhead. • Avoids collision problem. • Improves the adaptability. • Avoids the hidden and exposed terminal problems.	• Proposed MAC protocol waste a part of time for selecting the admin nodes and then producing the shift table to organize data transmissions between nodes. • So this design needs to do further research on admin nodes generative mechanism.

5.4. OXLP Protocol Performance Evaluation

In this section, the proposed OXLP protocol is analyzed in terms of packet delivery ratio, network lifetime, delivery delay to the BS and consumed energy for various traffic loads in the network. The simulated network is composed of 100 nodes. Key network simulation parameters are summarized in Table 5.1.

5.4.1. Optimum Number of Clusters

The considered key factors influencing the performance of network clustering is the number of cluster heads, therefore, it's worth to do research on cluster head aspect.

As in LEACH [65], the application-specific protocol architecture for wireless micro-sensor networks LEACH designers observe the optimal value for clusters number per round to achieve the best performance. In LEACH protocol [65], the optimum number of clusters p_{opt} for a cluster-based network has been illustrated in Equation 5.1, where *N* is the number of sensor nodes that distributed uniformly in an $M \times M$ region.

$$p_{opt} = \frac{\sqrt{N}}{\sqrt{2\pi}} \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \frac{M}{d_{to\ BS}^2} \qquad (5.1)$$

Where ε_{fs} and ε_{mp} are power amplifier (free space (ε_{fs}) model and multipath (ε_{mp}) model).

In Equation 5.1, $d_{to\ BS}$ is the distance from the cluster-head node to the BS. The minimum and maximum values of $d_{to\ BS}$ is substituted, the upper and lower bounds of the desired number of clusters can be also obtained. Though, p_{opt} will be selected regarding to:

- Average energy waste per round.
- Number of data packets received by BS per unit time which locates the quality of the network.

As in LEACH performance analysis, it takes 5% of the total number of nodes in network as the optimal number, as well the routing protocols also takes 5% for ideal working setting. Moreover, all cluster-heads send the compressed data to the BS directly in LEACH, which highlights a potential problem with LEACH. In general, sensor nodes might be distributed in a large area, and some clusters might be not close to the BS, while others are closed. This case can show great transmission energy waste when the nodes are used to transmit data to BS.

Without independently quantifying or further analyzing assumptions, most communication protocols spend the 5% cluster heads percentage as an ideal working setting [66]. Furthermore, it becomes imperative that the ideal cluster heads percentage having influence on the routing layer protocols design in WSNs, in addition the other protocol parameters should be re-investigated and its sensitivities studied such as: effect of network size and radio parameters.

This study obtained optimal number of cluster by simulation experiments. In this study, parameters as illustrated in Table 5.1 are used in simulation. Then by using different values for the percentage of nodes representing cluster heads, the total system energy consumption for the specific percentage has been obtained.

The total system energy consumption has been shown by Figure 5.7. Meanwhile, the total is presented as a function of the percentage of cluster heads for 100 nodes. As shown in the graphs, the ideal percentage of nodes that need to be cluster heads in order to get the minimum energy consumption is not exactly 5%, but it is around 3%

- 5% for the given density. As the obtained results, the node percentage changes with the changing node density.

Therefore, the study determined that the changing in the number of cluster-heads affects the consumed energy of the sensor network. This outcome will be able to determine the optimal number of cluster-heads.

In case, there is only one cluster, the non-cluster head nodes often have to transmit data via long distance to reach the cluster head node, and this is draining their energy. As well as, if there are more than five clusters, then no much local data aggregation is being performed. However, for the rest of the research experiments, p_{opt} is set to 3%.

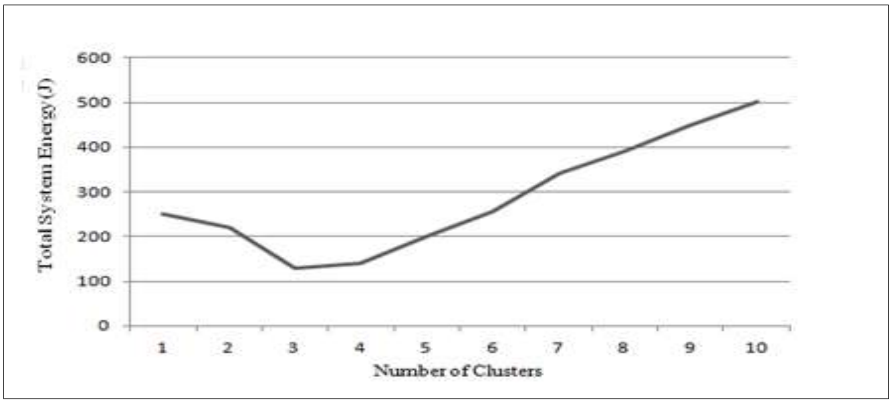
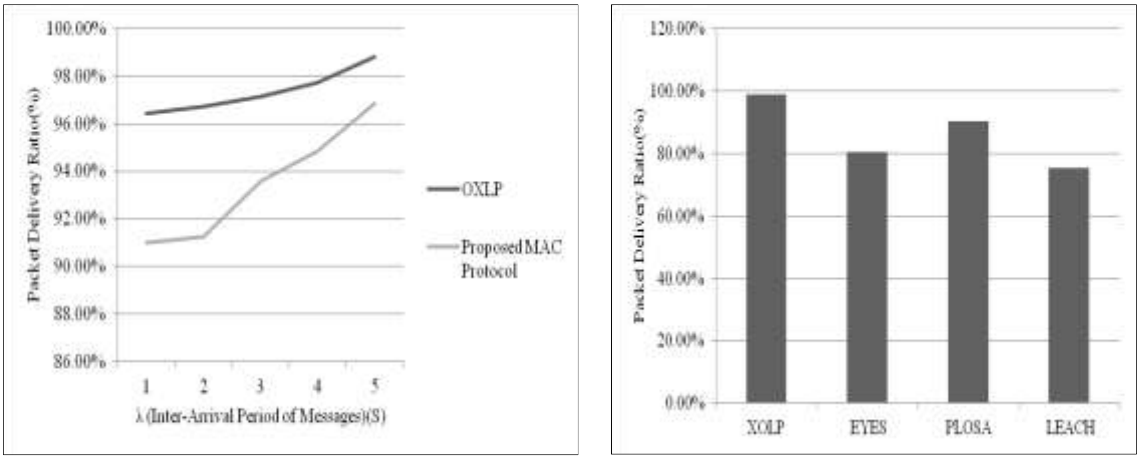


Figure 5.7: Energy Dissipated OXLP Protocol as the Number of Clusters is Varied between 1 and 10. This graph shows that OXLP is most energy efficient when these are between 3 and 5 clusters in the 100-node network.

5.4.2. OXLP Simulation Results

The results show that OXLP protocol outperforms the proposed MAC algorithm because of the improvement happening in the network layer in case of OXLP protocol. Hence cross-layer approach has proven to be most efficient optimization techniques as shown next, since they are able to take the behavior of the protocol at each layer into consideration.

Figure 5.8(a) shows the average packet delivery ratio for OXLP protocol against proposed MAC algorithm then EYES protocol, PLOSA protocol and LEACH protocol in Figure 5.8(b).



(a) (b)

Figure 5.8: Packets Delivery Ratio. (a) Delivery ratio for proposed MAC protocol and XOLP protocol. (b) Delivery ratio for WSN protocols.

Figure 5.9 shows the network life time for OXLP protocol against proposed MAC algorithm and other cross-layer based protocols.

In Figure 5.9(b), it is observed that the network lifetime for OXLP protocol is the longest network lifetime while the LEACH protocol gave the shortest network lifetime. This is expected since LEACH is energy-consuming task.

Figure 5.10(a) and 5.10(b) show end to end delay to the BS for OXLP protocol against proposed MAC algorithm and other cross-layer based protocols respectively.

LEACH protocol has higher delay. This is because the process of route discovery and queue in the data packet transmission. This causes a limitation of LEACH protocol.

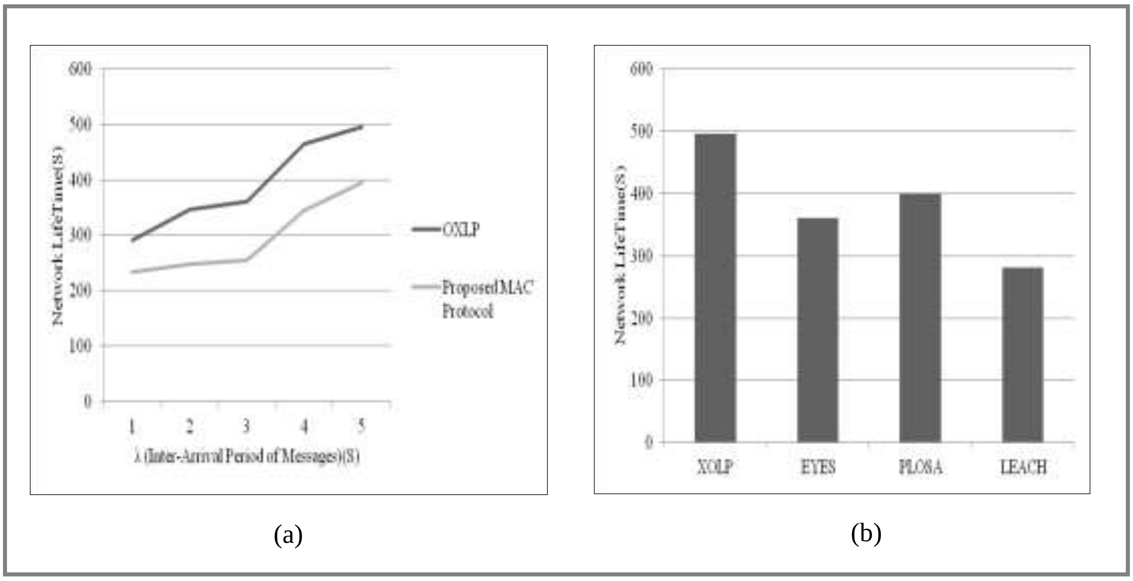


Figure 5.9: The Network Lifetime. (a) The network lifetime for proposed MAC protocol and XOLP protocol. (b) The network lifetime for WSN protocols.

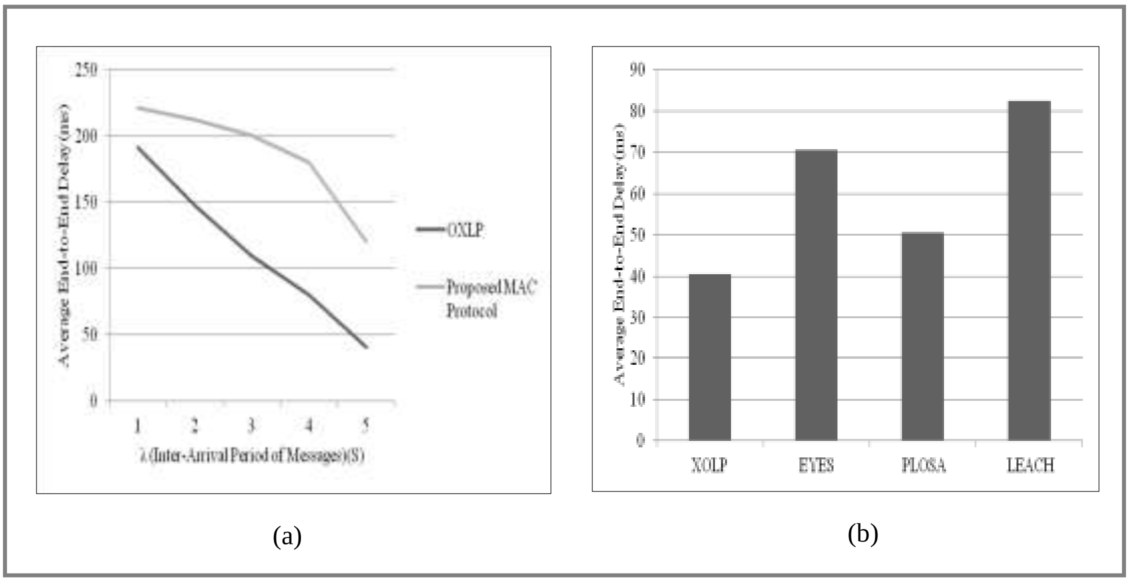


Figure 5.10: The Average End to end Delay. (a) The average end to end delay for proposed MAC protocol and XOLP protocol. (b) The average end to end delay for WSN protocols.

Figures 5.11 shows the energy consumed for OXLP protocol against proposed MAC algorithm and other cross-layer based protocols respectively. From the resulting routing scheme, Figure 5.11(b) shows that there obviously exist some redundant time slot allocations in EYES protocol and PLOSA protocol, which cause more energy consumption than necessary.

This is because the routing scheme for these protocols is functionality-oriented routing algorithm and the performance of these routing algorithms ignores energy consumption at nodes or in information transmission.

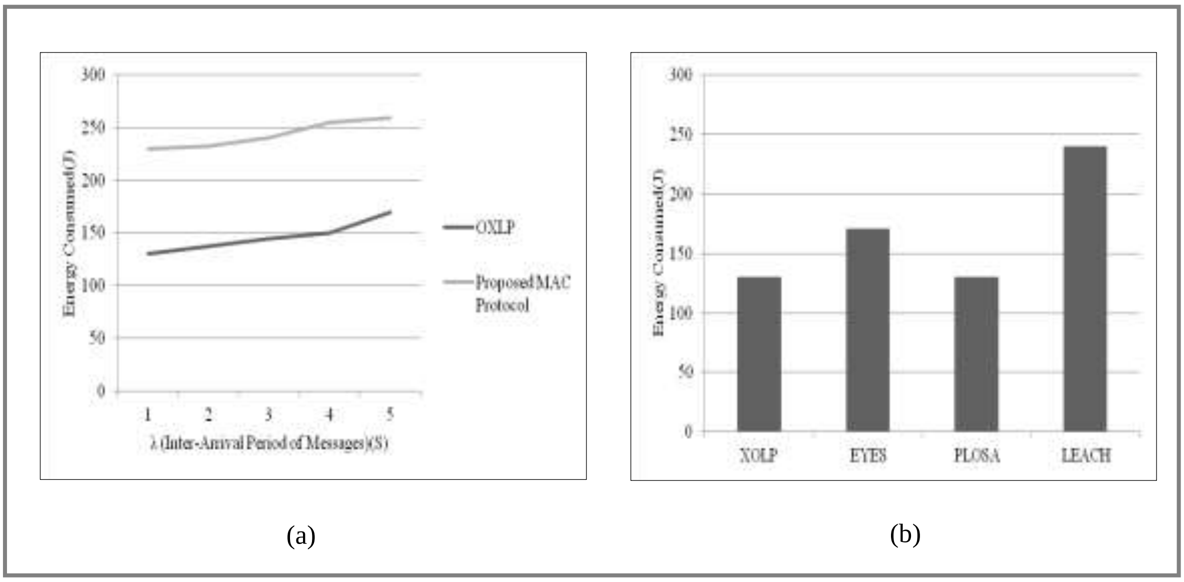


Figure 5.11: The Energy Consumed. (a) The energy consumed for proposed MAC protocol and XOLP protocol. (b) The energy consumed for WSN protocols.

That means the energy in transmission process can be ignored when the energy consumption at a node is high to an extent and the energy consumption at any of nodes is the same, the path that has the least number of nodes from origin node to object node consumes the least energy. To overcome this drawback, we add shortest path routing scheme by Dijkstra algorithm [Appendix A] in OXLP protocol which in turn caused more energy consumption in OXLP protocol.

5.4.3. OXLP Scalability

As mentioned in the previous results, scalability is also a significant factor in this study and should be highlighted. According to the network growth or the workload, scalable protocol develops itself to suit the changes in the network size. Mainly, the study experiment focused on the node density that is based on different performance metrics. In the WSNs, more nodes should be alive to have high network lifetime, since, the results are really monitored based on parameters performance. However, protocol performance index is presented as network lifetime for analyzing OXLP.

- **Alive Node Vs Network Lifetime**

In fact, sensor network demonstrates that the network application has been impacted by the active and monitor nodes. In addition, sensors network have a limitation in its battery-power, knowing, the node reach to a status called dead node when its power level becomes less than threshold or equal to zero. Figure 5.12, presents the simulation results for network lifetime the First Node Dies (FND) vs. a live node, also from Figure 5.12, it can be shown that the network lifetime will be decreased when the node density increased. Meanwhile, if the node density is decreased from 1000 nodes to 100 nodes, then the network lifetime will be increased. Thus, the node density should be always small to get best network lifetime. It is clear that, with high density network (1000 nodes), the network lifetime quickly reach zero. While with low density network (100-200 nodes) it takes long time for the network to die.

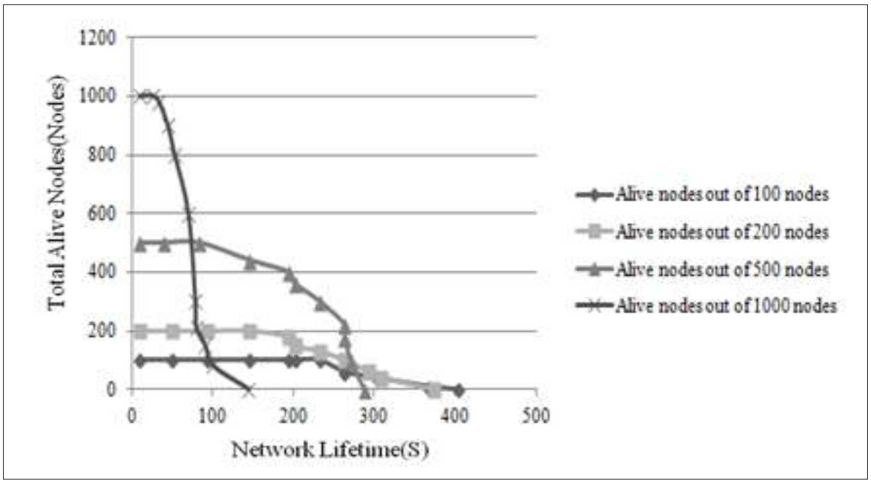


Figure 5.12: Alive Nodes Vs Network Lifetime for Different Node Density.

Actually, the OXLP protocol has disadvantage, since each node maintains a route structure to each different destination address. As well as, OXLP protocol uses a lot of memory space, which hinders the efficiency in large size network.

- **Data Vs Energy**

As shown by Figure 5.13, the relation between the node density and BS, whereas the increase of the node density will lead to increase the data received by the BS. No difference can be noticed while increasing the number of nodes.

Moreover, the network which has a minimum number of nodes actually dissipates less consumption of energy with an acceptable amount of data that can be received by BS. Since, Figure 5.13 shows that the network based 1000 nodes dissipates more energy with maximum amount of data, while the network based 100 nodes dissipate less energy with minimum amount of the data that is received by the BS among the considered configuration. Besides, in WSN, the OXLP protocol is a preferable choice in case of increasing the dense network.

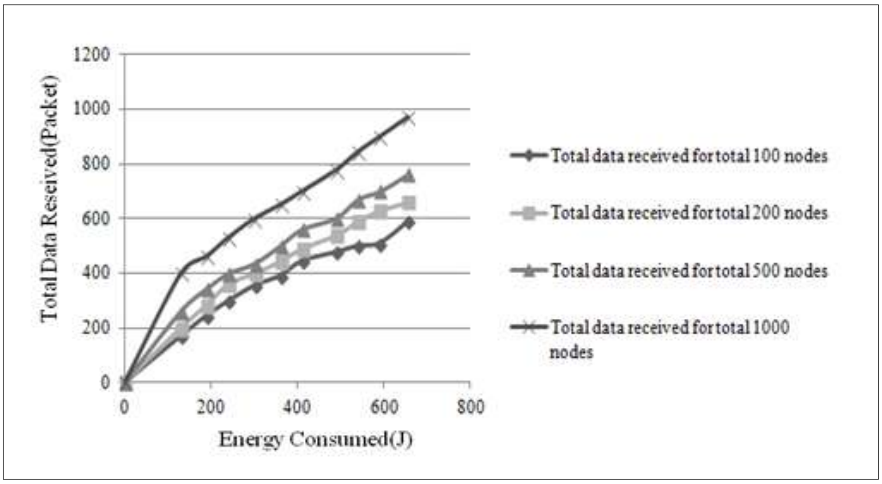


Figure 5.13: Data Vs Energy for Different Node Density.

5.4.4. Comparison of WSNs Protocols.

Comparison results between the proposed cross-layer approach OXLP and some other protocols, Table 5.3 shows that EYES and PLOSA protocols have been optimized and perform low power consumption to ensure a node lifetime of several years on a single battery compared to the traditional approaches. In a dynamic network topology, a network lifetime of EYES has at least three times the lifetime of SMAC network. EYES performs better in scenarios where the nodes are mobile than in static cases. This can be explained by the fact that the roles active and passive are not changed in the latter case, while in the mobile case the dynamic changes in network topology force the nodes to reconsider their role. This leads to better and more even energy consumption between the nodes, which results in longer network lifetime. Since this protocol has a small standard amount of data reserved for route updates; in the static case this space is wasted. On the other hand, PLOSA distributes the node access in the frame according to their distance to the collector for multi-hop mechanism. The forwarding process is then simplified and can be done within a frame. Furthermore, PLOSA optimizes sleeping periods of devices because each node can receive packets to be forwarded only in a specific part of the frame. However, if two nodes send packets in parallel using PLOSA, one node delays its transmission and enters sleeping mode. Nodes stay longer in sleep mode than other modes. Whereby, micro-sensor network uses data aggregation locally to reduce the amount of transmitted data that reduces energy dissipation and latency in data transfer. Furthermore, adapting the clusters in micro-sensor approach depending on which nodes are cluster heads for a particular round (as in LEACH), this process is advantageous because it ensures that nodes communicate with the cluster head node that requires the lowest amount of transmit power. LEACH provides the high performance needed under the tight constraints of the wireless channel.

In OXLP protocol, the performance of the proposed cross-layer approach has also compared against cross-layer approaches as shown by Table 5.3 Hence, OXLP improves energy conservation which performs high energy-efficient in WSN. It provides longer lifetime network. It uses an optimized MAC protocol that is based on TDMA and uses short-dynamic wake-up packets instead of the long preambles; these packets are carrying the ID for the intended node. Moreover, the proposed method assumes that all nodes sleep while the nodes is not scheduled to be active for sending or receiving data according to the presented shift table. Hence, shift table provide data routing table that enable the nodes in one cluster to be communicated based on its scheduled time slot without collision problem. OXLP protocol integrates both MAC and routing mechanisms to create an optimized routing table for data transmission in network clusters. However, the proposed OXLP protocol increases sleep states, reduce overhearing, reduce overhead, and avoids collision problem. It determines shortest path routs from all sensor nodes to the corresponding CH in intra-cluster and between CH nodes to BS node in the communication. Moreover, network changes should be handled rapidly and effectively for a successful adaptation: limited node lifetime and addition of new nodes to the network and varying interference which may alter the connectivity and then the network topology. The proposed OXLP protocol performs high delivery rate for data with very low delay as compared in Table 5.3. The proposed approach may has some limitations to find shortest path in some cases of expanding network scalability, so the used shortest path algorithm may not apply to large networks' size as well as dynamic case due to its overwhelming additional works.

Table 5.3: Comparison of WSNs Protocols.

WSNs Protocol	**Time Sync Needed**	**Type**	**Advantages**	**Disadvantages**
EYES Protocol	No	CSMA, Contention -based	- The nodes are mobile. While in the mobile case the dynamic changes in the network topology force the nodes to consider their role.	- EYES provide low efficiency in static network case. Since this protocol has a small standard amount of data reserved for route updates, in the static case this space is wasted.
PLOSA	No	Slotted Aloha	- Limits the increase in energy consumption thanks to a low packet loss rate, turns the transceiver of sensor nodes into a low power sleep state when it is not being used.	- If another node sends a packet, it delays its transmission and enters sleeping mode. Nodes stay longer in sleep mode than nodes using the PLOSA protocol.

Table 5.3: Comparison of WSNs Protocols. (Cont.)

WSNs Protocol	Time Sync Needed	Type	Advantages	Disadvantages
LEACH	Yes	TDMA/CSMA	- Adapting the clusters depending on which nodes are cluster heads for a particular round is advantageous because it ensures that nodes communicate with the cluster head node that requires the lowest amount of transmit power. - LEACH provides the high performance needed under the tight constraints of the wireless channel, using data aggregation reduces energy dissipation and latency in data transfer.	- Using fixed clusters and rotating cluster head nodes within the cluster may require more transmit power from the nodes.
OXLP Protocol	Yes	TDMA Wake-up Packet	- Determination of shortest path routes in intra-cluster communication from all sensor nodes to the corresponding CH and in inter-cluster communication between CH nodes to BS node in the communication. - Network changes should be handled rapidly and effectively for a successful adaptation, addition of new nodes to the network and varying interference which	- Like shortest path scheme does have disadvantages, the proposed OXLP protocol may has some limitations in some cases of expanding network as the size of network increases.

Table 5.3: Comparison of WSNs Protocols. (Cont.)

WSNs Protocol	Time Sync Needed	Type	Advantages	Disadvantages
			may alter the connectivity and the network topology. 🡅 Increases sleep stats, reduce overhearing, reduce overhead, avoids collision problem, and avoids the hidden and exposed problem.	

Chapter 6: Conclusions and Future Work

Chapter 6

Conclusions and Future Work

6.1. Conclusions

Wireless Sensor Network (WSN) is a collection of several sensor nodes deployed in defined area for certain application. These sensor nodes are equipped with other sensors that are sensing information from the environment to be sent then to the base station. However, WSNs have gained great importance these days due to its advantages. Despite these advantages, several challenges are introduced in the sensor networks. One of these challenges which is considered in this study is the providing an efficient communication method. Since, this challenge is actually defined as the main severe problem faced by the sensor networks. Several protocols have been presented in the literature review which is considered as not fully satisfy the network requirements.

Cross-layer design and optimization is a new technique which can be applied to design and improve the performance of wireless sensor networks. The major idea in cross-layer design is to optimize the control and exchange of information over two or more layers. This optimization is to achieve significant performance improvements by exploiting the interactions between various protocol layers.

The Optimized Cross-Layers Protocol (OXLP) is developed in this research to provide an efficient communication method for wireless sensor networks. The proposed protocol based on the integration of MAC protocol and routing protocol for energy efficient data delivery to the sink node. Furthermore, the proposed protocol considers an optimization by involving the medium access control layer and network layer. However, the proposed MAC method focuses on increasing the sleep periods as much as possible, reduce overhead, reduce overhearing, avoid collision, and avoid the hidden and exposed terminal problems.

6.1.1. Conclusion for MAC Protocol

It is evident from the simulation results that significant energy savings (since nodes can sleep for up to 53% of the time) can be achieved by proposed MAC depending on the offered load. The protocol also achieves higher throughput (around 18% over S-MAC and around 26% for WiseMAC) when compared to contention-based protocols since it avoids collisions due to hidden terminals.

Therefore for applications like military where energy consumption is not much to be bothered and more performance is required, proposed MAC protocol is the best choice as it is simple to construct.

6.1.2. Conclusion for OXLP

The simulation experiments showed the effectiveness of OXLP protocol in terms of energy consumption (around 26.7% over EYES protocol and 59.4% over LEACH protocol). In respect of network lifetime, the OXLP protocol outperforms EYES protocol around 30.2% and PLOSA protocol around 21.2%. In terms of end-to-end delay the OXLP protocol achieved improvement about 54.5% over EYES protocol and about 65.7% over LEACH protocol.

Other interesting characteristics of this protocol, that allow to mitigate some problems such as collision and idle listening which has been proved to be potential sources of energy wastage. Meanwhile the simulation experiment results show that OXLP significantly improved the communication performance and outperforms the proposed MAC protocol in terms of both network lifetime (around 22.5%) and consumed energy (around 41.3%) this improvement due to applying cross layering technique.

The overall conclusion is that OXLP protocol is best choice to move towards a network with less energy consumption as it involves energy minimizing techniques like multi-hop communication, clustering and data aggregation. Therefore, for applications where energy utilization is more critical like health monitoring, OXLP protocol is the best choice. For applications where network subjected to more scalability like environmental monitoring, OXLP protocol is good choice because it has high delivery rate for data with low energy consumed and no matter how large the network. The scalability in OXLP protocol can further improved by improving the routing technique.

6.2. Future Work

In the future, the proposed protocol has to be formally validated; the experimentation on real sensors has to be performed in order to verify the performances of proposed protocol. Also, we will improve real-time property (delivery ratio) under harsh conditions. This can be an issue in highly critical applications. Two solutions can be explored to address this issue. First, work can be done at the physical layer in order to make the radio links more reliable by optimizing decoding thresholds, for example (selection of the best links while keeping connectivity). Another solution could be an algorithm which reserves a good path in terms of links quality from the source to the sink, but this would imply more signalization thus more energy consumption.

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[2] Ahlam Saud Althobaiti, Manal Abdullah, "Medium Access Control Protocols for Wireless Sensor Networks: Classifications and Cross-Layering" "International Conference on Communication, Management and Information Technology." *ICCMIT 2015*, Prague, Czech Republic. April 20-22, 2015

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Appendix A

Appendix A

Dijkstra Algorithm

In literature, the Dijkstra-based routing algorithms are usually employed to get the shortest distance between two nodes in a WSN, and in general, the evaluation index of distance, the weight of the connective adjacent nodes is the physical distance between those two nodes. The basic idea of the Dijkstra is as follows:

Denote $G = (X , L)$ as a weighted directed graph, and divide the set of nodes (X) in G into two sub sets and L set of links between nodes. The first subset contains the node that have search the shortest path from the origin node (x) to itself (denote the first subset as S, and S only contains the origin node at the beginning. In the course of searching object node, if a shortest path is determined, add the other node at the path into S. Terminate the algorithm when the object node is searched). The second subset contains surplus nodes that have not search the shortest path (denote the first subset as U), and following an ascending order of the length of the shortest path in S, add the nodes in U into S, during which, the length of the shortest path from the origin node x to any node in S is less than that of the shortest path from the origin node x to any node in U. In addition, each node in G has the property of a distance d, the distance of the nodes in S is the length of the shortest path from the origin node x to this node, while the distance of the nodes in S is the length of the current shortest path from the origin node x to this node that only include the nodes in S as intermediate node. The algorithm flow of the Dijkstra is shown is Figure A and described. Denote the origin node as x, the distance of the shortest path from x to u as $d(x, u)$, the intermediate node as k', the distance of node u as $d(u)$, the weight of the edge form k to u as w_{ku}, and introduce β_k to denote the previous node of node k in the shortest path from x to k, and β_k is saved in matrix J.

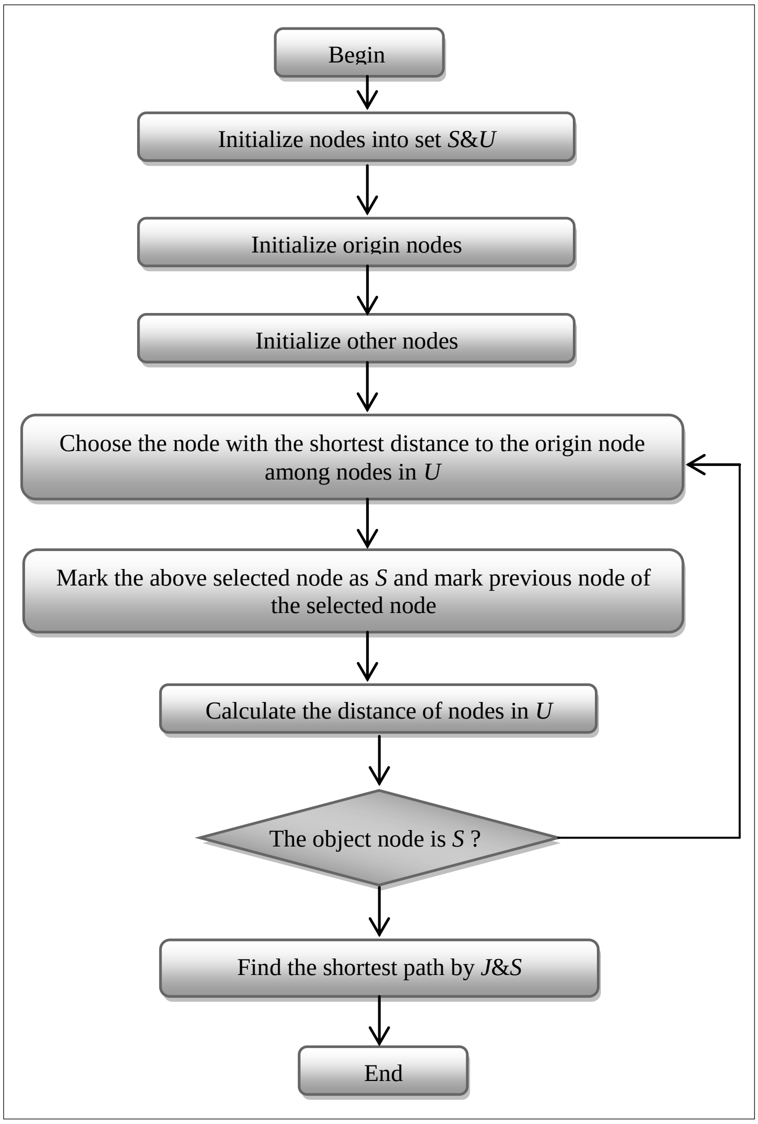

Figure A: Flow Graph of the Dijkstra Algorithm.

Appendix B

Appendix B

MATLAB Snapshots

B.1: Simulation Results for Schedule-Based MAC Protocol (Center BS)

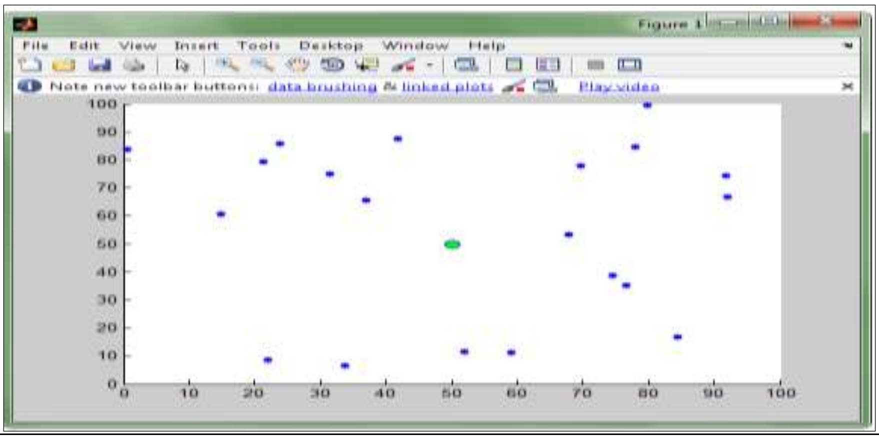

Figure B.1: Simulation Results for Centre BS. (Top) The network when sensor nodes are dead aft., (Bottom) The Report of Results.

B.2: Simulation Results for Schedule-Based MAC Protocol (Corner BS)

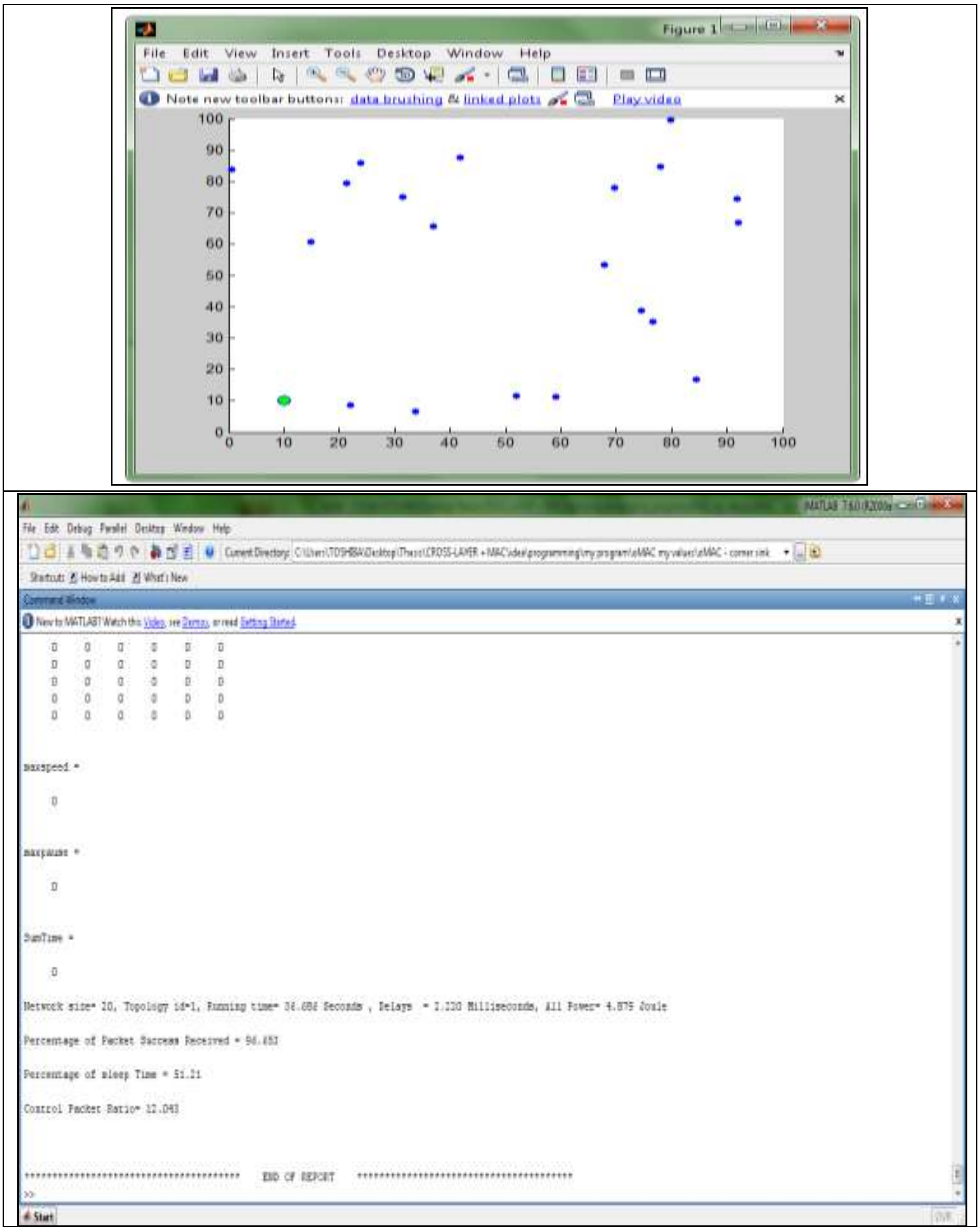

Figure B.2: Simulation Results for Corner BS. (Top) The network when sensor nodes are dead., (Bottom) The Report of Results.

B.3: Simulation Results for OXLP Protocol

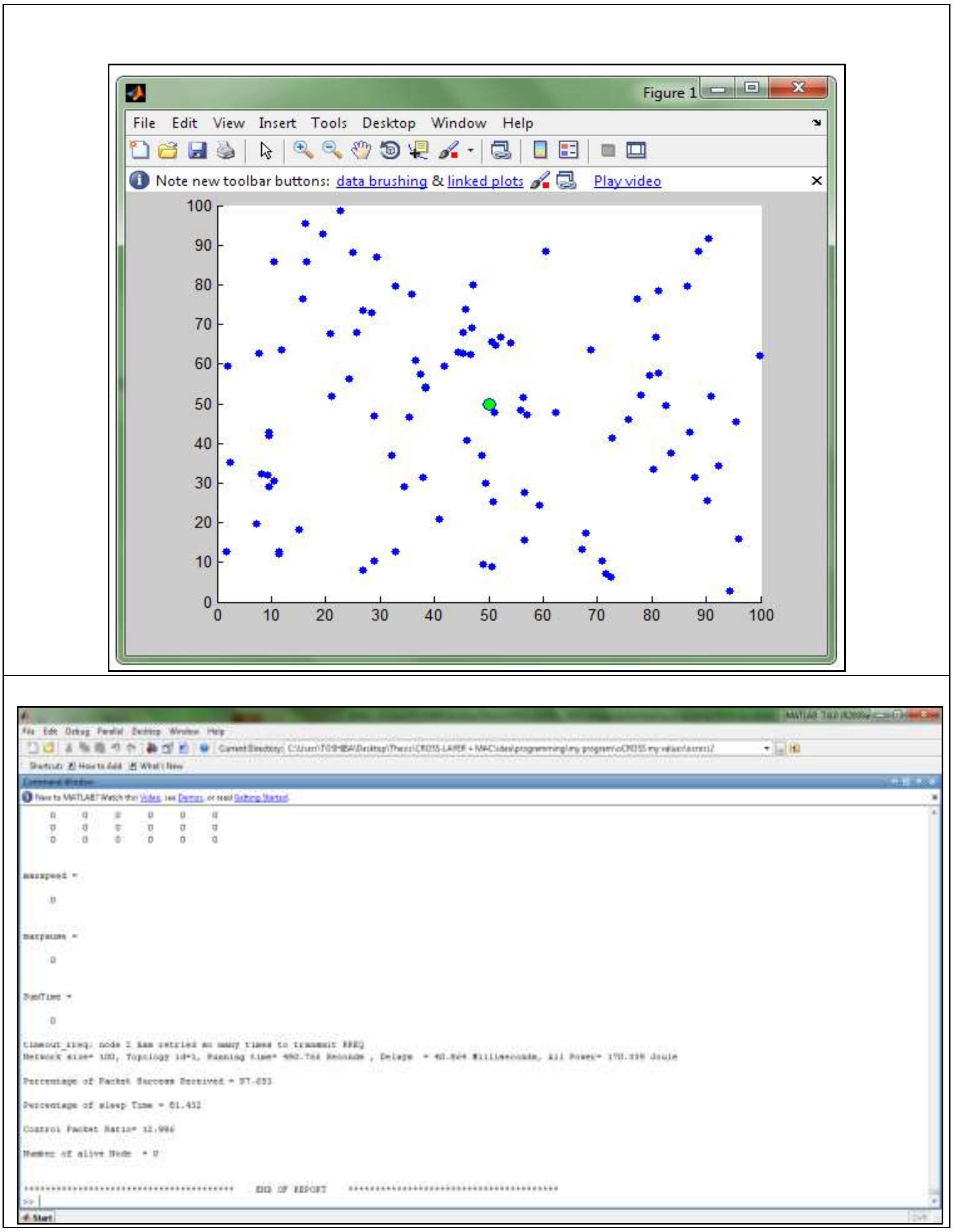

Figure B.3: Simulation Results for OXLP Protocol. (Top) The network when sensor nodes are dead. (Bottom) The Report of Results.

تحسين بروتوكول عبر الطبقات لشبكات الاستشعار اللاسلكية

أحلام سعود سعيد الثبيتي

ملخص

في الشبكات الحديثة ،شبكة الاستشعار اللاسلكية (WSN) يتم استخدامها على نطاق واسع لرصد الظروف المادية و البيئية مثل درجة الحرارة و الصوت الخ ، تعتبر هذه الشبكات من التكنولوجيات الناشئة التي يتم استخدامها في مجموعة واسعة من التطبيقات عبر الشبكات المفتوحة. تبنى شبكة الاستشعار اللاسلكية من الآلاف من العقد ؛يتم توصيل كل عقدة لاسلكيا إلى واحد أو عدة أجهزة استشعار ويعد أحد التحديات الرئيسية في تطوير شبكات الاستشعار اللاسلكية محدودية الموارد المتاحة لعقد الاستشعار ومع ذلك ،فإن التحدي الأكثر اعتباراً والذي يواجه هذه الشبكات هو متطلب التخفيضات الهامة في استهلاك طاقة عقد الاستشعار.

في هذا البحث ، تم اثبات أن نهج عبر الطبقات في WSN أكثر فعالية و كفاءة مما كانت عليه في نهج الطبقات التقليدية بينما نهج الطبقات التقليدية يعاني من تكلفة نقل النفقات العامة بشكل اكبر ،لذلك فان نهج عبر الطبقات يقلل من النفقات العامة من خلال تعاون الطبقات في نهج عبر الطبقات أما في النهج عبر الطبقات ،يتم التعامل مع حزمة البروتوكولات كنظام وليس طبقات فردية مستقلة عن بعضها البعض ،حيث أن الطبقات تتبادل المعلومات من كما لو أنها تعمل في منظومة واحدة كما أن تطوير مختلف البروتوكولات و الخدمات في نهج عبر الطبقات هو وتحسين وتطوير كلي.

في WSN يتأثر استهلاك الطاقة في عقد الاستشعار بشكل كبير ببروتوكول التحكم بالوسائط (MAC) الذي يسيطر على وظائف الراديو للعقدة. وهناك العديد من بروتوكولات MAC التي تم تصميمها بنجاح نحو الهدف الرئيسي من كفاءة استخدام الطاقة. ومع ذلك ،تعتمد الغالبية العظمى من الحلول الموجودة على بروتوكولات طبقات النهج الكلاسيكي ،مما يؤدي إلى أحمال كبيرة.

خلاف ذلك ،فإن المهام الرئيسية لطبقة الشبكة تتضمن اختيار المسار ،وتعدد الإرسال ،والتحكم في التدفق ،والتحقق من الخطأ ،والربط وما إلى ذلك .وهي بسيطة نسبيا لشبكة سلكية في حين أنها مهام معقدة للغاية بالنسبة WSNs حيث أن بنية الشبكة تتغير علية ،تساهم هذه الدراسة بشكل رئيسي نحو تصميم بروتوكول عبر الطبقات يربط بين المهام الأمثل لطبقة MAC وطبقة الشبكة. ويعتبر هذا البروتوكول بجانب استهلاك الطاقة ،تأخير الحزم ،وتسليم الحزم ،و التكرار ،و تكيف الحركة ،و التدرجية ،وما إلى ذلك ،لعقد الاستشعار.

البرتوكول المقترح يتكون من نافذتين : نافذة MAC ونافذة النقل. أداء البرتوكول المقترح في هذا البحث كان على اساس المحاكاة المصممة باستخدام بيئة الماتلاب. نتيجة المحاكاة اثبتت أن اداء البرتوكول المقترح افضل من حيث تسليم الحزمة و مدة حياة الشبكة و التسليم للمحطة الرئيسية وكذلك الطاقة المستهلكة من خلال استخدام عدد مختلف من الاحمال.