A Research on Clock-Synchronous Sleep and Wake Scheduling Scheme in Wireless Sensor Networks

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DEDICATION

Dedicated to
My Family and Friends

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ABSTRACT

A Research on Clock-Synchronous Sleep and Wake Scheduling Scheme in Wireless Sensor Networks Network

Wireless Sensor Network (WSN) consist of a unique set of resources like on-board battery and wireless communication devices with limited bandwidth. WSN offers a wide range of applications for monitoring space or targets. WSN is capable of performing simple processing tasks like tracking, detection of an event, or classification and may consist of multiple nodes that can process the information and communicate with nearby nodes in real-time for environmental monitoring, event detection, surveillance, object tracking, battlefield situation monitoring, and data collection etc. However, there are certain limitations in deploying WSN efficiently such as in terms of limited power resource for a single node in WSN, limited processing capability and varying network life time. It had been shown that wireless communication to and from sensor nodes consumes significantly more battery power in comparison to power expended in sensing, computation and memory access procedures. One of the possible solutions to this problem is to communicate as sparingly as possible through efficient sleep/wake scheduling for WSN nodes to extend node and network lifetime. A major research issue in WSN is to develop an energy efficient MAC protocol that not only provides increase in network lifetime but also addresses latency. In this research, a new MAC protocol is designed using sleep/wake scheduling for WSN. Though energy consumption in WSN is unavoidable due to communication necessity and for different stages like idle listening, retransmission, channel sensing and overhearing; this proposed protocol will help in decreasing this energy consumption. Energy efficiency and latency of the proposed sleep/wake scheduling scheme is evaluated and compared with the state of the art research. An AEL (Accounting for Energy and Latency) factor is introduced which is the deciding element for active and sleep cycles of the node. This said AEL factor defines the minimum duty cycle among the network nodes and is specified prior to nodes deployment depending upon application requirements. In the proposed protocol, the nodes adjust their duty cycles according to this AEL factor depending upon traffic load, their position and their connectivity in the network. The effect of this AEL factor on energy efficiency and delay is evaluated for different network densities in this research thesis. While incorporating sleep/wake scheduling for energy efficiency, delays are added in the network to route packet from node towards sink. Therefore, it is necessary to address latency for MAC protocol especially for delay constrained applications. This research thesis focuses on sleep/wake scheduling scheme ensuring energy efficiency, decreased latency and increased network lifetime by selecting an appropriate AEL value. The research includes the comparison of the proposed protocol with state of the art research and has shown significant percentage improvements in energy efficiency and delay from S-MAC and Anycast protocols.

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LIST OFABBREVIATIONS

WSN	Wireless Sensor Network
MEMS	Micro-electromechanical
WSAN	Wireless Sensor Actuator Network
WMD	Weapon of mass destruction
QoS	Quality of Service
BER	Bit error rate
MCU	Micro controller unit
RAM	Random Access Memory
MIPS	Million instructions per second
RF	Radio frequency
AEL	Accounting for Energy and Latency
MAC	Medium access control
IEEE	Institute of Electrical and Electronics Engineers
PHY & DLL	Data link layer and Physical layer
LLC	Logical link control
RTS/CTS	Request to Send/Clear to Send
CHs	Cluster head
TDMA	Time Division Multiple Access
TRAMA	Traffic-Adaptive MAC
FDMA	Frequency-Division-Multiple-Access
CDMA	Code Division Multiple Access
DCF	Distributed coordination function
DIFS	DCF inter frame space
CSMA/CA	Carrier sense multiple access/ collision avoidance
DC	Duty Cycling
S-MAC	Sensor-MAC
CS	Carrier Sense
NAV	Network Allocation Vector
T-MAC	Timeout-MAC

FRTS	Future Request to Send
AC-MAC	Adaptive Coordinated Medium Access Control
PMAC	Pattern MAC
D-MAC	Dynamic MAC
LPL	Low Power Listening
Z-MAC	Zebra MAC Protocol
CAP	Contention Access Period
CFP	Contention Free Period
SMED	Sleep/wake Scheduling Scheme for Minimizing End-to-end Delay
B-MAC	Berkeley Media Access Control
RSSI	Received signal strength indicator
YA-MAC	Yet-Another MAC
SYNC packet	Synchronization packet

Chapter 1. Introduction

1.1 Overview of Wireless Sensor Networks

Advancement in micro-electromechanical (MEMS) technology led the researchers to explore new areas of distributed networks composing of micro-sensor nodes. Wireless sensor network (WSN) usually involves large number of communicating, self-governing, minute, low powered sensor nodes randomly deployed in an ad-hoc manner without careful planning [1, 2]. WSNs have achieved remarkable recognition in the research areas over the past few years because of their extensive use in monitoring and tracking applications [3]. A WSN node is a tiny low cost device combining sensing, computation and communication in its simple circuitry. These devices are distributed across the geographical region to communicate between each other and to the central base station as shown in Figure 1.1. These nodes may include temperature sensors, humidity sensors, light sensors, sound sensors or can provide any other specific sensing using multiple sensors [3]. Sensors used in WSN sense the nearby surrounding and gather specific information and then send this information to a base station or to actuators deployed in a network for a specific action required on the information. Wireless Sensor Actuator Network (WSAN) is an extended form of WSN where actuators are already embedded in the network and incase of any threshold or alarm, nodes can direct the actuators for a specific type of action required [3, 4]. WSAN and WSN are used interchangeably in future WSNs.

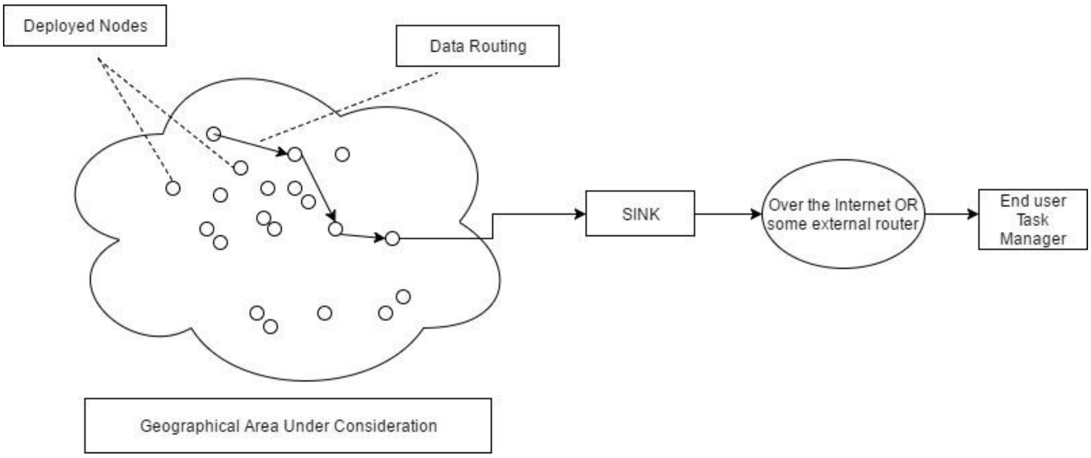

Figure 1.1: General Architecture of a WSN

WSNs are generally designed for a specific application and one WSN implemented architecture can address one type of application, however, data received from this application can be further used as a source for various applications. The future WSN architecture will have the capability of addressing multiple applications within a same network. It may lead to Heterogeneous Networks that involves multiple users and a large network. Structuring a large network may result in use of a small section or a small network within the large network while making all other nodes or networks in power saving mode. This strategy may help in efficiently utilizing a larger network without taking all its resources in full utilization [4]. Wireless sensor networks are considered as emerging technology for 21st century, though, utilization in practical life may require further research and solution to multiple issues of WSN that are efficient and cost effective [5].

1.1.1 WSN Network Topologies

There are four types of layouts that can be implemented in WSN which can be categorized as Star, Mesh, Tree and Hybrid Layout briefly described below and shown in table 1 below.

Topology	Power usage	Communication range	Requires time synchronization
Star	Low	Short	No
Tree	Low	Long	Yes
Mesh	High	Long	No
Hybrid	Low (Typically)	Long	Depends on configuration

Table 1: WSN Topologies

1) In Star layout, nodes communicate in a single hop, each node communicates directly to sink whenever possible and the communication between nodes is minimal [6].
2) In Mesh layout, information from node to sink can take multiple hops i.e. data travels via nodes in the network. Using multi-hop energy consumption can be minimized because nodes are deployed in a higher density and have a small or minimum distance between them i.e. close to each other [6].
3) Hybrid topology uses a hybrid combination of the above mentioned topologies, creating larger networks consisting of hundreds or thousands of nodes. A hybrid network is made from a combination of star and mesh topologies. This star-mesh network takes benefit from the star topology because of its low power

consumption and simplicity, and from the mesh topology because of its extended range and self-healing ability.

4) Tree topology consists of leaf nodes, relay nodes and parent nodes. The central node called the root node is considered to be the main communication router. It is the interface between the application and other nodes. Next are the relay nodes which comes one level down in hierarchy from the parent root nodes, and after that leaf nodes are present.

1.2 Applications of WSNs

The difficulty of gathering sensor data in remote areas where terrain is rough and difficult presents us with unique problems regarding setting up information networks in harsh terrain. This is where WSN networks come in that have small, low cost sensors capable of being easily set up and maintained in these remote regions to gather required data [5]. Due to the flexibility and unique advantages presented by WSN networks and their accompanying sensor types, several new application opportunities have opened up. Some of these WSN applications are depicted in Figure 1.2 and explained below [3, 7];

1) Environmental monitoring

While different end-user requirements demand different configurations of WSN sensor networks, we can broadly categorize the environmental protection applications of WSN networks into the following categories: Monitoring habitats, tracking animal populations, precision farming techniques, more accurate and sensitive forest fire detection. To elaborate on the different configurations for WSN networks required for different applications, two cases may be considered. A forest fire detection system requires that the time delay between the WSN sensors detecting a fire and the reporting of that sensor data which causes an alarm to trigger to be at a minimum. So the focus here is on time delay reduction between sensor detection and alarm triggering. On the other hand, a WSN application monitoring the environment requires the entire system to be energy efficient. This is because these applications monitor the environment for changes over a long period of time and if the WSN network is consuming huge amounts of energy, this makes the maintenance and continuous operation of the system more difficult and complex in remote, rural areas. This completely defeats the purpose of WSN networks.

2) **Health-care Applications**

WSN's have also revolutionised smart health care technologies by integrating sensors on the patient's body to their health care professional's medical information displays. One example could be the monitoring of glucose levels in diabetic patients. WSN sensors permit a patient's blood sugar level to be monitored and wirelessly transmitted to their doctor in real time. More advanced systems can even provide on the spot medical care in a timely manner, normalising blood sugar levels in this case, rather than waiting for the patient to reach a health care facility and for care to be provided by a doctor.

3) **Industrial sensing and diagnostics**

As part of the wave of automation and digitalisation sweeping across the globe, WSN networks and their sensor technology have gained increased focus in industrial sectors as part of an effort by industry to reduce costs and inefficiencies in industrial processes. A plethora of new sensors has entered the market ranging from lubricant level detectors to vibration detection technologies. They can be fitted into areas that cannot be reached by human operators or are hazardous to human health. Wireless sensors can enable an entire factory to be monitored remotely and can also make immense contributions to ensure safety standards are being met and maintenance procedures followed. Spectral sensors are the most popular category of sensors in use by industries. More specifically, Optical Sensors are heavily used in industrial applications to replace existing instruments and offer better miniaturization, composition measurements etc. These WSNs enable multipoint/matrix sensing in factories and the individual data streams from each sensor are compiled into one database for review and analysis by factory operators.

4) **Security applications**

WSNs are also used to secure critical infrastructure like power plants, communication centres etc. from terrorist activities. Integrated sensor arrays providing video, audio and other relevant data, deployed around critical facilities, can detect any suspicious activity rapidly and enable a fast response to any attack on such critical facilities.

5) **Smart Transportation**

Sensors are also being used in traffic control and traffic management systems.

They can monitor vehicle traffic and adjust traffic lights accordingly to enable the smoothest possible traffic on major routes. The sensors to enable vehicle detection can be placed on overhead bridges or at intersections and their data can also be sent to human operators. As already mentioned, the combination of WSN sensors and their accompanying communication system to stream data to traffic control centres are only possible on major routes and intersections due to cost. This is where WSNs come in as they enable low cost sensor networks to cover every route and intersection to monitor and control traffic across an entire city, an entire nation and even the entire planet.

6) Military Purpose awareness

WSN’s also having several military applications in the intelligence gathering and reconnaissance spheres. They can be deployed to monitor the usage of WMD’s like chemical weapons, a recent example being the civil war in Syria. They can also monitor movement of enemy troops and vehicles and collect information on enemy positions. This provides commanders with real-time battlefield knowledge and allows them to make the best possible decisions that minimise risk to their forces and take advantage of enemy weaknesses.

WSNs are also used for Smart buildings, context-aware computing (e.g., Intelligent Homes), precision agriculture, preventative management, logistics and smart Water Distribution Networks [3, 7, 8, 9, 10, 11, 12].

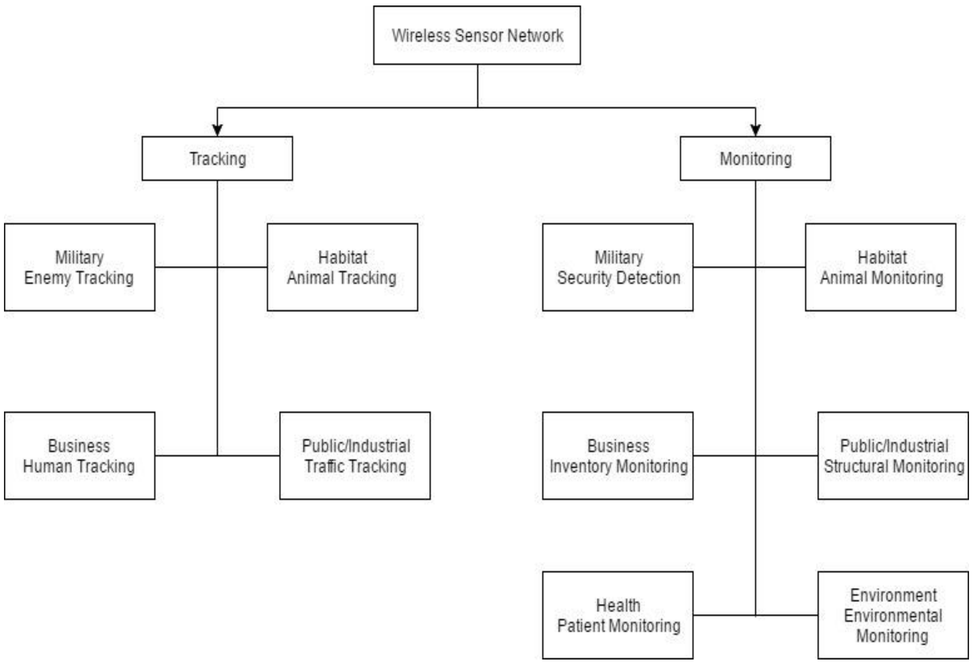

Figure 1.2: Applications of WSN

1.3 WSN Challenges/Performance parameters

The important factors affecting the WSNs performance are listed as follows and shown in Figure 1.3 [4, 5].

1) **Power conservation**

   WSN have a major issue regarding utilization of power resources as they are usually deployed in a field and numerous in numbers. Power resource in the form of the battery banks is usually required by the sensors to work for the prolonged duration as it is quite difficult to replace batteries. So the durability of the sensor network is strongly related to efficacy of the employed power conservation schemes.

2) **Inter-node communication**

   The power sustenance ability of the node determines the protocols of the communication to be followed between the nodes. The head on Communication of the one node to the other node separated by the long distance should be strictly avoided to increase the lifespan of the WSNs. Rather, nodes should use adjacent nodes to communicate with the distant one (multi-hoping) to increase the power efficiency as directly transmitting to the long distant node entails more power. For the monotonously distributed nodes, sink node receives data from the adjacent nodes. Multi-hop communication is then used to send the data away from the sink. In this scenario, the nodes which are placed near to the sink get energy drained rapidly and are not available for further communication. [13].

3) **Size of WSN**

   The desired sensing area entails multiple nodes which may sometime exceed tens of thousands in numbers depending on the size of the area to be covered. This scalability demands the usage of the highly credible network protocol which ensures seamless dataflow between the network nodes regardless of the size.

4) **Lack Global Identification**

   Sensors lack global identification for their implementation in a global network, Attribute-based names and clusters are used to overcome this problem. Using queries information regarding a specific attribute is requested and delivered or by requesting the statistical analysis of a sensor field. These protocols can handle information as data centric routing or in data aggregation.

5) **Operational life**

The operational life of the WSN is dependent on the power delivered by the energy source which should be adequate enough to sustain WSN for the maximum duration. The power efficiency should also be improved by utilizing the available power in effective manner during the operational activity.

6) **Network Quality**

The network quality also known as Quality of Service (QoS) defines the potential of the network to satisfy its end users in terms of the provided services. The quality of network is determined against various metrics such as BER, data rate, network congestion, latency and various others. [14].

7) **Class of output**

WSN is considered to be the network service which provides output in the more comprehensible manner for its clients. Clients desire to have their problems and queries addressed in the form of vivid response from the system. [15].

8) **Fault resistance**

Sensor nodes as mentioned above have power constraints and their energy can get drained quickly. External environmental factors may also prove pernicious for the node which in turn may lead to the failure of the communication between nodes. Redundancy is thus added in the nodes to compensate for the failed nodes in the network [16].

9) **Adaptation to varying densities**

Number of the nodes contained within the unit area is the density of the WSN. Numbers of the nodes in the network varies with the time and space depending on the operational requirements. It is then important for the network nodes to follow the changes timely that took place within the network [17].

10) **Adaptive Programming**

The data processing programming should be flexible enough to accommodate for the changes that takes place in the network. Adaptive programming according to the different scenarios needs to be incorporated [12].

11) **Adaptive Routing**

Nodes in a WSN are deployed randomly and location cannot be pre-determined. Therefore, routing in a WSN is a self-organized phenomenon.

12) **Health maintenance**

WSN should be capable enough to auto-regulate its operational health status. It must be able to react according to the modification that happens due to changed network in terms of the drained battery resource, node failure or initiation of new process. Quality of Service is safeguarded by interfacing the network with external systems [15].

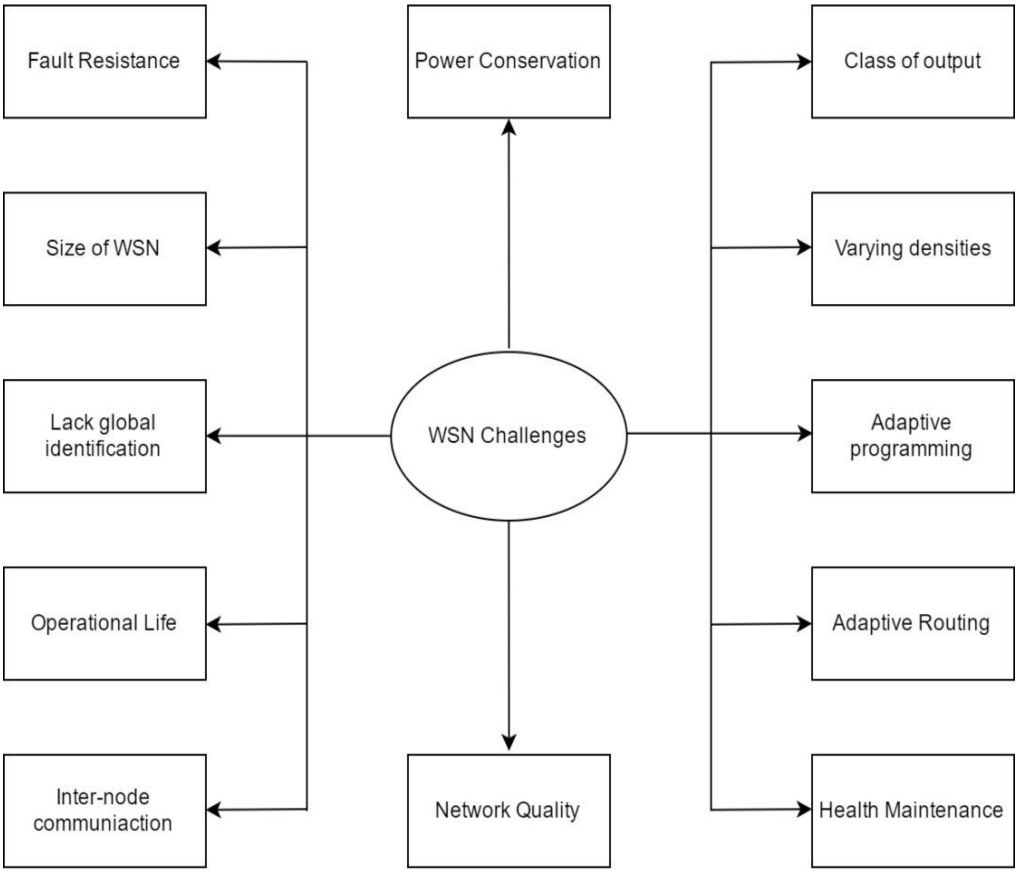

Figure 1.3: Challenges for WSN

1.4 Sensor Node Design and Architecture

For WSNs to be cost effective and easily deployable, a Sensor Node is mostly a tiny self-governing piece of equipment having an MCU (micro controller unit), a transceiver and some kind of sensing hardware in its general form. In addition, some networks demand sensor nodes to be equipped with memory module or actuators. Mostly equipped with a single sensor, a single transceiver and limited battery power; yet in some scenarios sensor nodes are also equipped with multiple sensors, different communication frequencies and energy harvesting equipment or a continuous power source [4]. For a given deployed network, sensor nodes are either homogeneous or heterogeneous. For homogeneous type of networks, all of the deployed sensor nodes have the same hardware platform, whereas different hardware platforms are used for sensor nodes in case of heterogeneous WSN networks. Whether homogeneous or heterogeneous, WSN can have static or mobile sensor nodes [4].

As explained above, sensor nodes come in different forms with respect to hardware, and it depends upon the specific application for which node is to be deployed. Five main hardware components shown in Figure 1.4 are described below defining a basic sensor node;

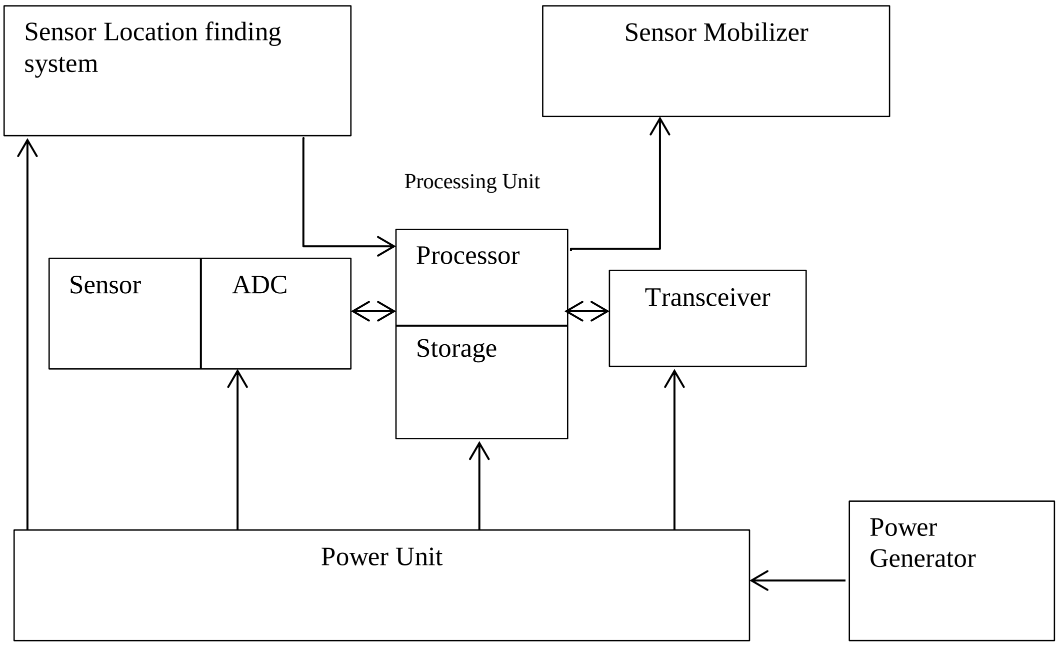

Figure 1.4: Sensor Node Architecture

1) **Processor**

The main processing of a sensor node is a done by micro controller unit (MCU) capable of processing all the information required to perform certain tasks like control of sensors, scheduling internal timers and accomplishment of communication protocols. MCU is the core of wireless sensor node and have limited memory therefore it demands the development of an efficient code that satisfies this memory constraint. For power management and efficient energy consumption, MCUs usually operate under different operating modes [4].

2) **Sensors and Actuators**

Sensors are responsible for sensing or recording the physical parameters of environment, while actuators perform the required task after sensing [4]. Sensor is the device that basically provides a bridge for interaction of a node and environment under consideration.

3) Storage

The data and programs are stored in the memory unit. It may be program, data or flash memory. Larger storages are not required for WSNs as data is stored in a sensor node for a short time and then it is transmitted to neighbouring node or base station [18].

4) Transceiver

The radio transceiver is necessary for sending and receiving information between sensor nodes, from sensor nodes to sink or from sink to sensor nodes over a wireless medium. The communication device used for WSNs is usually short range and can operate in four modes, namely transmit, receive, idle and sleep. When a node is neither sending nor receiving any information, radio is turned off rather than putting it in idle mode for efficient utilization of energy [4].

5) Power Unit

Power unit comprises of batteries that are responsible for suppling power to the node. As this limited battery is the sole means for power supply in most WSN scenarios, battery recharging by energy harvesting especially solar energy harvesting improve the network lifetime of WSNs as harvesting techniques provide nodes with an additional power [4, 18].

Several hardware platforms had been built for WSNs over the last decade. The early sensor nodes revealed their expediency around the year 2000. In 2002, Mica2 [19] was the first widely used sensor node platform that was also available commercially, followed by Telos, TelosB/Tmote and micaZ[20] developed in around 2004. Advancements over the most recent couple of years went in diverse directions, like Econotags [21], the Imote2 and the SunSPOTS [22]. They are built for much more performance than previous sensor nodes by using microcontrollers embedded with common XScale or ARM cores. Still some of the sensor network platforms opted the roots like the Zolteria Z1 [23] and extended a very popular Tmote platform with more powerful microcontrollers from the similar MCU variants as before. Present-day microcontrollers are designed with more than twice the RAM and flash memory with new hardware components supporting AES encryption utilizing the same power. Some other platforms like WASPmotes [24] attempt in finding a balance between the powerful Imote2 class and the energy efficient Tmote class of sensor nodes [4].

1.4.1 Unique Constraints for Sensor Nodes [25]

1) **Limited hardware**

   Each node has limited processing, storage, and communication capabilities, and limited energy supply and bandwidth.

2) **Limited support for networking**

   The network is peer-to-peer, with a mesh topology and dynamic, mobile, and unreliable connectivity. There are no universal routing protocols or central registry services. Each node acts both as a router and as an application host.

3) **Limited support for software development**

   The tasks are typically real-time and massively distributed, involve dynamic collaboration among nodes, and must handle multiple competing events. Global properties can be specified only via local instructions. Because of the coupling between applications and system layers, the software architecture must be code signed with the information processing architecture.

1.4.2 Nodes' Working Mechanism based on Data Reporting Method

As for Data Reporting method, WSN can be classified into two type of reporting, that is data driven or event driven [26]. In Event Driven Technique, nodes generate an alarm or data in case of meeting specific threshold limit or occurring of the event need to be monitored. These are immediate in terms of data transfer and need to send data/information as soon as the event occurred, for example in case of wireless health monitoring of a patient, data pertaining to patient's health e.g. heart beat need to send urgently in case it crosses the specific threshold so that a doctor in hospital can remotely access the data and can help the patient in urgent medical conditions. Similarly, in case of fire alarm system, sensors need to send data to SINK when they detect any fir/smoke or any change in the temperature, therefore, there is an urgent need to transfer information to the central control station about fire so that situation could be managed. These types of WSN systems are Event Driven. In Periodic reporting WSN, all nodes in a WSN are bound to report their data/information to the base station after a specific time. However, there is low real-time requirement of that data, for example, let's assume a WSN for crop monitoring, in this case we do need temperature, humidity data of that environment although there is no urgency for that data and any delay in the system is acceptable.

1.5 Motivation

WSN is an emerging technology and is being used in many applications; however, there are still many constraints to overcome before WSN becomes an established platform. One of the main factors is energy limitations in WSNs as a single WSN node has limited energy and thus limited lifetime. Current batteries are not going to solve the issue as bigger battery size leads to the size of node which is not a suitable compromise for a WSN system. There is need to design energy efficient node so that they have minimum dependency on Power resources and minimum energy would be consumed [1]. Among different component in WSN node, transceiver takes the maximum portion of energy; RF communication consumes much more energy as compared to computational resources. According to Kaiser and Pottie [27], energy required to transmit 1kb of data over 100m need energy of 3 joules. This energy when used in computational purpose, can process 3 million instructions using a normal general purpose processor with 100MIPS/W power. Therefore, WSN nodes should be designed in a way that they consume much of their energy in processing and thus only transfer limited and required information to the neighboring nodes. Only then an energy efficient node could be designed and contribute to the development of WSN applications. There are also techniques like sleep wake scheduling or using carrier sense over the medium so that RF power utilization can be minimized.

A trade off exists between energy efficiency of WSN nodes and their connectivity. For efficient energy utilization sensor nodes need to be in sleep state when they are not in communication to ensure energy efficiency, whereas, WSN nodes should always be in active state for maximum connectivity and minimum delay. Duty cycle of sensor nodes should be synchronized such that the packets can be routed using neighboring sensor nodes and in multiple hops to the central data station.

1.6 Problem Statement and Proposed Solution

Efficient sleep/wake scheduling is an essential requirement for WSN to extend the network lifetime. Sleep-wake scheduling techniques reduce the energy wastage such that transceiver of sensor node needs not to be in active state for the whole lifetime. It can switch between active and sleep states depending on traffic loads and other various factors including network density, node's position and node's importance in the network, which will be included in this research work. While dealing with sleep/wake scheduling, delays are added in the network to route packet from node towards sink especially in the case of multi-hop networks. To deal with this problem, so that all the tier nodes in the forwarding path share the same sleep/wake schedule, synchronization between nodes is very important in WSNs to share one common schedule. This research thesis will focus on sleep/wake scheduling scheme ensuring energy efficiency and delay minimization between sensor nodes.

1.7 Methodology

In this research, energy efficient sleep/wake scheduling scheme is designed and developed between sensor nodes for maximizing energy efficiency and network lifetime while minimizing delay. Below mentioned research methodology has been followed.

- Literature Review of existing sleep/wake scheduling schemes for in-depth understanding of MAC protocol design challenges. Existing sleep/wake scheduling schemes were studied in detail to understand the shortcomings of these existing schemes and the need to develop a single control parameter based sleep/wake scheduling scheme. Based on the outcomes of the literature review, energy efficient sleep/wake scheduling scheme was selected to perform further work on them.
- In this research, sleep/wake scheduling technique is devised for WSN having a single control parameter defined as 'AEL (Accounting for Energy and Latency) factor' that will account for trade-off between energy efficiency and delay. That single control parameter is computed based on various network parameters like network density, traffic loads, node's position relative to sink and node's importance in the network (connectivity critical or not). This control parameter then decides the sleep/wake scheduling for every sensor node in any provided scenario.
- In this research work, a comparison analysis is done between network lifetime and duty cycle with respect to the defined AEL factor. The performance comparison was evaluated with already existing sleep/wake scheduling schemes based on energy consumed and delay and results were computed in appropriate simulation tool.

1.8 Thesis Outline

The rest of the thesis is organized in the following manner.

Chapter 2 gives a comprehensive literature review about WSN MAC protocol and its design factors while covering literature review of different MAC protocols. Chapter 3 gives an insight to the proposed protocol and the scope/scenario of the designed protocol. Chapter 4 presents the simulation results of the proposed protocol and provides comparison with already existing protocols. Chapter 5 includes the conclusion and future aspects of the proposed protocol.

Chapter 2. Literature Review

A wireless sensor network is an ad hoc arrangement of various versatile sensor nodes in a wireless field, distributed over a large and in some cases remote area to gather information regarding some phenomenon. Incorporating collaborated efforts, sensor nodes work for a common interest of the network to the extent that the network will continue its function even if some of the sensor nodes have depleted their energy. Data is directed to the sink and ultimately to the end user in a multi-hop infrastructure-less manner. This chapter entails the protocol stack and detailed MAC layer insights for such an infrastructure-less wireless sensor network.

2.1 Protocol Stack for WSN

"A protocol, etiquette, code of conduct, is a set of rules that govern a certain behavior, in social or diplomatic activities, at work, when driving, etc. In communication networks, protocols govern, determine the functioning specifications and guidelines, and guarantee how networks fulfill their intended use [6]." The protocol stack for WSNs incorporated by the sink and the sensor nodes is given in Figure 2.1. A protocol stack for WSNs must assist their normal elements (features) and singularities. As per [6], the sensor network protocol stack is much similar to the existing traditional protocol stack with application, transport, network, data link, and physical layers. The physical layer is in charge of determination of frequency, generation of the frequency of carrier, detection of the signal, modulation and information encryption. The data link layer is in charge of the multiplexing of information streams, identification of data frame, medium access and error control. It helps in accommodating the transmission at the link level and guarantees point to point and point to multipoint transmissions for a communication network. The network layer deals with directing the information provided by the transport layer. The network layer plan in WSNs must consider the power efficiency, information accumulation, data-centric communication and so on. The network layer keeps up the information flow and might be essential if WSNs are intended to be connected through the Internet or other outside systems. Various types of application software have been defined to be used by the application layer depending upon the network requirement and sensing tasks [6].

WSNs should be well aware of several management levels so as to perform its roles efficiently, providing movability, quality of service and security management. Among them, the task functions, movability and power management levels have been explained by Akyildiz et al. in [28] and et al. in [29]. The protocol stack and the related levels utilized by the sink, parent node (might be cluster head) and sensor nodes are depicted in Figure 2.1 below.

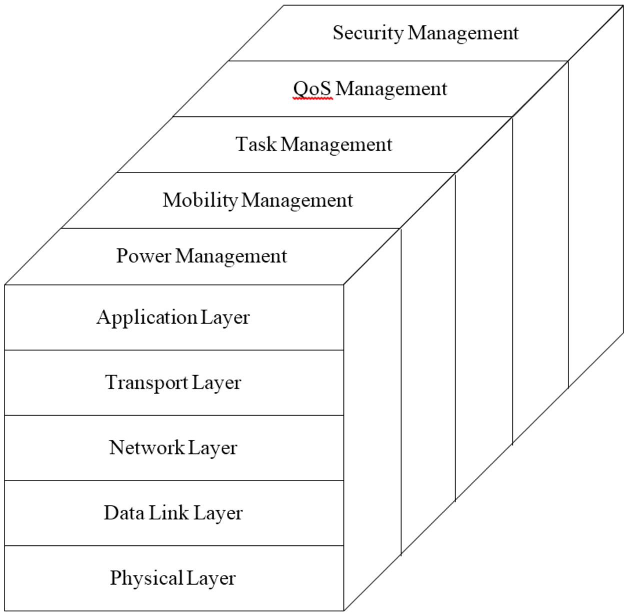

Figure 2.1: Protocol Stack of WSNs [6]

The power management block is in charge of limiting power utilization and may turn off functionality keeping in mind the end goal to preserve power. The mobility management block identifies and registers movement of nodes so that an information route to the sink is constantly kept up. The task management block makes sure that sensing tasks are assigned to required nodes only and other nodes focuses on routing the packets and data aggregation. QoS management in WSNs is essential for data services requirement in real-time scenarios. It deals with error control, fault tolerance, and performance optimization in terms of certain QoS measures. Security management deals with handling, checking, and regulating the security concerns of a network. The major role of security management is to control access points to sensitive and critical data. Security related tasks such as encryption, authentication and intrusion detection are also addressed by security management block [6].

2.1.1 Data Link Layer and Importance of MAC protocol

As defined earlier, the duties of the data link layer are the multiplexing of information streams, data frame discovery, providing suitable scheme for medium access (MAC) and minimizing error [6]. The most significant task among these in a shared medium is medium access control to decide which node will be given access to the medium for a specific time. Since numerous nodes are contending for the medium at the same time, the communication may be interfered. As the number of nodes varies from few hundreds to thousands, a plan is always required and all the nodes in the network ought to maintain the defined plan. This plan or arrangement is ordinarily known as a MAC protocol. The MAC protocol comprises of complex transactions and requirements. The protocol deals with the condition of the sensor nodes (i.e. transmitting, receiving, idle or sleeping). A MAC protocol for wireless sensor systems ought to concentrate on power utilization, and guarantee that sensor nodes are in not in active mode if not being used. Subsequently, the system can keep running for an increased time without any assistance from external sources [30]. A wireless sensor network must have a particular MAC protocol to address the issues of energy preservation and data-centric packet routing. The MAC protocol must ensure two main objectives. The first is to make a system foundation, which incorporates building up interfaces between a large number of nodes, and giving the network self-organizing capacities. The second objective is fairness of the network that is to efficiently share communication medium between every node in the network. As explained in chapter 1, wireless sensor networks demand no central control and much larger number of nodes than ordinary ad-hoc networks. The MAC protocol for WSNs should take into account the network topology changes because of failure of existing nodes and adding of new nodes. Power saving is a perilous task for the design of WSN due to nodes operating on limited batteries and due to unattended environment. Many research endeavors in the current years have concentrated on creating power efficient plans for wireless sensor networks. Design of an energy efficient MAC protocol is one of the procedures that drag out the lifetime of the system. Apart from power efficiency, delay and throughput are additionally vital elements for designing MAC protocol for WSNs [6].

IEEE 802.15.4 defines the IEEE standards for physical and MAC layers for Wireless Personal Area Networks (WPANs). It focuses on power efficiency, low data rates as well as less complexity. It is standardized for its low interference cost effective solution [101].

This standard deals with the same 2.4 GHz ISM band like Bluetooth, WiFi, and WiMax, providing enormous advantages over these technologies based on certain wireless applications. Depending upon the network scenario and application demand, IEEE 802.15.4 compliant devices have transmission capabilities ranging from 10 to 75 meters [31].

IEEE 802.11 offering power management system for decentralized wireless networks have been commercialized, in which the nodes can remain in idle state when there is less or no traffic thereby ensuring energy efficiency. Since significant amount of power is also wasted in idle mode, IEEE 802.11 is not a suitable solution for WSNs.

The 802.15.4 standard characterizes set of rules for data link layer (DLL) and physical layer (PHY) for supporting sensor nodes with negligible power consumption working in constrained area. These two layers ensure consistent connection between sensor nodes to improve efficiency by avoiding collision of data sent from different nodes over the medium [101]. The DLL is further partitioned into two sub layers, the medium access control (MAC) and logical link control (LLC). IEEE 802.2 has defined the standard for LLC sub-layer being much common among the IEEE 802 guidelines. The MAC layer gives an interface between upper layers and the physical layer [31].

Since the data link layer describes attributes for reliable data interchange between two neighboring nodes, MAC specifies the strategies that the nodes should opt for accessing the medium [30]. An efficiently designed MAC defines coordinated access in a way that support quality of service (QoS) and saves power [6].

In some WSN application scenarios, mobility of nodes as well as mobile targets is to be addressed along with the changing environment and node topologies. In these scenarios, the wireless sensor network needs to accomplish association and disassociation in an efficient way to attain a consistent and rational network topology for communicating and routing. In addition, the MAC protocol offers a critical task of maintaining virtual connection between node pairs in the wireless world. This is very important task especially in multi-hop networks where end-to end reliability cannot be achieved without point-to-point reliability [17].

2.2 Attributes of Medium Access Control

The three different functions of Medium Access Control impact a very critical parameter of a sensor node i.e. the energy consumption. The functional distribution of MAC is depicted in Figure 2.2 below [30]. One essential attribute of the Medium Access Control (MAC) protocol is collision avoidance by ensuring that sensor nodes which are interfering are restricted from data transmission simultaneously [32]. A few major phenomena which increase the overall energy wastage of the system are described in detail in the coming section [33].

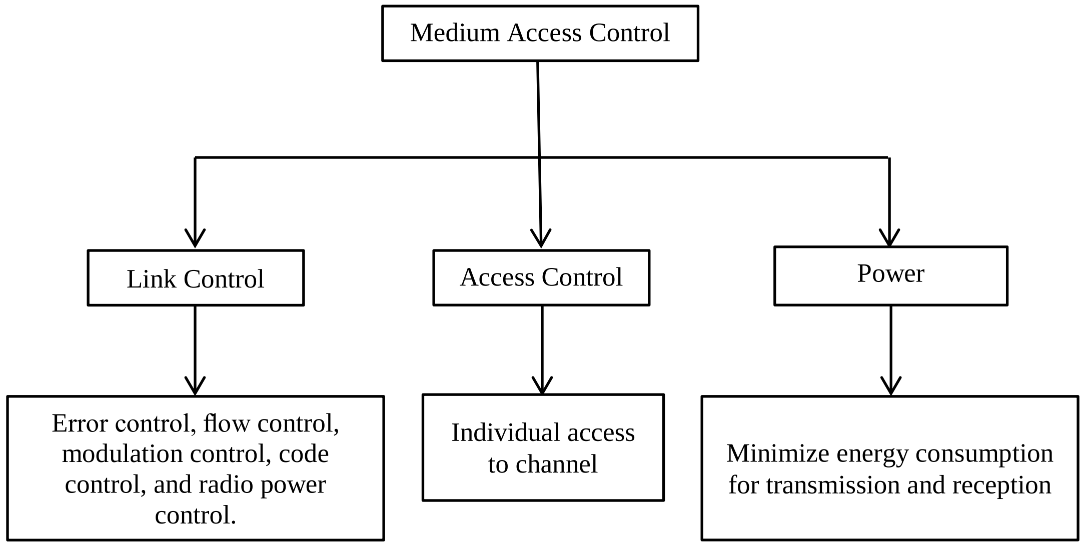

Figure 2.2: Functions of MAC

1) **Collision**

If a situation arises when a sensor node receives multiple packets from different interfering nodes simultaneously, the packets are discarded and data is lost until the sending nodes retransmit those packets [33]. Two frames collide when two interfering nodes access the transmission medium at the same time and start sending data intended for a particular node or multiple nodes. Collision of data frames result in corruption of data and retransmission of these corrupted frames is necessary.

Consequently, a significant amount of system resources such as time and energy gets wasted during the process of retransmission of previously sent data frames. An efficient control over use of the transmission medium by interfering nodes can drastically reduce energy wastage in frame retransmission. [34]

2) **Overhearing**

Another problem that needs to be addressed while improving the system’s energy efficiency is overhearing. Overhearing causes the sensor nodes to receive data frames which are not intended for particular node because of the fact that the radios of all sensor nodes are turned ON all the time. In order to avoid energy wastage, the nodes need to switch the radios OFF. The sensor nodes which are not the destined receivers for data packets are always ON and receiving/ decoding data causes significant energy consumption. In a shared transmission media where the transmitting and receiving nodes do not share a priori information about the frame destination the Overhearing is a major problem [34].

3) Control packet overhead

The control packets or headers in nay communication algorithm are essential for transmission medium control. An inefficient control mechanism increases the use of vital system resources whereas the transmission and reception does not contribute to data carrying capability of the media [33].

A network of sensor nodes without an efficient control algorithm only increases the overhead on the system. Uncoordinated acknowledgments, control signals and unnecessarily long headers appended ahead of useful application data in frames add to extra communication costs. [34]

4) Idle listening

Since WSNs require extra attention to energy consumption and efficient resource management, idle listening is a major cause of concern for system designers. The sensor nodes consume energy even when there is no data transmission being carried out over the communication medium. The nodes are always switched ON and in ready to receive mode which results in poor energy efficiency. Since the transmission medium is used infrequently and without a fixed pattern in WSNs, a mechanism to turn OFF and ON the sensor nodes is very important. This problem can be overcome to some extent by employing a strategy to put radios in sleep mode while there is no traffic in transmission channel. [34]

5) Over emitting

In WSNs, when one node continuously starts sending data frames to a particular node which is not listening to any communication intended for itself. It is called Over-Emitting. It has similarities with packet collision. Over-emitting can be overcome by using an efficient medium control mechanism with pre-defined communication times and scheduling [35].

6) Complexity

A communication system's complexity translates to the use of resources such as energy consumed while running software-defined protocols and algorithms. In WSNs, computationally efficient algorithm and simple control protocols is the ultimate design goal due to less computational capabilities of microcontroller of a sensor node [34].

2.2.1 Energy Saving Mechanisms for MAC

Primary focus of MAC protocols is in accessing wireless medium without collision, which can be avoided only by precise information of possible obstructing nodes. So, a valid wireless channel model is necessary for designing and evaluating MAC protocols.

There are many schemes suggested in literature for resolving the problem of accessing shared medium. These schemes try to attain energy efficiency for wireless sensor networks. The performance of WSN will mainly reside on the choice of MAC scheme. Conventional schemes are introduced and discussed in short [4].

2.2.1.1 Wakeup Scheme

This scheme has substantial ability to save energy for wireless sensor networks. Using wakeup scheme MAC protocol switches off sensor's radio for energy saving in case event occurrence is scarce and communication is not needed. Additionally, in some cases wakeup tone is transmitted to wakeup neighbor nodes.

2.2.1.2 Back-off Scheme

This scheme is applied in contention-based protocols (will be discussed later), if contention intervening time rises because of elevated traffic. In this scheme nodes have to wait for a random amount of time if a collision is observed during the contention interval. So, back-off scheme has the ability of decreasing probability of collision during higher traffic burden and decreasing latency during lower traffic burden.

2.2.1.3 Request to Send/Clear to Send (RTS/CTS) scheme

This scheme is applied to counter frame collisions presented by hidden node problem in wireless sensor networks. Hidden terminal problem arises when two nodes are sending a packet to a same receiver while not knowing about each other's transmission. The packets at the receiver node get collided and therefore discarded. This hidden terminal/node problem arises because the two sending nodes are not in each other's transmission range.

If a node needs to transmit data to some other node, it first transmits an RTS packet. The receiver node responds the RTS packet with a packet known as CTS packet. Transmitter node sends data packets only after receiving CTS packet. Transmitter node waits for CTS packet for a specified duration, so that transmission can be accomplished in a particular time. In case, CTS packet does not arrive in that time, transmitter node enters in exponential back-off mode.

2.2.1.4 Reservation Scheme

Field of wireless sensor networks faces the challenge of network scalability due to gradually increasing size and density. Reservation scheme is employed for monitoring applications if traffic is following a recurrent pattern. In this scheme, every node of the network transmits data to a sink node in its reserved slot, which results in collision-free communication. Also, energy is saved as duty cycle of nodes is reduced.

2.2.1.5 The use of beacons

To apply this scheme, MAC protocols takes help from beacon for synchronizing nodes in the network, for discovering the coordinators and waking up neighbor nodes. In result, this synchronization lets the nodes to sleep when no coordinated transmissions are taking place between transmitter and receiver nodes. So, this scheme not only saves energy for WSNs but also enhances network lifetime.

2.2.1.6 Clustering schemes

In wireless sensor networks, clustering is mainly identified by data aggregation by each cluster head (CHs) that decreases the traffic cost by a remarkable margin. Clustering schemes are distinctly successful in large multi-hop WSNs where they can achieve network scalability, decrease energy utilization, minimize data latency and attain an improved network performance. But there is a serious complication attached to these schemes. Energy-efficiency algorithm can choose some CHs for saving energy which are not stable enough or lack good connectivity because of low battery. These CHs result in exceptionally reduced network performance because of dropped packets and retransmission. In this case overall consumed energy can be even higher than without using this scheme. Hence, for a clustering algorithm that focuses on energy efficiency of the network, it is necessary to make sure of dependable communication.

2.3 MAC Protocols

Medium Access Control (MAC) design can be classified into two different network types as shown in Figure 2.3 below. A MAC protocol customized for energy efficiency over wireless transmission medium for a set of WSN nodes aims to get the most out of the likelihood of successful data packet exchange between different sensor nodes in the network all the while consuming the least amount of an important system resource of energy. Consequently, a computationally efficient algorithm adds to overall system life [30].

MAC is divided into contention-based and contention-free protocols by incorporating the control over individual nodes' access to communication medium, as shown below in Figure 2.3.

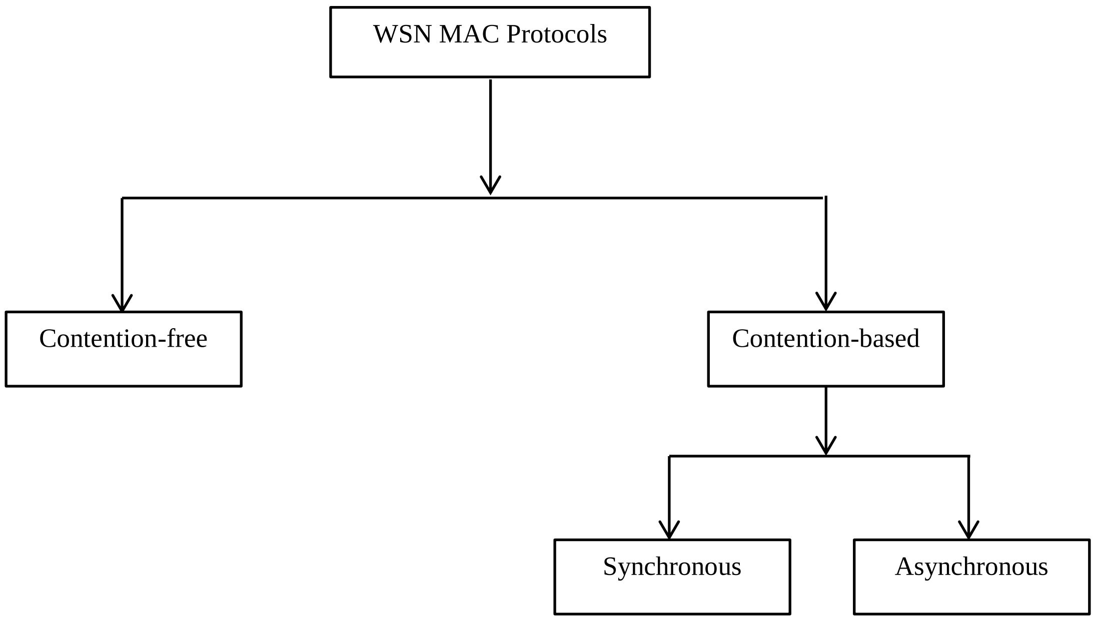

Figure 2.3: WSN MAC Protocols

2.3.1 Contention-free Protocols

Communication protocols which use scheduling are widely preferred for wireless sensor network application due to efficient energy and other system resource management. Each individual sensor is pre-allocated a slot in the network which helps in collision avoidance. These scheduled MAC protocols use an important element of duty cycling which is included with a particular aim of collision free communication thus minimizing the amount of extra energy used to retransmit lost data frames during packet collisions. However, scheduling increases the complexity of the protocol, because synchronization needs to be taken care of in such systems. Furthermore, contention-free algorithms are less flexible to changes in the overall network in terms of node density or sensor node movement along with the lack of peer-to-peer data exchange [7].

2.3.1.1 TDMA

In Time Division Multiple Access (TDMA) MAC, the wireless transmission medium is separated on the basis of fixed duration time slots. Since each sensor node is allotted an independent time slot to use transmission channel, ideally zero collisions are possible in such a system. Thus the obvious advantages of a TDMA based MAC protocol transmission controlled by schedule and energy efficiency by avoiding packet collision.

However, time slot based algorithms render ineffective when the data is transmitted in bursts instead of a stream. For example, since channel is divided into time slots and each node is only capable of sending data in its allocated slot, the case in which there is no need to send data results in wastage of time/slot by that particular node. This avoidable energy consumption can however be minimized by switching OFF the radio if there is no data reception detected at the start of allocated time slot. Another drawback of TDMA MAC is the amount of computational cost incurred by requirement of precise time synchronization and coordination between all nodes in a wireless sensor network. Therefore, in TDMA based MAC protocols, the energy efficiency and overall throughput can be lower along with longer system delays [36].

2.3.1.2 TRAMA

TRAMA [62] (Traffic-Adaptive MAC) is another MAC protocol that falls in the category of contention-free protocols and uses reservation-based strategy for channel allocation to individual nodes in sensor network. It exploits a scattered election protocol according to statistical information from each node about data traffic in order to make an allocation of time slot to any particular node. Time is separated into two independent slots of reservation period and transmission period. In the reservation slot, sensor nodes compete for the access of the communication channel with a map comprising of the information of the two-hop neighbors' priorities of each sensor node in the network. In the second step of transmit slot, the two-hop priority information will be gathered from each node and the sensor node with highest priority is given the next time slot consequently. Once the priority is defined and the transmission period starts, all the nodes transmit data packets in their pre-allocated slots eventually converting it into a TDMA MAC with zero collision [33].

Since TRAMA gathers a prior information about the nodes which have packets to send, it can significantly reduce energy utilization by only allocating time slots to the sensor nodes with requirement of channel access and rest of the nodes which are idle are put to sleep mode. The idea is to never use an idle node as an intended user which results in minimum collision possibility [33].

The reservation period at the beginning of transmission is classed into three separate periods: notification, contention and announcement slots. Notification phase marks the start of each data frame and is spread through the network by the base station to declare the start of contention phase. Once the notification has been sent via broadcast, contention phase is the time for nodes to declare that they have data to send and they will compete to transmit reservation data packet, following a p-persistent CSMA scheme. Finally, the announcement period is the chance of the base station to announce the allocation of slots to successful contenders and transmission then begins according to slot allocations [33].

2.3.1.3 CDMA

Code Division Multiple Access (CDMA) is a mechanism in which sensor node are allocated different codes while sending the data packet and the simultaneous communication between different nodes can be accomplished with some interference. CDMA systems provide full bandwidth to each node thus minimizing the impact of channel limitations faced in FDMA as well as time delays caused by TDMA's slot based access [37].

2.3.1.4 FDMA

In TDMA, each node in the network is required to be in active listening mode to receive the synchronization packet for marking the start of slots and transmission. This might induce extra system delay because of the time based access. Frequency-

Division-Multiple-Access (FDMA) evades this difficulty by dividing the bandwidth of the system in multiple independent channels for each sensor node to transmit data using its own channel without having to wait for designated time slots. In FDMA, individual nodes share their transmission schedules in order for overall network to get synchronized [37].

2.3.2 Contention-based MAC Protocols

Sensor Node in a contention-based MAC protocols before data transmission compete for medium access. In order to resolve the problem of contention in a WSN, the mechanism typically used is the 'carrier sense multiple access with collision avoidance (CSMA/CA)'. When a node has a data packet to send, it will sense the channel to check whether the medium is free to access or occupied already. If the channel is detected idle for a certain time defined by DIFS (distributed coordination function (DCF) inter frame space), then the node will start its communication by first sending a request to send (RTS) packet after waiting for a random back off time. When the intended receiver sends a clear to send (CTS) packet in reply and the sender receives it without collision, a data packet is then transmitted. When two or more nodes select the smallest back off time collision occurs. Even if the channel is error-free, packet transmission would be unsuccessful in the above mentioned collision case [38].

CSMA/CA is intended to be simple and flexible; it does not require any extra information from the rest of the network for data communication. In both academia and industries, the CSMA/CA based protocols and transmission schemes are popular [38].

2.3.2.1 Synchronous MAC Protocols

A synchronous MAC protocol empowers communications among energy saving nodes by synchronization of the active duration of all nodes [30]. Communication between two neighboring nodes is only possible when the active duration of transmitting and receiving nodes matches. Therefore, synchronous MAC protocols demands all nodes to coordinate their active times with their neighboring nodes. This synchronization helps neighboring nodes to maintain their sleep and active states accordingly as shown in Figure 2.4 [38].

A sync. period which is a part of the active period is allocated in order to facilitate this synchronization. Active period's remaining part is referred to as the data sending period, used for data interchange. Thus, synchronous MAC protocols' cycle is consecutively composed of a sync, a data and a sleep period, as shown in Figure 2.4 below [38].

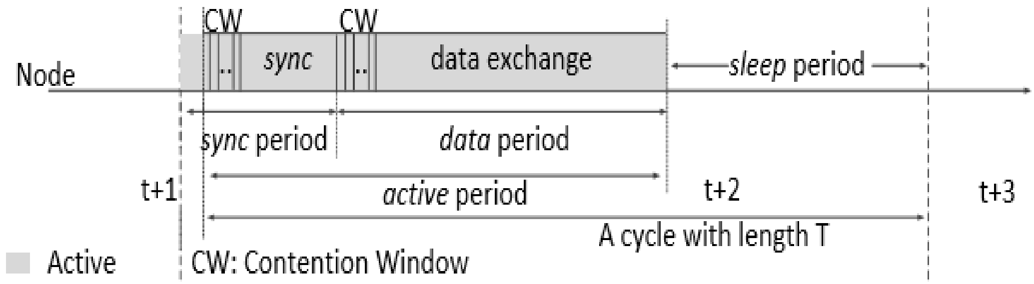

Figure 2.4: Duty cycle of a synchronous MAC protocol [38]

For sending either SYNC or data packets, the contention mechanism is done a priori. The nodes that lost competition for contending medium enter into the sleep state among all contending nodes, after hearing the initiation of data transmission from the winning node; while the winning node goes to sleep after finishing the communication, as portrayed in Figure 2.5.

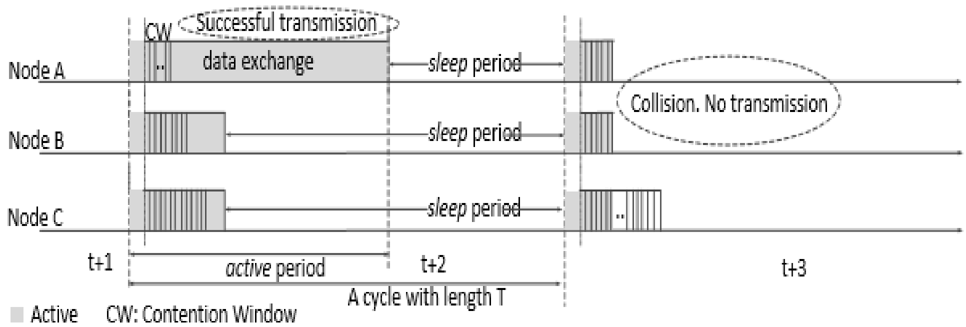

Figure 2.5: Operation of a contention based MAC protocol having synchronized wake-up schedule [38]

As exemplified in this figure, Nodes A, B and C are contending for channel access through selected back off times. For the duration of Cycle t+2, the winner node is A as it is the single node that has carefully chosen the shortest back off, so it transmits its packet effectively. Typically, in the competition of multiple nodes contending for a single medium, two or more nodes could select the same back off time. In the duration of Cycle t+3 equal smallest back off time is selected by the nodes A and B. As a result of which, the collision happened and a transmission chance is wasted. Here it must be noted that the back off value chosen by the Node C is greater than the node A and B. The timer of the node C in this case has to be reset for the new cycle after the hearing of the transmission or collision. Likewise, all nodes will follow the similar process in the upcoming cycles [38].

2.3.2.2 Asynchronous MAC Protocols

Another class of MAC protocols is Asynchronous MAC protocols which do not use any defined or agreed schedules between sensor nodes. In a single hop network, the network controller is simply communicated by the node, that it is either in the mode of data transfer or sleeping. In a sleeping mode, the sensor will turn off the radio and negligible amount of the energy will be utilized. During the mode of the data transfer, the sensor node is in active state for receiving or transmitting data [36].

However, for multi-hop networks, the process is different. The idea for the design of asynchronous multi-hop MAC protocol is actually based on the statistic that the transmission time is very insignificant as compared to the periodic active time. Similarly, the overhead of the synchronization consumes a lot of energy and so increases the complexity. In these protocols, the sleep and wake time of every node is periodic, and in its active duration a node checks if there is any sort of activity on the channel. If no activity is found, it will go back to sleep. If a node has a data packet to transmit, a long preamble is used to identify the receiver and the number of total hops occurring in between. In a variation of this protocol, the preambles are transmitted by receiver instead of sender node. The transmitter will just awake and then will do the channel sensing. If a channel is sensed free, data transmission is started by using RTS/CTS mechanism [30]. The drawback of using preambles is that these extra packets generally introduce delay into the system. Also, variable traffic loads introduce a limitation to protocol capabilities [30]. Figure 2.6 exemplifies the duty cycle procedure of an asynchronous MAC protocol. As revealed in the figure, that for the data exchange, the sending node waits till the receiver is in active state. In a situation when the receiver wakes up former to the sender, it could wait until it notices that the sender has woken up or it may go to sleep state after a duration which is predefined, as illustrated in Figure 2.6 below. MAC handshake procedure will determine which mode is to be adopted, whether receiver will wait for the sender or just go back to sleep state. In the former case, the receiver has to spend idle time in listening while in the latter one sender is idle listening. No matter which mode is working, significant amount of the energy consumption is faced due to idle listening. Apart from this energy issue, benefit attained by this group of MAC protocols is low latency [38].

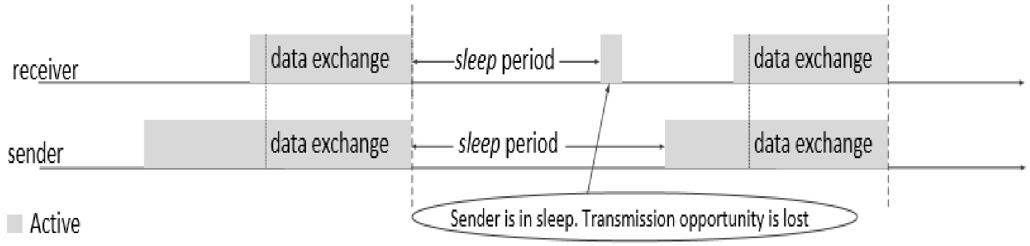

Figure 2.6: Duty Cycle of an asynchronous MAC protocol [38]

MAC	Self-organization	Energy	Latency	Throughput	Fairness	Robust	Scalability
Contention-free	poor	good	poor	medium	good	poor	poor
Contention based	good	poor	medium	medium	medium	good	good

Table 2: Comparison of contention-free and contention based MAC protocols [42]

2.3.3 Duty Cycling (DC) MAC Protocols

Duty cycle is defined by the ratio of active time to the total duration of time frame [39]. It can be chosen differently for different scenarios. For the energy saving purpose Duty cycling [40] is presented, that is organized by a MAC protocol. Following DC, every single time frame is divided into active and sleep cycles. It is defined by the equation below.

$$\delta = \frac{T_{active}}{T_{active}+T_{inactive}}, \qquad 0 < \delta < 1 \tag{2.1}$$

Where δ is the duty cycle and T_{active} & $T_{inactive}$ shows the active and sleep durations respectively.

Duty cycling protocols may follow synchronous or asynchronous protocol (defined earlier) depending upon specific application requirement. Nodes remain active for certain duration of time and will sleep in the remaining period of a time frame. We can also say that, a cycle will contain an active period and also a sleep period. In the active period, the radio transceiver of a node is ON and it might perform data communication, whereas in the sleep period it is OFF and no communication can be achieved. Therefore, by letting nodes into sleep state, DC reduces the idle listening and so also conserves the energy. For this reason, DC is extensively employed in WSN MAC protocols [38].

2.3.3.1 Sensor-MAC (S-MAC) Protocol

The most important feature in wireless sensor networks is the network lifetime. It typically depends on the node battery; in order to make it efficient (in terms of energy), a suitable MAC protocol is needed. A lot of energy is wasted by a node due to different phenomenon like collisions, overhearing and idle listening discussed earlier. The S-MAC protocol under discussion overcomes these factors. Its implementation was done by Ye, Heidemann, and Estrin [39] on a Mote using the TinyOS platform developed at University of California, Berkeley [37].

The Sensor-MAC (S-MAC) protocol [39] that has been proposed by Ye et al. presents a methodology known as virtual clustering which enables sensor nodes to achieve synchronization based on a common slot arrangement [40]. The basic idea of this algorithm is to reduce the amount of time needed to listen for each node through periodic sleeping mode and only allowing the nodes to listen when they are in active mode. While in sleep mode, each sensor node's radio is switched OFF and it is automatically turned ON based on a timer to wake the node up. There is an option to independently select a schedule of sleep/wake for each sensor node, but it is preferable that the schedules of neighbouring nodes synchronize. Once the sleep schedule is selected by a particular node, it is then communicated to adjacent nodes via broadcast, which ensures that even though the neighbouring nodes follow a different sleep schedule the adjacent nodes can communicate among themselves because of the information about schedules broadcasted earlier [33]. To complete the process, the sensor nodes often broadcast SYNC data packets at the start of an allocated slot, which allows other nodes receiving SYNC packets to adjust local clocks to compensate for drift during packet transmission between different nodes. The SYNC packets also present the lucrative benefit of permitting new incoming (mobile) nodes to become a part of the ad-hoc network and achieve synchronization immediately. The idea is to have a unified principle schedule for the overall network, but due to some important issues such as mobility and bootstrapping, various virtual clusters can exist inside a network [41].

S-MAC employs the idea that radios of sensor nodes are not required to be switched ON all the time because there is a lesser number of sensing activities and communication rates in the network. A SMAC mechanism that incorporates contention is designed similar to CSMA/CA, with autonomy of configuration and higher energy efficiency being the main design goals, however overall latency in the network and fairness are considered less vital [34].

2.3.3.1.1 Main characteristics of S-MAC

Following are the important features of the S-MAC protocol [37]

- Periodic Listening
- Collision Avoidance
- Overhearing Avoidance
- Message Passing

1) Periodic Listening

In order to reduce energy consumption, the SMAC protocol uses the concept of periodic listening, because the sensor nodes use significant amounts of energy even when they are in idle mode. SMAC enhances energy efficiency by switching node's radio OFF in the process when there is no event of listening or data transmission [37].

Sleep schedules and active-times (for listening) for each node differ for different applications. Although in a wireless sensor network, each node's sleep and listen schedule is customizable but system's overall efficiency can be improved by reducing the control overhead. Therefore, the adjacent sensor nodes get in synch with each other, to listen and go in sleep mode at the same instant [37].

For networks that use multi-hop techniques, sleep schedules for each individual node can be different and these schedules are broadcasted cyclically in order to allow other nodes to communicate. Each node in a wireless sensor network distributes its sleep and listen-time schedules to its adjacent sensor nodes before sleep mode is enabled. This allows neighbouring nodes in that particular location to have information about upcoming events of the node and the detail is maintained in a scheduling table [42].

Each sensor node needs to adopt a schedule and communicate it to its neighbouring nodes before it starts the periodic listen and sleep cycle. The information about the wake and sleep cycles of all the adjacent nodes are maintained in a schedule table. That particular sensor node follows the steps below to customize the listen and sleep schedule [39].

- At the start, a certain amount of time is dedicated for listening. If there is no transmission heard by the node (a SYNC packet from any other node that contains information about a schedule of a neighbouring node), a random sleep schedule is selected by this particular node and immediately, this schedule is broadcasted in a SYNC message, specifying that the sleep time for this node is arriving in t seconds. Such a node can be termed as a synchronizer, since it initiates and picks its schedule independently and makes the other nodes synchronize with it [39].

- In case the sensor node receives a schedule from another sensor node before it could select its own independent schedule, the node then selects that received schedule by synchronizing its sleep and listen time with it. Evidently, this type of a node is called a follower. Once the synch is achieved, it transmits a unique message after waiting for a random time delay td and rebroadcasts this schedule, announcing that this node will switch to sleep mode in t − td seconds. The idea of random delay is introduced to avoid collision between transmissions from various nodes, because a sensor network contains multiple followers and each follower using same synchronizer node might trigger a rebroadcast of the same schedule and systematically collide thus reducing system efficiency [39].
- In a situation where a node receives a schedule different from its own even though it has selected and broadcasted its own independent schedule to its neighbouring nodes, it has to adopt both schedules (i.e. it enables its wake mode at two time instances both at its neighbour and itself). Before going to sleep after a session of listening, such a node again broadcasts its own schedule [39].

Figure 2.7 explains the mechanism considering three scenarios that a node should opt while sending SYNC or data packets to neighbouring nodes [39].

a) **Scenario 1**: When Source node broadcasts the SYNC packet [39]
b) **Scenario 2**: When Source node wants to send data packet to other node [39]
c) **Scenario 3**: When Source node broadcasts SYNC and send data packet [39]

In scenario 1, the sender node wants a SYNC packet to be broadcasted containing its address/identification and the time information about its next sleep cycle. For sending its SYNC packet, it will sense the medium for a while denoted by ‘CS in Figure 2.7 below and then broadcast its SYNC packet once the medium is found free [37, 39]. In scenario 2, the sender node wants to establish a connection for sending its data packet, but first it has to contend for the medium. While the medium is sensed free for a certain time, the sender node will send the RTS packet to the intended receiver. After RTS has been received by the receiver node, it will send CTS packet in its reply and the sender node waits for this CTS packet to arrive for starting the data transmission [37, 39]. In scenario 3, the sender node wants to send both the SYNC packet as well as data packet. In the start of its frame, it will sense the carrier denoted by 'CS' in Figure 2.7 below and then send the SYNC packet once no other node is sending their SYNC packet. After the synchronization has been done, the sender node will again do carrier sensing and just like scenario 2, sends the RTS packet followed by CTS and data transmission [37, 39].

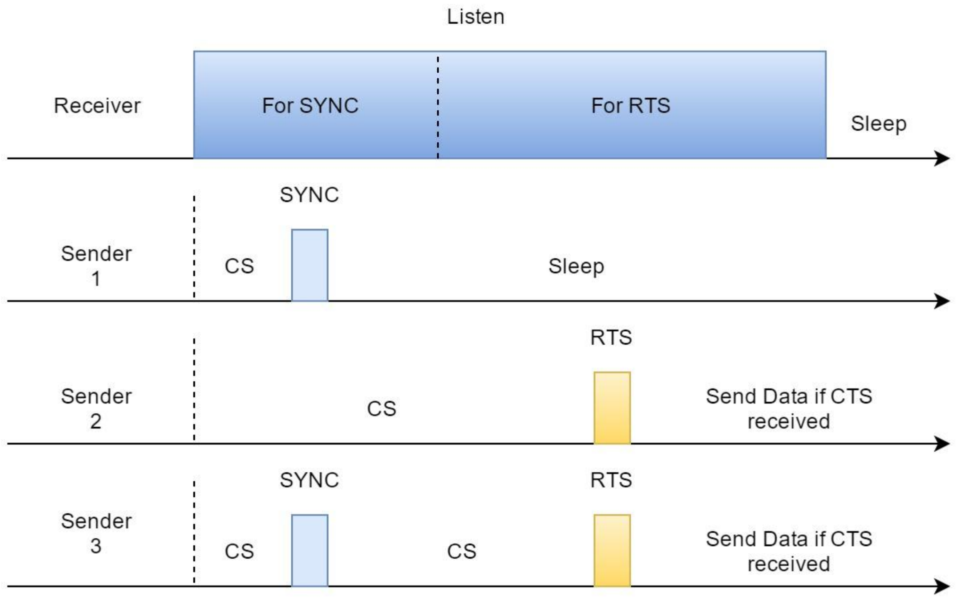

Figure 2.7: Timing relationship between different senders and one receiver. CS (Carrier Sense)

2) Collision Avoidance

As large number of nodes is usually deployed in WSNs, multiple nodes might communicate with a single node at a same time. In this case, multiple packets are received by the receiver node and these packets may collide with each other at the receiver node. This causes energy wastage. S-MAC protocol deals with this problem in a way mentioned below [43].

- **Network Allocation Vector (NAV)**

In each sent packet there is a section showing the remained transmission time. Others not included in this session however will get the packets, read to what extent they should not contend for the channel and put that time in their NAV, maintained in each node's memory. If the node wants to contend for the medium in case it has a data packet to send, it will check its NAV value that should be zero for data transmission [33].

- **Physical Carrier Sense**

  In contrast with the virtual carrier sense explained above (NAV timer), the sender node performs the physical carrier sense physically by listening to the channel. The contending node declares a channel as idle and thus uses medium, if both carrier sensing approves it to be idle [33].

3) Overhearing Avoidance

The algorithm for the transmission of data packets between the nodes needs to be efficiently implemented. The node for which the data package is not intended but if it still receives the message, then it leads to the drain of the node energy unnecessarily due to idle listening. To counter this inefficient use of energy, the SMAC protocol enhances the node efficiency by allowing it to receive the control data packet having its size smaller than the data packet which renders the node to sleeping mode for the data packet not destined for it. The node energy gets drained down much quickly if it receives the data packet not meant for it. SMAC allows the node to change its active state to the sleeping state to save its energy and node automatically wakes according to the NAV parameter set in its timer defined earlier [37].

4) Message Passing

The message is considered vital source of the event information in WSN. The length of the message varies depending on the information it carries. A message with large sizes enhances the transmission latency which is also the cause of the energy to get drained quickly. If the transmitted data gets altered in the way then the data need to be sent again which is the cause of energy wastage. The transmission latency can be countered by splitting the long message into small segmented packets and sending the control packet along each segment contributing further time delay. The SMAC protocol converts the long message packets into small segmented messages and sends them all in a burst. SMAC protocol utilizes single packet for Request to Send and Clear to send services to avoid frame collisions. In this scenario, the message transmitter waits for the acknowledgment and if the acknowledgement is received then the next frame is transmitted. If the acknowledgement receiving gets failed, then the packet is retransmitted which increases the time delay in sending the packet again [37].

The ongoing transmission can get altered if the source is not able to receive the acknowledgement message from the destination. If any of the nodes gets active from its sleep state during ongoing transmission then it can start utilizing the transmitting media if it is found free to use. It leads to the disruptive transmission at receiving side. Therefore, each packet data contains the field for the duration of the packet transmission. If any new node gets added in the network during ongoing transmission, then it goes to idle state after receiving the RTS and CTS messages and able to get the requisite information of time for getting awake again [37].

5) Adaptive Listening in S-MAC

The S-MAC protocol conserves the energy of the node by converting its active state to sleep state on regular intervals but due to this sleeping of the node at regular intervals, the time delay in the multi-hop networks get increased whenever there is some data to pass through the network. S-MAC therefore uses the adaptive hearing of the data which reduces the time delay [37]. This adaptive hearing is an intelligent kind of a technique which has varying time of getting active or online to handle the latency [41]. In this technique the subject node will respond actively to the transmit message by using the control packet along with the original message received at the end of the transmission. The subject node can send its message right away without waiting for the neighbour node to signal it. If there is found no data during the active period in adaptive listening, then the node will automatically go into sleep mode [37]. Adaptive listening dramatically reduces the regular offline (sleep) period of the node to one half of its normal value. The neighbour nodes are responsible for gathering data regarding the transmission time period from the RTS and CTS packets. Then accordingly the node gets online (active) when the transmission comes to an end [44].

There are some drawbacks of the S-MAC. Nodes can consume more power due to the useless listening of the data not destined for it. Because of multiple scheduling, border nodes may get drained quickly causing the partitioning along the borders node making up virtual clusters. The duty cycle of the S-MAC may be draining more energy thus decreasing the protocol efficiency. The duty cycle can be set to adapt to the varying applications requirements but S-MAC is not flexible enough to accommodate the changes. S-MAC also lack the control over the cluster size within the network and varying size may reduce the efficient performance of the protocol as large size of cluster increases the time delay associated with transmitting data [45].

2.3.3.2 T-MAC

To improve the performance of S-MAC protocol described in the previous section, T. van Dam and K. Langendoen introduced Timeout-MAC (shortly known as T-MAC) protocol [46]. It outperforms S-MAC firstly by liberating the application from the liability of choosing an appropriate duty cycle and secondly by adapting to varying traffic loads [41].

For synchronizing the duty cycles of sensor nodes, T-MAC adapts the virtual clustering mechanism as was implemented by S-MAC protocol. Unlike S-MAC where time slots' length is not defined, TMAC defines fix length slots of 615 milliseconds and time out mechanism is implemented for determining the end of active period. This timeout value of 15 milliseconds is introduced in a system for the purpose of spanning a small contention window and RTS/CTS packets exchange. When a node is in active state, if no activity is detected for this defined time-out interval while sensing the medium, this particular node assumes that no child node wants to send any data to it and therefore it goes to sleep state. In contrast, if a node hears any communication request or a collision, a new time-out interval is selected after that communication is finished. This whole mechanism of setting time-out interval is shown in Figure 2.8. For overhearing avoidance, a node simply goes into sleep state while there is ongoing communication in its neighbourhood not destined to this particular node [41], while for idle listening avoidance, packets are transmitted in bursts of variable length rather than sending a large packet once [47].

This early sleeping problem limits the number of hops, in a time frame, that a message can take. T-MAC faces long transmission latency problem even when it has a method to determine a nodes active duration [30]. The early sleeping problem, in which the destination node is in sleep state whereas the source node is ready to send data, is solved in TMAC using two following methods [37].

1) **Future Request to Send**

   In the Future Request to Send (FRTS) method, a Source node sends a FRTS packet informing the destination node that data is ready at the source node for transmission. The source node sends a FRTS packet to the destination node immediately on overhearing a CTS packet, so the destination node wakes up by the time an RTS packet will be sent from the source node [37].

2) **Taking Priority on Full Buffers**

Another scheme to overcome the early sleeping; Taking Priority on Full Buffers, sets a preference for sending over receiving whenever the memory that contains routing information, called node buffer, is full. If a destination node has a full buffer and receives a RTS packet from the source node, then instead of replying with a CTS packet it will right away send its own RTS packet, increasing the chances of the destination node of getting access to the medium. On the other hand, it limits the transmission flow. Therefore, this scheme is helpful in a node to sink or a node to node communication. It cannot be helpful in Omni-directional communication because of increased latency due to limited flow and high traffic loads. Hence the TMAC uses Taking Priority on Full Buffer scheme only after the node has lost access to the medium consecutively for two times [37].

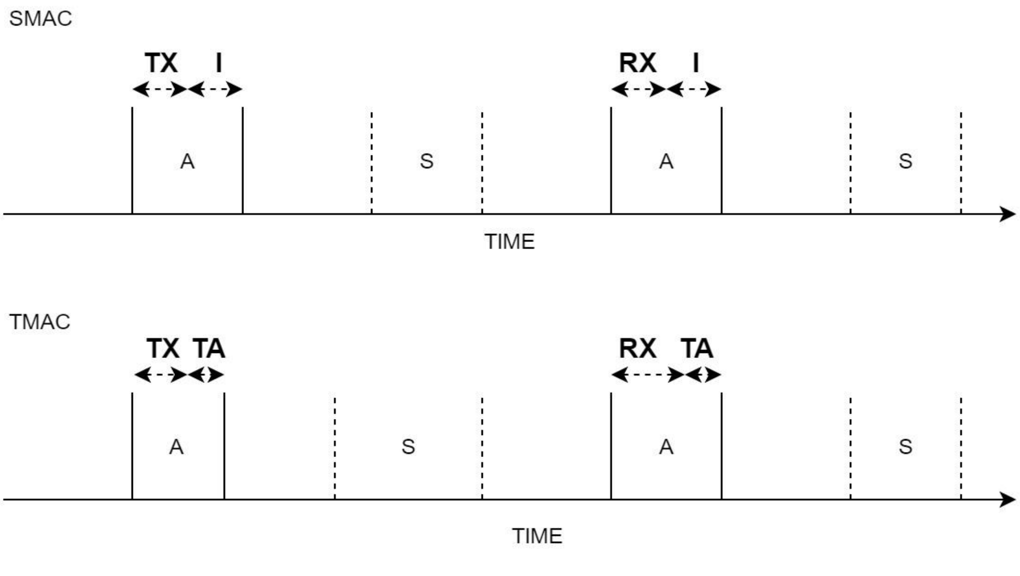

Figure 2.8: Comparison between duty cycles of S-MAC and TMAC
S-sleep, A-active, I-idle

2.3.3.3 Adaptive Coordinated Medium Access Control (AC-MAC)

While belonging to the S-MAC protocol class, the ACMAC [48] utilizes a unique technique, i.e. adaptive duty cycle. Despite not using more energy than the S-MAC, the ACMAC attempts to have lesser latency and increased throughput in the situations where the traffic load is significantly high. Especially for the sensor nodes having packet queues, it permits more than one data exchange periods utilizing one SYNC frame, depending on the length of the packet queue and the MAC-layer [45].

At the start of a duty cycle, every sensing node determines the length of the message queue present at its MAC-layer. It then broadcasts this information in the SYNC frame using the RTS packet. Other nodes receiving this information in the RTS packet can use it to evaluate the duty cycle for their use in the virtual cluster within the present SYNC period. Every sensing node backs off for a random amount of time from a contention window, the size of which is controlled by the number of packets in its queue. This way, the latency in communication and data throughput can be improved to the optimum value and the nodes having longer message queue get their turn on priority [45].

2.3.3.4 Pattern MAC (PMAC)

Similar to S-MAC, the PMAC [49] is a protocol that uses time slots. It allows the sensing nodes generating more data to use more time slots than the ones with lesser data by adjusting its duty cycle according to the conditions of the data traffic. In contrast to S-MAC, where a node can sleep for some time in a particular time slot and wake up for the rest of the time, nodes can only be asleep or be awake in any particular time slot [45]. The sensing nodes use a specific pattern sharing procedure to communicate their respective sleep and wake-up times for the upcoming frame in this protocol. By these patterns every node gets to know about the sleep and wake-up patterns of its neighbouring nodes. This information can let a particular node go into a sleep for a long time when it is expecting no data exchange with its neighbours. It can wake up according to the schedule whenever the communication is expected to take place. The nodes can potentially save a lot of power without having a negative effect on the data throughput, as compared to S-MAC and T-MAC [45].

PMAC gives an effective way to broadcast messages and create schedules about communication activities among neighbouring nodes. For the deployment of a sensor network, the PMAC's capability to cater for varying traffic patterns can be a very attractive attribute. However, there may be some practical issues in the implementation of the algorithm to generate wake-up and sleep schedules. Firstly, the latest version of the schedule may not reach some of the nodes because of errors in the channel. For this reason, the schedules available to different nodes may be different, causing collisions in data transmission, wasted time resources and some nodes attempting to receive while none of them is transmitting. Secondly, the schedule updating algorithm may become a significant computational overhead for a node if it remains active for several time slots consecutively, as each node updates its schedule every time it has an active time slot [45].

2.3.3.5 Dynamic MAC (D-MAC) Protocol

Dynamic MAC Protocol also makes use of adaptive duty cycle [44]. Dynamic MAC Protocol employs a communication structure with a many to one approach and hence help in decreasing the transmission latency. While comparing to S-MAC, D-MAC execution is far superior in terms of throughput, transmission latency and energy conservation as well [30]. D-MAC also wakeup all the sensor nodes during each cycle as comparable protocols like T-MAC and S-MAC do [30]. The latency value of one hop is broadcasted to the neighbors within the SYNC packet of Dynamic MAC (D-MAC) protocol. The receiver would halve its sleep time in case one hop latency time is high. The same is notified in SYNC packet and therefore the transmitter getting the SYNC modifies its schedule. The above process doubles the duty cycle keeping the neighbours intact [33].

2.3.3.6 B-MAC Protocol

An asynchronous process that has a stretched preamble with low power listening is B-MAC [50]. These two characteristics help B-MAC achieving low power operation [30]. B-MAC employs long preambles (a parameter to the upper layer) as the sensor nodes are functioning on stand-alone schedules [45]. A receiver is informed through a preamble normally longer than the wake up interval, broadcasted by the sender. This makes sure confirm and correct data transfer. The data transmission continues as mentioned. The nodes have to periodically wake up in order to get data. Also, they need to continue inspecting if there is an ongoing preamble or not. This means that the preamble must be equal to the interval for which receiver checks the channel. The receiver remains alert till receiving the packet after identifying the preamble. This way the lifetime of the nodes increases if the traffic load is low. Also, minimum periodic activation is confirmed. However, preambles wake all neighbours whether or not they are the desired audience [30].

Figure 2.9 below shows the mechanism used for communication in B-MAC. Whenever a source node wants to send a packet to its parent node, a preamble packet is added before the data packet with a length slightly longer than the sleep time of the intended receiver. In this way during the preamble transmission, the intended receiver node's wake time coincides with the preamble time at some point and thus the preamble packet is detected by the receiver, consequently it has to remain awake for receiving the data packet [45].

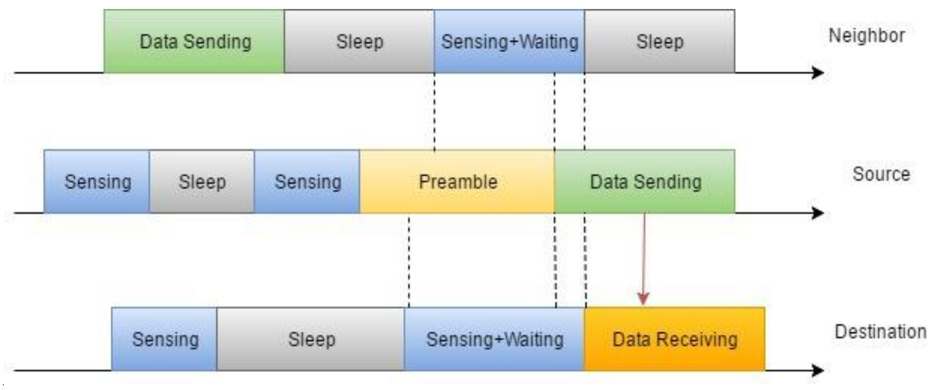

Figure 2.9: B-MAC communication

A core issue of B-MAC is defining check intervals that are too short, which guarantees an appropriate length for the preamble. Also the time duration for channel sensing must be small to reduce energy consumption by the receiver in idle listening; meanwhile this time duration should be accurate enough to reduce delays and energy consumption at sender node [45].

The prolonged preamble in B-MAC results in extra energy consumption when compared with synchronous protocols. Besides, the packet received is decrypted after its complete arrival therefore the non-intended neighboring receivers have to stay awake till the end of preamble packet. This results in significant energy wastage for the non-intended receivers [30]. The Low Power Listening (LPL) method opted by B-MAC which utilizes a long preamble is deficient in terms of energy consumption and results in overhearing as well as per hop latency. This issue creates three problems. First, the intended receiver has to wait the full preamble packet time before the data transmission can start, whether the receiver has woken up in the very start of preamble time or in the middle. Second, LPL suffers from the overhearing problem for the non-intended receiver that is a source of energy wastage for all non-intended receivers within sender's transmission range. Third problem arises for the multi-hop scenario, when per-hop latency is increased due to target receivers waiting for full preamble reception before data transmission [45]. The multi-hop latency is increases manifold due to this wait time [45].

2.3.3.7 X-MAC Protocol

B-MAC protocol discussed above was improved by X-MAC (A Short Preamble MAC) [51] by replacing the long packet of preamble used in B-MAC by a sequence of smaller preamble packets and these short packets are separated by small pauses between them as shown in Figure 2.10. The reason behind these pauses is to enable the intended receiver to send an early acknowledgement packet so that the sender will end the preamble packet earlier to consume less power. The target address is included in each short preamble packet so the receivers that are not intended for the current transmission will go back to sleep state as soon as they receive the preamble packet. This solution is particularly helpful for overhearing problem [30, 55]. The use of these short preambles help in reducing hop-to-hop latency and over-emitting problem, because of the fact that an early ACK sent from the receiver will help the sender node to stop sending excessive preambles and thereby starting data transmission [45].

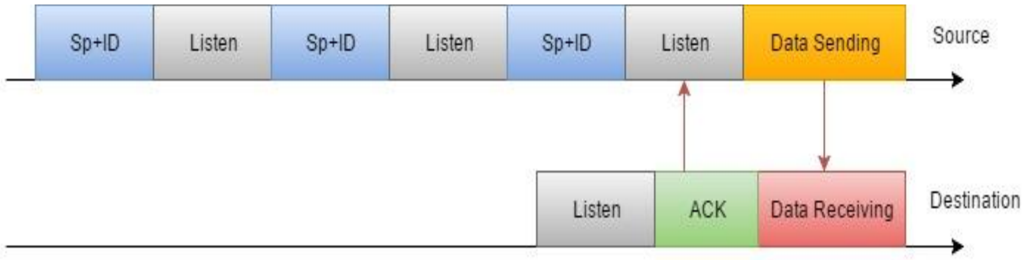

Figure 2.10: X-MAC mechanism for communication

The time period to detect short control packet is larger than that of preambles. Though these short preamble packets reduce latency and energy consumption compared with B-MAC, yet more energy is consumed as compared to synchronous protocols since more preamble packets are needed [30].

2.3.3.8 Wise-MAC

Wise-MAC [52] protocol reduced idle listening by using non-persistent CSMA with preamble sampling. CSMA is used for accessing control channel, while TDMA for data channel access. The communication format is depicted in Figure 2.11 [33]. As shown in Figure 2.11, preamble is added in the beginning of every data packet. The acknowledgement packet sent by a node during the transmission includes the sleep wake schedule of that particular node, thus helping every node to maintain a table for its neighbouring nodes' schedules by extracting the schedule part from that ACK packet. This sustained table helps in such a way that if a particular node wants to send a packet, it'll send the preamble opting the appropriate time, ensuring the intended receiver will wake up in the middle of that preamble time.

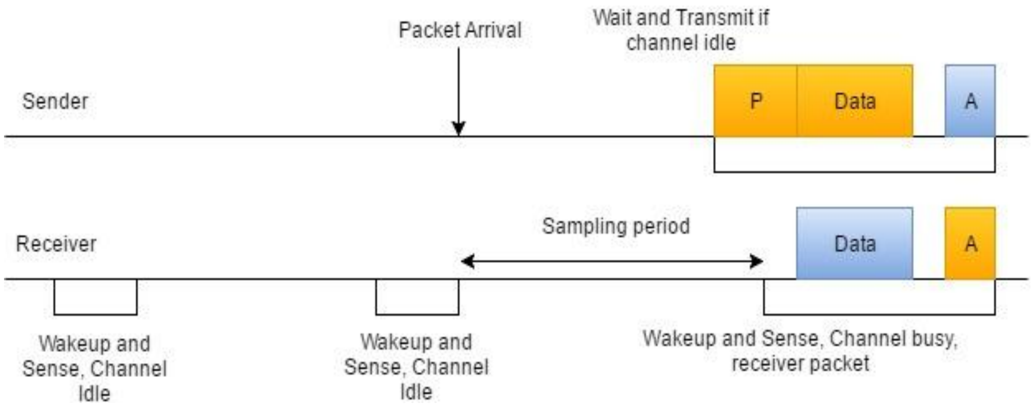

Figure 2.11: Wise-MAC messaging mechanism
P-preamble, A-acknowledgement

Preamble length should be long enough so that the receiver can wake up and sense the channel in that time. The smallest length of the preamble is depicted in Figure 2.11 above and is defined from the equation below [33].

$$\text{Preamble}_{\text{Shortest}} \geq \text{Min.}\, T_{s(Rx)} + \text{Clock drift} \qquad (2.2)$$

Where $T_{s(Rx)}$ is the sampling period of the sender and Clock drift is the clock drift between sender and receiver.

Referring to the simulation results of WiseNet presented in [63], WiseMAC outperforms one of the S-MAC variants. For variable traffic loads it gives better performance due to dynamic preamble length adjustment based on above mentioned equation 2.2. Furthermore, clock drifts are also addressed in this protocol thereby mitigating the need for external time synchronization [45].

The main downside of WiseMac lies with the decentralized sleep/wake scheduling resulting in different sleep and active times for every neighboring node. This problem mainly arises when doing broadcast type of communication, because the broadcasted packet might be sent to neighboring nodes in their sleep state and will be distributed many times as each neighbor wakes up. This redundant broadcasting results in higher latency and decreased energy efficiency. Moreover, as WiseMAC choses non-persistent CSMA therefore it may suffer more from the hidden terminal problem resulting in collisions. These collisions occur when one node transmits a preamble to a receiver node that is already communicating with another sending node. This scenario happens when the two sending nodes are not in each other's communication range [45].

2.3.4 Hybrid Sensor MAC protocols

Hybrid MAC protocols work towards increasing the advantages and reducing the disadvantages of the asynchronous and synchronous protocols. Traffic loads and patterns are what these protocols try and adapt their behaviour on [45].

2.3.4.1 Zebra MAC Protocol (Z-MAC)

Z-MAC [53] combines CSMA and TDMA. It adapts to the contention level in the network. If the contention is low, it operates like CSMA, but if the contention is high then it operates like TDMA. Z-MAC uses CSMA as the base MAC scheme and uses a TDMA plan to improve contention resolution and give time slot through the network deployment phase [45].

An algorithm is adapted that schedules the reuse of a centralized channel. Each node reuses its given slot periodically in each fixed period of time called frame. The node assigned to a time slot is the owner node. The other nodes are non-owners of that particular slot. The Z-MAC switches between CSMA and TDMA using a priority scheme which is depending on the amount of contention. The sensor node may transmit during any slot of time. When the channel is clear, it samples the channel and transmits a packet. However, the higher priority resides with the owner of that slot over its no-owners, in accessing the channel. The owner's slots are scheduled a priority to dodge collision and the owners are given previous chances to transmit, but the non-owners can steal the slot when it is not in use by the owners. Each sensor node identifies its two-hop neighbors and then is assigned to a time slot and chooses its time frame and sends its slot number and frame size to its neighbors, during the deployment phase. [45]

The results conclude that under low contention (in terms of efficiency in energy especially) the Z-MAC has slightly less performance than B-MAC; while in medium to high contention, the B-MAC is outperformed by the Z-MAC. Applications in which two-hop contention and expected data rates are medium to high, Z-MAC finds its usefulness [45].

2.3.4.2 CSMA/TDMA hybrid MAC Protocol (hybrid-MAC)

In this protocol [54], the writers recommend a mixture MAC protocol in view of IEEE 802.15.4 standard. Their primary idea comprises for including a dynamic TDMA period into contention access period of this standard. IEEE 802.15.4 standard comprises of two operational modes, beacon-enabled mode and non-beacon mode. Channel access is only based on CSMA/CA in non-beacon mode. However in beacon-enabled mode, a beacon frame has to transmit in specified time intervals by the coordinator. The beacon frame is divided into 2 parts, an active and an inactive part. For energy sparing purposes, the devices would be in sleep mode throughout the second period. The active period additionally comprises of a Contention Access Period (CAP) and a Contention Free Period (CFP) as shown in Figure 2.12. This beacon permits the units synchronize themselves for gaining access to the channel. The writers utilize the beacon-enabled mode and recommend a modified beacon frame by giving TDMA slots to sensor nodes during the cap period [45].

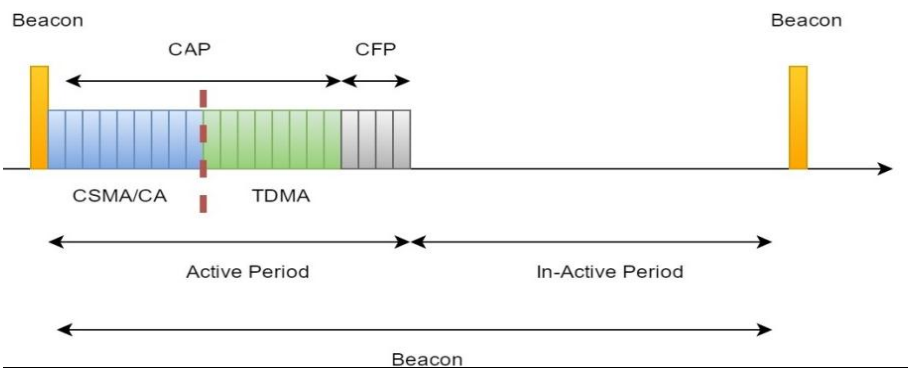

Figure 2.12: Hybrid MAC mechanism for communication
CAP: Contention Access Period CFP: Contention Free Period

In this protocol, the number of nodes contending for medium access is decreased and therefore fewer collisions take place. It is due to the fact that a node is not allowed to send data in the same beacon frame in which the TDMA slot is assigned. Furthermore, under-utilization of assigned slots in TDMA schemes is avoided by assigning TDMA slots only to nodes having data in their buffer. Though, the core benefit of this protocol is defined by the use of coordinator node [45].

2.4 Design factors for WSN communication protocols

There are some design factors that should be considered while designing MAC protocols:

1) **Latency**

Latency describes time delays in communication networks. However, an exact definition can vary depending on the viewpoint of the user. In WSNs, latency can on the one hand describe time delays for pure packet transmission, such as the time interval from transmitting the packet at the sender's site to the reception of the packet at the destined receiver. On the other hand, and more often, latency in WSNs is the delay from sampling at the node to reception at the sink. Due to the shared medium and the possibly large number of nodes, latency in this way can be considerable large [35].

2) **Throughput**

Throughput is the amount of successfully transmitted data via a communication channel. It usually is measured in terms of bits s−1, but might also be measured in number of packets per defined time period. In Wireless Sensor Networks nodal throughput is mostly used as a qualitative measure (i.e., low, medium, high), because quantitative description is rather difficult. It is influenced by packet delivery ratio, number of competing nodes in the same broadcast domain and communication overhead [35].

3) **Fairness**

Fairness is usually important when a large amount of communication nodes share a common transmission medium. As opposed to first-come-first-served approaches, in a fair communication protocol every node has a chance to transfer its data and nodes cannot block the channel. However, depending on the application, in WSNs fairness might intentionally be removed by providing priority to a subset of nodes or types of packets. [35]

4) **Energy Efficiency**

Energy efficiency gains more attention, when the communication devices involved are not mains powered (e.g., battery powered). Often energy efficiency is related to the lifetime of the communication systems, and describes how much energy is spent for the transmission of a certain amount of data. Especially in networks with typically low traffic, such as WSNs, idle energy consumption has a larger impact on the overall consumption. In these networks, protocol optimization for reducing energy consumption, which mostly means reducing active time, is of great importance. [35]

5) **Self-organization [42]**

In many envisioned scenarios, the sensor deployment distribution will be very dense, in order to provide higher accuracy and fine-grained information about the environment and also because a larger aggregate amount of energy is available in a dense deployment. Because of the environment and large scale of nodes, the nodes are usually randomly deployed and there can be little human management. Thus the MAC protocol must be able to self-organize the communication infrastructure for data transfer.

6) Reliability and Robustness [42]

Because of the harsh channel quality, frequent nodes failures and dynamic topology changes, the MAC protocols must be robust and reliable to enable efficient communication.

7) Scalability [42]

MAC protocols must be able to handle large networks with dynamic changes since wireless sensor networks can have hundreds or even thousands of deployable nodes [25].

Among these important requirements for MACs, energy efficiency is typically the primary goal in WSN. It is often difficult to achieve good performance on all the above features for a MAC protocol. It is important to trade off secondary requirements to the most important factors when designing a MAC protocol for a specific sensor network application. Figures below show the trade-off between energy, latency and throughput for different MAC protocols.

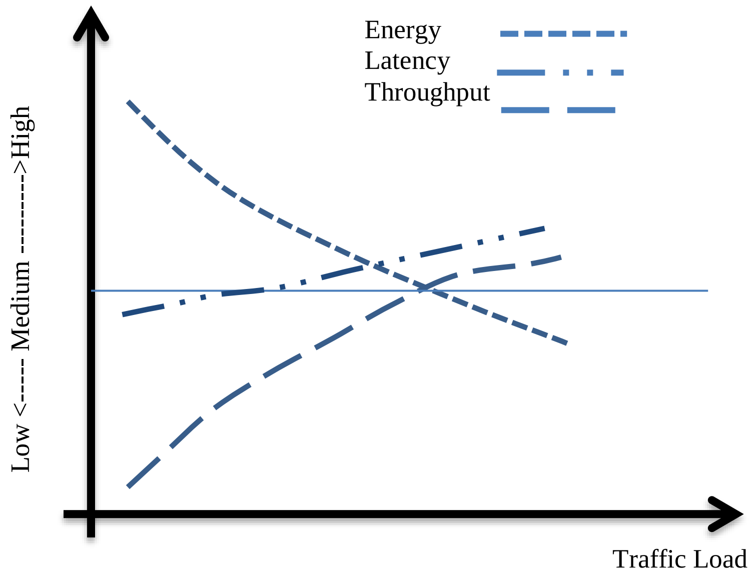

Figure 2.13: General performance of Synchronous MAC protocols

Figure 2.13 presents the general qualitative performance of synchronous MAC protocols showing that these protocols show good performance in terms of energy efficiency with low traffic load. But as the traffic load is increased, this energy efficiency decreases while reaching an undesirable point where network lifetime is decreased too much. On the contrary, increasing traffic load results in increased latency as end-to-end delay will be increased. In case of throughput, the curve increases and finally get stabilized at a certain due to the queuing traffic when the traffic load becomes high.

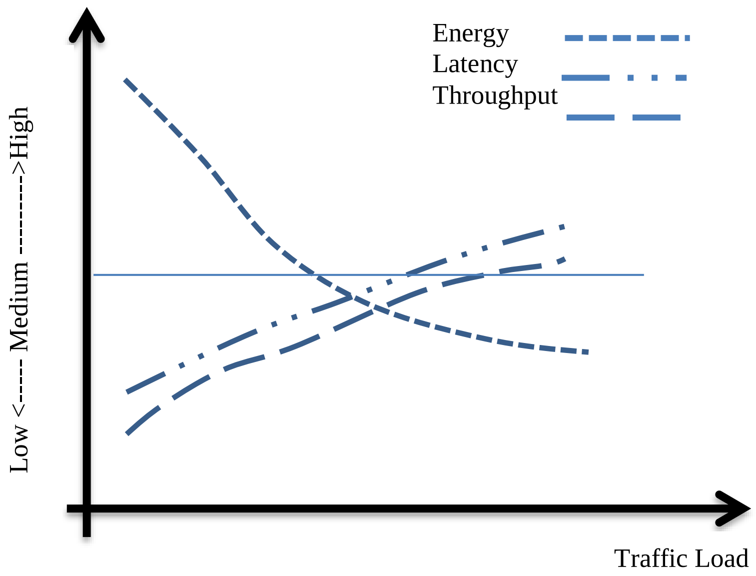

Figure 2.14: General performance of Asynchronous MAC protocol

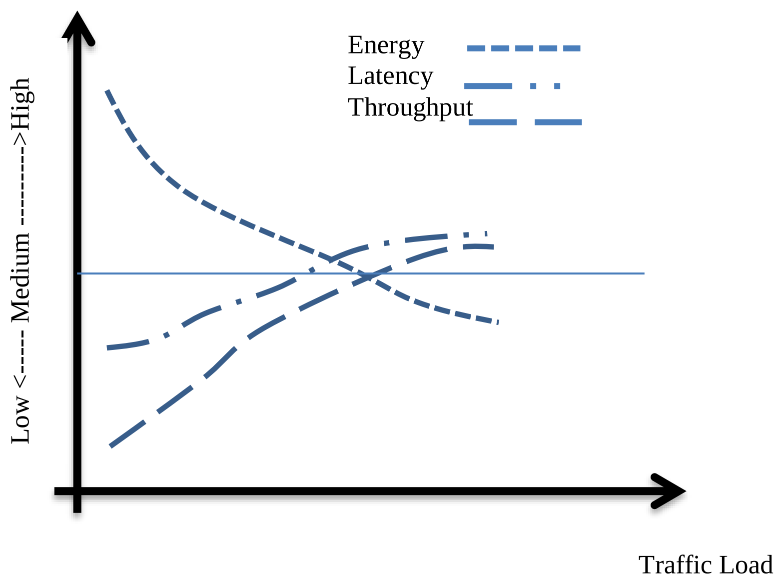

Figure 2.15: Hybrid MAC protocol general performance

Figure 2.14 shows the general qualitative performances for these protocols. Unlike synchronous protocols, the energy curve reaches the dashed horizontal line early due to the influence of Overhearing and the hidden terminal problem over energy efficiency. Latency and throughput is improved due to adaptive active /sleep period. Figure 2.15 shows the general qualitative performances of the hybrid MAC protocols. These protocols give an intermediate performance level comparing with the pervious protocols.

2.5 Literature Survey

For any sleep/wake scheduling protocol, minimum delay should be kept under consideration in multi-hop WSNs to cater for the case where node's forward packet is delayed due to sleep state of next-hop neighbor. Authors in [16] developed the any cast-based asynchronous sleep/wake packet forwarding scheduling scheme for minimizing the expected packet-delivery delays from nodes to sink and maximizing network lifetime. Three control variables namely wake-up rates, forwarding sets and priority; were used to elaborate their effect on network lifetime and the end-to-end delay experienced by a packet. Authors followed the assumption that there is a single source that sends out event-reporting packets to the sink and the basic protocol overlooked the detailed effects of collision. However, in [55] sleep/wake schedule protocol for minimizing end to end delay for event driven multi-hop WSN has been proposed, by adapting their sleep/wake schedule based on traffic loads in response to three important factors, the distance between sending node and sink node, the importance of the node's location from overall network connectivity's perspective, and node's location with respect to event occurrence. Authors validated their results by comparing their proposed SMED protocol (Sleep/Wake Scheduling Scheme for Minimizing End-to-end Delay) with Anycast and S-MAC protocols. The results demonstrated that SMED improved the QoS routing parameters like average energy per packet, packet loss ratio, throughput, and network lifetime. Authors in [56] used cut-vertex method used in [57] to determine that whether the node's location is connectivity critical or not. For the purpose of determining importance of node's location in network regarding bottle-necks in network for packet forwarding, there are various methods proposed in literature like in [58] where authors proposed a fully distributed method to detect and reduce cut vertices for large scale and highly dynamic overlay networks. Authors assigned sleep schedule to the nodes based on the transmission power that is accumulated from the broadcast packets received from the sink.

While dealing with energy efficiency, asynchronous sleep scheduling is preferred as synchronous scheduling needs explicit synchronization for nodes' internal clocks that requires an extra exchange of additional information and more communication overhead implying more energy consumption [58]. Therefore, authors in [58] proposed asynchronous sleep scheduling by using an adapted duty cycle and variable preamble length, where the duty cycle is based on the RSS density estimation for each sensor node. Authors showed that the expected number of the received nodes is a function of the sensor node density, the transmission range, the preamble and the duty cycle. Wireless sensor network based solution for estimating crowd density is devised in [59], where authors followed an iterative process containing detection and calibration phase in each time slot for crowd density estimation. Authors obtained RSSI data by WSNs using K-means algorithm and highlight critical role it plays in obtaining accurate density measures.

To address both uni-cast and broadcast traffic in Duty-Cycled Multi-hop Wireless Sensor Networks (DCM-WSN), authors in [14] introduced YA-MAC, an agile Medium Access Control (MAC) protocol to provide high throughput and maximizing sleep times. Synchronicity between sensor nodes was addressed by defining Synchronicity threshold to be set by the upper layers in the WSN stack and incorporate this synchronicity threshold to switch between different phases defined by YA-MAC. In [15] also, authors defined this Synchronicity threshold to allow trade-off between the maximum throughput achievable and the degree of duty cycling (energy consumption) the network can tolerate.

Mostly in WSNs, especially in dense networks where there is only one sink present, multi-hop communication through data forwarding is preferred rather than single-hop communication between nodes and sink. As single-hop communication between far-away nodes to sink is not preferable as energy of these nodes will deplete very soon because of transceiver. Y. Zhao et al in [60] proposed novel sleep-scheduling technique called Virtual Backbone Scheduling (VBS) by forming multiple overlapped backbones using backbone redundant sensor nodes which work alternatively to forward network traffic so that rest of the sensor nodes can turn-off their transceivers to prolong the network lifetime. VBS combined Back-bone scheduling with Duty Cycling method by letting backbone sensor nodes work in a duty-cycled fashion. VBS achieved longer network life-time in dense WSNs while performed worse in networks with imbalanced energy distribution.

S. Suthaharan et al. in [61] proposed an energy efficient scheduling scheme model based on Discrete Time Markov chain models used in DNA evolution prediction. They defined a single control parameter to control three state changes of wireless nodes (Active, Sleep and No-sensing state) and obtained a compromise between network throughput and network lifetime. The proposed scheme outperformed traditional “standard” model by improving the average battery life, and the packet reception rate.

Chapter 3. Proposed Protocol

3.1 Proposed Protocol Design

The object of the study under consideration is the wireless network comprised of randomly deployed sensor nodes with one base station (BS) in the centre. The base station's/sink's energy constraint is not under consideration. All the nodes are aware of their neighbouring nodes by the distance calculated based on RSSI. The nodes can reach the base station/sink by multiple hops or single hop depending on the location of the node. The proposed protocol focuses only on the energy efficiency in MAC layer, not other OSI layers. The simulations are performed on abstract level meaning the evaluation is done on single data packet. The data packet is assumed to be of a fixed size assuming that the headers from layers below are treated as a payload. The link features such as modulation, coding, data aggregation and sampling are not under consideration. Furthermore, the proposed protocol assumes multi-hop scenario rather than clustering. Each node will compute its shortest path and the packets follow that specific route.

The proposed protocol defines sleep wake scheduling scheme for wireless sensor networks for optimizing nodes' energy as well as packets' latency. As defined earlier that in most WSN applications, nodes need not to be in active state all the time rather nodes must be in sleep state in most of the frame duration. This sleep wake states gives rise to duty cycling MAC protocols defined in sec.2.3.3. This protocol defines an 'AEL factor' for computing the duty cycle of every particular node taking into account the node's proximity from the sink, the node's importance in the network and the traffic load. This AEL factor defines the sleep wake schedule of a particular node.

In Figure 3.1 below, the nodes lying in Region 1 (red coloured nodes) will be having greater value of AEL factor than the nodes lying in Region 2 (blue coloured nodes) or Region 3 (green coloured nodes). As these nodes are near to the sink, they adapt longer active period than other nodes lying farther from the sink. This scheme helps in lesser packet delay as will be described in later sections.

The AEL factor or the active period of node also depends on the number of neighbours and the network traffic load. The more the number of forwarding nodes to a particular node, the more active time is adapted by this particular node. Similarly, AEL factor is also adjusted according to the network traffic load. Unlike the scheme adapted by S-MAC [39] where all the nodes had 10% duty cycle, the proposed protocol presents adaptive duty cycle based on the network model and parameters.

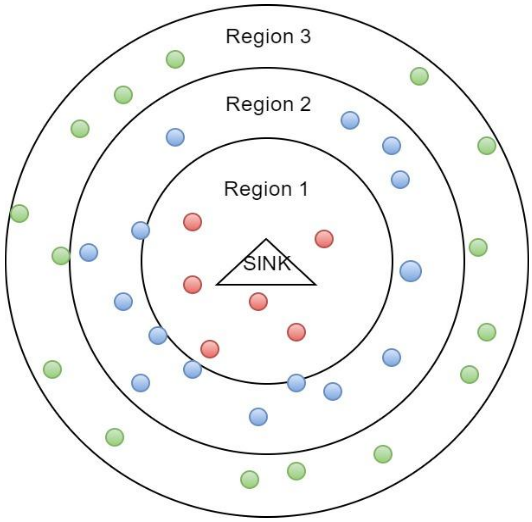

Figure 3.1: Region wise distribution of nodes for different values of AEL

3.1.1 Network Model

There is numerous radio models proposed in the literature to account for energy efficiency. The energy model taken for the proposed protocol is based on the time of the node in each of the states (idle, active or sleep) [64]. The total energy consumed for a particular node say ‘i’ is simply defined as:

$$E(i) = \sum P(j) * t(j) \quad (3.1)$$

Where,

E(i) defines the energy of a particular node under consideration, while P(j) and t(j) defines power and time of that particular node in a particular state.

P(j) is simply calculated as given below:

$$P(j) = I_j * V \quad (3.2)$$

Where, I_j defines the current drawn in that particular state and V is the Voltage in that state.

Apart from the energy consumed in these states, the proposed protocol accounts for the switching energy needed to switch between sleep and idle state. Although its value is very low as compared to other above mentioned energy consumed, yet it is of much importance when there is no energy harvesting scheme applied to nodes or there is no other external battery source.

The above mentioned parameters are taken from CC2420 (2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver) data sheet that supports applications like wireless sensor networks, Industrial Control and Home/building automation [65].

The specifications for the proposed protocol are shown below:

Idle Current	426 micro amps
Transmit Current	17.4 milliamps
Receive Current	19.7 milliamps
Sleep Current	20 micro amps
Voltage	3 volts
Switching time	0.86 milliseconds
Switching energy	0.575 micro joules
Data Rate	250 kbps

Table 3: Specifications of proposed Protocol taken from CC2420 data sheet

3.1.2 Working of Proposed Protocol

The proposed protocol consists of two main phases that is Setup phase and Operation Phase as shown in Figure 3.2. Setup phase is further divided into initialization and route update phase, while operation phase is divided into sleep wake scheduling and data forwarding phase.

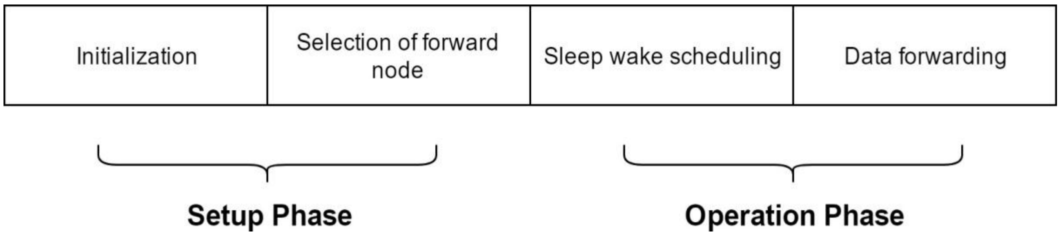

Figure 3.2: Phases of proposed protocol

3.1.2.1 Setup phase

The sensor networks should have the ability to self-organize themselves with respect to their neighbourhood and network model, therefore this phase help the nodes to gather the information of their neighbours as well as the master node (sink in this case). This gathered information is then used in successive phases.

1) Initialization Phase:

This is the first phase after the nodes deployment has been done. In this phase, the sink broadcasts the 'hello' message with the transmission power same as that of nodes. In this way, only the first hop nodes from the sink will receive this hop message and declare themselves as the first hop nodes. These first hop nodes will then broadcast the 'hello' message with the same transmission power and hop count 1. The neighbouring nodes on receiving this message will update the hop count to 2 and declare themselves as two hop neighbours from the sink.

This broadcasting will go on and so forth while all of the nodes have been reached. Referring to Figure 3.1 in previous section, the red coloured nodes are first hop nodes while blue and green coloured nodes are two and three hop nodes respectively. It is worth mentioning that if the parent node receives the hop count value from its child node, the parent node will not update its hop count value as the value received from its child node would certainly be more than that previously stored in its memory.

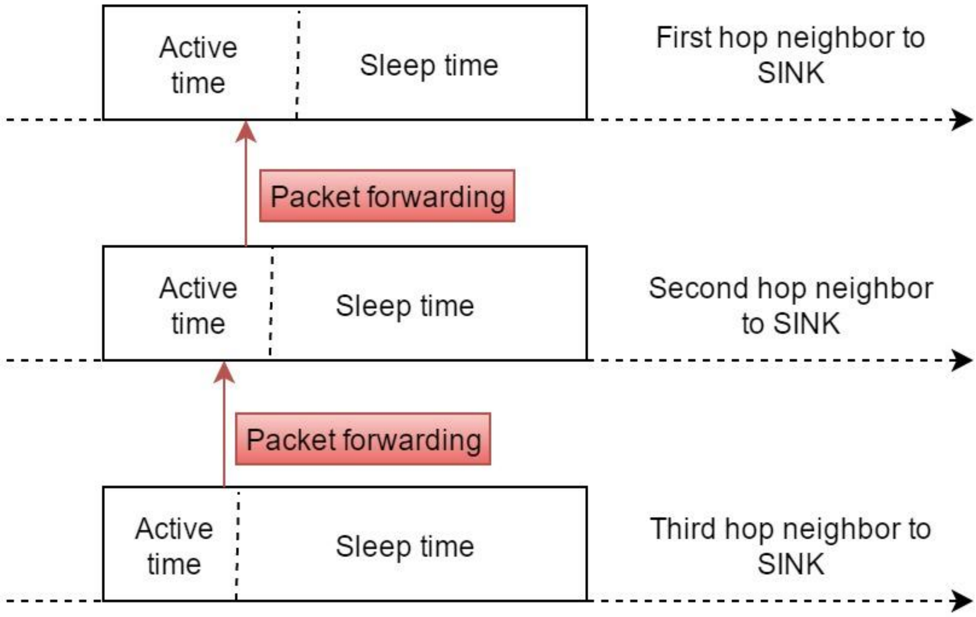

Figure 3.3: Duty cycles defined w.r.t hop count

This hop count will help in setting the AEL factor thereby defining the sleep wake schedule for all network nodes. The AEL factor of the nodes near to the sink will be more and thus the duty cycle is increased. In this way, the packets originated at the end nodes that are far from the sink, will face lesser delay as the active period of parent nodes are more than this far node. Unlike the scheme opted by S-MAC [39] in which all nodes have the same duty cycles, thereby increasing end to end latency. The proposed protocol defines adaptive duty cycles so that the child nodes will not be waiting for their parent nodes to wake up and the sleep delay will be reduced as shown in Figure 3.3 above. It can be seen that third hop neighbour's packet while reaching to first hop neighbour might get delayed beyond the active time of first hop neighbour, but this issue is mitigated by having first hop neighbour's active time greater than its child nodes' active times.

2) **Route-update phase/Selection of forward node:**

This phase accounts for the shortest path that the node should take in order to achieve minimum energy consumed. Route update phase uses the information from the initialization phase. The hello message received in the initialization phase by every node is also used in terms of RSSI measurement. Every node computes the RSSI (received Signal Strength Indicator) value of the received packet, thereby achieving distance information. Before this phase, every node knows its neighbour information that was updated in the initialization phase. Upon knowing this information, the nodes declare their nearest neighbour from which maximum RSSI was received. In this way, every node updates its table and forwards its packets to that particular parent node. This forwarding scheme is based on the assumption that the parent node giving maximum RSSI is the nearest neighbour parent node and all the packets will be forwarded to this particular parent node.

3.1.2.2 Operation Phase

After the neighbour information has been stored and forwarder information retained, the operation phase is started where nodes define their sleep wake schedule and share it to their neighbouring nodes in the SYNC packet. After this scheduling has been done, traffic generation and event reporting is started.

1) **Sleep wake scheduling:**

This phase defines the sleep wake scheduling for all the network nodes, keeping in view the parameters like forwarding child nodes, nodes proximity to the sink and traffic loads. In the very start of this phase, all the nodes are in active state so that they can communicate well with each other and will be well aware of their neighbouring nodes' schedules at the end of this phase.

After the node has selected its sleep wake schedule, it will broadcast the selected schedule to its neighbours by the scheme proposed below:

In the S-MAC protocol [39], all the nodes are listening for a certain amount of random time. If in that random time (that is assumed to be different for all the nodes), the node does not receive a SYNC broadcast from another node, it broadcasts its sleep wake schedule to its neighbouring nodes and become a synchronizer. All the neighbouring nodes still waiting for their random time to broadcast their SYNC packet will then opt this broadcasted schedule.

The first problem with this broadcasting and synchronizing scheme is that if two nodes broadcast simultaneously, the receiving nodes will follow two schedules and will have to be active state for more time. The second drawback with this scheme is that the first hop neighbours need not to synchronize with each other as they are both the parent nodes and if they wake up at the same time, the collisions are increased. This can be elaborated by the assumption when both the parent nodes near to the sink receive the packet from their child nodes, wait for the same random time and therefore send the RTS (Request to Transmit) simultaneously to the sink. On the other hand, if they define their active periods independently there will be lesser chances of collisions.

In the proposed protocol, the SYNC packets are broadcasted in rather refined manner. The sink will transmit a radio signal with high power so as to ensure that every network node will receive this signal. All the nodes on receiving this radio signal will calculate the RSSI of this radio signal thereby calculating the distance from the sink. Now the whole network is distributed with respect to RSSI from this radio signal. After this, the first hop neighbour with maximum RSSI (that is nearer to the sink) will broadcast its SYNC packet after some random time. This random time is calculated based on the RSSI received from that radio signal generated from the sink. Therefore, the random times chosen by all first hop neighbours will be different from each other. Unlike S-MAC, the nearest first hop neighbour after broadcasting its SYNC packet will go to sleep state as it does not need to know schedules from other nodes. This is because of the fact that first hop neighbours have larger duty cycle defined in the proposed protocol than their child nodes, and also because the child node will adjust its active period depending upon this SYNC packet from this parent node.

After this broadcasting of SYNC packet from nearest first hop neighbour,

the other first hop neighbours will define their sleep wake schedule depending upon this SYNC packet and will ensure different wake schedule than each other as shown in Figure 3.4. This different schedule can be ensured by defining the start of the frame randomly that will depend on the distance of the node from the sink. Each parent node after broadcasting its SYNC packet will go to sleep state. The child nodes will follow the sleep wake schedule similar to their parent nodes. It is worth mentioning that the route-update has already been done in previous protocol phases and therefore all the child nodes are well aware of their shortest path parent nodes. This mechanism of opting different schedules minimizes collisions and is explained in detail by Figure 3.3 & 3.4 below.

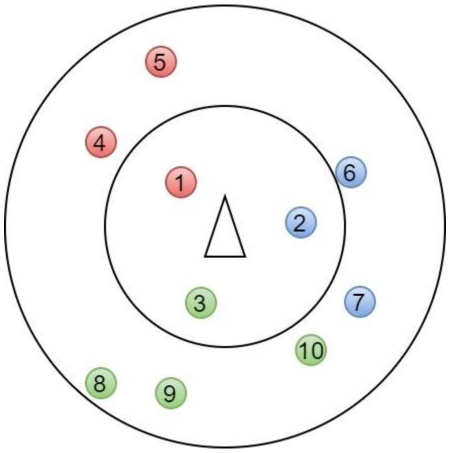

Figure 3.4: Parent and child nodes (first hop and second hop)

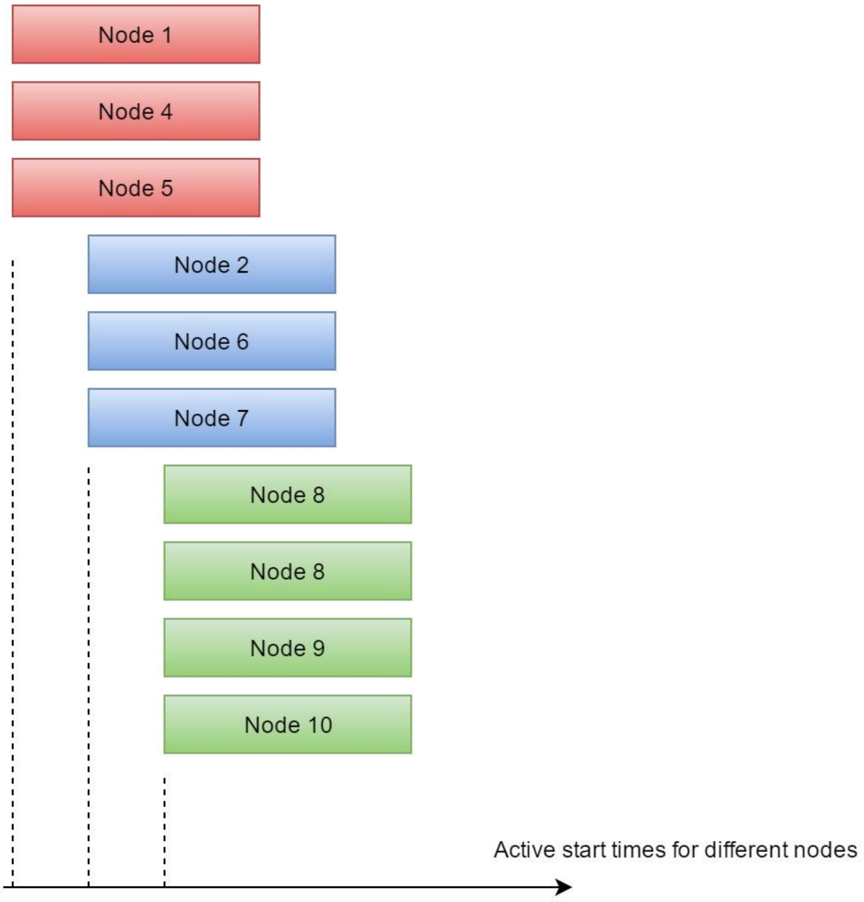

Figure 3.5: Active times defined for different nodes

It can be seen from Figure 3.5 that active start time of first hop neighbours are different from each other thereby reducing the number of collisions. In Figure 3.3, it can be seen that node 7 and node 10 are nearby neighbouring nodes and collisions occur in case these both nodes have a packet to send at the same time.

But on the contrary it can be seen from Figure 3.4 that the active start time of both of these nodes is different depending upon their parent nodes. Therefore, even if they both have a packet to send with a same random wait time, the start time of the timer will avoid collisions.

This SYNC broadcasting scheme will follow through all of the network nodes and every node after broadcasting its SYNC packet will go to sleep state. Note that the farthest nodes from the sink will not broadcast the SYNC packet as they are well aware of the fact that they are not a parent node for any network node.

2) **Data Forwarding Phase:**

The same Collision avoidance and Overhearing avoidance mechanism is adapted in the proposed protocol as was adapted by the authors in [39]. When the node has a packet to send, it will send a RTS (Request to Send) packet to its parent node, which then reply with a CTS (clear to send) packet. The hidden terminal problem is also addressed by using these RTS/CTS packets. The nodes on receiving the RTS or CTS packet (that contains the destination address) checks whether it is meant for them. If yes, the data transmission is continued and if it is not intended to the receiver node, the receiver node on receiving this unwanted RTS/CTS packet will go to sleep state for the mentioned data transmission time. The proposed protocol uses a random wait time to send RTS packet. This random timer is defined by the distance of this particular node to the parent node (RSSI calculated in the setup phase) and the no of hops to the sink. The node farther from the sink is given more priority to send its packet than the node near to the sink. It is because that the active time of farther node is less than that of its parent node, therefore it should send its packet with high priority. It is to be noted that the random timer set for the packet sending operates inverse of the random timer set for the SYNC broadcast. This is because the nodes should SYNC according to their parent node, but the packet should flow from child node to parent node. The RTS and CTS packet sent by any node contains its destination address and the time for which the communication goes on. In S-MAC protocol, this helps in increasing the active time of receiving node to ensure successful transmission. In this proposed protocol, this obligation is nullified by the fact that active time of receiving parent node is always greater than that of child node. Although the proposed protocol also contains destination address and communication time in RTS/CTS packets, to counter for hidden terminal problem. Unlike S-MAC, the message is not fragmented into small fragments, rather single transmission is considered for one packet. The packet size and simulation parameters will be discussed in next chapter.

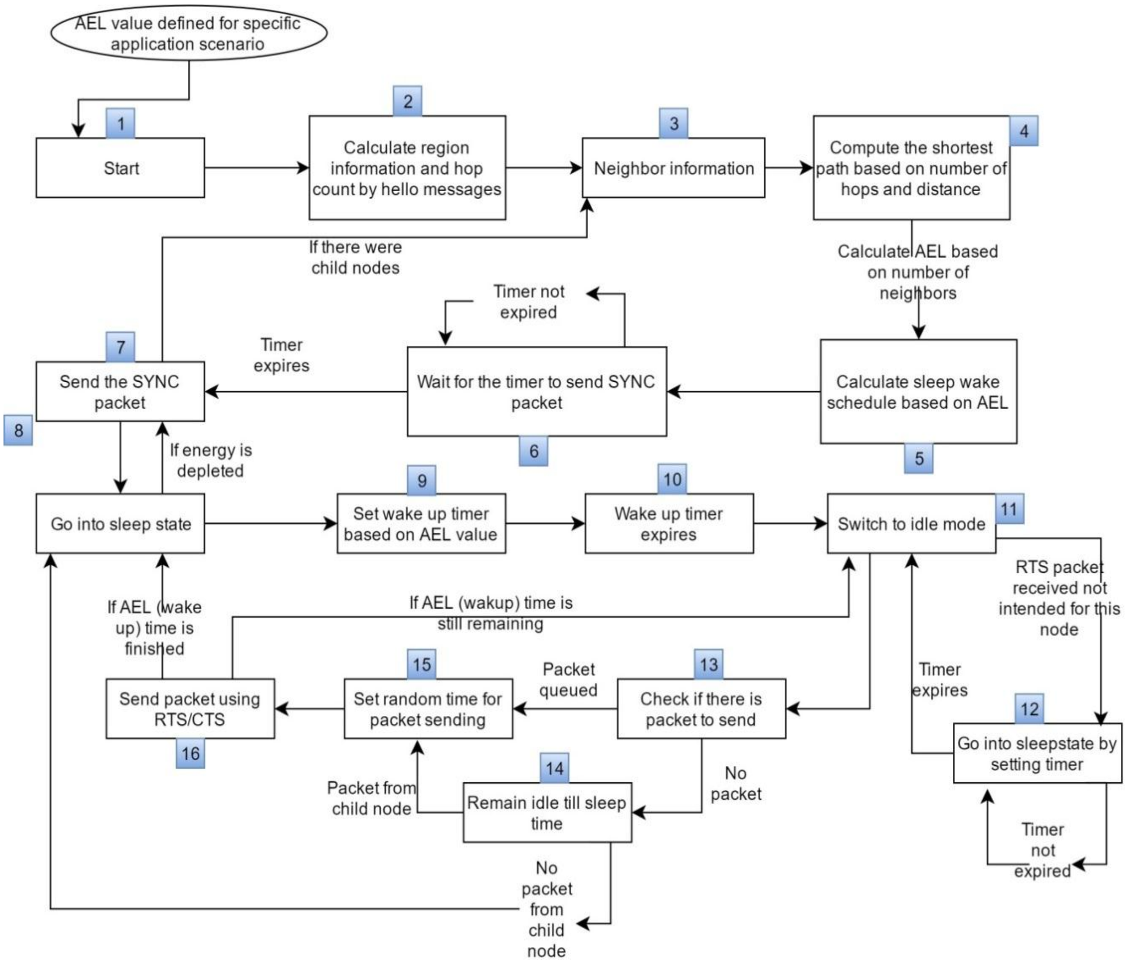

Figure 3.6: Flow Chart of Proposed Protocol

The whole working of the proposed protocol is depicted in Figure 3.6. All the step numbers are mentioned in blue colour. From step no. 1 up to step no 4 is setup phase in which neighbour information is collected and shortest path is calculated based on hop count and distance between the sender and receiver node as explained earlier. This distance calculation is obtained from RSSI (Received signal strength indicator) that a sender node calculates from the 'hello' packet sent by receiver node. The minimum RSSI from any receiver node received by any child node is opted to be the parent node for that particular child node. It is obvious from the flow chart above that the AEL information is retained by the nodes till the end of network lifetime. If a parent node relaying packets from its child nodes to the sink is dead after sometime, that particular parent node broadcasts its energy depletion information. After that, the flow is shifted to step no 3 and again neighbour information is calculated and shortest path is computed. This phenomenon goes on until all the nodes near to the sink are dead and network lifetime is ended. It is pertinent to mention that the AEL factor defined in the very start prior to the nodes' deployment is dependent on the application scenario.

Chapter 4. Simulation and Results

4.1 Simulation Setup

In order to verify the correctness of proposed protocol, it is simulated in Matlab R2017a. Various scenarios have been taken into account by choosing different number of nodes ranging from 20 to 220. Network size has been chosen depending upon number of nodes varying from 25x25 to 500x500.

The sink node is placed in the middle of the grid for every simulation setup. Range of the network nodes vary from 9 to 125 meters depending upon network sizes. Various parameters used are mentioned below:

Initial Energy	0.5 Joules
Transmitting current	17.4*0.001 amps
Receiving Current	19.7*0.001 amps
Idle Current	0.000426 amps
Sleep Current	0.02* 0.001 amps
Voltage	3 V
Data Rate	250000 bps
Speed of light	3.00*10^8 m/s
SYNC packet length	8 bytes
RTS packet length	20 bytes
CTS packet length	20 bytes
Message packet length	100 bytes
Sync window	30 mill seconds
Frame time	1 second
Symbol period	0.000016 seconds
Time before sending short packet	8 Symbol periods
Time before sending message packet	12 Symbol periods
Receiver time	12 Symbol periods
Switching energy	575*0.000000001 Joules
Initial energy	0.5 Joules

Table 4: Simulation Parameters

4.2 Performance Metrics

The following performance metrics are used for evaluation of the proposed protocol and its comparison with S-MAC protocol (described in section 2.3.3.1). The S-

MAC is a novelest and fundamental protocol among sleep/wake scheduling protocols.

4.2.1 Average Energy per Packet

As described above, energy efficiency is the primary concern in designing wireless sensor network. Average energy per packet is a measure of energy spent for forwarding a packet to the sink node. It is an indicator of the lifetime that can be achieved by the protocols. The average energy is computed against different number of nodes and is compared with S-MAC protocol. Simulation was run for single packet transmission for all simulation setups. Node density was increased and average energy was computed. The average energy refers to the energies of all the nodes divided by the number of nodes.

4.2.2 Average Delay per packet

Delay is referred as the time taken for a sensor node to deliver packet to a next hop node. It is the time span between the packet send from any sensor node and packet received at the sink. The average delay refers to the delays of all packets divided by the number of nodes in the network.

“Delay is estimated in a one-hop fashion and its extension to multi-hop cases for estimating the end to end delay is not possible due to the impossibility to characterize the input traffic arriving to intermediate nodes [3].”

For the proposed protocol, multi-hop scenario is considered for traffic routing. Certain delays are inherent for contention based MAC protocols in multi-hop scenarios including carrier sense delay, back-off delay, transmission delay, propagation delay and processing delay. These delays are same for duty cycled MAC protocols or 802.11 like protocols where nodes are always in active state. An extra delay specific to sleep/wake scheduling protocols is ‘sleep delay’. It occurs when sender node is sending its packet but the receiver node is in sleep state and does not correspond to the on-going transmission [39].

This sleep delay caused by the receiver sleep state is defined in [39] by the following equation.

$$D_s = T_{frame}/2 \tag{4.1}$$

Where, T_{frame} is the frame length (in seconds) and D_s is the sleep delay. The above equation is based on the fact that the packet can arrive at the sender anytime within a frame with equal probability.

4.2.3 Network Lifetime

Network lifetime is defined as the time when the network can deliver packets to the sink successfully. Whether it is a dense network or a sparse one, network lifetime is increased by the increase in energy per node. As there is always an energy constraint for sensor nodes, therefore the protocol should be designed in away so as to maximize network lifetime even with less node energy. Furthermore, the network lifetime is not necessarily linked with the energy drain of a single node. For example, in the case where there is more than one node near the sink, the death of a single node near to the sink will not end the network lifetime. Rather, the neighbouring child nodes of this specific dead node will update their route to reach the sink node. After all the nodes near to the sink are dead which means no traffic can be routed towards sink, this means the end of network lifetime.

4.2.4 Tradeoffs

There is a certain trade-off between energy efficiency and the latency in the network. If we expect the energy efficiency to increase beyond specific limit, the delay is increased manifold. As can be seen from the case where sleep time is much more than active time and traffic generation is very high. The packets have to wait certain sleep time to be sent to the parent nodes therefore increasing end-to-end delay of the packet. Similarly, if delay is expected to be decreased beyond certain point, energy efficiency is disturbed. As is the case where nodes do not sleep for much time and expect traffic for most of the time, delays are less due to less sleep time but energy is dissipated very quickly.

To design an energy efficient MAC, it is essential to turn the radio off when a node does not participate in any data delivery. However, a node that is sleeping is no longer part of the network, and thus cannot help to deliver the sensor data from its neighbours to its destination. When a node has a packet for its neighbour that is in sleep state, it has to wait until its neighbour is active. This creates a fundamental trade-off between energy and latency [42].

While comparing with the protocols having no duty cycling mechanism, the relative energy savings for S-MAC defined in [39] is defined by the following equations in which E_s defines the energy savings.

$$E_s = \frac{T_{sleep}}{T_{frame}} = 1 - \frac{T_{listen}}{T_{frame}} \quad (4.2)$$

$$T_{frame} = T_{listen} + T_{sleep} \quad (4.3)$$

Where T_{listen} and T_{sleep} are active and sleep times of a particular node respectively. Now, for the proposed protocol the listen time and sleep time of nodes depend upon the AEL factor specific to every node therefore the average energy savings will also be different as compared to S-MAC protocol. Average listen time and average energy savings for the proposed protocol are given below.

$$T_{listen} = \frac{\sum AEL\ values}{Total\ no\ of\ nodes} \quad (4.4)$$

$$E_s = \frac{T_{sleep}}{T_{frame}} = 1 - \frac{\frac{\sum AEL\ values}{Total\ no\ of\ nodes}}{T_{frame}} \quad (4.5)$$

Consequently, the average sleep delay defined above in equation 4.1 will also change.

Trade-off between energy savings and average sleep delay for different active times/listen times is shown in Figure 4.1 below. Note that these listen times are computed against different AEL times shown above in equation 4.4.

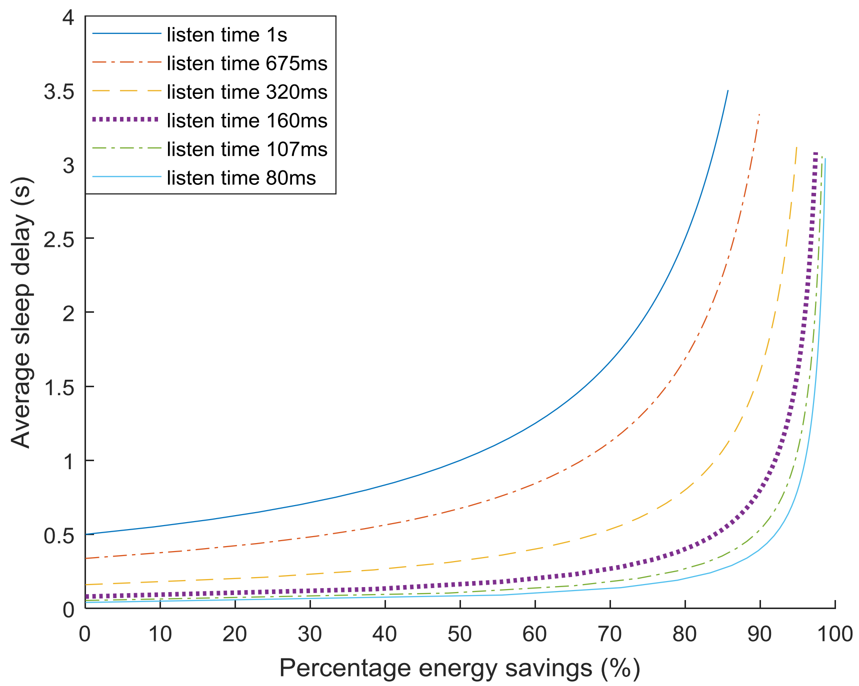

Figure 4.1: Trade-off between Average sleep delay and Energy savings for different active times

It can be seen from Figure 4.1 that sleep delay and energy savings are inter-related and have an inverse relation. By increasing values of average sleep delay, better energy efficiency is achieved. For all listen times, zero percentage of energy savings mean that there is no sleep time and the node is in active state for the whole frame duration. Furthermore, for larger active times, the average sleep delay is always greater. It is because the frame length is increased (by keeping sleep time constant) in equation 4.3, thereby increasing sleep delay in equation 4.1.

4.3 Simulation Results

Figure 4.3, 4.4 and 4.5 show the nodes deployment with SINK in the middle of the network, for different network sizes under consideration.

4.3.1 Nodes Deployment

The nodes deployment for different nodes density is taken into account ranging from 20 to 220 nodes with a network size ranging from 25x25 to 500x500 respectively as shown in Figures 4.2 to 4.4 below. The red nodes, blue nodes and green nodes are first hop, second hop and third hop nodes respectively. The SINK is placed in the centre of the network denoted by blue triangle.

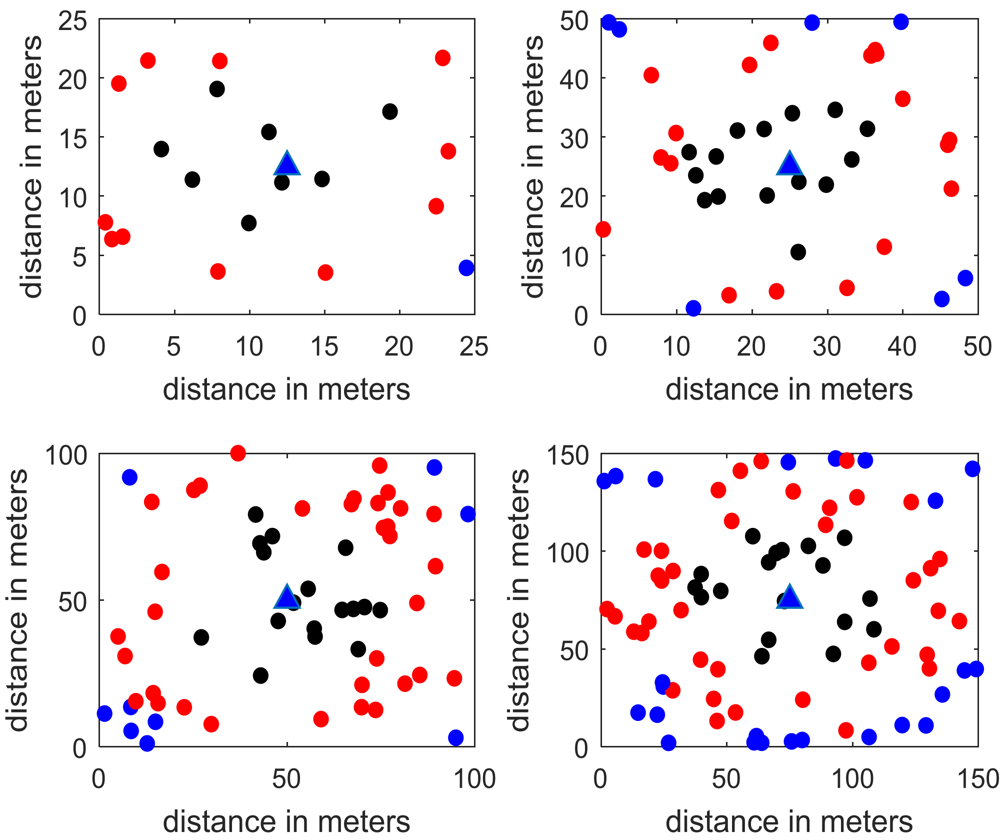

Figure 4.2: Nodes deployment for 20, 40, 60 & 80 nodes

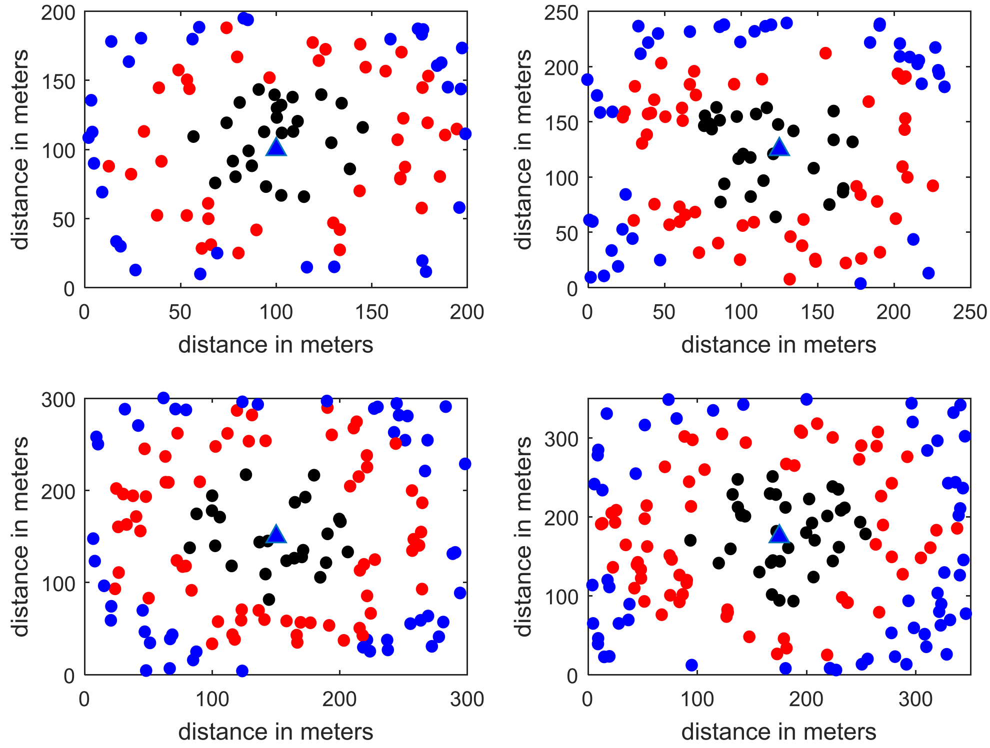

Figure 4.3: Nodes deployment for 100, 120, 140 & 160 nodes

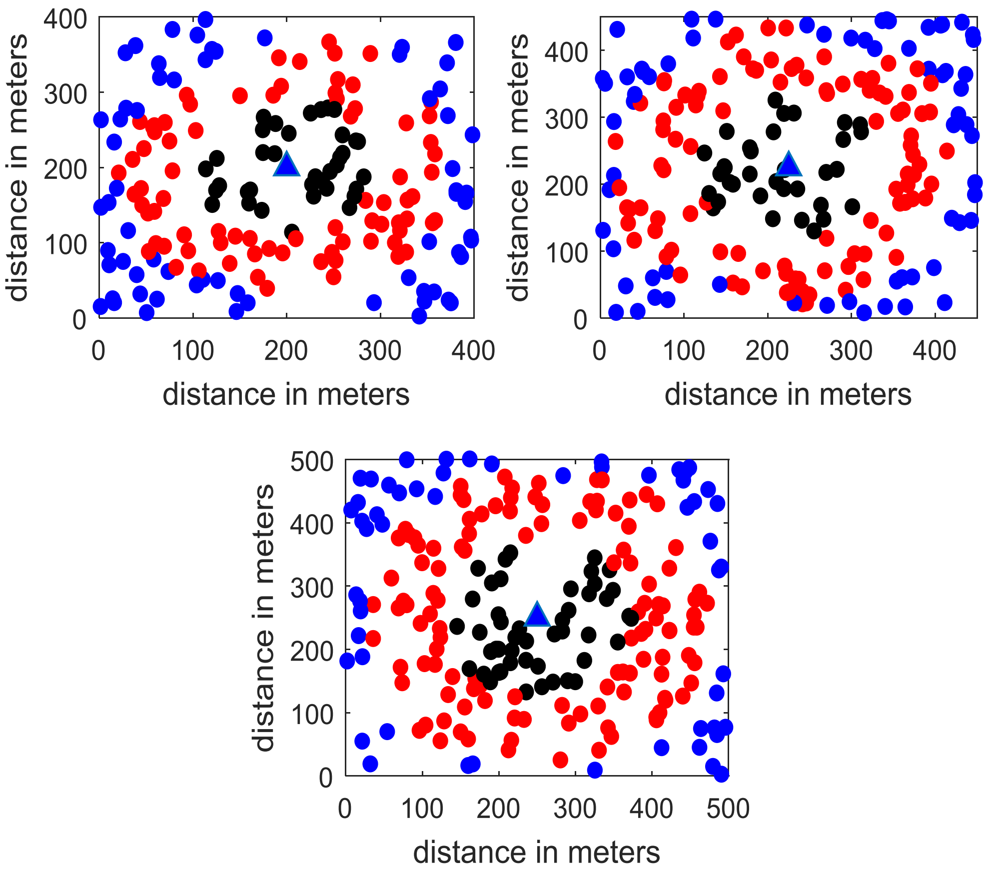

Figure 4.4: Nodes deployment for 180, 200 & 220 nodes

4.3.2 Average energy per packet

Average energy per node is computed for different number of nodes as shown in Figure 4.5 & 4.6 below. It is assumed that every node has a single packet to send to the sink whether through multi-hop or a single hop. It can be seen that average energy used in the proposed protocol is less as compared to S-MAC and Anycast.

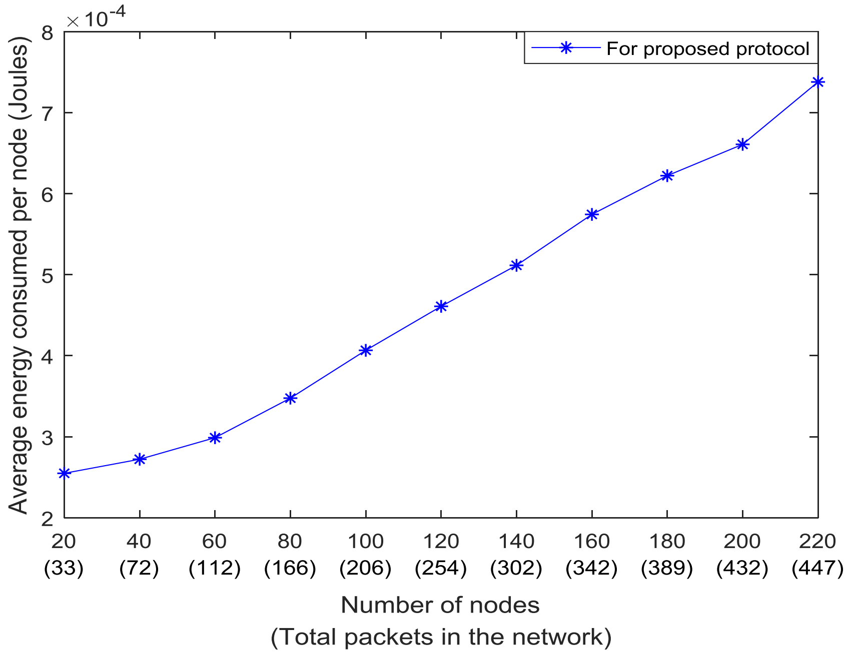

Figure 4.5: Average energy consumed per packet per node

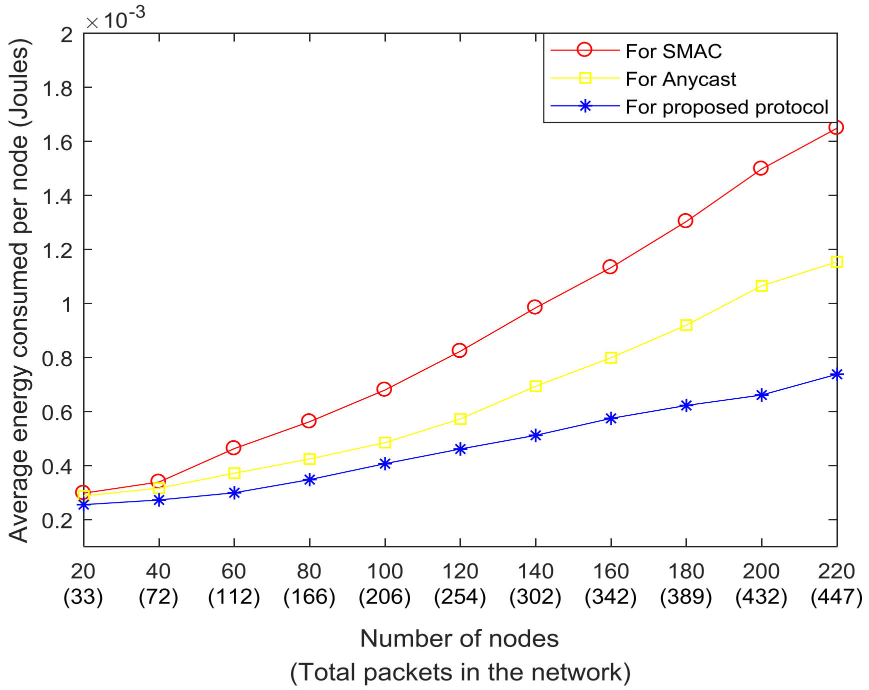

Figure 4.6: Average Energy Consumed per packet for different Network sizes

The increase in energy efficiency with respect to SMAC protocol is mainly due to two reasons. Firstly, the nodes in S-MAC protocol adapts a random wait time for sending RTS packets to their parent node and also fixed duty cycle for all of the nodes. Due to independent selection of this random wait time by every node, there are collisions and retransmissions especially in dense networks. But in the case of proposed protocol, there is lesser number of collisions and retransmissions as compared to S-MAC protocol because this random wait time is calculated on the basis of nodes' distance from the sink and AEL factor, particular to every node. It can be seen in Figure 4.7 that RTS packet retransmissions are much greater for SMAC than for proposed protocol. It is because the nodes are contending in the same duty cycle of fixed length. Thus, greater number of RTS retransmissions results in decreased energy efficiency and increased consumed energy.

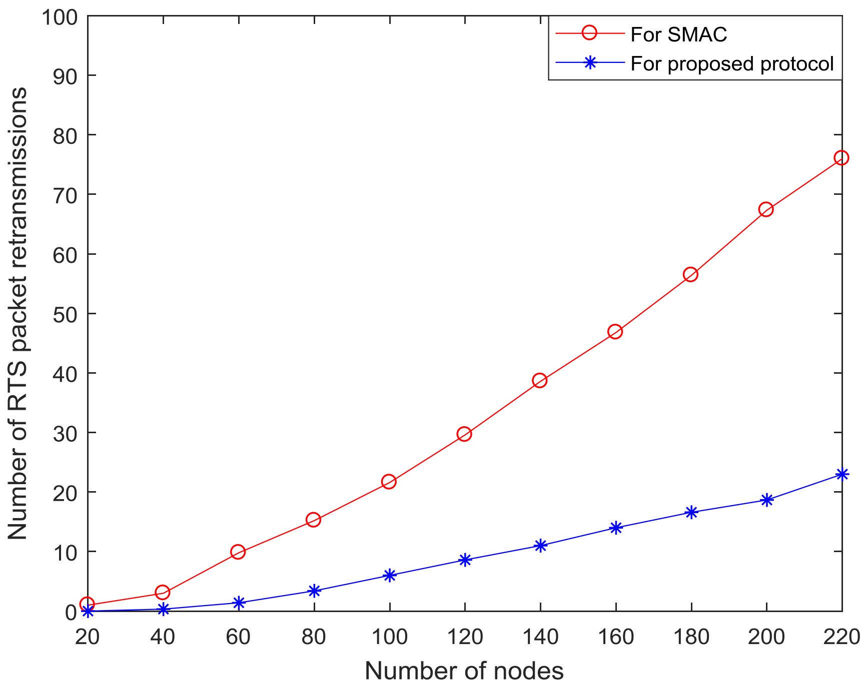

Figure 4.7: RTS packet retransmissions

Secondly, in the case of S-MAC protocol this random wait time does not depend on the location of node. For example, the parent node might adapt shorter random wait time to send RTS packet than its child node. Therefore, the parent node sends its RTS and data packet earlier to the sink, and after its communication with the sink it receives packet from its child node. The packet received from its child node is then transferred to the sink again demanding RTS/CTS exchange between parent node and sink. In this way, S-MAC demands extra RTS/CTS exchange packets as any node can adapt any random wait time. This results in increased energy consumption. Unlike the approach opted by S-MAC protocol, the proposed protocol adapts random wait time depending on its duty cycle. The nodes nearer to the sink (parent nodes) have larger random wait time than nodes far from the sink (child nodes). Therefore, the parent node will always send its RTS and data packet after it has received packet from its child node/nodes. In this way, the parent node will send only one RTS packet to next hop node/sink thereby reducing energy consumption.

Anycast protocol refers to the forwarding scheme where nodes need not to wait for a single parent node to wake up as there is multiple number of parent nodes. Alternate paths are provided to every node for routing their data traffic. Due to this single to many routing scheme, energy consumed is increased because of the fact that nodes stay awake to provide alternate traffic routing paths whether they are receiving packets or not. This in turn increases the idle listening and therefore decreases the energy efficiency. Again, the retransmissions will be more in case of anycast protocol as compared to the proposed protocol because one-to-many forwarding scenario results in multiple nodes contending for the medium in the same slot resulting in collisions.

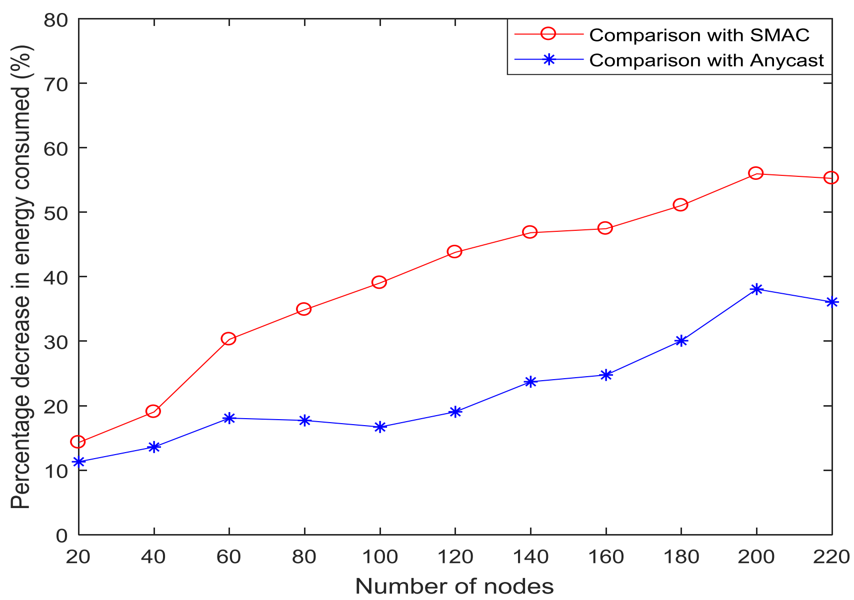

Figure 4.8: Percentage decrease in energy consumption for proposed protocol

The percentage decrease in average energy per packet is simulated in Figure 4.8 above. The percentage decrease is compared with SMAC as well as anycast protocol for different nodes deployments. The percentage decrease has an increasing trend with increasing network density. This shows that the proposed protocol outperforms both these protocols in terms of energy efficiency especially in high network densities.

4.3.3 Average delay per packet

Average delay per packet per hop is also enhanced as compared to S-MAC and Anycast protocols. Because the parent node will certainly be in active state when the child node is sending the packet, therefore the child nodes need not to wait for the parent node to switch from sleep state to active state. Therefore, the one hop delay from the node to its neighbouring parent node will be reduced. This approach is different from the one adapted in S-MAC protocol in which the parent node might not be in active state when child node has sent the packet and therefore the parent node will forward this particular packet in its next frame. While anycast protocol ensures that the child node do not need to wait for parent node to wake up, it still inherent more delays than the proposed protocol. It is due to the fact that packet forwarding in anycast does not follow minimum distance routing algorithm. The packet is just forwarded who so ever neighbour node is active. Therefore, the packet might be routed through a time-consuming forwarding path. Also, due to this reason, end to end delays in anycast protocol are increased.

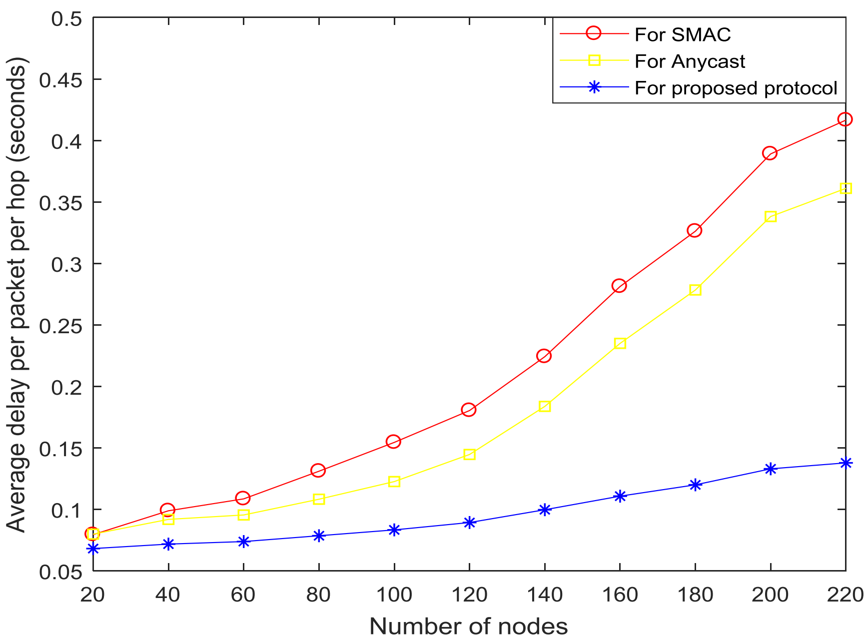

Figure 4.9: Average Delay per packet for different Network sizes

Figure 4.9 above shows the comparison between average delay per packet for the proposed protocol and S-MAC.

The percentage decrease in average delay per hop per packet is simulated in Figure 4.10 below. The percentage decrease is compared with SMAC as well as anycast protocol for different nodes deployments. The percentage decrease has an increasing trend with increasing network density. This shows that the proposed protocol outperforms both these protocols in terms of latency especially in high network densities.

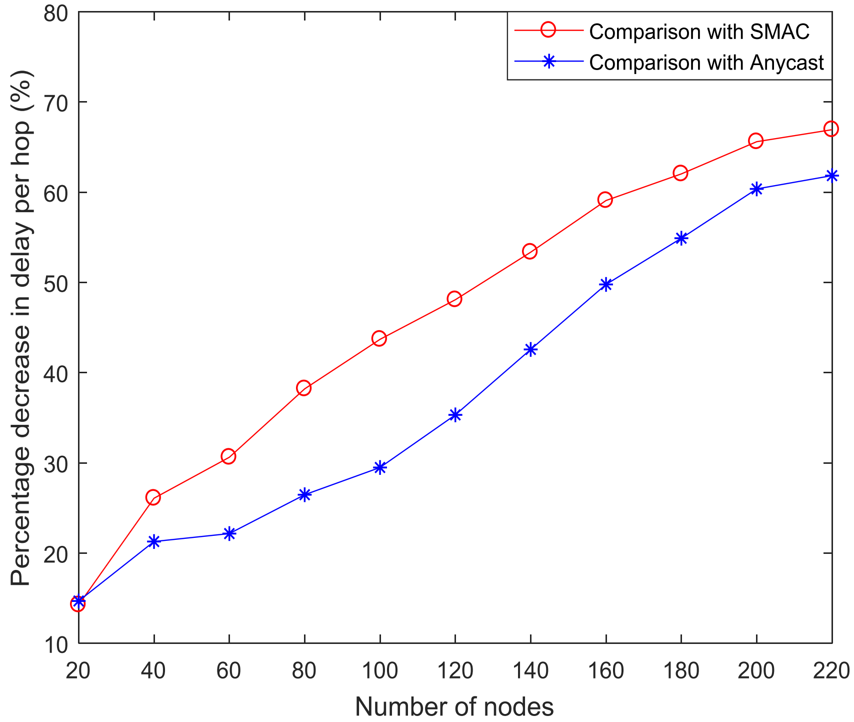

Figure 4.10: Percentage decrease in delay per hop for proposed protocol

4.3.4 AEL factor

Below Figure 4.11 shows the relationship between AEL and active times of nodes depending upon the number of neighbouring nodes. Different values of AEL are chosen depending upon the frame length. Frame length is assumed to be 1 second, and AEL values vary from 1s, 0.5s, 0.2s, 0.1s, 0.067s and 0.05s. It can be seen from the simulation results that decreasing the value of AEL results in lesser duty cycles and longer sleep cycles. Before the deployment of sensor nodes, AEL value can be chosen as is required by the specific application and after that the nodes will chose their active times based on their location in the network.

For first case where AEL is the same as frame time that is AEL equals 1s, the node will be in active state whether it has no child neighbour or multiple number of child neighbors. This is the special case where there is no sleep time for any node, implying all the nodes will be in active state all the time with no sleep wake scheduling. Therefore, choosing AEL same as frame time would be the worst choice even for delay intolerant applications, as the duty cycle of 100% implies maximum energy wastage. This energy wastage is mainly due to the idle listening for most of the active time. For the second case where AEL is half the frame time that is 500 milliseconds, nodes with no child neighbouring nodes are active for 0.5s. But again this AEL value consumes a large amount of energy because the nodes having one or multiple neighbouring child nodes will be active for the whole frame duration. For the third case where minimum AEL value is one by fifth of frame-time, active duration of a particular node varies until the neighbouring child nodes are 3 or less. After that the duty cycle is 100% when neighbouring child nodes vary from 4 to 6. Obviously it will be the same for more than six neighbouring child nodes.

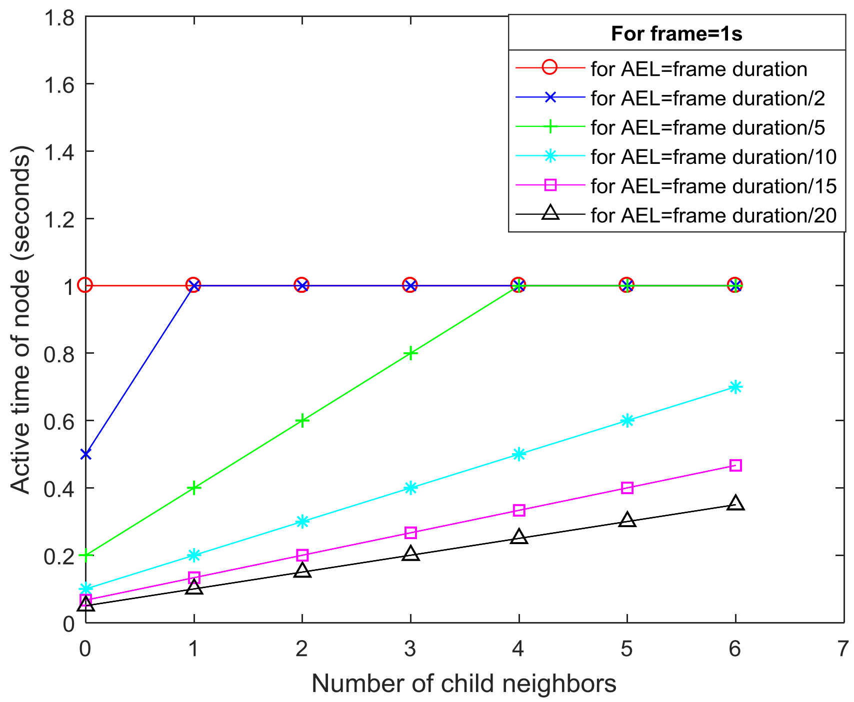

Figure 4.11: AEL factor for different number of child neighbors (affecting active time of nodes)

For the fourth, fifth and sixth case, the active time is always less than frame duration (1 second). In this simulation, maximum number of neighbouring child nodes is six. Although they can be further increased, yet the trend will remain the same. The AEL value should be selected in such a way that will ensure maximum achievable energy efficiency as well as lesser delay. Below is the effect of AEL factor on energy consumed and latency for 40 nodes deployed randomly.

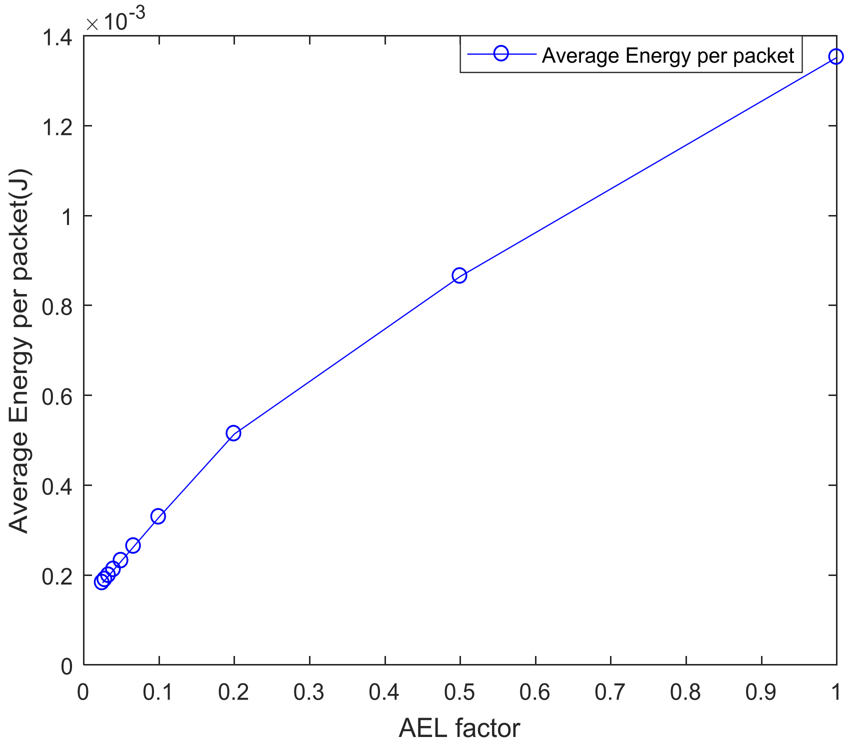

Figure 4.12: Average Energy per packet for different values of AEL

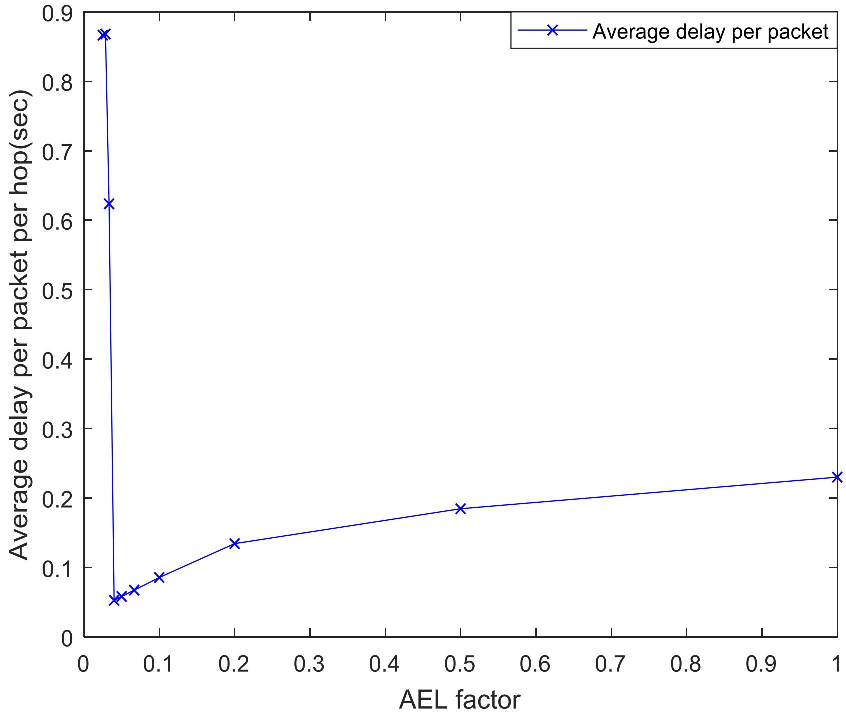

Figure 4.13: Average Delay per packet for different values of delay

Figure 4.12 and Figure 4.13 above show the average energy consumed per packet and average delay per packet for different values of AEL respectively. For the purpose of detailed analysis, 40 nodes are deployed as shown previously in Figure 4.2. The deployment is random and sink is assumed to be in the middle of network. Total of 10 AEL values are taken in the current simulation for computing average energy and delay. AEL values are defined in the same manner as described previously in Figure 4.11. AEL values vary from 100% active time to 2.5% of active time in the total frame (from 1 second to 25 milliseconds).

In Figure 4.12, it can be seen that as the value of AEL decreases, the average energy per packet also decreases. It is obvious from the fact that the decrease in AEL value implies less active time and more sleep time. For the maximum AEL value when nodes are never in sleep state, the consumed energy is much higher as most of the time nodes are in idle mode. After certain value of AEL, there is not a significant decrease in average consumed energy. This is due to the fact that AEL is already decreased enough (one by fifteenth of the total frame) to provide minimum average consumed energy.

Computation of average delay per packet is not as simple and obvious as average consumed energy. In Figure 4.13, the average delay is decreased up till certain values of AEL and then again started increasing for bigger values of AEL. It is contradictory to the fact that when the AEL value increases, the active time increases and therefore the delay should decrease. Based on the proposed protocol scenario, this contradiction is nullified. This is due to the fact earlier that unlike S-MAC protocol, the proposed protocol uses the random wait time for channel access based on the AEL factor. The more the AEL factor, the more time a node waits to access the channel and send RTS packet. This approach helps particularly in multi-hop networks as the random time of parent node will always be greater than child nodes. Therefore, after certain value of AEL, the delay starts increasing as greater value of AEL infers larger amount of random wait time to send the packet.

This larger amount of random wait times arouses a question on energy efficiency because if node is waiting for more time, it means its idle time will be increased and thus more energy will be consumed. But, in the current scenario of the proposed protocol there is no effect over consumed energy. For example, when AEL factor has value=1 that is 100% active time, thereby increasing random wait time to send the packet. Now if this random wait time was not increased and node was allowed to send packet earlier, the idle time would have been decreased. But as is obvious from the AEL value that the node still has to be in active state for the rest of frame duration, this implies that idle time will be same for both scenarios. Concluding the above argument, whether the node is sending the packet earlier or after larger random wait time (depending upon AEL); the idle time of node remains the same.

Referring again to the Figure 4.13 above, it can be seen that decreasing AEL value after a certain value (1/25 of frame time in current scenario) resulted in increase in average delay. This can be referred as the threshold to decrease AEL value because after this threshold value, the AEL is decreased beyond the 'sync window plus random time to send the packet' and therefore, the packet will be sent in next frame. It can be simplified in an equation below:

$$SYNC_{\,window} + t_{R.W} > AEL\ value \qquad (4.6)$$

Where $t_{R.W}$ defines the random wait time and $SYNC_{\,window}$ defines the synchronization window. When the above mentioned condition specified in equation 4.6 is met for any value of AEL, the packet will be sent in next frame and therefore the delay of that packet is increased manifold as can be seen in Figure 4.13 above. The left hand side of the above equation defines the time to send the packet. When it is more than AEL value (that specifies the active time of the node), it means the node is in sleep state and cannot send packet in this frame.

4.3.5 Network Lifetime

In Figure 4.16, network lifetime is evaluated across message inter arrival rate. The inter-arrival rate varies from 1 second (high traffic) to 10 seconds (low traffic). Network lifetime is computed for worst case scenario when every node has a packet to send and there are only 2 one hop neighbouring nodes near to the sink (4 and 8) as shown in Figure 4.14. For the purpose of simplifying the analysis, nine nodes are assumed to be deployed randomly as shown in Figure 4.14. The arrows in the Figures 4.14 & 4.15 show the next hop neighbours.

In the starting scenario, the maximum number of hops to the sink is 3. The traffic varies depending upon the inter-arrival rate. As shown in Figure 4.16, the network lifetime increases as the traffic is decreased. After the certain threshold of energy consumed, the node declares itself as a dead node and goes into permanent sleep state. For the current scenario, this threshold is assumed to be 0.49 Joules.

It is obvious from the Figure 4.14 that the network lifetime depends mainly on two relay nodes nearer to the sink (4 and 8). Among these two nodes, node 4 is much critical than node 8 as node 4 has more neighbouring child nodes than node 8. Due to this reason, node 4 will be dead sooner than node 8. It can be seen in Figure 4.16 above that for all inter-arrival times, node 4 dies sooner than node 8.

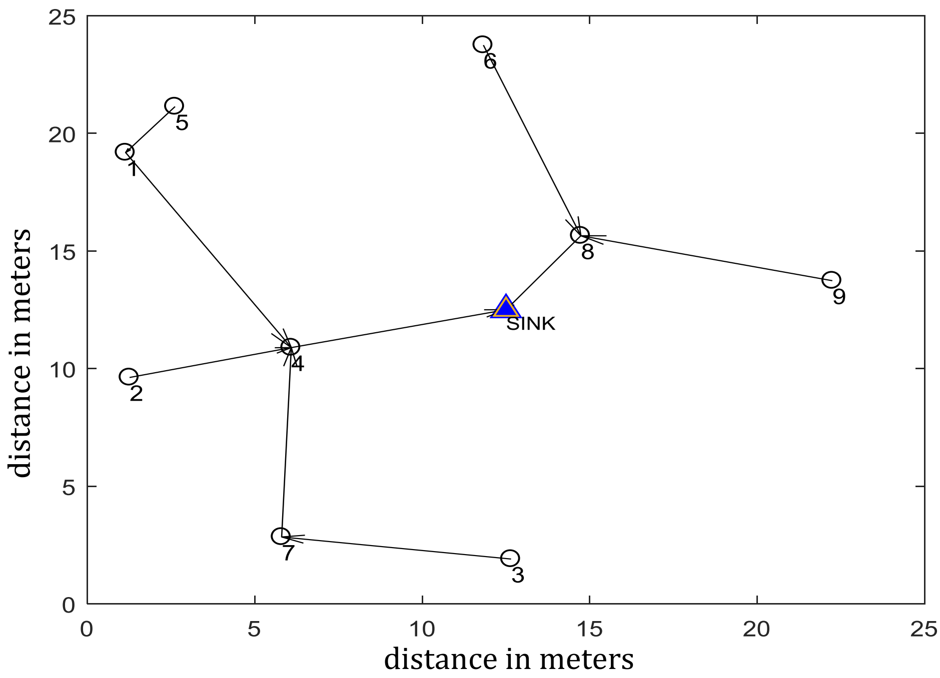

Figure 4.14: Nodes Deployment for Computing Network Lifetime (with Minimum Distance Routing)

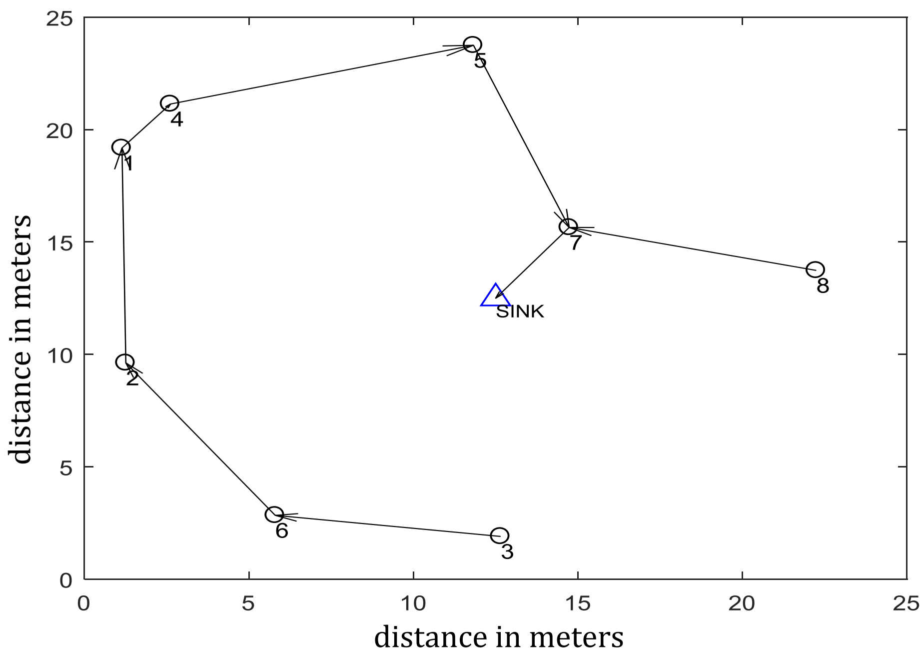

Figure 4.15: Nodes Route update after node 4 is dead

Before node 4 enters into permanent sleep state, it declares itself dead by broadcasting in SYNC window to all its neighbouring nodes. In this way, all the network nodes that were using node 4 as the relaying node for traffic forwarding will update their route and shortest path to the sink. It is obvious from the node deployment shown in Figure 4.15 that after node 4 is dead; all the traffic is relayed from node 8 to the sink. This new route update and shortest path to the sink can be seen in Figure 4.15 above.

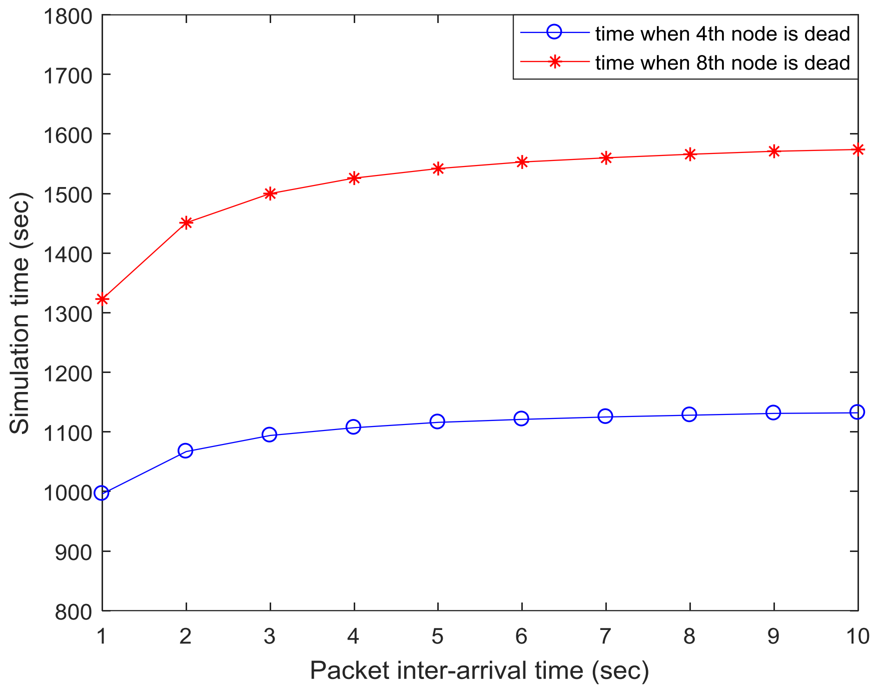

Figure 4.16: Network lifetime for different packet inter-arrival times (with fixed AEL factor)

It is pertinent to note from Figure 4.16 that by increasing the packet inter-arrival time (decreasing traffic load), there is no significant increase in simulation time. In other words, the network lifetime is not increasing as expected by decreasing the network traffic. It is because of the fact that for the current scenario under consideration, the AEL factor (active time of the node) was not changed with changing traffic load and therefore the idle time is same for all inter-arrival times. Because of this reason, after certain value of inter-arrival packet time, there is no significant effect on the network lifetime. The effect of changing AEL value with traffic loads will be explained in the next scenario.

4.3.5.1 Changing AEL with traffic loads

In the current scenario, the AEL value varies as the traffic load varies. Four AEL values were defined varying from 1/15th of frame to 1/30th of frame for four different traffic loads. The same number of nodes and deployment is considered as was chosen for the previous scenario. The simulation time is computed against inter-arrival time for changing values of AEL.

It can be seen from the Figure 4.17 that there is a considerable change in network lifetime by changing the values of AEL for varying traffic loads. Unlike the previous scenario where AEL was constant for all traffic loads, this current scenario provides considerable increase in network lifetime by decreasing traffic loads. This is because of the fact that as the inter-arrival packet time increases (traffic load decreases), the AEL value also decreases and as a result the node active time is decreased. This consequently decreases the idle time for the node and increase the sleep time, which is actually desired when traffic load is decreased.

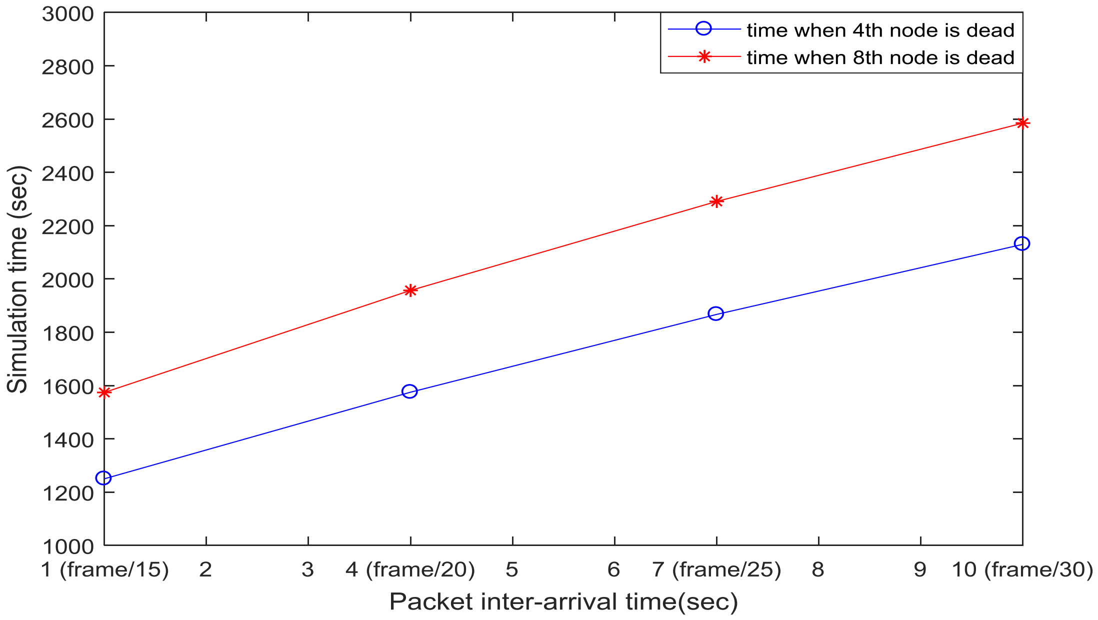

Figure 4.17: Network Lifetime for different packet inter-arrival times (with varying AEL factor)

Chapter 5. Conclusion and Future Work

5.1 Conclusion

Energy efficiency and latency are the main constraints for designing MAC protocol of wireless sensor networks. Extensive work has been done in literature to enhance energy efficiency while reducing delay as discussed in Chapter 2. While some protocols provide enhanced energy efficiency, they are not suitable for delay constrained applications. In the proposed protocol energy consumed and delay per packet were evaluated on the basis of AEL factor. A simple AEL factor was defined that varies depending upon certain factors incorporated in this thesis. It was shown that energy consumed goes on decreasing with decreasing value of AEL, while delay shows some significant patterns with changing AEL value. This shows that while designing wireless sensor networks, the AEL factor should be chosen according to the application requirements. Network lifetime simulated against different traffic loads (for varying AEL values) also shows that while deploying sensor nodes in a specific region for a specific application, AEL factor should be chosen in such a way so as to enhance energy efficiency and decrease end to end latency.

The proposed protocol was compared with already existing protocols and it outperformed S-MAC and anycast protocols both in terms of energy efficiency as well as delay minimization. The proposed protocol has shown percentage improvement of 55% and 38% from SMAC and anycast protocols respectively in terms of energy efficiency; while 68% and 62% from SMAC and anycast protocols respectively in terms of delay minimization.

The AEL factor refers to the minimum value of active time for any sensor node. As self-organizing is the key to wireless sensor networks, the nodes will define their active times themselves by increasing their AEL values. The AEL factor (given prior to the node deployment) will be the defining factor for nodes' active times.

5.2 Future Work

For future work in the light of the proposed protocol, following directions could be pursued.

- The proposed protocol did not take into account wireless channel degradations. Designing the protocol to address wireless channel degradations based on different network load conditions will help in more realistic environment. The

AEL value will then incorporate the network parameters like channel degradation, RSSI degradation due to shadowing effect and topological changes due to coarse deployment areas. Due to these channel degradations, the AEL factor should take into account the number of retransmissions.

- The proposed protocol did not set any threshold for the maximum value of AEL value a node should adapt because the neighboring number of child nodes was assumed to be in a certain limit and also due to the fact that even with worst case scenario with maximum traffic load the AEL factor was not increased vigorously. For more realistic environment, the AEL value should be given certain threshold because after incorporating wireless channel degradations and retransmissions, the AEL value can increase manifold to ensure successful transmission.
- The SYNC window in every frame was set for scalability of network. The new nodes are added in the network and they will broadcast their own schedule. But this SYNC window in-turn wastes a significant amount of energy due to idle listening. A better approach should be taken to mitigate this problem while ensuring scalability.
- The proposed protocol assumed that the nodes are not mobile neither is sink. For increasing network lifetime, specific mobility model might be specified for nodes in such a way that a connectivity critical nodes or highly connected nodes will have a residual node at in their very near vicinity and these two nodes will sleep and wake alternatively by distributing active time between them. In other words, the nodes with no neighbors will be assisting highly connected nodes by moving towards them. In this way, the time of first node death will increase.
- Scalability needs to be addressed for the proposed protocol as the active timer for nodes are different from each other. For example, two single hop neighboring nodes select different active timers and so do their child nodes. The new nodes joining the network might not get synched from its minimum distance parent node, but rather adapt its parent node which is active at that time.

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