MODULAR ENERGY EFFICIENT PROTOCOLS FOR
LOWER LAYERS OF WIRELESS SENSOR NETWORKS

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MODULAR ENERGY EFFICIENT PROTOCOLS FOR
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ABSTRACT

Wireless sensor networks (WSNs) emerged as one of the compelling research areas in recent years. It has produced promising solutions for several potential applications such as intrusion detection, target detection, industrial automation, environmental monitoring, surveillance and military systems, medical diagnosing systems, tactical systems, etc. WSNs consist of small size of sensor nodes that are disseminated in a targeted area to monitor the events for collecting the data of interest. Meanwhile, WSNs face many challenging problems such as high energy consumption, network scalability and mobility. These problems profoundly affect the lifetime of the network, limit the access to several WSN application areas, and the Quality of Service (QoS) provision parameters including throughput, latency, bandwidth, data buffering, resource constraints, data redundancy, and medium reliability.

Although, there has been significant research conducted in WSNs over the last few years to maintain a high standard of communication, especially coverage, challenges of
high power consumption, mobility and scalability to name a few. The major problem with WSNs at the low layers are the excessive energy consumption by the sensor’s transceiver. Other related challenges are mobility and scalability that limit the QoS provision.

To handle these issues, novel modular energy efficient protocols are proposed for lower layers of WSNs. These modular based protocols improve the energy consumption, providing cross-layering support to handle mobility, scalability and data redundancy. In addition, there is a protocol that automates handling the idle listening process. Other protocols optimize data frame format for faster channel access, data frame transfer, managing acknowledgement time and retry transmission, check the capability of sensing the nature of environment to decide to use either active or passive mode that help save energy, determine shortest efficient path, packet generation rate, automatic active and sleep mode, smart queuing, data aggregation and dynamically selection of the cluster head node. All these features ensure the QoS provision and resolve many problems introduced by mobility and scalability for multiple application areas especially disaster recovery, hospital monitoring system, remotely handling the static and mobile objects and battlefield surveillance systems. Finally, modular energy efficient protocols are simulated, and results demonstrate the validity and compatibility of the proposed approaches for multiple WSNs application areas.
DEDICATION

I would like to dedicate this work to God Almighty and my ancestors without whose blessings this would have been impossible.
ACKNOWLEDGEMENTS

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<th>Description</th>
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<tr>
<td>AB</td>
<td>Automatic Buffering</td>
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<td>AAS</td>
<td>Automatic Active and Sleep</td>
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<td>ACK</td>
<td>Acknowledgement</td>
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<td>ADC-SMAC</td>
<td>Adaptive Duty Cycle SMAC</td>
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<td>AAIA</td>
<td>Adaptive Application Independent Aggregation</td>
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<td>A-MAC</td>
<td>Advertisement-based MAC</td>
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<td>AP</td>
<td>Anchor Point</td>
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<td>BDIF</td>
<td>Broadcast Destinations Inter Frame</td>
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<td>Bin-MAC</td>
<td>Binary MAC</td>
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<td>BN-MAC</td>
<td>Boarder Node Medium Access Control</td>
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<td>BNIS</td>
<td>Boarder Node Indication Signal</td>
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<td>BNVSP</td>
<td>Boarder Node Volunteer Selection Process</td>
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<tr>
<td>BSIF</td>
<td>Broadcast Source Inter Frame</td>
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<tr>
<td>BT node</td>
<td>Bluetooth- Enabled Node</td>
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<tr>
<td>CAT</td>
<td>Channel Access Time</td>
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<td>Ch-S</td>
<td>Channel Sampling</td>
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<td>CD</td>
<td>Clock Drift</td>
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<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<td>CP</td>
<td>Check Period</td>
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<td>CTS</td>
<td>Clear-TO-Send</td>
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<td>Abbreviation</td>
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<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
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<td>DA</td>
<td>Destination Address</td>
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<td>DBNSP</td>
<td>Dynamic Boarder Node Selection Process</td>
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<td>DP</td>
<td>Data Payload</td>
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<td>EAR</td>
<td>Energy Aware Routing</td>
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<td>EFB</td>
<td>Election Flag Bit</td>
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<td>FC</td>
<td>Frame Control</td>
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<td>FIFO</td>
<td>First-In &amp; First-Out</td>
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<td>G-MAC</td>
<td>Gateway Medium Access Control</td>
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<td>HRPs</td>
<td>Hierarchal Routing Protocols</td>
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<td>IDM</td>
<td>Intelligence Decision Model</td>
</tr>
<tr>
<td>IE</td>
<td>Indoor Environment</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<td>IOE</td>
<td>Indoor and Outdoor Environment</td>
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<tr>
<td>ISC</td>
<td>Intra Synchronous Communication</td>
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<td>LDSNS</td>
<td>Least Distance Smart Neighboring Search</td>
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<td>LEI</td>
<td>Level of Energy Information</td>
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<td>LMM</td>
<td>Lattice Mobility Model</td>
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<td>LPR-MAC</td>
<td>Low power Real Time MAC</td>
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<td>MAC</td>
<td>Medium Access Control</td>
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<td>MA-MAC</td>
<td>Mobility-Aware MAC</td>
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<td>ME-MAC</td>
<td>Mobility-Aware and Energy-Efficient MAC</td>
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<td>MobiSense</td>
<td>Mobile Sensor</td>
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<td>Abbreviation</td>
<td>Full Form</td>
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<td>MPD</td>
<td>Maximized Probability of Detection</td>
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<td>MS-MAC</td>
<td>Mobility-Aware MAC</td>
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<td>OE</td>
<td>Outdoor Environment</td>
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<td>ns2</td>
<td>Network Simulator-2</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>PAN</td>
<td>Personal Area Network</td>
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<td>PLCP</td>
<td>Physical Layer Convergence Protocol</td>
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<td>PT</td>
<td>Pheromone Termite</td>
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<td>ROC</td>
<td>Relative Operating Characteristics</td>
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<td>RRMAC</td>
<td>Real-Time and Reliable MAC</td>
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<tr>
<td>RSD</td>
<td>Relative Standard Deviation</td>
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<td>RTS</td>
<td>Request-To-Send</td>
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<td>RX</td>
<td>Receiver</td>
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<tr>
<td>SA</td>
<td>Source Address</td>
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<td>SF</td>
<td>Synchronized Frames</td>
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<td>SFD</td>
<td>Start of Frame Delimiter</td>
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<td>S-MAC</td>
<td>Sensor Medium Access Control</td>
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<tr>
<td>SN</td>
<td>Sequence Number</td>
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<tr>
<td>SP</td>
<td>Short Preamble</td>
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<tr>
<td>Speck-MAC</td>
<td>Speck-MAC</td>
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<td>SPIN</td>
<td>Sensor Protocols for Information via Negotiation</td>
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<td>SPIN-EC</td>
<td>Sensor Protocols for Information via Negotiation Energy-Conservation</td>
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<td>SPIN-BC</td>
<td>Sensor Protocols for Information via</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>Negotiation Broadcast Channel</td>
<td>SPIN-PP</td>
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<td>SPIN-RL</td>
<td>Sensor Protocols for Information via negotiation Reliable Link</td>
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<td>SQ</td>
<td>Smart Queuing</td>
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<td>T-MAC</td>
<td>Time MAC</td>
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<tr>
<td>TX</td>
<td>Transmitter</td>
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<tr>
<td>UE</td>
<td>Unknown Environment</td>
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<tr>
<td>VTS</td>
<td>Virtual TDMA for Sensors</td>
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<td>WSNs</td>
<td>Wireless Sensor Networks</td>
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<td>X-MAC</td>
<td>Extended Medium Access Control</td>
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<td>Z-MAC</td>
<td>Zebra Medium Access Control</td>
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CHAPTER 1: INTRODUCTION

Wireless Sensor Networks are considered one of the appealing research areas in recent years[1]. WSNs consist of many sensor nodes with limited power, which gather and process data from specific domains and return data back to specific locations (e.g., disaster control centers and headquarters). The emergence of the latest wireless sensing technology brought a revolutionary change that helps address the several shortcomings related to wired-sensors. However, wireless sensor network applications experience the problem due to excess energy consumption, mobility and scalability. We study in detail the tradeoffs involved in low level protocols for realistic WSN applications.

1.1. Problem and Scope of the Research

Wireless sensor networks (WSNs) typically consist of small sensor nodes, each of which performs its job as a unit by using sensing capabilities to monitor static and mobile events. Thus, it introduces four key requirements for maintaining the Quality of Service (QoS) provisioning and improving the network lifetime at the lower layers: 

i) To maintain long-lived WSN applications, we require an energy efficient paradigm to handle the issue of excess energy waste.

ii) To maintain the QoS parameters, the deployed sensors which detect the events may experience a problem due to the absence of mobility. As a result, sensor nodes experience the issues of emitting, increase in latency, jitter,
broken links and congestion. This requires a robust mechanism to control the mobility prior to this inception of the problems. III) The network topological change and node density may affect the network lifetime and QoS provisioning. This topological adjustment of joining and leaving the nodes requires scalable paradigm. IV) Existing data frame format may increase the channel access time, data frame transfer time, acknowledgement and retry transmission times. It requires modifications to the existing IEEE802.15.4 data frame format to improve QoS provisioning and network lifetime[2].

The second and third parts of the problem are related to emerging wireless sensor applications, which deal with disaster recovery, handling the mobility of objects, target detection, battlefield surveillance, hospital monitoring, etc.[3]. The sensor applications in such areas require a robust, scalable mobility-aware paradigm[4]. The performance of such applications depends on the mobility that performs a significant role in handling different situations in order to maintain QoS. For example, biomedical sensor nodes are attached to patients, doctors and nurses to monitor their activities. Rescue team members also need high mobility during disaster-recovery operations and monitoring the activities at the oil-extracting refineries[5]. Mobile sensor nodes are also deployed to provide debriefing reports to soldiers concerning actions encountered during the mission[6]. The deployment of emerging applications in WSNs experiences the problem due to lack of mobility support; so, it is hard to maintain the QoS provisioning and prolong network lifetime. The problem statement of dissertation, therefore, is:

The existing restrictions on WSNs (such as excessive energy consumption, mobility, data aggregation and scalability) interrupt the smooth communication process over
WSNs. These restrictions are challenging to solve. The key question is how to enable WSNs to maintain QoS provisioning and improve the network lifetime in an efficient manner with respect to the WSN constraints and various applications’ requirements”.

The state-of-art research in this area primarily focuses on energy efficiency, mobility, data aggregation and scalability. However, there is high demand of modular based approach that can support all necessary features of application adoption in WSN environments such as handling idle listening, congestion, synchronization, overhearing, emitting, reliable queuing the data, dynamic head node selection, reduction in size of preamble, addressing methodologies, faster channel access data delivery, and removing data redundancy. Additionally, a WSN requires the cross-layering support for the discovery of deterministic efficient paths for packet forwarding. Therefore, idle listening, congestion, synchronization, asynchronization and overhearing issues have drawn considerable attention from the WSN researchers[7],[8],[9],[10],[11],[12], [13],[14],[15], [16],[17],[18],[19],[20],[21].However, the existing techniques[22]were also unable to resolve these issues fully.

Furthermore, addressing methodologies such as broadcast, unicast, multicast and anycast need to be addressed. The first three addressing methodologies were discussed in the context of WSNs[23],[24],[25],[26],[27], which do not maintain a balance between the energy consumption and the packet delay in the WSNs[28].The fourth (Anycast) is not investigated from WSN perspective. All the existing techniques at the lower layer suffer due to different problems such as lack of effective queuing model, unnecessary energy consumption of transceiver, mobility, scalability, dynamic head node selection,
large data frame format and data aggregation. Hence, QoS provisioning is highly affected due to the absence of these modules as well as the limited network lifetime. A more detailed consideration to the problem results in the following questions:

1. How do we design an energy efficient mechanism to be compatible with multiple WSN applications?

We propose energy efficient modular based protocols at the lower layers, which improve the QoS provisioning for WSN applications. Therefore, the question that arises is what should be the most compatible WSN paradigm to accept new features at the lower layers and even support to higher layers, such as smart queuing, dynamic head node selection, reduction in data frame format size, introducing anycasting addressing methodology, congestion and incorporating the cross layering features to manage deterministic links for packet forwarding. The existing research at lower layers is around accessing the medium and sending the data, rather than considering an adaptable mechanism to accept new modification for improving QoS parameters in order to handle multiple applications with one adaptable paradigm[29],[30],[31]. The question arises:

2. How should we design a compatible mechanism to provide cross-layering support?

This question refers to QoS provisioning such as latency, throughput, jitter, delay and bandwidth. Among these challenges posed by these questions, sink and node mobility, including shrinking and expanding the network are also two fundamental issues that highly affect the QoS parameters and also cause the extra energy consumption for WSN applications. This raises another new question in this area.
3. What should be the appropriate features required for interconnecting MAC sub-layer with network layer for providing cross layering support to maintain QoS provisioning?

Many cross layering approaches have been proposed based on data aggregation and data-centric approaches. However, existing aggregation approaches for cross layering depend only on the intermediate node to compress data using aggregation functions [32]. These approaches are suitable for static wireless sensor applications, but it requires a new mechanism to handle network adaptability and impairing factors such as node mobility, sink mobility, and scalability[33]. Therefore, to support cross layering approach, mobility constraint should be considered prior to designing any mechanisms for emerging applications. We need an analytical mobility based paradigm that should control and determine the location of a node, distance, packet generation rate and an appropriate link selection on the network. The scope of this paradigm should not be limited to only handling single WSN application area. Rather, it should exceed the boundaries to other heterogeneous WSN environments and multiple application areas such as ubiquitous sensor network, smart sensor network, intelligent sensor networks, etc. Therefore, the last question of this dissertation document is:

4. What type of network should be used to incorporate mobility and scalability features? In addition to being compatible with heterogeneous WSN environments, there should also be multiple application areas.
We need WSN to be distributed into different regions. Each region should individually work as a unit as well as collaborate with other regions to obtain and process the relevant data from different areas to the base station. The WSNs mostly scattered over a vast area experience the problem of coverage[34] because real-time information can be lost due to long distances prior to achieving their deadlines in the dangerous and risky situations. In addition, existing WSNs used in real-time applications face significant challenges because of these applications that require high data fidelity and a high QoS provision[35]. Otherwise, there is a risk that packets may be dropped and missed their deadlines for delivery.

The deployment of sensor nodes plays a major role in guaranteeing QoS provisioning. It is important to project a well-organized placement network that would reduce the costs, minimize the end-to-end communication delay, and provide a high degree of coverage[35],[36]. Thus, distributed WSNs in different regions can be ideal for reducing considerable amounts of energy and improving the QoS provisioning.

2.1. **Motivation behind the Research**

There are different WSNs application areas and their associated challenges which need to be dynamically improved and adapted. Thus, this research focuses on multiple applications such as disaster recovery, hospital monitoring, handling the mobile objects and battlefield surveillance. Sensor nodes in such situations can detect several types of ambient context features, such as motion, occupancy, fire, smoke and also health conditions of dwellers. Dynamicity of the mentioned WSN application areas is
considered from two diverse perceptions. Firstly, such applications are categorized as long-lived applications that may be deployed in large scale areas for handling hazardous and critical situations. To easily maintain real-time communication, minimum latency, superior throughput, energy preservation and saving bandwidth, the deployed sensors should be flexible in a dynamic environment. Thus, these WSN applications need to be scalable and support a mobility-aware paradigm to balance the need for the QoS parameters.

Secondly, the existing protocols at MAC sub-layer are application dependent. A protocol designed for one application cannot easily be adapted to another type of application. As a result, additional resources are required for development of a new protocol at MAC sub-layer; that is also a time-consuming and cumbersome process. Therefore, the motives behind this research are to introduce energy efficient modular protocols for prolonging the network lifetime and maintaining the QoS provisioning.

2.2. Potential Contributions of the Proposed Research

The emergence of the latest wireless sensing technology brought a revolutionary change that helps address several shortcomings related to wired-sensors[37]. In this document, we introduce a novel data frame format and cross layering hybrid MAC protocol named Boarder node medium access control (BN-MAC) protocol, which reduces the size of the existing data-frame to achieve faster channel access, data frame transfer, acknowledgement and retry transmission management. In addition, introducing an anycasting addressing methodology, dynamic head node selection and shortening the
preamble size at MAC sub-layer. These features help reduce the node wake up time, bandwidth consumption, and increase the network lifetime. This is the answer to the first question of the problem statement.

To preserve additional energy, the Automatic Active and Sleep (AAS) model and Intelligence Decision Model (IDM) are introduced. These models help preserve energy and reduce the idle listening time at MAC sub-layer. To determine the shortest distance between the sensor nodes for forwarding the data, the Least Distance Smart Neighboring Search (LDSNS) methodology is introduced that helps improve the node search capability at the network layer. Handling real-time and non-real-time traffic, smart queuing model is introduced to classify and schedule the traffic for smooth data communication and to control congestion.

To handle mobility, scalability, determining the packet receiving and forwarding on each link, pheromone termite model and lattice mobility model are added. Both models address cross-layering architecture to resolve the issues of identifying the node position, determining the accurate distance of mobile sensor node, packet generation rate, and selection of the appropriate link on the network. These features improve the network lifetime and maintain the QoS provisioning. This is the answer to the second and third questions of the problem statement.

The data aggregation is a critical issue in the WSNs; to handle this, the adaptive application independent aggregation model is introduced that helps in managing the data aggregation, utilizing the communication channel efficiently, and controlling the flow of
the packets to avoid the congestion and network bottleneck. Furthermore, we designed a region based wireless sensor network. Each region is handled and controlled by a border node using the dynamic Border Node selection process (DBNSP) approach. The topology of this WSN has the capability to adopt the dynamic behavior of several multiple applications.

The capability of accepting new features makes it a guaranteed QoS provisioning network. This is the answer to the fourth and last question. To demonstrate the correctness and performance of modular protocols; we created several realistic scenarios.
comprised of disaster recovery/emergency situation, handling the mobile and static objects, battlefield surveillance, mass-destruction and hospital monitoring system. These scenarios cover major application areas and are simulated using network simulator-2 ns2. Figure 1.1 provides a schematic of the integrated components of the modular design presented in this dissertation document.

2.3. Outline

Chapter 2 is a literature survey for the taxonomy of medium access control protocols. This chapter presents the different categorizes of MAC protocols in detail.

Chapter 3 is an elaborate discussion of the hybrid MAC protocols with respect to their scope, strengths and limitations. The comparison of hybrid MAC protocols based on scalability, mobility, residual energy, real-time communication, overhead, common pattern-support, data aggregation and coverage efficiency is described.

Chapter 4 discusses the mathematical models and formulation of the problem statement. Next, the proposed mathematical models, BN-MAC, Dynamic selection of boarder node, Optimized data frame format (ODFF), Smart queuing, Adaptive application independent aggregation, Least distance smart neighboring search, Intelligence decision-making and Automatic active and sleep models are presented in detail. And the validation of these models is also formulated. This chapter also presents the results of some models.
Chapter 5 discusses the pheromone termite and lattice mobility models, which improve the mobility and scalability of the network. Pheromone termite model presents several features including two important features; pheromone sensitivity and packet generation rate. Lattice mobility model describes and determines the node location, covered distance, and the node speed by reducing the extra pause time, control packets, and the node dependency.

Chapter 6 presents simulation setup, system model, evaluation of simulation results in detail. Next, based on the simulation results, the characterization and improvement of the proposed modular protocols is shown in detail.

Chapter 7 summarizes the work and draws some conclusions.

Chapter 8 gives future directions.
CHAPTER 2: LITERATURE SURVEY FOR TAXONOMY OF MEDIUM ACCESS CONTROL PROTOCOLS

Based on various research concerns, we have classified WSN MAC protocols into six categories: contention-based, schedule-based, hybrid, low-duty-cycle, mobility-aware and real-time MAC protocols depicted in Figure 2.1. We have also shown the relevance of various types of communication (e.g., asynchronous, locally synchronous and globally synchronous) and their association with MAC protocols. This classification represents the unique characteristics of each MAC protocol. It also provides some idea of the obstacles that each category must overcome. It is important for researchers to identify the key challenges they will face when designing MAC protocols. For instance, synchronicity and asynchronicity are related to the structure of the duty cycle of a WSN because the efficiency of a WSN depends on how much time each node spends awake or asleep according to a given MAC protocol. In addition, during synchronous processes, nodes are synchronized with neighboring nodes to set their clocks such that their schedules of waking and sleeping can be maintained.

Therefore, communication should be expedited to reduce delays and increase throughput. The taxonomy of MAC protocols emphasizes the individual characteristics of each MAC protocol to aid in choosing the most suitable MAC protocol for a particular WSN application. It also identifies research issues that may arise in the case of multi-featured MAC protocols for WSNs that permit the deployment of several applications at once. By focusing on the features of each category, the robust and energy-efficient MAC
protocols can be designed to address the challenges of idle listening, overhearing, congestion, emitting, scalability, etc. In addition, the critical issue of channel utilization can be addressed in an effort to avoid wasting slots in the assignment of slots to neighboring nodes.

Figure 2.1: Complete taxonomy of well-known MAC protocols
With a clear understanding of the mechanisms associated with each category, researchers will be able to select the optimal features of various categories of MAC protocols to develop novel, robust, energy-efficient MAC protocols. In this section, we also note the weaknesses and strengths of all categories of MAC protocols. Below, we discuss the six categories of MAC protocols and their strengths and weaknesses.

**2.1 Schedule-Based MAC Protocols**

The proposed schedule-based protocols use the TDMA technique. They strive to be energy efficient by decreasing energy wastage. Schedule-based MAC protocols reduce the necessity for data retransmission because contention does not occur. Several schedule-based MAC protocols have been proposed for WSNs, but no protocol is recognized as a general standard. One of the primary reasons for this lack of consensus is that this class of protocols is strongly application dependent: a protocol designed for one application cannot easily be adapted to another type of application. Thus, there is no single standard schedule-based MAC protocol for WSNs. Additional reasons for this lack of a standard protocol are the lack of standardization of the physical layer and issues related to the compatibility of sensor hardware. Schedule-based MAC protocols possess the natural advantage of collision-free medium access, but some protocols experience problems of interference caused by the reuse of slots. Thus, time synchronization is critical for these protocols; if it is not maintained, problems related to clock drift arise.

Scalability is another challenge for these protocols because the insertion and deletion of nodes as a result of the exhaustion of battery capacity and broken links can cause
degradation of the WSN performance and disturb the sleep schedule of relay nodes. In addition, slot allocation is hard to change within the decentralized environment of traditional schedule-based TDMA MAC protocols. There are other problems faced by schedule-based MAC protocols, such as problems of throughput, latency, and extraneous control messages during schedule exchange, but these problems are considered to be secondary.

### 2.2 Contention-Based MAC Protocols

Most of the contention-based MAC protocols are based on S-MAC, which is specially designed for particular applications of WSNs[16],[17],[19]. Nodes, that follow the contention-based mechanism, are not required to support their clusters. These protocols have network adaptability and support the inclusion and departure of nodes, but a node cannot determine when to turn on/off its radio. It is difficult to use sleeping mechanisms to avoid needless energy consumption while achieving the desired latency and throughput. When contention-based protocols attempt to synchronize neighboring nodes, they consume considerable energy to maintain the synchronization. They experience problems of idle listening, overhearing, collision and packet overhead.

### 2.3 Real-Time MAC Protocols

Real-time MAC protocols are classified into two categories based on their proposed WSN applications, soft and hard real-time protocols. We provide a summary for both categories.
2.3.1 Soft Real-Time MAC Protocols for WSNs

Soft real-time MAC protocols are protocols based on S-MAC that are energy aware and reuse channels. The operational procedures of Soft real-time are similar to those of S-MAC, but data are sent only in their reserved slots. A node can send data packets during an NC cycle, where NC is the length of the super-frame. When all nodes forward their first CTL packets, then timeslots are generated. Nodes have the capability to adjust dynamically to other nodes joining and leaving the cluster while modifying the size of the super-frame.

All nodes wake up and sleep simultaneously at the start and end of each time slot. The proprietor of a time slot initiates the carrier assignment and broadcasts a CTL. The CTL is used to synchronize schedule discovery and new node discovery and to maintain beacons and channel reservations. Virtual TDMA for sensors (VTS) [38] is an example of Soft real-time MAC protocol that reduces the energy consumption and latency of data transmission in WSNs of small size, but when the size of the WSN increases, the energy consumption is also higher.

2.3.2 Hard Real-Time MAC Protocols for WSNs

Hard real-time MAC protocols are based on TDMA, message ordering, traffic management and dual-mode operation[39]. The Real-time and Reliable MAC (RRMAC) protocol is an example of hard real-time MAC protocol for WSNs. RRMAC relies not only on successful communication but also on the time during which it is operating.
However, RRMAC can experience difficulties in maintaining global synchronization in large, distributed, multi-hop WSNs.

### 2.4 Mobility-Aware MAC Protocols

Before designing a realistic, energy-efficient, mobility-based model, it is important to understand the behavior of mobility patterns. Based on predictable mobility patterns, the design of a protocol can adopt reasonable assumptions to address the communication handover. We discuss top-level mobility patterns in WSNs. Mobility reflects the behavior of real objects in the world, such as people and vehicles, which can be categorized in terms of attributes. These attributes are limitations, dimensions, predictability and group behavior. There are three known types of mobility patterns that are applicable to WSNs:

a. Dynamic-medium mobility pattern: This pattern is used when nodes represent elements of a medium (e.g., water, the wind and other fluids). This mobility pattern may consist of one, two or three dimensions depending on the nature of the medium.

b. Walking mobility pattern: This pattern reflects the motions of people. In this model, sensor nodes represent the bodies of people as they move. This pattern is characterized by its restricted speed, chaotic nature, and obstacle-avoidance behavior. The movement of persons is measured in two dimensions in this model.

c. Vehicular mobility pattern: This model consists of vehicles that are equipped with sensor nodes. The vehicles communicate with each other while evaluating traffic
conditions and can exchange information quickly. The movement of a vehicle is measured in only one direction and describes group actions at high speed.

A mobility model falls into one of the two categories: synthetic and trace-based models [40]. Real-life mobility patterns are collected from many participants using trace-based models. However, the physical positions of sensor nodes are complex to capture. Synthetic models also represent the activities of real-world sensor objects. However, they do not provide a picture of any particular mobility pattern. There are many synthetic mobility models, but three well-known examples of mobility models are the random walk mobility model, the group mobility model, and the entity mobility model. Before inserting mobility-aware features into a MAC protocol, both sink and node mobility should be considered.

In a sink mobility model, the sink is the final destination of a data transmission in a WSN, which travels and routes itself through the network to gather data from stationary nodes. However, complex situations can arise by virtue of node mobility, in which distinct sensor nodes dynamically change their positions during their movement while attempting to maintain an end-to-end communication link.

### 2.5 Low-Duty-Cycle MAC Protocols

The basic concept of low-duty-cycle protocols is to decrease the idle time and overhearing activities of sensor nodes in WSNs. The ideal situation for low-duty-cycle protocols is to allow sensor nodes to sleep most of the time and for these nodes only to begin to transmit and receive data packets when necessary. Low-duty-cycle protocols use periodic wake-up mechanisms.
A complete cycle of such a protocol consists of one sleep/wake-up period. The ratio of the listening time to the total wake-up period is considered to be the duty cycle of the nodes. An ideal low duty cycle is deemed to be one in which the node sleeps most of the time to reduce overhearing and its idle listening time. However, a stable duty-cycle length must be maintained to avoid high transient energy usage and high latency attributable to start-up costs.

Several low-duty-cycle protocols have been proposed for WSNs that possess a variety of features in terms of synchronization, transmitter- or receiver-initiated processes, the number of required channels, etc.[41]. We classify low-duty-cycle protocols into two broad categories: synchronous and asynchronous mechanisms. The idea of synchronization is associated with data exchange in the WSN[42]. In an asynchronous mechanism, there are two fundamental approaches: transmitter-initiated and receiver-initiated approaches. In a transmitter-initiated approach, a node sends requests for packets (control, preamble and data packets) until one of them "hits" the listening time period of the destination node, whereas in a receiver-initiated approach, a node sends frequent data packets (control, preamble, and acknowledgment) to notify neighboring nodes regarding the disposition of the node to receive packets.

The first approach places the primary energy cost at the transmitter, whereas the latter approach shifts the cost to the receiver. Another variant of a low-duty-cycle protocol is to maintain a synchronous mechanism in which all nodes, that are grouped into a single cluster, follow the same wake-up period. Synchronized low-duty-cycle MAC protocols are usually equipped with pre-programmed periodic wake-up schedules for data
exchange; such a schedule comprises a sleep period “Tsleep” and an active period “Tactive,” which are repeated at time intervals of Twakeup_period. Synchronization is easy to maintain within a small cluster or network, but it is difficult to maintain in clusters of larger size because of problems of global synchronization.

2.6 Hybrid MAC Protocols

Hybrid protocols leverage the characteristics of TDM and CSMA[1]. The contention-based component provides free access to nodes to access the medium. The TDMA-based component is required to form clusters. Time is divided into different time slots. Each node uses its time slot. Each node can access the medium during its allotted time slot. This approach reduces idle listening and collisions. Transceivers receive their sleep schedules without excessive overhead. However, such a mechanism also suffers some drawbacks. The clusters face difficulties related to dynamic changes in time slots. Scalability and mobility are major issues in the event of a node change.

A protocol of this type also faces difficulties related to inter-cluster communication and requires tight time synchronization. Different hybrid MAC protocols are needed to support different WSN applications. Thus, certain modifications of hybrid MAC protocols can alleviate their inherited weaknesses. Furthermore, most hybrid MAC protocols have been developed for ad-hoc networks[43]. Thus, before designing hybrid protocols, the following points should be considered: Nodes are likely to fail, have limited energy resources and processing power, and exist in large quantities; new nodes are frequently deployed; and the network topology can change.
CHAPTER 3: LITERATURE SURVEY OF HYBRID MEDIUM ACCESS CONTROL PROTOCOLS

In this section, we present the hybrid protocols at MAC sub-layer to support wireless sensor networks. Hybrid protocols leverage the characteristics of TDM and CSMA[44]. The CSMA-based protocols are flexible to provide the access to nodes to the medium. The TDMA-based component is required to form clusters [45]. In TDMA, time is divided into different time slots. Each node uses its time slot. Each node can access the medium during its allotted time slot.

This approach reduces idle listening and collisions. Furthermore, the transceivers receive their sleep schedules without excessive overhead. However, such a mechanism also suffers some drawbacks. The clusters face difficulties related to dynamic changes in time slots. Scalability and mobility are major issues in the event of a node change. A protocol of this type also faces difficulties related to inter-cluster communication and requires tight time synchronization. Different hybrid MAC protocols are needed to support different WSN applications. Thus, certain modifications of hybrid MAC protocols can alleviate their inherited weaknesses.

Furthermore, most hybrid MAC protocols have been developed particularly for ad-hoc networks[46]. Thus, before designing hybrid protocols, the following points should be considered: Nodes are likely to fail, have limited energy resources and processing power, and exist in large quantities; new nodes are frequently deployed, and the network topology can be changed.
Here, we emphasize well-known hybrid protocols at MAC sub-layer that attempt to address energy efficiency, mobility, and scalability features.

### 3.1 Advancement-Based MAC (A-MAC) Protocol

The A-MAC hybrid protocol was introduced in [47] to control collision, overhearing and modest idle listening. In A-MAC, TDMA is used as a baseline for MAC, and CSMA is used to improve the convenience of wireless channels. A certain numbers of particular time slots are assigned to each node within a set of two-hop neighbors. These allocated time slots are used to transmit data without causing any interference with other nodes. A-MAC also uses an advertisement to permit the sender to inform its neighbors of its transmission schedule.

The primary advantage of A-MAC is its ability to inform nodes in advance when they are assigned the responsibility to become senders or receivers, while they otherwise remain in sleep mode; this method avoids the misuse of energy on idle listening and overhearing. However, the overhead associated with control packets in A-MAC is high because of the advertisement scheme. In addition, the latency is also high because of the transition between two different mechanisms.

A-MAC is specifically designed for monitoring and long-term surveillance applications. A-MAC also does not support mobility and real-time communication. Architecture of A-MAC is depicted in Figure 3.1.
3.2 Binary MAC (Bin-MAC) Protocol

The Bin-MAC protocol was developed for resource-constrained WSNs[48]. Bin-MAC consists of a deterministic contention-resolution mechanism that enables it to achieve bounded latency. It operates in pull mode: the base station initiates query messages, and nodes that constitute part of the sink then reply to these messages. Bin-MAC works using a round-robin method in the absence of a scheduling phase.

Bin-MAC consists of four mechanisms: establishment of a binary tree, contention resolution, duty-cycle adjustment and slot consolidation. Query messages are directed at ranges of node IDs rather than at single node, thus increasing throughput, but Bin-MAC
does not have topological support because the nodes are fixed in their initial topology. The contention-resolution mechanism of Bin-MAC is shown in Figure 3.2.

### 3.3 X-MAC: A Short Preamble MAC Protocol for Duty-Cycled WSNs

X-MAC is a hybrid-based low duty cycle MAC protocol based on short preambles[49]. In X-MAC, the transmitter sends a short preamble. If the transmitter does not get acknowledgment, the transmitter node considers that the target node is asleep. The transmitter node attempts to send a short preamble again until the transmitter node reaches the threshold value.

![Comparison of the timelines between LPL’s extended preamble and X-MAC: Redrawn from:[49]](image-url)

*Figure 3.3: Comparison of the timelines between LPL’s extended preamble and X-MAC: Redrawn from:[49]*)
In X-MAC, CSMA is performed before the preamble packet transmission. Having received the preamble, the receiver has to wait for a short period to provide a chance for other nodes if they want to send data packets. An advantage of X-MAC is minimization of energy consumption and latency. In addition, idle listening to the receiver side and overhearing at the neighboring nodes can be reduced. However, the gaps between series of preamble packets is a problem that can be considered as idle listening. As a result, the goal of preserving the energy remains unfulfilled. Mechanism of X-MAC is compared with LPL and depicted in Figure 3.3.


The Z-MAC incorporates both features of TDMA and CSMA techniques[50]. In Z-MAC, CSMA builds the baseline and TDMA resolves the conflict. Z-MAC uses the owner slot idea. The nodes in Z-MAC use the novel flexible time-frame regulation without global synchronization. Nodes, however, require the operating global clock synchronization when setting up a phase, which is considered a complicated process. As a result, nodes consume significant energy resources. Z-MAC also introduces a node highest priority scheme. All the nodes can compete for the channel for data transmission, but only the allocated node gets the most top priority. Under the high competition conditions, the slot assignments decrease the collisions. However, Z-MAC suffers latency problems due to the use of a long preamble that increases the chance of striking the active period of the receiver. The nodes in Z-MAC are fixed to limit the network scalability. As
a result, the mobility and scalability support cannot be fully attained. Once a new node intends to join the network, the setup phase must be repeated several times, which decreases throughput and consumes additional energy depicted in Figure 3.4.

![Figure 3.4: Working mechanism of Z-MAC: Redrawn from [50]](image)

3.5 Mobility-Aware MAC Protocol for Sensor Networks (MS-MAC)

The MS-MAC [51] is introduced as an extension of SMAC. MS-MAC uses coordinated sleep/listen duty cycles and periodically synchronizes the schedule of the nodes. The process of synchronization is done using a broadcasting SYN packet at the start of the listening phase. A node first attempts to follow a prevailing schedule while listening for a given period. If no SYNC message is received, the nodes randomly pick time to go for sleep and instantly broadcasts this information. However, if a node obtains different schedules, then that node chooses one, but the nodes adopt both schedules. MS-MAC uses border nodes that make a virtual cluster that may follow two or more different
schedules. MS-MAC enables each node to determine the mobility and its level within its neighborhood. An advantage of MS-MAC is to handle different cluster schedules.

MS-MAC can continue communication with the original neighbor while making a new virtual cluster. The synchronization can be adjusted with the speed of the neighbor nodes. However, nodes get confused by following different schedules that could lead to congestion and a waste of energy under a heavy traffic load. In addition, neighbor of the sensor node wastes a significant amount of energy even it is static. The duty cycle of MS-MAC with mobility-support is depicted in Figure 3.5.

![Figure 3.5: MS-MAC duty cycle with different mobility level: Redrawn from[51]](image)

### 3.6 Short Packet Medium Access Control (Speck-MAC) Protocol

Speck MAC[52] is hybrid MAC protocol that is a deviation from the B-MAC protocol. Speck MAC integrates destination address and superfluous transmission of short packets. The first goal of Speck-MAC is to reduce the transmission energy, and the second is to
decrease the significant overhearing problem during a heavy traffic situation. Speck-MAC is also efficient during the transmission of unicast packets. However, Speck-MAC experiences the problem of extra consumption of energy by sending wake-up frames even though frames are already received by the receiver Wake-Up[53]. Speck-MAC also suffers due to the excess latency problem. Speck MAC is not supported for real-time communication and mobility. Overview of Speck MAC is depicted in Figure 3.6.

![Figure 3.6: Overview of Speck MAC: Redrawn from[52]](image)

### 3.7 Mobility-Aware MAC (MA-MAC) Protocol

The MA-MAC protocol is proposed in [54] as an extension of X-MAC. MA-MAC enables a node to extend sleep time and switch to the radio when the packets are arriving. MA-MAC covers two scenarios: static and mobility. In the static scenario, the performance of MA-MAC is similar to X-MAC. MA-MAC divides the preamble into several strobes to send an early acknowledgment packet to preserve energy. In the mobility scenario, MA-MAC uses a seamless handover to relay the data to a new node.
before the collapse of the link. During mobility, if a transmitter notices that the distance of the receiving node exceeds the first threshold, the transmitter starts to discover an intermediate neighbor node. To do this task, the transmitter broadcasts a data message in which handover requests are included. If the transmitter receives one acknowledgment packet from a new node, then the transmitter directs the data transmission to the newly discovered node. An advantage of MA-MAC is handling the mobility in time, and relay nodes are identified during data transmission. However, MA-MAC has a weakness because MA-MAC depends on the network density and the schedule of nodes shown in Figure 3.7. Further, in MA-MAC, it is also hard to maintain two threshold values.

Figure 3.7: MA-MAC network density: Redrawn from [54]
3.8 Adaptive Duty Cycle Sensor-MAC (ADC-SMAC) Protocol

The ADC-SMAC [55] is a hybrid MAC protocol that is an improved version of S-MAC[56]. ADC-SMAC adds two additional features to S-MAC. First, the node calculates the energy consumption rate of the forwarding node and the average sleep delay at the time of sending the synchronized packets. ADC-SMAC also adjusts the duty cycle according to the network conditions and broadcasts the new schedule to the neighbor nodes. Hence, ADC-SMAC reduces the energy consumption, but it increases the latency, and it is difficult to manage the network scalability. In addition, ADC-SMAC is not adequately robust in mobility conditions. ADC-SMAC makes star topology shown in Figure 3.8.

![Cross-layer mechanism of ADC-SMAC](image)

*Figure 3.8: Cross-layer mechanism of ADC-SMAC: Redrawn from[55]*

3.9 Mobile Sensor MAC (MobiSense) Protocol

MobiSense is a cross-layer mobility-based MAC protocol that combines MAC and the network layer to perpetuate energy efficient data communication within a micro-
mobility scenario. In the scenario, the nodes are structured into clusters, in which stationary nodes perform as cluster heads. The non-cluster head nodes interchange data packets between cluster head nodes[57].

MobiSense implements multi-channel data communications to increase throughput and simplify the network management. The goal of MobiSense is to decrease the intervention between the clusters and to permit the cluster-heads to schedule traffic dynamically. MobiSense manages a super-frame using synchronized slots, transmission slots, downlink and uplink, discovery slots and data admission mini-slots shown in Figure 10. The cluster heads send synchronized data packets at the start of each frame to notify mobile nodes about changes in downlink and uplink data transmission.

The strength of MobiSense is to obtain quick network discovery information. MobiSense also confirms fast admission and rapid network convergence. However, MobiSense experiences the problem of managing the multi-channel. As a result, the node mobility is difficult to handle in time and therefore causes the collisions.

*Figure 3.9: Cluster-head sub-frame shows the synchronization slot, the downlink slots, the scheduled slots, and the access mini-slots. Mobile node attempts to join that cluster after selecting a random access mini-slot: Redrawn from[57]*
3.10 Low-Power Real-Time MAC (LPRT-MAC) Protocol

The LPRT-MAC protocol is proposed in [58] for actuation and wireless systems. LPRT-MAC consists of an infrastructure-based star topology. The stations communicate with base stations directly. The LPRT-MAC includes a super frame that is divided into mini slots and is used for transmission of the base station depicted in Figure 3.10. LPRT-MAC reduces power consumption and coordinates with the channel. The beauty of LPRT-MAC is handling overhead by using a star topology. However, LPRT-MAC is limited and not suitable for large multi-hop wireless sensor networks. As a result, the topological change causes the additional energy consumption, and the nodes reduce the throughput. LPRT-MAC is also not suitable for mobility scenarios.

![Super-frame structure for the LPRT protocol](image)

Figure 3.10: Super-frame structure for the LPRT protocol: Redrawn from[58]

3.11 Mobility-Aware and Energy-Efficient MAC (ME-MAC)

ME-MAC is proposed in [59]. ME-MAC inherits the features from TDMA and CSMA and dynamically adjusts the frame size depicted in Figure 3.11. ME-MAC consists of the
prediction model that depends on the accuracy of the localization mechanism. ME-MAC also uses order-autoregressive that helps predict the current mobility state. ME-MAC protocol achieves its task through two phases: a data transfer phase and a clustering phase. The advantage of this protocol is to reduce delay to improve the packet delivery rate. However, ME-MAC suffers due to network adaptability.

![Frame Format Structure]

*Figure 3.11: Frame format structure: Redrawn from [59]*

### 3.12 Conclusion of Literature Survey

Based on the survey, we demonstrate that existing Z-MAC, ADC-SMAC, X-MAC, LPRT-MAC, A-MAC, Bin-MAC, and Speck-MAC hybrid MAC protocols attempt to be energy efficient, but experience a problem in mobility and scalability conditions. Mobility based MAC protocols such as MobiSense, ME-MAC, MS-MAC, MA-MAC are good candidates in mobility conditions. However, they experience a problem due to network density, management of multi-channels and following the dual schedule in the network. In addition, they are not scalable and also having no proper real-time support.

Finally, we conclude that these protocols are designed as application-specific, and their weaknesses and strengths are given in Table 3.1. In this dissertation document, we introduce the modular energy-efficient protocols at lower layers that handle network
scalability, mobility, and data redundancy. Furthermore, they improve the network lifetime, the real-time communications, and maintain the QoS provisioning. The advantages of modular energy-efficient protocols at lower layers are highly disseminated because of their design-architectures, which support to multiple WSN application areas.

Table 1:3.1: Characterization of hybrid MAC protocols

<table>
<thead>
<tr>
<th>Parameters</th>
<th>A-MAC</th>
<th>ADC-SMAC</th>
<th>MS-MAC</th>
<th>X-MAC</th>
<th>MobiSense</th>
<th>Z-MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Pattern Support</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>May be</td>
</tr>
<tr>
<td>Scalability</td>
<td>67-72%</td>
<td>71-78.4%</td>
<td>72-82.1%</td>
<td>78-84%</td>
<td>79-88.2%</td>
<td>76.1-85%</td>
</tr>
<tr>
<td>Latency</td>
<td>0.03 to 0.16 seconds</td>
<td>0.03 to 0.15 seconds</td>
<td>0.02 to 0.1 seconds</td>
<td>0.02 to 0.13 seconds</td>
<td>0.015 to 0.1 seconds</td>
<td></td>
</tr>
<tr>
<td>Energy-Efficiency (saving)</td>
<td>7.2%</td>
<td>7.8%</td>
<td>6.6%</td>
<td>8.1%</td>
<td>7.3%</td>
<td>8.4%</td>
</tr>
<tr>
<td>Coverage Efficiency</td>
<td>70-84%</td>
<td>71.2-83%</td>
<td>72-82.2%</td>
<td>72.2-84.4%</td>
<td>70-84.1%</td>
<td>71.1-82.5%</td>
</tr>
<tr>
<td>Data Aggregation</td>
<td>87%</td>
<td>84.3%</td>
<td>78.9%</td>
<td>91.2%</td>
<td>74.4%</td>
<td>87.9%</td>
</tr>
<tr>
<td>Mobility</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Real time support</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
CHAPTER- 4: BN-MAC AND SUPPORTIVE ENERGY EFFICIENT PROTOCOLS

For several applications, low duty cycling protocols are superior in the context of latency, energy consumption, mobility, scalability, and throughput. We propose BN-MAC and its supporting modular energy-efficient protocols at low layers. The goal of introducing new protocols is to support multiple applications especially for disaster-recovery, military, health, controlling mobility-aware and static devices from remote places.

4.1 Boarder Node Medium Access Control Protocol

BN-MAC is based on a hybrid approach that leverages the features of contention-based medium access control protocols and scheduled-based medium access control protocols. The schedule-based part is helpful for those applications that require higher throughput and less latency. Contention-based part is suitable for maintaining the mobility and scalability of the network. For these motives, BN-MAC builds on the grounds provided by hybrid low duty-cycled MAC protocols.

A visual representation of BN-MAC is depicted in Figure 4.1. When a node has to send data that the node first senses the carrier. If the node finds the carrier free, then the node uses optimized data frame format model that includes the short preamble (SP) without inclusion of the destination address. The least distance smart search
neighboring[41](LDSNS) model is used for sending the short preamble to sort out the one-hop shortest path nodes. The short preamble message is Anycast to the specific nodes at one-hop neighbors.

![Figure 4.1: BN-MAC message mechanism process](image)

When the particular node wakes up according to its schedule and samples the medium, if the node finds the short preamble message, then the node sends a clear-to-send (CTS) packet. When the sender receives the CTS control packet, the sender sends the data to a
particular node at the one-hop destination. The particular node adopts the same method for the next second hop. This process is said to intra-process. Finally, the data are delivered to the last destination node (border node).

The Boarder node (BN) either forwards data using the IP networks to the control room (base station) or sends to an adjacent BN. When the BN intends to send received data to an adjacent BN, the BN sends the RTS message. Once an adjacent BN receives the RTS, the BN responds with the CTS. When the last destination node (BN) receives the CTS, it sends the Boarder Node Inter Frame (BNIF) that is data collected through intra-communication. Once data are delivered to an adjacent BN, the BN acknowledges. BN-MAC consists of following phases: finding the list of one-hop neighbors, intra-synchronous communication (ISC), inter-synchronous communication and selection of border node.

4.1.1 Finding the list of one hop neighbors

To improve the efficiency of BN-MAC, We have introduced Intelligence Decision-Making (IDM) model that supports BN-MAC over WSNs. This model decides the nature of the environment whether it is indoor or outdoor environment. IDM enforces the sensor nodes to work either in passive or active mode of communication with respect to the nature of the environment. IDM model helps save the energy in both modes, but especially in the passive mode. IDM takes the decision of the environment; then a node starts to send Anycast message to its one-hop neighbor nodes to get the detail of neighboring nodes. This process helps reducing the overhead and manages network load-balancing.
The process of sending the Anycast ensures that intended neighboring nodes can talk with each other even if they possess different schedules of sleeping and communication. The neighbor discovery process consists of short messages (short preambles), which consumes less network bandwidth and improves the throughput.

Each node sends short preamble for finding a list of intended neighbor nodes using Anycast randomly after interval of two seconds for 15 seconds. The reason for sending messages after two seconds for 15 seconds is to get maximum throughput because we have checked the option of the packet sending interval from 1 second to 10 seconds. A time interval of 2 seconds gives optimized throughput. Additionally, we have set packet sending time 15 seconds that helps finish the packet sending process successfully. If we set time less than 15 or higher than 15 seconds, then node energy is wasted.

![Figure 4.2: Throughput at different time intervals](image)

*Figure 4.2: Throughput at different time intervals*
In the case of less than 15 seconds, node is unable to complete packet sending cycle whereas the time more than 15 seconds. As a result, the node goes in idle situation because finishing the packet sending task; node waits on channel until a node reaches the level of fixed time. We show the performance of BN-MAC at different time intervals and packet sending durations in Figure 4.2 and Figure 4.3. If we compare BN-MAC with Z-MAC that nodes in Z-MAC uses 30 seconds for neighbor discovery process. As a result, Z-MAC wastes extra energy.

![Figure 4.3: the Packet sending duration versus energy consumption](image)

The node discovery process in BN-MAC consists of 1-hop neighbor node, but nodes can get two-hop neighbor information that is intuitively helpful to expand cross-layering support. Additionally, the obtained two-hop information is also used for slot allocation.
The slot allocation enables the node to handle the mobility because node keeps the information when two-hop node is even moving using lattice mobility model described in the next chapter.

BN-MAC is scalable because one-hop topological change is easy to handle because each node knows schedule of one-hop neighbor node. BN-MAC uses promising time schedule because assigned slot is not exceeding more than one-hop neighborhood. BN-MAC also performs localized time slot allocation without changing time slots of already existing nodes. This feature of re-use slot allocation improves throughput and reduces the latency of nodes. In many applications, nodes remain mostly in idle in the WSN for longer periods of time if no sensing event occurs. The pace of the data delivery rate remains low during this mode, but it is not a good practice to keep the nodes listening all the time.

4.1.2 Intra Synchronized Communication

This mode uses semi synchronized low duty cycle. Intra semi synchronized process starts with carrier sensing. The node wakes up for a short period to sample the medium. Channel sampling is done once during channel allocation time. After channel sampling, each node initially sends a short preamble message using Anycast approach within 1-hop neighbor node to get the list of one-hop neighbor nodes. When sender gets reply from one-hop neighbor nodes, then sender attempts to fix the schedule with intended one-hop neighbor nodes (Node that are chosen for future communication) before sending the data. Each node knows the wake-up and sleep schedule of its intended neighbors.
The advantage of using short preamble message is to reduce overhead and latency at each hop. Short preamble enabled MAC protocols have an edge over long preamble enabled MAC protocols in low power duty cycle mechanism. The existing lower power listening (LPL) technique uses long preamble and suffers from the overhearing problem that consumes excess energy at non-targeted receivers such as Z-MAC. The existing LPL protocol uses a long preamble and experienced the overheating problem. As a result, additional energy is consumed at non-targeted receivers. The LPL protocol also introduces extra latency at each hop[1]. In the long preamble technique, the node needs to wait until the long preamble is received. This approach consumes excess energy at both the sender and the receiver sides.

In X-MAC, the destination address is incorporated into each preamble that increases the size of the preamble packet. Additionally, each node checks the preamble packets broadcasted on the network because the sensor nodes are not intelligent. If the node is not the intended recipient, then that node goes to sleep. If a non-intended node discards the preamble packet, then there is no chance for a short preamble packet to be delivered to the destined node. If the node is not the intended recipient receiver, even if it checks and ignores the preamble packet, this process also causes energy waste. If the node is the intended recipient, it remains awake for the subsequent data packets. Further, X-MAC is based purely on an asynchronous mechanism, and it does not have the schedule of the neighbors. As a result, the node consumes excess energy while waiting on the medium for the traffic.
The BN-MAC semi-synchronous duty cycle feature that reduces the latency and overhead that causes the improvement in the QoS parameters. It also saves energy and is preferable for several applications. When multiple nodes communicate with the same neighbor node, BN-MAC uses a slotted contention window to control the congestion and emitting problem. The nodes select the slots randomly in the contention window. As a result, the winner of the slot gets the medium for communication and therefore provides a collision-free medium. BN-MAC also uses randomization and sampling that avoid the packet loss, in case of the selection of same slots. Furthermore, smart queuing model is also introduced to handle the real-time and non-real time traffics.

The characteristic of BN-MAC is that it can be incorporated into all types of radios, including any packetizing radio such as the CC2420 feature of TelosB motes and MICAz. CC2500 and XBe can send a series of short packets. Such a unique position through packetizing radios is not accurate for the traditional long preamble LPL. Additionally, the short preamble packets are also compatible with all radios using bit- streaming interfaces, including the CC1000 that is available in the MICA2 mote. Another key advantage of BN-MAC is an automatic buffering capability that also saves energy and increases the lifetime of the network. We here demonstrate the process of a long preamble (LPL), short preamble (X-MAC) and BN-MAC in Figure 4.4.

BN-MAC uses the automatic buffering process to reduce the wake up time and increase the lifetime of the network. In automatic buffering, the node uses a promiscuous
Promiscuous mode: It causes the controller to permit all traffic rather than allowing only the frames. Promiscuous mode is also used to detect network connectivity problems.
The short preamble improves the network lifetime by consuming less power. Let us determine the energy consumed for carrier sensing and sending a short preamble. The energy consumed for carrier sensing is ‘\(\gamma\)’, the check time is ‘\(t\)’, and the average energy consumed for carrier sensing is ‘\(\Delta p\)’. Thus, energy consumed for carrier sensing is obtained as

\[
\Delta p = \frac{\gamma}{t}
\]  

(4.1)

The energy consumed for the short preamble ‘\(E_{sp}\)’ and the consumed energy for synchronization is ‘\(E_{syn}\)’. Thus, energy consumed for short preamble can be obtained as follows:

\[
E_{sp} = \Delta p + E_{syn}^2 \times C_{drift}
\]  

(4.2)

We use clock drift, ‘\(C_{drift}\)’ that is consumed time for synchronization, and ‘\(E_{syn}^2\)’ is the energy consumed by the transmitter and the receiver for the synchronization. The node that transmits its clock at the one-hop neighbor during intra-region-communication is called the source node, and the node that receives the clock at the one-hop neighborhood is called the particular node (principal or backup node). The synchronized nodes send a short preamble before sending data without using the target address because a short preamble is sent to particular node at the one-hop neighbor that reduces the energy consumption.

Let us assume that the source and the particular node consume energy for one work cycle that is ‘\(\beta\)’ and ‘\(\delta\)’, respectively. The average short preamble reception time could be reduced because the particular node wakes up based on the stored schedule. Thus, the
source node and the particular node consume the energy that can be obtained as given as follows:

\[
\beta = \sum_{i=0}^{n} S_j \frac{(\Delta \phi \cdot \mu \cdot \Delta v^2) \cdot (E_{syn}^2 \cdot C_{drift}) + (E_{ct} + \Delta p)}{\Delta t} \tag{4.3}
\]

This is the energy consumed by the source node.

\[
\delta = \sum_{i=0}^{n} S_j \frac{(\Delta \phi \cdot \mu \cdot \Delta v^2) \cdot (E_{syn}^2 \cdot C_{drift}) + (E_{ct} + \Delta p)}{\Delta t}
\]

\[
+ \frac{(E_{syn}^2 \cdot C_{drift}) + (E_{ct} + \Delta p)}{\Delta t} \tag{4.4}
\]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>System Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>Collision on channel</td>
</tr>
<tr>
<td>Cdrift</td>
<td>Clock drift</td>
</tr>
<tr>
<td>E_{ct}</td>
<td>Energy consumed for channel access time</td>
</tr>
<tr>
<td>E_{sp}</td>
<td>Energy consumed for short preamble</td>
</tr>
<tr>
<td>E_{syn}^2</td>
<td>Energy consumed for synchronization at both transmitter and receiver sides</td>
</tr>
<tr>
<td>i</td>
<td>Starting number of the short preamble</td>
</tr>
<tr>
<td>n</td>
<td>Ending number of the short preamble</td>
</tr>
<tr>
<td>S_j</td>
<td>Short Preamble</td>
</tr>
<tr>
<td>s</td>
<td>Symbol sent over the channel to determine the availability of channel</td>
</tr>
<tr>
<td>\Delta \phi</td>
<td>Size of the short preamble</td>
</tr>
<tr>
<td>\Delta p</td>
<td>Average energy consumed for carrier sensing</td>
</tr>
<tr>
<td>\Delta \phi</td>
<td>Initial backup time</td>
</tr>
<tr>
<td>\Delta t</td>
<td>Time consumed for sending the short preamble</td>
</tr>
<tr>
<td>\Delta v^2</td>
<td>Short preamble speed</td>
</tr>
<tr>
<td>t</td>
<td>Check time</td>
</tr>
<tr>
<td>\beta</td>
<td>Energy consumed by source node</td>
</tr>
<tr>
<td>\delta</td>
<td>Energy consumed by the particular node (principal or backup node)</td>
</tr>
<tr>
<td>\mu</td>
<td>Nature of location</td>
</tr>
</tbody>
</table>

This is the energy consumed by the particular node (principal or backup node) that is available at one-hop destination. Table 4.1 explains used factors in Intra-region-communication.
To validate the effectiveness of the analytical model, we have simulated and compared its result with IEEE 802.15.4, Low power listening (LPL) and X-MAC. We are here interested to determine consumed time and energy for the used metrics such as the channel access, the short preamble, and data forwarding that is calculated and given in

Table 4.2: Showing time and energy consumption for MAC protocols

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LPL</th>
<th>X-MAC</th>
<th>BN-MAC</th>
<th>IEEE802.15.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time for sending short preamble</td>
<td>4.214 ms</td>
<td>4.197 ms</td>
<td>4.16 ms</td>
<td>4.256 ms</td>
</tr>
<tr>
<td>Time for forwarding the data of 5 MB</td>
<td>406.5 Seconds</td>
<td>385.3 Seconds</td>
<td>350.2 Seconds</td>
<td>415.8 Seconds</td>
</tr>
<tr>
<td>Energy consumed for channel accessing</td>
<td>0.886 X 10-6 Joules</td>
<td>0.839 X 10-6 Joules</td>
<td>0.619 X 10-6 Joules</td>
<td>0.936 X 10-6 Joules</td>
</tr>
<tr>
<td>Energy consumed for sending short preamble</td>
<td>1.832 X 10-6 Joules</td>
<td>1.659 X 10-6 Joules</td>
<td>1.152 X 10-6 Joules</td>
<td>1.805 X 10-6 Joules</td>
</tr>
<tr>
<td>Energy consumed for forwarding 5 MB data</td>
<td>0.964 X 10-1 Joules</td>
<td>0.928 X 10-1 Joules</td>
<td>0.821 X 10-1 Joules</td>
<td>0.976 X 10-1 Joules</td>
</tr>
</tbody>
</table>

![Graph showing average energy consumed for channel access vs. number of sensor nodes](attachment:graph.png)
Table 4.2. In addition, energy consumed for channel access, short preamble, and data forwarding is shown in Figure 4.5a-4.5c.
Figure 4.5: (a) Average energy consumed for accessing the channel; (b) Average energy consumed for forwarding the short preamble and (c) Average energy consumed for forwarding 5 MB data (Joules)

4.1.3 Inter synchronous communication

We have already discussed that BN-MAC is introduced for WSNs consisting of different regions. The previous section highlights how to access the channel and forward the data inside regions with support of other models. This section explains how to set the schedules within regions and outside regions. Each region of the WSN contains a Boarder Node (BN). The inter-synchronized transmission schedule is done from one region to other regions. The Boarder Node receives intra data packets within the region and forwards the data packets to outside the region. The Boarder Nodes of each region follow a schedule-based method.

The Boarder Node first broadcasts three ‘hello’ messages to warn the region nodes to be ready for getting the boarder node indication signal (BNIS). BN does not wait to receive an acknowledgment from all region nodes. If the BN takes a single acknowledgment from one region node, the BN assumes that the ‘hello’ message is delivered successfully. We have already discussed that neighbor nodes exchange the schedule. Thus, if any node is unable to receive the ‘hello’ message, the neighbor node informs other nodes at the time of transferring the schedule. In this way, each node of the region knows the schedule of the BN.

BNIS consists of the current time, the next distribution time, the next collection time and the schedule for getting intra data packets from the nodes of the region. Once the
Boarder Node announces the schedules for the nodes of the region, all of the nodes are responsible for following the given schedule.

The announcement of the schedule gives the permission to the region nodes to send and receive intra-data messages during the distribution time. The nodes go to sleep after sending the intra-data transmission is already explained in the previous section. Once a node is not scheduled for exchanging the message, that node remains asleep during the whole distribution time. At the end of the scheduled time of the region nodes, the Boarder Node synchronizes with another Boarder Node of the region to exchange the inter-synchronous schedule to send the data. When the contention period starts again, only one node with a data exchange responsibility requests a schedule-slot for next scheduled distribution time.

![Inter-synchronized transmission schedule with region nodes and Boarder Nodes](image)

*Figure 4.6: Inter-synchronized transmission schedule with region nodes and Boarder Nodes*
The nodes remain active only during BNIS and other than BNIS time, and the nodes remain in a sleep state that produces the energy saving. In addition, the automatic feature of going to sleep after performing the task causes control of the idle listening time of the region. When the BN intends to communicate with an adjacent BN of the region, the BN starts with the inter-synchronized transmission schedule by using carrier sensing. Carrier sensing makes it possible to forward the message of request-to-send (RTS). In response, the BN will get a clear-to-send (CTS) message from the BN of the other region depicted in Figure 4.6.

There is no hidden terminal problem in BN-MAC because BNs of all regions are synchronized with adjacent regions. The network is divided into the different number of regions. The scheme is very simple, and each BN just tracks the schedule of neighbor BNs for forwarding the intra data packets received from the region nodes. This process makes smooth and easy communication.

### 4.1.4 Selection of Boarder Node

The Boarder Node is selected periodically using the dynamic Boarder Node selection process (DBNSP) model that chooses the Boarder Node based on residual energy, signal strength, and memory allocation resources. The energy level of the BN is decided based on Table 1 using DBNSP and level of energy information (LEI).

The function of LEI is to announce the level of energy for each node, and DBNSP decides to declare the Boarder Node. We categorize the level of energy into six levels as given in Table 4.3.
When the energy level of an already working BN goes down, the shift of responsibility from one BN to another BN is accomplished by using the election flag bit (EFB). The EFB specifies the process of immediate BN election. To reduce the overhead of shifting the responsibility of one BN to another BN, BN-MAC uses a proactive method to decide the next BN. The next BN is chosen based on computing the contention time for the election using the available energy, the signal strength, and the memory allocation resources.

The DBNSP model helps determine the energy of each node in each region to select the BN. Each sensor node determines its residual energy after completing some rounds of detecting the events. This residual energy decides whether the node should be considered as a candidate to become a BN or not. The nodes detect the BN in its region based on multiple processes of WSNs using multiple rounds. The benefit of this model is to give enough options to each node to be declared BN based on set criteria. The process of choosing the BN consists of several steps. First, the base station broadcasts a short preamble to the network. In response, each node calculates its distance from the base station based on the signal strength. A node, that receives a short preamble with high radio frequency, becomes a candidate BN.

Table 4.3: Showing the sensor node distribution energy level

<table>
<thead>
<tr>
<th>Energy Level</th>
<th>Sensor Voltage level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very High</td>
<td>3.3 to 3.7 Volt</td>
</tr>
<tr>
<td>High</td>
<td>3.0 to 3.3 Volt</td>
</tr>
<tr>
<td>High Moderate</td>
<td>2.7 to 3.0 Volt</td>
</tr>
<tr>
<td>Moderate</td>
<td>2.4 to 2.7 Volt</td>
</tr>
<tr>
<td>Low</td>
<td>2.1 to 2.4 Volt</td>
</tr>
<tr>
<td>Lowest</td>
<td>&lt; 2.0</td>
</tr>
</tbody>
</table>
Each node in the network compares its memory allocation, residual energy and radio range. If no alert-signal is received by another node, that node is selected dynamically as the next BN. The selected BN sends a message to its neighbor nodes to let them know about its selection as the new BN for future communication. We determine the residual energy of each node in each region. Let us assume that the single-hop communication is used among sensor nodes to detect events and to transmit the information. Each node forwards data ‘d’ at distance ‘r’ within region ‘R’ and located at the $N^*N$ area of WSN. We determine the residual energy of two types of nodes: the BN and the Non-Boarder Node (NBNs) that can be expressed as follows.

BN-MAC requires three types of messages for communication that include ‘$E_{sch}$’ shows the energy consumed for scheduling, ‘$E_{adv}$’ is for the advertisement and ‘$E_{dat}$’ is for sending the data. Thus, consumed energy and residual energy of BN-MAC and can be computed as follows:

$$E_{sch} = \frac{n*(A_{cp}+R_e) + n*(A_e + A_{cp})}{2M_e} + r^2 (N - 1)$$  \hspace{1cm} (4.5)

Equation (4.5) shows the consumed energy for scheduling the nodes

$$E_{adv} = \frac{(A_{cp}+R_e) + (A_e + A_{cp})}{2M_e}$$ \hspace{1cm} (4.6)

Equation (4.6) shows the consumed energy for advertising the message for intra and inter-communication.

$$E_{dat} = \frac{(n*(A_{cp}+R_e) + n*(A_e + A_{cp}))^2}{2M_e} + r^2 (N - 1)$$ \hspace{1cm} (4.7)
Equation (4.7) shows the consumed energy for receiving the data from a region nodes (Intra-communication) and forwarding the data to either base station or adjacent BN-MAC node of another region.

By combining the equations 4.5-4.7, we can determine the consumed energy of BN-MAC. Finally, the consumed energy of BN-MAC will be subtracted from initial energy, which gives the residual energy of BN-MAC described in equation (4.8).

\[
BE_{res} = \left[ E_{ini} - \left\{ \frac{n \cdot (A_e \cdot \Delta p) + n \cdot (A_e \cdot \Delta c_p)}{2M_e} + r^2 (N - 1) \right\} + \left\{ \frac{(\Delta c_p \cdot R_e) + (A_e \cdot \Delta c_p)}{2M_e} \right\} + \right]
\]
\[
\left\{ \frac{(n \cdot (\Delta p \cdot R_e) + n \cdot (A_e \cdot \Delta D_p))^2}{2M_e} + r^2 (N - 1) \right\} \right]
\]

\[(4.8)\]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_e$</td>
<td>Energy consumed for amplifying the signal</td>
</tr>
<tr>
<td>$E_{adv}$</td>
<td>Energy consumed for advertisement</td>
</tr>
<tr>
<td>$E_{dat}$</td>
<td>Energy consumed for sending the data</td>
</tr>
<tr>
<td>$E_{ini}$</td>
<td>Initial energy of the boarder node or non-boarder nodes</td>
</tr>
<tr>
<td>$E_{res}$</td>
<td>Residual energy of the node after performing the some cycles</td>
</tr>
<tr>
<td>$E_{sch}$</td>
<td>Energy consumed for synchronization</td>
</tr>
<tr>
<td>$2M_e$</td>
<td>Mean Energy consumed for radio and amplifying the signal</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of messages</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of the nodes</td>
</tr>
<tr>
<td>$r^2$</td>
<td>Number of hops</td>
</tr>
<tr>
<td>$R_e$</td>
<td>Energy consumed for the radio signal</td>
</tr>
<tr>
<td>$\Delta D_p$</td>
<td>Data packets</td>
</tr>
<tr>
<td>$\Delta c_p$</td>
<td>Control packets</td>
</tr>
</tbody>
</table>

Table 4.4: Showing used parameters and its description

Similarly, we can determine the consumed energy of NBNs, but the NBNs do not use advertisement message in our case. NBNs only use $E_{sch}$ and $E_{dat}$ messages. Thus, consumed energy of NBNs is obtained in equation (4.9).
\[ NBE_{res} = E_{ini} - \left\{ \frac{n \times (\Delta C_p \times R_e) + n \times (A_e \times \Delta C_p)}{2M_e} + r^2 (N - 1) \right\} \]

\[ + \left\{ \left[ \frac{n \times (\Delta D_p \times R_e) + n \times (A_e \times \Delta D_p)}{2M_e} + r^2 (N - 1) \right] \right\} \]

Based on equations (4.8) and (4.9), signal strength and memory allocation, the decision of new BN is taken. The detail of used parameters is described in Table 4.4.

### 4.1.5 Conclusion

BN-MAC is designed to address the problems of existing hybrid MAC protocols such as QoS provisioning and energy efficiency. BN-MAC also addresses the issue of low power listening: reducing the size of the preamble without inclusion of the destination address in each data packets. BN-MAC incorporates automatic buffering that helps improve the network lifetime and saves enough energy of each node.

The sampling and randomization features of BN-MAC avoids the congestion in the network. In addition, anycast addressing methodology helps pick distinct nodes at 1-hop neighbors. As a result, additional consumption of the energy can be avoided and handled on the consumption of the overhearing problem. Dynamicity of BN extend the network lifetime and also maintains the load-balancing.

### 4.2 Optimized Data Frame Format

The goal of optimized data frame format is to enable sensor nodes to improve QoS provisioning. The ODFF for BN-MAC is preferred over IEEE802.15.4 due to some modification in the existing features depicted in Figure 4.7.
The architecture does incorporate a number of characteristics that are compatible to a robust and reliable wireless link. It can individually detect every radio in a WSNs, as well as the process and layout of communications between the radios. It also works beyond Physical and MAC-layer, providing the cross layering support.

ODFF reduces channel access time, data transfer time, preamble transfer time and acknowledgement time. The performance of small devices especially sensor nodes’
depend on reduced amount of time. Hence, timing overhead can affect the lifetime of the node. In addition, high duty cycled applications cannot be benefited due to additional consumption of time on medium.

ODFF is particularly based on low-duty-cycle communication that reduces the short preamble size, addition of automatic buffering and employing the anycasting message addressing methodology for communication. This modification enables data payload (DP) to transfer more data as compared with DP of IEEE802.15.4 standard. Based on the modifications, we focus on the following parameters to determine the impact of the changes.

- Channel Access time
- Data frame transfer time
- Transmission Timing for Acknowledgement
- Retry transmission
- Possible transfer data rate in an ideal and worst case scenario

4.2.1 Channel Access time

BN-MAC gets the features from both CSMA and TDMA. In this section, we focus on CSMA portion and determine the time consumed for accessing the channel. During, CSMA phase, the sensor node needs to wait for random back-off period like IEEE 802.15.4 within the range of \(\{0, 2^\gamma - 1\}\). Here, \(\Delta \varphi\) is the initial back-off exponent that is set to the minimum back-off exponent of MAC \(\gamma\). We use three by default value for \(\gamma\).
and assume that channel is free, in the worst-case, the channel access time \( C_{at} \) can be calculated as follows:

\[
\Delta \varphi + c = (2^\gamma - 1) \times (U_{bt})^2 + \omega \times \beta \tag{4.10}
\]

Hence,

\[
C_{at} = \Delta \varphi + c \tag{4.11}
\]

\[
C_{at} = \Delta \varphi + c = (2^\gamma - 1) \times (U_{bt})^2 + \omega \times \beta \tag{4.12}
\]

Where, \( U_{bt} \): Unit back-off time and \( \Delta \varphi \): initial back-off time.

We use maximum 8 symbol \( \omega \) for determining the availability of the channel. Each symbol requires symbol-period-time \( \beta \) 16 \( \mu \)s.

### 4.2.2 Data frame transfer time

We have reduced the preamble size from 4 bytes to 1 byte because 4 bytes preamble size creates overhead and reduces the throughput. Based on the standard transfer rate of the modem, we have calculated the frame transfer time \( T_f \) given as:

\[
T_f = \frac{(P_{max} + P_l + F_{del} + F_l) \times \omega}{\Delta R} \tag{4.13}
\]

Where, \( P_{max} \): Maximum packet size; \( F_{del} \): Start frame delimiter; \( F_l \): Length of the frame; and \( \Delta R \): Standard transfer rate.
4.2.3 Transmission Timing for Acknowledgment

We have already discussed that our objective is to reduce the preamble size. Therefore, total acknowledgment frame size is 8 bytes that can reduce the substantial amount of time in transferring acknowledgment frame depicted in Figure 4.8. Based on standard data rate of the modem, we can calculate the acknowledgment transmission time ‘$T_{ack}$’ given as:

$$T_{ack} = \frac{(M_{pdu} + P_l + F_{dl} + F_l) \ast \omega}{\Delta R} \quad (4.14)$$

Where, $M_{pdu}$: Medium access control protocol for data unit.

![Figure 4.8: Graphic view of acknowledgment Frame](image)

4.2.4 Retry transmission

The transmitting node can wait to get MAC acknowledgment before attempting to a retry. We have set 48 symbols wait time. Each symbol takes 16 microseconds. If the number of symbols increase, the transmitting node stay longer time in ideal mode.
Based on experiments, we have determined the ideal-wait time for MAC is between \{30, 36, 42, 48 and 54\} symbols. We have chosen 48 symbols, but it can also be chosen smaller number. If the network consists of multi-hops, then smaller number is not right choice. So, 48 works perfectly on single-hop as well as multi-hops wireless sensor networks. Thus, retry transmission can be calculated as follows:

\[ T_{\text{retry}} = T_{s\Delta} \times \beta \]  

(4.15)

Where, \( T_{s\Delta} \): Total symbol wait time for acknowledgement, and \( \beta \): Time for each symbol.

### 4.2.5 Possible transfer data rate in an ideal and worst case scenario

The potential data rate can be determined using ideal and worst case scenario. In an ideal situation, CSMA based approach finds the free channel for sending the data on non-beacon enabled network. It also includes the maximum data payload and acknowledgment. In worst case scenario, it should be assumed that 25\% data packets require retry limit. Thus, possible transfer rate in an ideal and worst case situation can be calculated as follows:

\[ T_{ti} = C_{at} + T_f + T_{\text{turn}} + T_{\text{ack}} \]  

(4.16)

Equation (4.16) shows the total time consumed in transmitting the data frame in an ideal scenario.

\[ I_{\text{data}} = \frac{(D_p \times \omega)}{T_{ti}} \]  

(4.17)

Where
\(D_p\): Data payload; \(T_{\text{turn}}\): Turnaround time, \(I_{\text{data}}\): Ideal data transfer, and \(T_{\text{tt}}\): Total time for channel access, acknowledgment, turnaround and data frame time in an ideal scenario.

Equation (4.17) shows possible data rate in an ideal situation using CSMA approach.

\[
T_{tw} = C_{at} + T_f + T_{\text{retry}} + C_{at} + T_f + T_{\text{turn}} + T_{\text{ack}}
\] (4.18)

Equation (4.18) shows the total time consumed in transmitting the data frame in worst case scenario.

As, we have already calculated total time consumed for \(T_{\text{tt}}\) that is set for 75% data frame packets, which do not require retry transmission. 25% data frame packets are assumed to go under retry transmission. Thus, date rate in worst case scenario can be calculated as follows:

\[
T_{time} = (T_{\text{tt}} \ast 75\%) + (T_{tw} \ast 25\%)
\] (4.19)

\[
W_{data} = \frac{(D_p \ast \omega)}{T_{time}}
\] (4.20)

where \(W_{data}\): Worst case data transfer.

When, specific amount of data is transmitted over the network using CSMA approach that can be calculated as follows:

\[
T_{td} = \frac{S_{d}}{D_p} \ast T_{time}
\] (4.21)

Where, \(S_d\): intended amount of transfer data.
Based on the mathematical formulation, we have validated significant parameters of ODFF and existing IEEE802.15.4. The obtained data validates the performance of both models shown in Table 4.5.

**Table 4.5: Comparison between ODFF and IEEE802.15.4 based on data frame model**

<table>
<thead>
<tr>
<th>Name of the parameter</th>
<th>Numerical Calculation for Optimized Data Frame Format</th>
<th>Numerical calculation for IEEE802.15.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chanel access time</td>
<td>Thus, ( Cat = (23 \cdot 1) \times 16 + 8 \times 16 = 1.92 ) ms</td>
<td>2.368 ms</td>
</tr>
<tr>
<td>Data frame transfer time</td>
<td>( T_f = \frac{(127 + 1 + 1 + 1) \times 8}{250 \times 10^3} = 4.16 ) ms</td>
<td>4.256 ms</td>
</tr>
<tr>
<td>Transmission Timing for Acknowledgment</td>
<td>( T_{\text{ack}} = \frac{(5 + 1 + 1 + 1) \times 8}{250 \times 10^3} = 0.256 ) ms</td>
<td>0.352 ms</td>
</tr>
<tr>
<td>Turnaround time</td>
<td>0.192 ms</td>
<td>0.192 ms</td>
</tr>
<tr>
<td>Retry transmission time</td>
<td>( T_{\text{retry}} = 48 \times 0.016 = 0.768 ) ms</td>
<td>0.864 ms</td>
</tr>
<tr>
<td>Total access channel, frame transfer and acknowledgment and turnaround time in an ideal scenario</td>
<td>( T_{\text{II}} = 1.92 + 4.16 + 0.192 + 0.256 = 6.528 ) ms</td>
<td>7.168 ms</td>
</tr>
<tr>
<td>Total access channel, frame transfer and acknowledgment and turnaround time in worst case scenario</td>
<td>( T_{\text{w}} = 1.92 + 4.16 + 0.768 + 1.92 + 4.16 + 0.192 + 0.256 = 13.376 ) ms</td>
<td>14.656 ms</td>
</tr>
<tr>
<td>For sending data of 1 MB</td>
<td>( T_{\text{td}} = \frac{2^{20}}{117} \times 8.24 = 70 ) Seconds</td>
<td>Seconds</td>
</tr>
</tbody>
</table>

Furthermore, demonstrating the correctness of the ODFF and IEEE802.15.4, we have simulated both models using ns2 and ns3 depicted in Figure 4.9a-4.9e. The obtained simulated results were compared with the results obtained from mathematical calculation, which are exactly same. Thus, our proposed ODFF model is validated through simulation and mathematical formulation.

Thus, ODFF model can be used for improving the QoS provisioning and prolonging the network lifetime.
Average Acknowledgment Time (Seconds)

Number of Sensor Nodes

ODFF

IEEE802.15.4

$4 \times 10^{-3}$

Average Retry Transmission Time (Seconds)

Number of Sensor Nodes

ODFF

IEEE802.15.4

$9 \times 10^{-3}$
Figure 4.9: (a) Average channel access time (seconds); (b) Average data frame transfer time (seconds) (c) Average acknowledgment time (seconds); (d) Average retry transmission time and (e) Average consumed time for sending 1 MB file using optimized data frame

4.3 Smart Queuing (SQ) Model

The goal of designing the smart queuing model is to handle the co-occurrence of real-time and non-real-time traffic. We use two different types of queues for real-time and non-real-time traffic. The priority queue is used for real-time traffic and standard queue for non-real time traffic. The standard queue applies First-In & First-Out (FIFO) concept. The packets are labeled based on the type of traffic. Each node uses the classifier that helps examine the inbound packet. Then node stores it to the right queue. The selection process of the priority queue and standard queue can be described using algorithm 4.1.
Algorithm 4.1: Selection of priority and standard queues and end-to-end delay for real-
time traffic and non-real-time traffic

1. Initialization of queues (\( \Delta P_q \): Priority Queue, \( \Delta S_q \): Standard Queue)
2. Initialization of traffic (\( T \): Traffic; \( T_r \): real-time traffic & \( T_{nr} \): Non-real-time)
3. Initialization of parameters (\( T_d \): Delay time, \( T_p \): Propagation time, \( \frac{D_p}{T_s} \): Transmission time of data into medium, \( D_e \): end-to-end delay, \( T_{pt} \): Processing time of \( T_p \) at each node, \( r \): Number of hops, \& \( h_o \): Hop-overhead)
4. While node ‘\( k \)’ send ‘\( T \)’ to node ‘\( k_1 \)’ at cluster ‘\( L \)’,
5. If \( T = T_r \) then
6. node \( k_1 \), putting \( T \) into \( \Delta P_q \)
7. else if \( T = T_{nr} \) then
8. node \( k_1 \), putting \( T_{nr} \) into \( \Delta S_q \)
9. end if
10. end if
11. Examining delay time ‘\( T_d \)’ for \( \Delta P_q \)
12. Do \( \frac{T_d}{T_p} \) // Transmitting data from source to destination
13. If \( \frac{T_d}{T_p} \in \Delta P_q \) then
14. Calculate \( D_e = r \times \frac{D_p}{T_s} + T_{pt} + \frac{T_d}{T_p} + (r \times h_o) // end-to-end delay for real-time traffic
15. else if \( \frac{T_d}{T_p} \in \Delta S_q \) then
16. Calculate \( D_e = r \times \frac{D_p}{T_s} + S_{q \_delay} + T_{p} + \frac{T_d}{T_p} + (r \times h_o) // S_{q \_delay} : Additional delay for standard queue & \( \Delta T_{pt} \): additional processing time at each node; end-to-end delay for non-real-time traffic
17. end if
18. end if
19. end while
The node also uses a scheduler, which decides the order of packets to be forwarded from the appropriate queue based on the bandwidth ratio $'B_r'$ of each type of traffic. The smart queuing model is depicted in Figure 4.10.

![Smart queuing model for real-time and Non-real-time traffic](image)

*Figure 4.10: Smart queuing model for real-time and Non-real-time traffic*

The amount of bandwidth is decided for each type of traffic on the particular outbound link. However, the bandwidth can be borrowed by both classifiers if non-co-occurrence traffic occurs.

Let us determine the assigned bandwidth for both type of traffics to sensor node ‘k’.

$$R_{B_r} = k(\Delta s)$$

Equation (4.22) shows assigned bandwidth rate for real-time traffic to sensor node k with particular service rate.

$$NR_{B_r} = k(1 - \Delta s)$$

(4.23)
Equation (4.23) shows assigned bandwidth rate for non-real-time traffic to sensor node $k$ with particular service rate.

where $R_{B_r}$: Real-time bandwidth rate, $\Delta s$: service rate for real time traffic, $NR_{B_r}$: Non-real-time bandwidth rate, and $(1 - \Delta s)$: service rate for non-real-time traffic.

Once the sensor node requires borrowing the bandwidth for sending the traffic on the appropriate link, which can be determined by using algorithm 4.2

**Algorithm 4.2: Bandwidth-Borrowing Process**

1. Variable Initialization ($BW_b$: Bandwidth borrow; $(1 - \Delta s)$: service rate for non-real time traffic; $\Delta s$: service rate for real time traffic; & $k$: sensor node)
2. Set $k \leftarrow 1$  // Initially set queue for sensor node $k$
3. Real-time traffic class forwards the real-time traffic for sensor node $k$
4. if $k$ requires additional bandwidth for real-time traffic from non-real-time traffic class then
5. set $k \leftarrow BW_b(1 - \Delta s)$// real-time traffic class borrows from non-real-time traffic class
6. end if
7. if $k$ requires additional bandwidth for non-real-time traffic from real-time traffic class then
8. set $k \leftarrow BW_b(\Delta s)$// non-real-time traffic class borrows from real-time traffic class
9. end if
4.4 Data Aggregation Model

We introduce an adaptive application independent aggregation (AAIA) model. The AAIA resides between network layer and MAC sub-layer, and it is entirely independent of application. The primary objective of this AAIA is to address the issues of energy limitation, low bandwidth inherited by sensor technology. Another goal is to employ the AAIA model to utilize the communication channel efficiently. The AAIA module aggregates with network layer to reduce the overhead experienced by acknowledgment and channel contention.

4.4.1 AAIA Design Components

AAIA consists of following three components, which collectively perform the joint task of data aggregation depicted in 4.11.

- Processing Unit
- Aggregation Function Unit
- Service Access Unit

The processing unit performs the task of packet aggregation and de-aggregation. Whereas, service access unit controls timer setting and fine-tunes to perform the required data aggregation. Once outgoing packets come from the network layer, which are sent to the processing unit. Subsequently, the processing unit forwards the packets to aggregation function unit. The responsibility of aggregation function unit is to apply one of the four packet formats for building the aggregate including anycasting, multicasting, Unicasting, and Broadcasting. Finally, the built aggregated is forwarded to the MAC sub-layer for transmission.
The service access unit has to decide how many packets need to aggregate and when to forward to MAC sub-layer. Incoming traffic like out-coming traffic is sent by the MAC sub-layer and then forwarded to AAIA module. As a result, AAIA module re-fragments into its original network unit, then it passes to the router at the network layer. The multiple network unit aggregation turns into a single aggregation to transmit the data, which causes the reduction in channel overhead, transmission overhead and including control overhead packets such as RTS/CTS/ACK in IEEE802.15.4. Single aggregation helps save the contention time on each transmission. Let us calculate the delay incurred at MAC protocol.
where $\Delta$: MAC delay for the packets, $\Delta_c$: MAC delay without collision, $\varphi$: Successful transmission during the number of collisions in period of time ‘$t$’ and $C_{delay_{rt}}$: Total time for collision delay including time incurred for resolving the collision.

Let us assume that several packets from different sensor nodes in particular time interval ‘$t_{int}$’ are ready for transmission. However, AAIA model sends only an average number of packets $P_{avg}$ to compete for the channel to avoid the possible collision. Thus, the number of transmitted packets ‘$\omega_{tr}$’ at given time with respect to an average collision probability ‘$P_{col}$’ can be obtained as

$$P_{col} = \{1 - (1 - \omega_{tr})^{1 - t_{int}/P_{avg}}\}$$

(4.25)

We need to identify the number of an average transmission for the successful packet transmission ‘$P_{str}$’ that is obtained as

$$P_{str} = \frac{1}{(1 - P_{col})}$$

(4.26)

After successful packet transmission, there is a need to detect an expected number of collision ‘$E_{col}$’ against each successful packet transmission, which can be calculated as follows

$$E_{col} = \frac{1}{\{1 - (1 - \omega_{tr})^{1-t_{int}/P_{avg}}\}}$$

(4.27)

Combining the equations (4.24) & (4.27), we can obtain the approximate correlation
'C_{MAC}' between number of aggregated packets and MAC protocol delay.

\[
C_{MAC} = M \mathcal{F}c + \sum_{k=0}^{n} k[(\omega \varphi_2) + (\omega \varphi_2), \ldots, (\omega \varphi_n) \times t \times C_{delay_{rr}}] \\
+ \left\{ \frac{1}{1 - (1 - \omega_{tr})^{1-t_{int/p_{avg}}}} \right\} 
\]

(4.28)

To validate the AAIA model, Figure 4.12 demonstrates the saving time vs. number of aggregation on the different packet sizes. From the Figure 4.12, we observe that as the number of aggregation increases, the average saving time also increases significantly. Furthermore, we also observe that as packet size increases, then, time-saving also decreases. This situation happens when data transmission time becomes a high ratio of the entire transmission time.

![Figure 4.12: Number of aggregation VS time saving at different packet sizes](image)

*Figure 4.12: Number of aggregation VS time saving at different packet sizes*
4.5 Least Distance Smart Neighboring Search (LDSNS)

The goal of this model is to determine the shortest distance between one-hop neighboring nodes. In LDSNS, each node monitors the channel after every 500 ms. If the gain of channel is less than set threshold value, it shows that there is no activity on medium from its neighbor nodes; resulting that the node decides to sleep again. When a transmitter wants to communicate, it first sends short preamble to alert one-hop neighboring nodes for transmitting the data. When the targeted receiver senses short preamble, it wakes up and responds with an acknowledgment (ACK) to the transmitter. After the transmitter gets ACK, it starts to send the data packets. Pictorial illustration of the protocol is given in Figure 4.13.

Figure 4.13: Mechanism of LDSNS to communicate with 1-hop neighbor nodes
Let us prove this idea by using Lemmas and definitions. The least distance smart neighboring search is based on 1-hop distance and route discovery. The designed WSN consists of different regions. The node that communicates with region that maintains local connectivity, whereas node, that communicates out of region and schedules within region, is called BN, which is already explained in the previous sections. Let us assume that directed graph $D = (V, A)$, consisting of the set of sensor nodes $V$. The set of edges are called arcs that are $A \subseteq V^2$. It helps to differentiate between 1-hop destination and more than 1-hop destination nodes. The digraph distance between nodes is simply the number of the shortest path between them. We assign a name to each sensor node in $(V, A)$ local route discovery method is based on relay scheme that works as follows.

For any destination node in ‘$V$’ specified by name ‘$v$’, the scheme targets the 1-hop destination nodes ‘$u$’ on basis of stored information in routing table regarding the shortest path 1-hop destination node. Each 1-hop destination node delivers the shortest path to its predecessor during exchange of the control message. Finally, destination ‘$v$’ is acquired with efficient path. We apply the method [60] for estimation of global technology of sensors by dividing nodes into routable boundaries and extracting adjacency associations between these boundaries. The objective of creating each boundary is to make the topology simpler so that the searching process works efficiently within the boundaries. For a number of sensor nodes ‘$V$’ and communication digraph ‘$D$’.

We pretend that $D$ is connected. Thus, we just consider connected components autonomously. Therefore, $u: (u, v) \in A$ can be denoted for hop count of neighboring search between ‘$u$’, ‘$v$’ in communication digraph.
**Definition 4.1.** Let \( P(x, y) \) denote set of paths from ‘x’ to ‘y’ for 1-hop neighbor nodes in direct graph \( (D_g) \). Hence, \( S(x, y) \) is the distance (S) between two neighbor nodes \( x, y \) in \( D_g \), which shows the shortest path from node ‘x’ to ‘y’. It can be computed as:

\[
S = (x, y) = L_{\text{min}}(p) \in p \in P(x, y)
\]

Where

\( L_{\text{min}} \): Minimum length from one node to another node.

\( p \): path value

If \( D_g(x, y) = \emptyset \) then \( D_g(x, y) = \infty \).

Therefore,

\( D_g(x, \hat{E}) \) between node ‘x’ and subset of nodes \( \hat{E} \subseteq E \) that is defined as:

\[
D_g = (x, \hat{E}) = \min D_g(x, y) \& y \in \hat{E}
\]

Thus, \( X, \hat{E} \subseteq E \), be the distance between two neighbor nodes that can be computed as:

\[
\min D_g(x, \hat{E}) \& x \in \hat{E}
\]

Thus, we can add random infinitesimal for the unique path.

**Definition 4.2.** For a digraph \( D = (V_1, V_2) \), be the set of 1-hop destination nodes for vertex ‘v’ that is explained as:

\( \lambda - D(v) = \{ u : (u, v) \in V_2 \} \), and beyond of 1-hop destination nodes are explained as:

\[
\lambda + D(v) = \{ u : (u, v) \in V_2 \}
\]

Where,

\( \lambda \): Total number of neighboring nodes

\( D(v) \): Pair of one-hop neighboring nodes

\( v \): Value of link between two neighboring nodes
$V_1$: Vertex of node

$V_2$: Vertex of a neighbor node

We describe 1-hop destination nodes of a vertex $V_1$ as union with a set of 1-hop destination nodes vertex $V_2$. If the distance exceeds more than 1-hop destination nodes, it can be expressed as:

$$D_1(v) = \lambda + D(v) U \lambda - D(v) \quad (4.32)$$

The range and out of range distance can be found as:

$$D_{range}(v) = \lambda + D(v) \quad (4.33)$$

Above equation, (4.33) shows that the node is within range.

$$D_{outrange}(v) = \lambda - D(v) \quad (4.34)$$

Equation (4.34) shows that the node is out of range.

From the equation (4.33) and (4.34), we deduce that

$$D_{range}(v) \neq D_{outrange}(v)$$

We may again exclude subscript if digraph $D_g = (V_1, V_2)$ is clear from the context. The weighted graphs also get association of assorted length, cost and strength. We only focus on edge-weighted graph that is opposite to node-weighted graphs. We also need to restrict edge weights to one that yield an un-weighted graph.

Consider digraph $D_g = (V_1, V_2)$ and its subset for boundary of regions $R \subset V_1$, explain boundary $B(v)$ of a node. Therefore, $v \in R$ and whose nearest region is ‘$v$’.

Thus, boundary of all regions can be expressed as follows:

$$B(v) = \{ u \in V_1 | \forall w \in R, \lambda(u, v) \leq \lambda(u, v) \} \quad (4.35)$$
Lemma 4.1. Let simple path \( P = (d, a_1, a_1, \ldots, a_{e-1}) \) that connects two region nodes \( d = a_1 \) and \( t = a_e \) with ‘e’ edges and path of length is ‘p’. The related boundary path ‘p*’ has a maximum length in boundary dual graph \( B_d^* \) such as \( L(P*) \leq e \cdot L(P) \).

Proof: The path includes \( e-1 \) that is used for more than 1-hop destination nodes and ‘e’ edges that pass through \( e+1 \) multi-hop in the same region. The most of regions \( e+1 \) are intrusive regions, it means that the original path does not go directly to those nodes, but the shortest path does. The \( L(P) \) in the original graph is the sum of edge weights that can be defined as:

\[
L(P) = d(s, t) = \sum_{i=0}^{e-1} w(a_i, a_{i+1})
\]

Equation (4.36) shows the creation of the path from transmitter to receiver. ‘e’ is an edge between two nodes of boundaries on path \( P^* \) that is bounded as follows:

\[
P^* = [d^* \cdot N_{bou}(a_i), N_{bou}(a_i + 1) \leq N_{bou}(a_i), a_i) + W(a_i), (a_i + 1)
+ d((a_i + 1), N_{bou}(a_i + 1))] \quad (4.37)
\]

\( N_{bou} \): Node in region

\( d^* \): Connecting two region nodes

Let us assume that ‘s’ and ‘t’ be two nodes of the region that could be source and target nodes, and defined as follows:

\[
d(a_i, N_{bou}(a_i) \leq d N_{bou}(s, a_i) \cdot d (a_i N_{bou}(a_i) \leq d(t, a_i) = d(N_{bou}(a_i), a_i)
\]

It yields:
\((P^*) \leq d^* (s, t)\)

\[
= d^* (s, N_{bou}(a_i)) \sum_{i=1}^{e-2} [d (N_{bou}(a_i), a_i + w (a_i, a_{i+1})]
+ d (a_i + N_{bou}(a_i + 1)_{i+1}) + d^* (N_{bou}(a_i - 1), t)
\]

\[
\leq w(s, a_i) + d(a_i, N_{bou}(a_i))
\]

(Simplifying the equation (4.39), we get as:

\[
\sum_{i=1}^{e-2} [d (N_{bou}(a_i), a_i) + d (a_i + 1, N_{bou}(a_1 + 1))] \sum_{i=1}^{e-2} d(a_i, a_{i+1}) + d (N_{bou}(a_i - 1), (a_i - 1, t) \leq (s, t) + \sum_{i=1}^{e-2} d(s, a_i) + (a_i, t)
\]

(4.39)

L(P) = e. L(P)

(4.40)

From the equation (4.40), we see that Bound is observed to be tight because constructions exist.

For example, If any choice for \(m > \lambda > 0\), thus edge graph weights of the graph for two nodes of regions can be described as:

\[
d(a_i, N_{bou}(a_i = m - \lambda, w (a_i, a_i + 1) = \lambda
\]

(4.41)

And

\[
W(s, a_i) = W(a_{e-1}, t = m
\]

(4.42)

Since \(2m + (e-2) \lambda\) is the length of path and \(2m + (e-2) \lambda\) is the length of whole region.
Therefore, the worst case for ‘λ’ can be written as:

\[ \lambda \rightarrow 0 \] and the ratio can be shown as follows:

\[
\frac{LP^*}{L(P)} \rightarrow e
\]

(4.43)

If region nodes are available on the shortest path. Thus, maximum expansion will be shorter than the number of edges on the shortest path. We hereby prove that the maximum expansion is proportional to the largest gap between region nodes on the path.

**Lemma 4.2.** For any node, \( u \in B(v) \), the shortest path from node \( u \) to \( v \) is entirely included in \( B(v) \).

**Proof:** If lemma were incorrect, there would exist \( w \neq B(v) \) on the shortest path from node ‘\( u \)’ to destination node ‘\( v \)’.

Therefore,

\[ \lambda(w, y) < \lambda(w, u) \]

And such that:

\[ \lambda(x, y) \leq \lambda(x, w) + \lambda(w, v) < \lambda(x, w) + \lambda(w, u) = \lambda(x, u) \]  \hspace{1cm} (4.44)

This statement contradicts with hypothesis, such as \( x \in B(u) \); thus lemma must be correct. One inference of this lemma is connection of boundary cells on spanning graph. Region cells are Dirichlet, connecting all points of the sensor field. Region has simple topology in all dimensions that are stronger point of connectivity. The simpler topology helps to make subsets of sensor fields, when sensor filed experiences large holes. Thus, edges \( u_1, u_2 \in B(v) \).

**Lemma 4.3:** For a node in each region of WSN, calculates maximum cost for all one-hop neighboring nodes for selection of lowest cost path.
**Proof:** Let ‘x₁’ be node, which estimates the cost for each 1-hop neighboring nodes ‘x₂’

Here, ‘T\text{cost}’ is a total cost for all 1-hop neighbor nodes, and ‘S\text{cost}’ is the cost for one neighbor node, which can be calculated as follows.

\[
T_{\text{cost}} = S_{\text{cost}}(x_1) + S_{\text{cost}}(x_2) + \text{Level}(x_1, x_2) \tag{4.45}
\]

We set value zero to \( T_{\text{cost}}(x_1) \) because ‘x₁’ is initiating node that calculates the path cost that will be starting point. Energy Level is used to calculate transmitting and receiving cost of the node with remaining energy of nodes. Nodes with value of the high cost are discarded, and the cost of each 1-hop neighbor node is saved into routing forwarding table (RFT).

Thus, ‘x₂’ calculates the minimum cost distance ‘D’ for reaching 1-hop destination node with RFT using following the formula.

\[
S_{\text{cost}}(x_1) = \sum_{k \in \text{RFT}} D_{x_1, x_2} * T_{\text{cost}} \tag{4.46}
\]

It is proved that the minimum cost of establishing the path from ‘x₁’ to ‘x₂’ is set in RFT of ‘x₁’.

### 4.6 Intelligence Decision-making Model

To improve the efficiency of BN-MAC, We have introduced Intelligence Decision-Making (IDM) model that supports BN-MAC over WSNs. This model decides the nature of the environment whether it is indoor or outdoor environment. IDM enforces the sensor nodes[61] to work either in passive or active mode of communication according to the nature of the environment. IDM model helps to save the energy in both modes but especially in the passive mode. The sensor nodes working in passive mode do not
consume energy from their battery but might be harvesting energy from the environment such as solar.

Let us assume ‘K’ is the number of sensor nodes available in WSN, which are deployed to detect the presence or absence of indoor and outdoor environment (IOE). Sensor ‘K’ collects information regarding IOE then decides the nature of the environment. We have set values for IOE environments.

If \( D_i \geq 1 \) that announces the presence of the indoor environment (IE) otherwise \( D_i < 1 \), it means that is an outdoor environment (OE). To prove ‘IE’ and ‘OE’, we also use third environment that is unknown environment (UE). The detection process is based on the maximized probability of detection (MPD) method used by Neyman-Pearson Lemma[62].

The sensor nodes ‘K’ start the discovery process from ‘UE’ the environment because the sensor node is initially unaware of the environment nature. We set the probability of ‘UE’ and pick the random variable that explains the constraint of the optimized problem in the form of \( UE = \alpha \) (alpha) given in equation (4.47).

\[
E(UE) = \alpha
\]  
(4.47)

One of the important selections for statistically optimized quantity is to find the expected value of ‘UE’. Hence, we maximize the expected value of the probability to detect ‘UE’ with respect to constraints of expected value of the probability.

\[
\alpha = \sum_{k=0}^{\infty} PK (K = k) f(\gamma^c (\beta^c))
\]  
(4.48)
Substitute value of $\alpha$ (alpha) in equation (4.48) to determine unknown environment. It helps sensor node to sense rest of two ‘IE’ and ‘OE’ environments.

$$E(UE) = \sum_{k=0}^{\infty} PK(K = k)\gamma^c(\beta^c)$$

(4.49)

$\gamma^c$ and $(\beta^c)$ are linked by relative operating characteristics (ROC), which are required to determine ‘UE’. To detect ‘IE’ and ‘OE’ environments, we use the following probabilities.

Where,

$$UE_i = P(D_i < 1 | IOE \text{ outdoor}), \beta_i = P(D_i < 1 | IOE \text{ outdoor}) \text{ and } PD_i = P(D_i > 1 | IOE \text{ indoor}), \gamma_i = P(D_i > 1 | IOE \text{ indoor}).$$

Let us assume that the sensor nodes detect the environment independently. Thus, ‘$K$’ sensor nodes detect ‘UE’ on the basis of the set values of probability.

$$Di = IOE - \sum_{k=0}^{\infty} PK(K = k)f(\gamma^c(\beta^c))$$

(4.50)

If we get the value $Di = 1$, it means the passive mode is initiated and sensor nodes ‘$K$’ save the energy. If $Di \geq 1$ && $Di \leq 2$, then the environment is known, and the sensor nodes stop using energy of battery and activate the passive mode to gain energy from the environment. This condition declares ‘OE’ the environment.

We can obtain the saved energy as follows:

$$EN(X) = \sum_{i=0}^{N} E(i)\gamma(\alpha)$$

(4.51)
Let us assume EN(X) and EN(Y) be the total energy saved by two different regions of WSN. E(i) and E(j) indicates the energy saved by node I and j during transmission. Thus, total saved energy is calculated as follows:

\[
T_{\text{saved}} = EN(X) = \sum_{i=0}^{N} E(i) \rho(i) + EN(Y) = \sum_{j=0}^{N} E(j) \rho(j) + \ldots, EN(n)
\]

\[= \sum_{j=0}^{N} E(n) \rho(n) \quad (4.53)\]

Where, \(T_{\text{saved}}\) is the total amount of saved energy.

If we get \(D_i < 1\), it means the active mode is activated. If \(D_i \geq 0\) and \(D_i < 1\), then ‘IE’ the environment is active and the sensor nodes use battery and external energy. The amount of consumed energy is obtained as

\[
D_i = IOE + \sum_{K=0}^{\infty} PK(k = k)f(y^k (\beta^K))
\]

\[\quad (4.54)\]

Therefore, we measure the total saved and consumed energy of WSNs using passive and active modes basis on ‘OE’ and ‘IE’ environments.

We also prove the preserved energy of WSNs using Lemma1.

**Lemma 4.4.** Bluetooth-enabled sensor nodes follow energy preservation process during the passive mode using integration method.
Here we show the numerical time integrators that cause preserving energy $P(e)$, we begin by assuming an $x$-point quadrature formula with nodes $N_i$. The required weight of $a_i$ is obtained through Lagrange basis polynomials in interruption that is shown as follows:

$$\lim(\tau) = \prod_{j=1, j \neq i}^{x} \frac{\tau - Nj}{N_i - Nj}, \quad a_i = \int_0^1 \lim(\tau) d\tau$$

(4.55)

Let $a_1, a_2, a_3, \ldots a_x$ be different real numbers (usually $0 \leq N_i \leq 1$) for which $a_i \neq$ for all $i$. We use polynomial $p(d_0)$ for satisfying the degree.

$$p(d_0) = xo$$

(4.56)

$$p(d_0 + Nej) = A(p(+Nej) \int_0^1 \frac{\delta y}{\delta x} \nabla S (p(d0 + \tau s)dx$$

(4.57)

The quadrature formula with nodes $N_i$ and weights $a_i$ decrease integrator to the particular collection of methods. We use polynomial degree $2x - 1$.

Thus, Gauss pointed $N_i$ that is equal to 0 and shifted with Lagrange polynomial particular collection for $A(x)$.

It is the reason arguments in $A(x)$ and $\nabla S (x)$ are treated with a different way that is considered as partitioned numerical method. The solution of these methods depends on the specific factorization of a vector field.

Assume, If $A(x) = A$ is a constant matrix, let $(1, 1)$ be Hamiltonian system. Thus, it becomes energy saving integrator. It is proof that sensor nodes also consume a minimum amount of energy during passive mood.

4.7 Automatic Active and Sleep (AAS) Model

We set a threshold value for idle and ‘OFF’ modes to save energy.
The total idle time can be computed by equation (4.59). Assume \( CE_{idle} \) is consumed energy during idle time; \( M_{idle}(t) \) is the minimum time required for sensors to remain in an idle state; \( E_{idle/on} \) is the energy consumed during the ‘idle’ or ‘ON’ state, and \( CS_{idle/off} \) is the energy required to change state from (idle to off).

\[
Idle_{time} = CE_{idle} * M_{idle}(t) + E_{idle/on} * CS_{idle/off}
\]

(4.59)

Idle time must always be less than or equal to ‘OFF’ time because nodes consume energy during idle time (listening) without doing anything.

Total ‘OFF’ time can be calculated by equation (4.60). Assume \( E_{off} \) is the preserved energy during ‘OFF’ time, \( M_{off}(t) \) is the minimum time required for sensors to remain in the idle state and \( CS_{off/on} \) is the energy required for going from the ‘OFF’ state to the ‘ON’ state.

\[
t_{off} = PE_{off} * M_{off}(t) + CS_{off/on}
\]

(4.60)

Assume that \( M_{off}(t) \) is the time that sensor nodes stay in the ‘OFF’ state (higher than the idle state, as already proved) and given in equation (4.60). Thus, equation (4.60) can be satisfied by substituting the remaining values.

\[
M_{off}(t) \geq [0,(PE_{off} - CE_{idle}) * CS_{idle/off}]
\]

The purpose of the AAS model is to bring the sensors into the sleep mode if no data are being delivered. We infer and generalize from equations (4.59), and (4.60) that the operating mode of sensors can automatically be set up. Let us assume \( \alpha \) (alpha) and \( \beta \)
(beta) for active (ON) and sleep (OFF), respectively. The automatic change of transitions can be justified if equation (4.61) is satisfied.

\[ C_{S_{a}} \geq \max [0, (CE_{on} + CE_{idle} - PE_{off}) \times C_{S_{\beta}}] \]  

(4.61)

Where \( CE_{on} \) is the energy is consumed during the active mode and \( C_{S_{\beta}} \) is the consumption of energy from going active (ON) to sleep (OFF) mode that is a negligible amount of energy. Thus \( C_{S_{a}} \) is greater than or equal to the amount of energy consumed in the active mode, preserved energy in the sleep mode and energy consumed for change of transition to ON/OFF mode.

Therefore, in our case, we have maintained 93.6% of the energy by letting sensors go into sleep rather than remaining in idle mode. We have just wasted 6.4% of the energy. The total preserved energy in sleep and idle modes are shown in Figure 4.14.

![Figure 4.14: Total percentage (%) of energy preserved in sleep mode VS consumed in idle mode](image)
The consumption and preservation processes are observed when the node finishes the monitoring process and continues sensing the medium. Such a situation wastes additional energy in the idle listening process. With the incorporation of the AAS model, nodes are forced not to stay in idle listening. This model restricts additional waste of energy.

Similarly, we have calculated the total energy consumed in the monitoring process and idle listening and also shown preserved energy using AAS in Figure 4.15.

Without this model, energy could not be saved. Hence, nodes only consumed 220 joules during the entire process. If the nodes should have been in the active as well as the listening states without the use of AAS, then all nodes could consume a total energy of 1406 joules. The energy measuring process is done using two metrics: Relative Standard
Deviation (RSD)$^2$ and Gini coefficient$^3$. As a result, we can determine the reduced amount of energy.

The BN and the scheduled nodes are active during the compilation time. In the case of an empty network, BN takes the same timeout as the GMAC nodes[63] take for sensing the traffic of the network during both distribution and collection time while the rest of the nodes remain in the sleep. Furthermore, AAS saved the substantial amount of energy and compared with one of the best existing mechanism of T-MAC[21] available in the literature for handling an idle listening problem depicted in Figure 4.16.

![Figure 4.16: Energy efficiency of AAS and T-MAC mechanisms at different time intervals](image)

$^2$**Relative Standard Deviation (RSD):** It is the absolute value for the deviation of the coefficient and defined as a percentage. It is also commonly used when doing quality assurance.

$^3$**Gini coefficient:** An inequality distribution measure that is expressed as a ratio with values between 0 and 1.
In a wireless sensor network, mobility and scalability are two of the most significant factors. The performance of the network is highly dependent on these two factors. The adaptable and scalable mobility model can be used for multiple wireless sensor network applications. The mobility behavior in the mobile sensor node can be categorized by a two-phase process; Active and inactive phase. During an active phase, the compressed data are transmitted to other nodes or sinks or base station. During an inactive period, a mobile sensor node moves to a new location, salvages the sensing information from the field of interest, and makes local compression of the collected data. To handle the mobility and scalable routing, we introduce two models; lattice mobility model and pheromone termite model.

5.1 Lattice Mobility Model

To frame this mobility behavior, we introduce the LMM to control the random movement of sensor nodes over WSNs. The idea of the lattice comes from a moderately ordered set in which every pair of elements is based on a supremum (known as join or upper bound). And an Infimum (known as meet or the greatest lower bound). The idea of the "join and meet" is applied in the LMM, which helps the sensor nodes maintain connectivity and choose the node with higher energy and the shortest distance during the communication.
We select the particular node for targeting the mobility-aware node based on the least distance and high residual energy using the concept of Infimum and supremum depicted in Figures 5.1-5.3. Let us assume; ‘K’ is a sensor node with Infimum (greatest lower bound), means this node can be on the lowest or equal distance from location-determining node ‘L’. ‘K’ is the nearest node of ‘L’ in the region ‘R’ in the network ‘N’.

We initially pick three nods, including ‘K’ in the region. These nodes are ‘K’, ‘L’ and ‘M’ (supremum) with highest residual energy. Subsequently, we apply the approach of greatest lower bound (infimum) to choose a single node from the list of three nodes based on the shortest distance from transmitting the node. The selected node is called as lattice node. In Figures 5.1 and 5.2; three nodes are selected based on high residual energy and least distance from the transmitting node respectively.

Figure 5.1: Selection of supremum node based highest residual energy using the upper bound
Figure 5.2: Selection of infimum node based on the shortest distance using the greatest lower bound

In Figure 5.3, the final lattice node is chosen based on satisfying above both conditions of supremum and infimum.

Figure 5.3: Selection of lattice node based on the shortest distance and highest residual energy using greatest lower bound and upper bound respectively (Satisfying both conditions of supremum and infimum)

**Definition 5.1:** A region ‘$R$’ is the set of sensor nodes; thus, it can be expressed as $R \subseteq N$ of sensor nodes in the network ‘$N$’ is bounded from upper. If there exists a sensor
node ‘K’ in the region ‘R’, then $K \in N$, called the upper bound of ‘R’. Thus, the remaining sensor nodes ‘γ’ in region ‘R’ can be defined as $\gamma \leq K$ for every $\gamma \in R$. It helps determine the highest residual energy of a node in the region ‘R’ at the one-hop neighborhood destination.

Similarly, ‘R’ is bounded from lower if there exists $K \in N$ that is called the greatest lower bound of ‘R’ such that $\gamma \geq K$ for every $\gamma \in R$. Thus, a single node is selected from the list of three sensor nodes based on shortest distance using Infimum and the highest residual energy using supremum. If, both conditions are satisfied, then this search continues until reach to the desired moving sensor node for discovery of the location and path.

**Definition 5.2:** Suppose that $R \subseteq N$, consisting of sensor nodes available in the region ‘R’, which is a subset (part) of the network ‘N’. If $K \in N$ is the upper bound of ‘R’ such that $K \geq \hat{K}$ for every upper bound in region ‘R’, where ‘$\hat{K}$’ is the list of sensor nodes with lower upper bound; then ‘K’ is called a supremum in region ‘R’, represented by $K = R_{\text{Supnum}}$. If $K \in N$ is the greatest lower bound in the region ‘R’ such that $K \leq \hat{K}$ for every greatest lower bound. Thus, ‘K’ is called the greatest lower bound or Infimum (A node at the shortest distance from the transmitting node) in the region ‘R’, represented by $K = R_{\text{Infnum}}$.

If ‘R’ is not bounded, then we can write $R_{\text{Supnum}} = -\infty$. If $R = \{\}$ is the empty region, then every sensor node is a greatest lower, and upper bound in region ‘R’, and we can write $\varphi_{\text{Supnum}} = -\infty$, $\varphi_{\text{Infnum}} = \infty$. We can conclude that the sensor node can be supremum
or infimum in the region ‘\(R\)’ if each region consists of a finite number of nodes. For region \(R= \{ \gamma_K: K \in \mathbb{N} \}\), it can be written as follows:

\[
R_{\text{supmum}} = \sum_{K \in \mathbb{N}} \gamma_K \quad \text{and} \quad R_{\text{infmum}} = \sum_{K \in \mathbb{N}} \gamma_K
\]  

(5.1)

**Corollary 5.1:** The region ‘\(R\)’ consisting of the set of sensor nodes is bounded.

**Remark 5.1:** If a sensor node ‘\(K\)’ is infimum (with shortest distance) at one hop neighborhood in the region ‘\(R\)’, then a sensor node ‘\(K\)’ will be the greatest lower bound on the list of remaining sensor nodes ‘\(\gamma\)’; thus, \(K \leq \gamma \in R\) is the greatest lower bound.

Notation 1: We can write \(\Delta L(R)\) for the set of the greatest lower bound (Infimum: shortest distance at one-hop neighborhood) and \(\Delta U(R)\) for set of upper bound (Supremum: Highest residual energy of one-hop neighborhood node) in the region ‘\(R\)’.

The above remark can be expressed as follows:

\(K \in \Delta L(R) \text{ and } K \leq \gamma \text{ then } \gamma \in \Delta L(R)\). Similarly, \(K \in \Delta U(R) \text{ and } K \geq \gamma \text{ then } \gamma \in \Delta U(R)\).

**Definition 5.3:** A sensor node ‘\(K\)’ is called a supremum (A node with the highest residual energy) in the region ‘\(R\)’ at one-hop neighborhood if

a. \(K \in \Delta U(R)\)

b. \(K \geq \gamma \text{ for all } \gamma \in \Delta U(R). \text{ i.e. } \text{‘}K\text{’ is the Upper bound in } \text{‘}R\text{’}\.\)

Thus, a sensor node ‘\(K\)’ is called as the upper bound in the region ‘\(R\)’. A sensor node ‘\(K\)’ can be called as an infimum (A node available at the shortest distance) in the region ‘\(R\)’ if

a. \(K \in \Delta L(R)\)

b. \(K \leq \gamma \text{ for all } \gamma \in \Delta L(R). \text{ i.e. } \text{‘}K\text{’ is the greatest lower bound in } \text{‘}R\text{’}\.\)
Therefore, a sensor node ‘K’ is chosen as lattice node while satisfying both conditions.

**Example 5.1:** Let \( R = \{ K \in N \mid 0 < K \leq l \} \). Then \( R_{\text{Supmum}} = 1 \) & \( R_{\text{infnm}} = 0 \).

**Remark 5.2:** If \( R_{\text{Supmum}} \in R \); and then it is also called as the maximum in the region ‘R’.

Similarly, If \( R_{\text{infnm}} \in R \); and then it is also called as the minimum in the region ‘R’.

**Proposition 5.1:** The Infimum and Supremum sensor node is the lattice node in the region ‘R’, which is unique, if it exists. Additionally, if both conditions exist, and then \( R_{\text{infnm}} \leq R_{\text{Supmum}} \).

**Proof:** Assume that a sensor node ‘K’ is the supremum in the region ‘R’. Then \( K \geq \gamma \);
thus, a sensor node ‘K’ is the upper bound in the region ‘R’. Similarly, if ‘K’ is the infimum sensor node in the region ‘R’, then \( K \leq \gamma \). Thus, ‘K’ is the greatest lower bound in the region ‘R’. It can be expressed as follows:

If \( K \geq \gamma \), and then \( K = \gamma \).

If \( R_{\text{infnm}} \) and \( R_{\text{Supmum}} \) exist, then region ‘R’ is nonempty. Thus, select ‘K’ sensor node that is the nearest node with highest residual energy. It can be written as:

\( K \in R, \, \& \, R_{\text{infnm}} \leq K \leq R_{\text{Supmum}} \).

As, \( R_{\text{infnm}} \) and \( R_{\text{Supmum}} \) are the greatest lower bound and upper bound respectively in the region ‘R’. It trails that \( R_{\text{infnm}} \leq R_{\text{Supmum}} \).

If \( R_{\text{Supmum}} \in R \), then we can represent this by \( R_{\text{high}} \), and call it the highest residual energy of the node ‘K’ in region ‘R’, & If \( R_{\text{infnm}} \in R \), then we can represent this by \( R_{\text{low}} \), and call it the shortest distance of node ‘K’ from location-determining node ‘L’ in the region ‘R’.
**Theorem 5.1:** Every nonempty search of ‘K’ node with below infimum and above Supremum in the region ‘R’ is bounded, then this theorem provides foundation for much existences results in realistic scenarios and study. For example, once we validate that a sensor node is bounded from above, then we may emphasize the existence of the supremum without determining its real value.

Based on the concept of infimum and supremum, Lattice mobility model starts searching the unique node with highest residual energy and shortest distance from the source node to destination node.

The idea of infimum and supremum is applied with LMM to augment three types of mobility patterns: dynamic medium mobility patterns, walking mobility patterns, and vehicular mobility patterns. Dynamic medium mobility patterns are used when the sensor nodes are in a medium (e.g., the wind, water, or other fluids) and typically supports two to three dimensions. Walking mobility patterns are suitable for people; movements in these patterns are two dimensional. These patterns are characterized by restricted speeds, a chaotic nature, and obstacle avoidance. Vehicular mobility patterns support vehicles, which are equipped with sensor nodes. The vehicles communicate with each other while using traffic conditions and exchanging information. The movement of the vehicle is measured in only one direction.

**Theorem 5.2:** The greatest lower bound is constructed on Infimum. Let $V= (a, t)$ be the speed of the mobile sensor node at a given time ‘$t$’ and at the location $X = (X_1, X_2)$. In the greatest lower bound, $D= (a, t)$ is the node distribution along the direction ‘$\Delta d_i$’.
Each sensor node has three nearest neighbor nodes as \( a + R. \Delta d_i (\gamma = 1, 2, 3) \). ‘R’ is the region of the network. Thus, direction ‘\( \Delta d_i \)’ can be defined as follows:

\[
\Delta d_i = \begin{cases} 
\frac{1}{2} \cos(i) \pi, & i = 1 \\
\frac{1}{2} \sin(i) \pi, & i = 2, 3
\end{cases}
\] (5.2)

Greatest lower bound (Infimum) can be governed by following equation:

\[
D_l (a + R. \Delta d_i , t + R) - D_l (a, t) = \tau_i (V). [D_l^\beta (a, t) - D_l (a, t)] (i = 1, 2, 3) \] (5.3)

Where ‘\( D_l^\beta \)’ is the distribution of the nodes that can be predicted by value of \( D_l (a, t) \).

We set \( D_l^\beta (a, t) \) to be an average speed of \( v = (a, t) \).

\[
D_l^\beta (a, t) = \frac{V(a, t)}{3} (i = 1, 2, 3) \] (5.4)

The greatest lower bound requires that the speed of mobile sensor node is measured during the progression. Mathematically, it entails that the summary of a left-hand side of the equation (5.4) over all the three neighborhood must be equal to 1.

\[
D_l^\beta (a, t) = \sum_{i=1}^{3} \tau_i (V). [D_l^\beta (a, t) - D_l (a, t)] = 1 \] (5.5)

Substituting equation (5.5) into equation (5.4), we get:

\[
V = (a, t) = \sum_{i=1}^{3} \tau_i (V) . D_l (a, t) \sum_{i=1}^{3} \frac{\tau_i (V)}{3} = \sum_{i=1}^{3} D_l^\beta (a, t) \] (5.6)

Thus, we summarize the result of theorem based on the greatest lower bound (Infimum) in the one step of the algorithm given in 5.1.

The goal of this contribution is to focus on the walking mobility patterns because there is no seamless mobility model attainable in the literature to support thoroughly to the walking patterns. Hence, random waypoint mobility model and group mobility model are
available with few capable features that can be modified to support many scenarios[64]. However, both are closer to ad-hoc and wireless networks rather than wireless sensor networks.

**Algorithm 5.1**: The greatest lower bound (Infimum).

A). For all neighbor nodes

\[ D_i (a, K + 1) = D_i (a, K) + \tau_i (V) \left[ \frac{V(a, K)}{3} - D_i (a, K) \right] (i = 1, 2, 3) \]

B). For each neighbor node

\[ D_i (a + \Delta d_i , K + 1) = D_i (a, K + 1) (i = 1, 2, 3) \]

C). For each border node

\[ D_i (a + \Delta d_i , K + 1) = D_i (a + \Delta d_{i+1} , K + 1) (i = 1, 2, 3) \]

D). Update the speed for all moving nodes

\[ V = (a, K + 1) = \sum_{i=1}^{3} \tau_i (V) \cdot D_i (a, K + 1) / \sum_{i=1}^{3} \frac{\tau_i (V)}{3} \]

The LMM helps improve the throughput, energy efficiency and reduce latency. Let us define how to use the lattice mobility model in the region based wireless sensor networks to handle walking mobility patterns.

Let ‘K’ be a sensor node that reaches location ‘L’. The probability ‘\( P_K (L) \)’ of the sensor node can be defined as:

\[ L = K_1 x_1 + K_2 x_2 + K_3 x_3 + K_4 x_4 + \ldots + K_n \]  \hspace{1cm} (5.7)

Let us assume that the sensor nodes in the lattice are periodic with a periodic location ‘L’. Thus, no boundary condition exists, so the probability ‘\( P_K (L) \)’ of the sensor node can be satisfied using the following recurrence formula:
Where $T(L - \hat{L})$ is the probability of a sensor node when it moves from location 'L' to location 'Ł'. We introduce a generating function for the moving sensor node as follows:

$$\psi(L, a) = \sum_{k=0}^{\infty} a^k P_k(L)$$  \hspace{1cm} (5.9)

where 'a' is the trajectory of the sensor node and 'ψ' is the state of the node in WSNs.

We express the case in which the sensor node starts moving from the origin to another destination as

$$L, a) = -a \sum_{L} T(L - \hat{L}) \psi (\hat{L}, a) = \delta_{L,0}$$ \hspace{1cm} (5.10)

$$P_0(L) = \gamma_{L,0} = \begin{cases} 1, & L = 0, \\ 0, & otherwise. \end{cases}$$ \hspace{1cm} (5.11)

where $\delta$ is the Kronecker delta.

We measure the walking patterns in two dimensions, which involve five types of Bravais lattices; rectangular, oblique, hexagonal, rhombic, and square. These five Bravais lattices help in determining the location of a sensor node. We apply the Fourier transform to Equation (5.11) to determine the accurate location of the moving sensor node. In the case of rectangular Bravais lattice, the new location of mobile sensor node is depicted in Figure 5.4 and obtained by multiplying both sides by $\exp(2\pi i C \ast L/M)$ and summing over $L$.

$$\psi(L, a) - a \mathbb{V}(C) \psi(C, a) = 1$$ \hspace{1cm} (5.12)

With
\[
\psi(L, a) = \sum_L \exp[2\pi i C * L] \psi(L, a)
\]  \hspace{1cm} (5.13)

In the rectangular lattice, the node moves to a new location and creates the 90° angle from the distance of lattice node, but does not meet the x-axis, and y-axis coordinate points.

The oblique is another type of Bravais lattice that helps in determining the location of mobile sensor node when moving, but creates the trajectory less than 90°. Accordingly, the new location of the moving sensor node is obtained slightly different way and its curve is depicted in Figure 5.5 and obtained as:

\[
\psi(L, a) = \sum_L \exp[2\pi i (C + L)]
\]  \hspace{1cm} (5.14)

The hexagonal of Bravais lattice is used to determine the location of a mobile sensor node when it creates the trajectory exactly 120° at the new location.
Thus, the new location of moving sensor node is obtained by applying the Fourier inverse of \( \psi(c, a) \). The location of a mobile sensor node is depicted in Figure 5.6.

\[
\psi(L, a) = \frac{1}{L^2} \sum_c \exp\left(-2\pi i c \frac{L}{M}\right) \frac{1}{1 - a \nabla(\theta)}
\]  

(5.15)
The rhombic is the type of Bravais lattice that helps in finding the location of mobile sensor node, when it creates the trajectory from 30° to 60°. Hence, the new location of mobile sensor node is obtained by using following integrands. And the trajectory of mobile sensor node is depicted in Figure 5.7.

\[
\psi(L, a) = \frac{1}{(2\pi)^2} \iiint_{\pi} \exp(-i\theta \cdot L) \frac{1}{1 - a\nabla(\theta)} d\theta
\]

(5.16)

Figure 5.7: Discovery of the new location of moving sensor node using rhombic Bravais lattice

The last type of two dimensional Bravais lattice is the square that helps locate the mobile sensor node, which creates the trajectory of 90° and satisfies the x-axis, and y-axis coordinate points. Therefore, the trajectory of mobile sensor node is depicted in Figure 5.8, and its location is obtained as

\[
\psi(L, a) = \frac{1}{(2\pi)^2} \iiint_{\pi} [\nabla(\theta)]^K \exp(-i\theta \cdot L) d\theta
\]

(5.17)
The transition probability ‘\( T(L) \)’ is used to determine the distance from the original location of the moving node to its current location using the lattice structure. A simple cubic lattice has the following property:

\[
T(L) = \begin{cases} 
\frac{1}{4} & \text{for } L = (0, 0 \pm 1), (0, \pm 1, 0), (\pm 1, 0, 0) \\
0 & \text{otherwise}
\end{cases}
\]  

Therefore, we can determine the exact current distance to the sensor node as

\[
\mathcal{V}(\theta) = \frac{1}{4} \left( \tau^{i\theta_1} + \tau^{-i\theta_1} + \tau^{i\theta_2} + \tau^{-i\theta_2} \right)
\]  

\[
\frac{1}{4} \left( \tau^{i\theta_1} + \tau^{-i\theta_1} + \tau^{i\theta_2} + \tau^{-i\theta_2} \right) = \frac{1}{2} \left( \cos \theta_1 + \cos \theta_2 \right)
\]

Thus,

\[
P_K(L) = \frac{1}{(2\pi)^2} \int_{-\pi}^{\pi} \left[ \frac{1}{2} \left( \cos \theta_1 + \cos \theta_2 \right) \right]^K \exp(-i\theta + L) d\theta
\]  

And
\[
\psi(L, a) = \frac{1}{(2\pi)^2} \int_{-\pi}^{\pi} \int_{0}^{\pi} \frac{\exp(-i\theta_1 L) \exp(-i\theta_2 L) \exp(-i\theta_1 \theta_2) \exp(-i\theta_1 \theta_2)}{1 - a \cos\theta_1 \cos\theta_2} d\theta_1 d\theta_2 
\]

(5.22)

For \( L = 0 \), we set
\[
\psi(L, a) = \frac{1}{(2\pi)^2} \int_{-\pi}^{\pi} \int_{0}^{\pi} \frac{d\theta_1}{1 - \frac{1}{2} a (\cos\theta_1 + \cos\theta_2)} \exp(-i\theta_1 L) \exp(-i\theta_2 L) \exp(-i\theta_1 \theta_2) \exp(-i\theta_1 \theta_2) 
\]

(5.23)

Equation (5.23) provides the actual distance between the original location of the moving sensor node and its current location. Let us now find the distance of the moving node from its current location to the final destination. We assume that the final distance is \( \infty \), so \( L \rightarrow \infty \). Therefore,
\[
\psi(L, a) \sim \frac{1}{(2\pi)^2} \int_{-\pi}^{\pi} \int_{0}^{\pi} \frac{\exp(-i\theta_1 L) \exp(-i\theta_2 L) \exp(-i\theta_1 \theta_2) \exp(-i\theta_1 \theta_2)}{1 - a + \frac{1}{4} a (\cos^2\theta_1 + \cos^2\theta_2)} d\theta_1 d\theta_2 
\]

(5.24)

\[
\psi(L, a) \sim \frac{1}{(2\pi)^2} \int_{-\pi}^{\pi} \int_{0}^{\pi} \frac{\exp(-i\theta_1 L) \exp(-i\theta_2 L) \exp(-i\theta_1 \theta_2) \exp(-i\theta_1 \theta_2)}{1 - a + \frac{1}{4} a (\cos^2\theta_1 + \cos^2\theta_2)} d\theta_1 d\theta_2 
\]

\[
= \frac{2}{2\pi a L} \exp\left(-2\pi L \left[ \frac{2(1 - a)}{a} \right]^\frac{1}{2} \right) 
\]

(5.25)

where \( L = |L| \). Thus, the energy consumed in updating the locations of the sink nodes and the cost for each complete cycle is identified as.
\[
P_k(L) = \frac{1}{(2\pi)^2} \exp\left(\frac{L^2}{K} \right) 
\]

(5.26)

This model helps accurately determine the moving location, the distance from the original location of the sensor node to the current location, and the distance from the
current location to the final destination. In addition, it reduces the amount of control packets, energy consumption, and end-to-end delay.

The mobile sensor nodes in LMM sense the event from the target location and use the LMM to transfer the generated events to the base station. If any sensor node moves from its original position, another node fills the gap. The location of the moving node is determined to manage the data transmission rate.

The lattice provides scalability to WSNs because the locations and distances of the moving sensor nodes are easily determined to control the mobility. The LMM is suitable for single-hop destinations, but its performance on multi-hop destinations has not been tested. Moreover, multiple hops on the path, create nonlinearities in the WSN. Before a packet can be transmitted, a node should wait for the node of the next hop to wake up. The packet is held for a variable amount of time on every path. This feature creates uncertainty for several types of WSN applications, especially surveillance and military applications.

5.2 Pheromone Termite Analytical Routing Model

Here, we introduce the PT model for disaster recovery process, which provides cross-layering support. The model connects the data link layer with the network layer to find the optimal path to transmit data packets to one-hop neighbor nodes.

The network working process starts in the disaster recovery, once a carrier is accessed, the sensor nodes set the schedule to forward the data packets using the optimal path. Let us assume that ‘$C_R$’ is the communication range, and the distance between the
two nodes is ‘r’ in meters. Therefore, we can apply the free space propagation model to measure ‘$C_R$’, as illustrated in Equation (5.27):

$$C_R = \frac{T_X R_X P_t \lambda^2}{(4\pi^2)r^2 N_l}$$  (5.27)

where ‘$R_X$’ and ‘$T_X$’ are the energy gains of the receiver and transmitter, respectively, in watts, $N_l$ ($N_l \geq 1$) is the network loss, and ‘$\lambda$’ is the wavelength in meters/second. It is typical to set $R_X = T_X = 1$ and $N_l = 1$.

The distance between the two sensors, ‘r’, is calculated at a time interval to generate new entries in the table. This process removes the old entries and calculates ‘r’, which is used to update the trajectory pheromone in the sensor nodes. The trajectory pheromone is the group of termites from the source to the destination $(l, s)$. We deploy the features of the trail pheromone and ant control algorithm[65]:

$$p^{(N)}_{l,s} = \left\{\begin{array}{ll}
p^{(N)}_{l,s} * e^{-(r_c-r_{sn})\beta} + p^a & ; l = h^p \\
\end{array}\right.$$

(5.28)

where $p^{(N)}_{l,s}$ is the number of pheromones$^4$ from the source sensor node ‘s’ that are forwarded onto the link to the one-hop neighbor ‘l’ for node ‘n’, $h^p$ is the previously determined hop of the packet, ‘$P^a$’ is the amount of pheromone that each packet carries, ‘$r_c$’ is the current distance from the neighbor node ‘n’ at link ‘l’, ‘$e$’ is the distance from the same neighbor node at link ‘l’ to the destination node where the last packet was delivered, and ‘$\beta$’ is the packet generation rate.

$^4$Number of pheromones: Transmitted number of total packet over the network.
The calculated trail pheromone\(^5\) is used to determine the forwarding power (power capacity of sending the packets) of each neighbor node, which can be calculated as:

\[
P_{q,r}^{(N)} = \frac{(P_{q,r}^{(N)}+C_p^{Ps})}{\sum_{u=1}^{K}(P_{u,r}^{(N)}+C_p^{Ps})}
\]  

(5.29)

where \(P_{q,r}^{(N)}\) is the power strength of each neighbor node ‘u’ that forwards the packet destination ‘r’ to node ‘n’, ‘K’ is the total number of neighbor nodes, ‘\(C_p\)’ is the pheromone threshold, which is constant, and ‘\(P_s\)’ is the level of pheromone sensitivity. In a WSN, two nodes work as routers to establish the communication link to send the data packets. The pheromone threshold and pheromone sensitivity\(^6\) can also be used to find the second best alternate path to forward the packets to the desired destination.

We determine an average predicted amount of pheromone ‘\(P\psi\)’ on different links of the WSN. Let us assume that ‘X’ is the source node and ‘Y’ is the destination node that uses multiple links (\(Link_1, Link_2, Link_3, \ldots, Link_n\)) to send the pheromone (carrying or transferring the substance as a signal to other termites for communication). Each link has attributes that are characterized by a non-negative random operation \(\lambda o(r)\) with a mean value of \(\Phi_o(r)\).

Each packet carries a fixed amount of pheromone ‘\(P^a\)’. Let us assume that each node generates the pheromone at a constant rate ‘\(\beta\)’. Suppose that two nodes, X and Y, are

---

\(^5\) **Trail pheromone**: Initial control message sent by termite either for discovery of route or informing next termite to follow the chosen route.

\(^6\) **The pheromone sensitivity**: It is the detection power (emitted signal) that the termite uses to communicate with other termites.
located at two locations separated by a distance ‘r’ and are uniformly distributed over the WSN. The sensor node distance distribution is applied using a Rayleigh distribution. If the transmission power of a sensor node is less than the WSN area, then the separation distance is divided into a range from 0 to r, and the distribution can be described as a probability density function as follows[66]:

\[
V(r) = \frac{R_e^{-\beta R}}{2R^2}
\]  

(5.30)

where \( V(r) \) is the node separation distribution, which can be used to compute the predicted pheromone generation \( P(Re^{-\beta R}) \) at a node separation distance ‘r’ that corresponds to the number of arrival packets. This probability density function is used to determine the density of the WSN.

Let us assume that ‘Z’ is used to describe the rate of pheromone generation \( Z = (Re^{-\beta R}) \) at a node separation distance ‘r’ that corresponds to the packet arrival rate.

Thus, we can obtain the node separation distribution \( V(r) \), the rate of pheromone generation ‘Z’, and the separation distance ‘r’. \( V(r) = \frac{R_e^{-\beta R}}{2R^2} \) for \( 0 \leq r \leq R \) and \( Z = (Re^{-\beta R}) \); then,

\[
r = -\frac{\log Z}{\beta}
\]

We use the generated pheromone ‘Z’ as the input and apply the node separation distribution \( V(r) \) to determine the total generated predicted pheromone as follows:
\[ V(Z) = \frac{R_e^{-R\beta}}{2R^4} \frac{(\log z)}{\beta} \frac{1}{Z\beta} \]

Enumerating the order-of-equalities results in

\[ V(Z) = \frac{R_e^{-R\beta}}{2R^4} \frac{1}{Z} (-\log z) \quad R_e^{-r^2} \leq Z \leq 1 \]  

(5.31)

Thus, the predicted generated pheromone can be calculated as follows:

\[
P(R_e - r^2) = P(Z) = \int_{R_e^{-R\beta}}^{0} \frac{2}{R^2\beta^2} \frac{1}{Z} (-\log z) rz
\]

\[
P\left(R_e^{-R\beta - r^2}\right) = \frac{2}{R^2\beta^2} \int_{R_e^{-R\beta - r^2}}^{0} -\log z (rz)
\]

\[ P\left(R_e^{-r^2}\right) = \frac{2}{R^2\beta^2} \left[-(z\log z - z)^1\right] R_e^{-R\beta}
\]

\[ P\left(R_e^{-r^2}\right) = \frac{2}{R^2\beta^2} \left[1 - R_e^{-R\beta}(R\beta + 1)\right] \]  

(5.32)

The predicted pheromone generation rate is used to compute an average predicted amount of pheromone on single and multiple links using the pheromone update generation function. However, the analytical model of pheromone generation must be

---

7**Pheromone generation**: Packet generation rate.
validated. Let us assume that ‘P’ is the population at a distance ‘h’ and that ‘P_i’ is the initial population. Therefore, \( \frac{rp}{h} = \beta P_i \)

Substituting the value of \( p_i \) yields Equation (5.33), where \( P_l = rh \):

\[
\frac{rp}{h} = \beta \cdot rh ; \quad rp = \beta \cdot rh^2 ; \quad P = \beta \cdot h^2 \log p = -\beta \cdot h + \omega
\]

\[ p = \omega \cdot R_e^{-\beta h} \quad (5.33) \]

The pheromone update function can also be written as:

\[ p = \omega \cdot R_e^{-\beta h} = \omega \cdot R_e^{-h} \cdot \beta \quad (5.34) \]

This function is used to calculate an average predicted amount of pheromone on single and multiple links. Based on the following assumptions, an average predicted amount of pheromone on a single link can be obtained using the pheromone update function for several packets for ‘n’ consecutive times.

For a number of delivered packets, let us assume the following:

a. The number of delivered packets for a distance ‘r’ is a Poisson distribution with an average wavelength \( \lambda = \frac{v}{f} \) packet/meter. These packets consume resources in the network.

b. The average amount of received pheromone is ‘\( P_{\psi} \)’.

---

\(^8\)Initial population: Number of termite at the beginning of activity (sensor nodes) taking part for performing the activities.

\(^9\)Poisson distribution: The number of dropped packets in the network.
c. The initial amount of pheromone on a single link is ‘$P_i$’.

Thus, the pheromone update equation is used ‘$n$’ consecutive times to determine the number of delivered packets on a single link.

\[
p(n) = R_e^{-\left( \sum_{x=0}^{n} r_x \right)} \beta + p\psi \left( \sum_{y=1}^{n} R_e^{-\left( \sum_{x=y}^{n} r_x \right)} \beta \right)
\]  

(5.35)

The predicted amount of pheromone PP($n$) for ‘$n$’ delivered packets can be calculated as follows:

\[
PP(n) = P_l \times (P \left( R_e^{-r^2} \right))^n + p\psi \left( \frac{(P(R_e^{-r^2})^n}{P(R_e^{-r^2})} \right)
\]

Let \( \sigma = \frac{2}{R^2 \beta^2} [1 - R_e^{-\beta R} (1 + \beta R)] \) then

\[
PP(n) = P_l \sigma^n + p\psi \left( \frac{1-\sigma^n}{1-\sigma} \right)
\]  

(5.36)

Thus, the predicted amount of pheromone for ‘$n$’ arrived packets ‘PP($r$)’ on a single link for a node separation distance ‘$r$’ is expressed as a Poisson distribution:

\[
f(z) = \frac{\lambda^z e^{-\lambda}}{z!}
\]  

(5.37)

Where ‘$\lambda$’ is the average number of successfully received packets, ‘$Z$’ is the number of successful attempts, in which we are interested, and ‘$R_e$’ is the base of the logarithmic function. We map and apply the Poisson distribution in our problem; the details are as follows:
\[ PP(r) = \sum_{i=0}^{\infty} \text{poisson} \left( \lambda r, n \right) \left[ PP(n) \right] \]

\[ PP(r) = \sum_{i=0}^{\infty} \left[ R e^{-\lambda r} \frac{(\lambda r)^i}{i!} \right] \cdot \left[ p_i \sigma^n + p \psi \left( \frac{1 - \sigma^n}{1 - \sigma} \right) \right] \]

\[ PP(r) = \frac{p \psi}{1 - \sigma^n} + R e^{-\lambda r} \frac{(\lambda \beta r)}{\lambda + \beta} \left( p_i - \frac{p \psi}{1 - \sigma} \right) \]  \hspace{1cm} (5.38)

An average pheromone performance for a longer time can be obtained as follows:

\[ \lim_{r \to \infty} PP \left( r \right) = \frac{p \psi}{1 - \sigma ; \quad PP \left( r \right) = \frac{p \psi (\lambda + \beta)}{\beta} ; \quad \text{and} \quad \lambda = \frac{v}{f} ; \quad \text{Thus,} \]

\[ PP(r) = \frac{p \psi (\lambda + \beta)}{\beta} \]  \hspace{1cm} (5.39)

If we use only a single link to send the packets, then PP(r) provides the predicted amount of pheromone on the single link. We can determine the predicted amount of pheromone on multiple links in a similar fashion. On multiple links, the value of the constant pheromone threshold ‘C’ is set to 0, and the pheromone sensitivity level ‘P_s’ is 1.

Let \( P_0, P_1, P_2, \ldots, P_n \) be the multiple links that forward the data over the WSN with a packet degeneration of \( P \left( R e^{-R \beta} \right) \). Thus, the average pheromone for the multiple links can be calculated as follows:

\[ P_{0Y}^X = \]

\[ P_{0Y}^X \left[ \frac{2}{R^2 \beta^2} \left[ 1 - R e^{-\beta R} \left( 1 + \beta R \right) \right] \right] + \left[ \frac{(P_0 Y + C)^P s}{(P_0 X + C)^P s + (P_1 Y + C)^P s + (P_2 Y + C)^P s + \cdots + (P_n Y + C)^P s} \right] \times \]

\[ p \psi \]  \hspace{1cm} (5.40)
A termite maintains the pheromone table to store information about each neighbor node. Similarly, each node maintains a routing table to preserve the amount of pheromone for each neighbor link. The node possesses a different pheromone trail and table in the form of a matrix with listed destination nodes, including side nodes and neighboring nodes across the top.

Rows represent the destination nodes, and columns represent the neighbor nodes. An entry made in a pheromone is represented by $P_{k,r}$, where ‘$k$’ is the neighbor index and ‘$r$’ is the destination index, as explained in [67]. The value stored in the pheromone Table 5.1 helps to calculate the probability of each node.

### Table 5.1. Pheromone routing table for node N

<table>
<thead>
<tr>
<th>Neighbor/Destination Nodes</th>
<th>V</th>
<th>W</th>
<th>X</th>
<th>Y</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>$P_{V,B}$</td>
<td>$P_{W,B}$</td>
<td>$P_{X,B}$</td>
<td>$P_{Y,B}$</td>
<td>$P_{A,B}$</td>
</tr>
<tr>
<td>C</td>
<td>$P_{V,C}$</td>
<td>$P_{W,C}$</td>
<td>$P_{X,C}$</td>
<td>$P_{Y,C}$</td>
<td>$P_{A,C}$</td>
</tr>
<tr>
<td>F</td>
<td>$P_{V,F}$</td>
<td>$P_{W,F}$</td>
<td>$P_{X,F}$</td>
<td>$P_{Y,F}$</td>
<td>$P_{A,F}$</td>
</tr>
<tr>
<td>D</td>
<td>$P_{V,D}$</td>
<td>$P_{W,D}$</td>
<td>$P_{X,D}$</td>
<td>$P_{Y,D}$</td>
<td>$P_{A,D}$</td>
</tr>
<tr>
<td>V</td>
<td>$P_{V,V}$</td>
<td>$P_{W,V}$</td>
<td>$P_{X,V}$</td>
<td>$P_{Y,V}$</td>
<td>$P_{A,V}$</td>
</tr>
<tr>
<td>W</td>
<td>$P_{V,W}$</td>
<td>$P_{W,W}$</td>
<td>$P_{X,W}$</td>
<td>$P_{Y,W}$</td>
<td>$P_{A,W}$</td>
</tr>
<tr>
<td>X</td>
<td>$P_{V,X}$</td>
<td>$P_{W,X}$</td>
<td>$P_{X,X}$</td>
<td>$P_{Y,X}$</td>
<td>$P_{A,X}$</td>
</tr>
<tr>
<td>Y</td>
<td>$P_{V,Y}$</td>
<td>$P_{W,Y}$</td>
<td>$P_{X,Y}$</td>
<td>$P_{Y,Y}$</td>
<td>$P_{A,Y}$</td>
</tr>
<tr>
<td>Z</td>
<td>$P_{V,Z}$</td>
<td>$P_{W,Z}$</td>
<td>$P_{X,Z}$</td>
<td>$P_{Y,Z}$</td>
<td>$P_{A,Z}$</td>
</tr>
</tbody>
</table>

Figure 5.9 presents the work process of the termite. When a packet is received at node ‘N’ from the previous hop $P_{hop}$, that node could be a source node. Thus, the source, the pheromone decay, and the pheromone are added to the link $NP_{hop}$. Therefore, node ‘N’ consists of A, V, W, X, and Y neighbor nodes.
The shortest link to reach the desired destination node is \( \rightarrow_{NYC} \). The possible links to forward the data to destination C are \( \rightarrow_{NXADC} \), \( \rightarrow_{NADC} \), \( \rightarrow_{NVFC} \) and \( \rightarrow_{NNWYC} \), but \( \rightarrow_{NYC} \) is the shortest link to reach the destination. Thus, the whole path-following process of each node, transmitting the packets, sensing capabilities of termite and using single link or multiple link according to situation.

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**Figure 5.9:** Routing process of the pheromone termite model
6.1 System Model and Experimental Setup

We have implemented and simulated modular energy efficient protocols at lower layers of wireless sensor networks for realistic disaster application that covers indoor and outdoor activities. The disaster recovery scenario is implemented and simulated using ns-2.35-RC7 on Ubuntu 13.10 operating system. In addition, ODFF is also confirmed with NS33 on Ubuntu 14.10. In this application, different activities are performed, and then monitored. As, we have already studied that the emergence of the latest wireless sensing technology helps address the several shortcomings related to wired sensors. Wired sensor technology is used in emergency rooms to monitor the injured and patients. The heap of wires is attached to the body of injured or patient, which makes the affected person uncomfortable.

As a result, their mobility is restricted and increased anxiety is observed. The increased stress level is also difficult for the staff to handle. When injured or patient is moved from one unit to another, the sensors need to be removed and reattached, which is considered a cumbersome process. The wireless sensor networks should be mobility-aware to help reduce both the jumble of wires. There are already existing triage protocols for handling emergency situation. However, the performance of those protocols can be degraded due to the state of mobility and increasing numbers of casualties.
There is a need to augment the evaluation of the mass casualty during increased mobility and scalability to report the triage levels of several victims automatically. To handle such a situation, we have simulated a WSN disaster-recovery scenario that tracks the indoor injured or patients who are examined by local practitioners and remote practitioners.

Further, outdoor casualties and movements of victims are monitored and reported to the control room to take immediate measures for reducing the number of casualties as depicted in Figure 6.1. The simulated WSN disaster-recovery scenario consists of different regions, and each region is controlled by a BN. On the other hand, the WSNs experience the problems and limitations due to mobility and scalability. Therefore, the energy-efficient MAC protocol including low-level protocols will be able to reduce such problems to some extent. We have, therefore, implemented the BN-MAC protocol and other supporting models in this scenario to handle the mobility and scalability to reduce the number of casualties in a mass disaster area. One of the primary goals for deploying the BN-MAC is to reduce energy consumption while maintaining a high degree of scalability, mobility and collision avoidance.

The sensor nodes are deployed to monitor the different types of activities in the each region of the network. The deployed sensor nodes are static and mobile and can move to any region. Whenever a node leaves one region, then it needs to join another adjacent region based on activities assigned to the node. Maintaining the smooth data exchange and efficient use of the bandwidth, WSNs require the bi-directional end-to-end reliability.
End-to-end reliability is accomplished when each event is reported to the BN, and every task of the BN is delivered to the sensing field effectively.

The lack of bidirectional reliability weakens event detection and provides inappropriate data collection. We achieve end-to-end reliability using a new AAIA model. In this scenario, the sensor nodes communicate with each other using short-range and one-hop communication rather than long range communication to preserve energy. The message forwarding process is done with intra- and inter-communications. The intra-communication process is done within regions using hybrid features.

The hybrid features consist of scheduled and contention-based approaches. The contention-based feature uses the semi-synchronous communication to find the availability of the channel for communication, whereas schedule-based helps fix the schedule of the nodes for sending and receiving the data within the regions. Single-hop communication has a little edge over multi-hop communication. Multi-hop communication increases the latency because each node stores and forwards the packets. If the transmission covers many hops, then more energy is consumed during data forwarding packets, but this situation can even be worse if the packet size is larger.

The sensor nodes inside the region, that monitor different events and forward the collected data to BN node, are static and mobile. Each BN forwards the information obtained from sensor nodes using inter-communication to the base station.

Each base station further forwards the information to “control room” using the IP network. The LDSNS model is also used to help find the efficient shortest path. As a
result, the sensor node uses Anycast communication for maintaining the load balancing to save additional energy. In this scenario, different events occur simultaneously including indoor injured reporting, outdoor casualties, rescuing the victims from the area of mass destruction, detecting the movement of victims, monitoring the rescue activities and handling the faster recovery process. In the scenario, the PT mobility routing model is incorporated.

PT model\(^\text{10}\) encompasses two important features; packet generation rate and the pheromone sensitivity to handle the task of observing the rescue events and maintaining a faster recovery process. Furthermore, most recent WSN applications in the area of surveillance and monitoring also require mobility and scalability. Currently, surveillance and monitoring applications cover multiple scenarios ranging from vigilance of travelers to moving aircraft. Without mobility and scalability support, it is not possible to cover the whole surveillance process.

The scenario reflects the real WSNs environment. The obtained simulation results are quite convincing and identical to realistic experimental results. The primary goal of simulation is to handle the disaster-recovery emergency situation consuming less energy with faster data delivery. We evaluate the performance of the BN-MAC protocol including its supporting models and compares with known hybrid and mobility MAC

\[^{10}\text{Pheromone termite:}\] It provides routing support and based on two important features: Pheromone sensitivity and packet generation rate. This model also helps in the detection power (emitted signal) that node uses to communicate with other nodes. In addition, packet generation rate informs the node to handle the variable number of packet generation rate and adopt the network condition.
protocols Z-MAC, X-MAC, MS-MAC, A-MAC, ADC-SMAC, and MobiSense at MAC sub-layers. The similar parameters have been used for all MAC protocols for simulation.

The simulation scenario consists of 450 and 480 nodes with a transmission radius of 30 meters. The nodes are randomly placed in a uniform fashion in the area of 1200 * 1200 square meters. The network is divided into equal 400 m x 400 m regions. The initial energy of the nodes is set 3.7 joules.

Table 6.1: Summarized simulation parameters for proposed disaster recovery scenario to involve indoor monitoring and outdoor handling of mass casualties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Range</td>
<td>30 meters</td>
</tr>
<tr>
<td>Sensing Range of node</td>
<td>20 meters</td>
</tr>
<tr>
<td>Initial energy of a node</td>
<td>3.7 Joules</td>
</tr>
<tr>
<td>Bandwidth of node</td>
<td>50 Kb/Sec</td>
</tr>
<tr>
<td>Number of sensors</td>
<td>450 &amp; 480</td>
</tr>
<tr>
<td>Size of network</td>
<td>1200 * 1200 square meters</td>
</tr>
<tr>
<td>Size of each region</td>
<td>400 * 400 square meters</td>
</tr>
<tr>
<td>Buffering capacity</td>
<td>50 Packets buffering capacity at each node</td>
</tr>
<tr>
<td>Data Packet size</td>
<td>256 bytes</td>
</tr>
<tr>
<td>Simulation time</td>
<td>Different (35 minutes &amp; 45 minutes)</td>
</tr>
<tr>
<td>Initial pause time</td>
<td>30 Seconds</td>
</tr>
<tr>
<td>Tx energy</td>
<td>16 mW</td>
</tr>
<tr>
<td>Rx energy</td>
<td>12 mW,</td>
</tr>
<tr>
<td>Power Intensity</td>
<td>-20 dBm to 12 dBm.</td>
</tr>
<tr>
<td>Sink location in each region</td>
<td>(0, 455)</td>
</tr>
<tr>
<td>Hybrid MAC protocol</td>
<td>BN-MAC, Z-MAC, X-MAC, MS-MAC, A-MAC, ADC-SMAC and MobiSense</td>
</tr>
<tr>
<td>Aggregation Models</td>
<td>MCMP, EQSAR, EQSR &amp; SQM</td>
</tr>
<tr>
<td>Routing Models</td>
<td>SPIN, EAP &amp; PT</td>
</tr>
<tr>
<td>Deployed models</td>
<td>AAS, LDSNS, IDM, SQ, AAIA models</td>
</tr>
<tr>
<td>Mobility model</td>
<td>LMM, CMM, WMM &amp; RWMM</td>
</tr>
<tr>
<td>1-Hop Neighbor Search Models</td>
<td>MEAR, AQWS, MERR &amp; LDSNS</td>
</tr>
</tbody>
</table>
Mobility (Speed of the nodes) | 0 m/sec to 9 m/sec, 14 m/sec and 18 m/sec
Routing Protocol | Pheromone termite SPIN, & EAP

The bandwidth of the node is 50 kb/sec, and maximum power consumption for each sensor is set 16 mW. Sensing and idle modes have 12 mW and 0.5 mW, respectively, but in our case, there is no idle mode. The total simulation time is 35 minutes, and the pause time is set to 30 seconds for phase initialization at the start of the simulation. The results demonstrate an average of 15 simulation runs. The energy consumption pertaining to different radio modes and simulation parameters is summed up in Table 6.1.
6.2 Boarder Node Medium Access Control (BN-MAC) Evaluation

Based on test plan and experimental setup, we collected several results but used the following metrics to demonstrate the performance of the BN-MAC with supporting models. And also compared their performance with other protocols at MAC level in the health scenario.

- Network coverage efficiency and lifetime in static and mobility situation.
- Latency of BN-MAC, Z-MAC, X-MAC, MS-MAC, A-MAC, ADC-SMAC and MobiSense in static and mobility situation.

6.2.1 Throughput Performance

We analyze the throughput efficiency of BN-MAC with its supporting models and other competing hybrid MAC protocols: X-MAC, Z-MAC, MS-MAC, A-MAC, ADC-SMAC and Mobisense in Figures 6.2 and 6.3. We used static and mobility scenarios for determining the throughput based on the varying number of transmitting nodes. In Figure 6.2, we set 30% of the nodes to be mobile, including transmitting nodes throughout the simulation.

In the given scenario of the hospital for disaster recovery that involves the indoor patients, outdoor victims and movement of local and remote practitioners is 30% mobile.
We have noticed that BN-MAC and other competing MAC protocols initially produce an average throughput of 450 to 500 Kbits/sec. When the number of transmitting nodes increases, then performance of BN-MAC slightly decreases as compared with other MAC protocols.

BN-MAC reduces the throughput from 500 Kbits/sec to 400 Kbits/sec by using one transmitter to 18 transmitter nodes, whereas other decrease throughput from 475Kbits/sec to 260 Kbits/sec with the same number of transmitters. A-MAC and ADC-SMAC are highly affected by the increased number of transmitters. BN-MAC is superior to other competing MAC protocols and achieves 12.5% to 37.5% higher throughput in the mobility scenario. This mobility analysis is based on two methodologies: analysis based on synthetic traces and analysis based on real-world traces as discussed in[68].

![Throughput graph](image)

*Figure 6.2: Throughput at heavy traffic load using mobility*
In Figure 6.3, all nodes are stationary. Similarly, BN-MAC and other competing MAC protocols produce throughput. BN-MAC initially obtains 500 Kbits/sec whereas competing MAC layer protocols get 462-483.5 Kbits/sec at one transmitter when the number of transmitters increase, then the throughput performance of all MAC protocols starts dropping.

We have observed that an increase in the number of transmitters also causes a decrease in throughput even though the nodes are static. Once again, BN-MAC also outperforms other MAC protocols in the static scenario, and BN-MAC achieves 15% to 40.25% higher throughput.

![Figure 6.3: Throughput at heavy traffic load using static nodes](image)

Mobisense and ADC-SMAC are profoundly affected in the static scenario because they are specially designed for handling the mobility of nodes. The simulation results
demonstrate that BN-MAC is the superior choice for several WSN applications.

6.2.2 Network Coverage Efficiency

We validate network coverage performance of BN-MAC using static and mobility nodes. We have scaled the network coverage scenarios for handling the monitoring activities of a hospital including the recovery of mass victims. We have conducted several tests while deploying from 1 to 450 sensor nodes. In Figures 6.4 and 6.5, we have created a mobility scenario covering 25% and 50% mobility\(^\text{11}\) of the nodes, respectively. The speed of the nodes is set from 0-9 m/sec.

The BN-MAC has achieved 98.2% and 96.2% network coverage with 25% and 50% mobility, respectively, whereas Z-MAC, A-MAC, ADC-SMAC, X-MAC, MobiSense and MS-MAC get 70.5-83.6% network coverage when 25% sensor nodes are mobile, as shown in Figure 6.4. When mobility increases up to 50%, then competing MAC protocols get 68-78.5% network coverage performance using 450 sensor nodes, as illustrated in figure 6.5. We have established 18 sessions in both scenarios simultaneously to determine the exact behavior of the network with high congested traffic.

We observe that ADC-SMAC, A-MAC, and MS-MAC are significantly affected due to mobility. In addition, BN-MAC has obtained the same network coverage with 302-384 sensor nodes as other MAC protocols get with 450 sensor nodes. Based on simulation results, we demonstrate that mobility brings a trivial change in the network coverage by

\(^{11}\text{Mobility: Number of mobile nodes (moving nodes)}\)
using the BN-MAC protocol. In addition, we have also validated that the duration of the simulation (either increases or decreases) does not affect the efficiency of BN-MAC.

Figure 6.4: Coverage efficiency at 25% mobility of nodes
6.2.3 Network Lifetime

In Figure 6.6, we show the lifetime of the WSN based on a different number of sensor nodes. BN-MAC gets a higher lifetime than other MAC protocols. The other MAC protocols are less capable of utilizing energy efficiently to get an improved network lifetime with the increased size of the nodes. BN-MAC possesses the capability of maintaining the traffic and reducing the WSN ideal listening time.

The nodes using BN-MAC die after 472 days compared with other MAC protocols, where nodes die between 373-438 days. A-MAC behaves worse, and all nodes die in 373 days. BN-MAC takes 7.2-20.97% additional network lifetime.

![Diagram showing network lifetime vs number of sensors for different MAC protocols](image)

*Figure 6.6: Lifetime of MAC protocols using different number of sensors*
6.2.4 Latency

In this section, we introduce the latency by using BN-MAC and other competing MAC protocols. We measure the latency in terms of how much time one packet takes to travel from sender to the destination point. In addition, we measure and display different types of latencies, including propagation delay, transmission delay, router delay and storage delay. Furthermore, these four types of delays are collectively shown in Figures 6.7 and 6.8.

![Figure 6.7: Average packet delay at different mobility rates](image)

We also used the mobility and the static scenario for determining the latency. In Figure 6.7, the latency is shown at the different mobility rates. We observe in Figure 6.7 that, based on the simulation, when mobility increases, the latency also increases. BN-MAC gets 0.015-0.06 seconds of latency to 0-9 m/sec speed with 50% mobility, whereas
other competing MAC protocols show higher latency 0.0156-0.17 seconds at the same mobility rates. A-MAC produces higher latency than other MAC protocols. BN-MAC achieves 4-183.33% less latency than other MAC protocols. We validate that BN-MAC can be used for different types of applications for faster delivery of data.

In Figure 6.8, we show the latency of BN-MAC and other competing MAC protocols based on the static scenario. In this scenario, latency covers propagation delay, transmission delay, router delay and storage delay. We use a different packet generation interval on the x-axis. We observe that BN-MAC outperforms all other MAC protocols because BN-MAC gets 0.015-0.016 seconds latency from 0 to 18 packet generation intervals. Other MAC protocols also experience the problem due to an increase of packet generating rates.

Figure 6.8: Average packet delay when sensor nodes are static
The average latency for other MAC protocols is counted as 0.015-0.034 with a similar packet generating rates. The BN-MAC gets 6.25-106.25% less latency when nodes are stationary. We conclude that mobility is a factor affecting performance, especially when mobile sensors move randomly. Mobility is a core parameter for performance analysis, especially in massive multi-user virtual environments (MMVEs)[69]. BN-MAC has the capability to manage its timeframe, the number of random access frames, and the rate of transfer frames in the static and mobility scenarios, but the average delay remains almost unstable with Z-MAC, X-MAC, and other MAC protocols, which exhibit higher latency and reduced throughput.

6.2.5 Result Discussion of BN-MAC

Based on the simulation results, we have compared the performance of our approach BN-MAC with known low duty-cycle protocols such as X-MAC, and also compared with hybrid and mobility MAC protocols including Z-MAC, MS-MAC, A-MAC, ADC-SMAC, and MobiSense over WSNs. Simulation results demonstrate that BN-MAC and its supporting models have achieved 12.5-37.5% and 15-40.25% higher throughput than other competing MAC protocols in mobility and static scenarios respectively.

BN-MAC has also outperformed other MAC protocols in latency and network coverage. BN-MAC gets 4-183.33% and gets 6.25-106.25% less latency compared with other MAC protocols in mobility and static scenarios respectively. In mobility situation, the network coverage of BN-MAC is higher (that is, approximately 99.1%) as compared with other MAC protocols that get 89-96.5%. In addition, BN-MAC receives 7.2-20.97% additional network lifetime. Based on the outcomes, we claim that BN-MAC with its
introduced supporting models can be a good candidate for multiple applications for handling the mobility, scalability, and data aggregation. As a result, the higher QoS provisioning can be achieved.

6.3 Least Distance Smart Neighboring Search Evaluation

To demonstrate the validity of LDSNS model in disaster-recovery scenario, we conducted several tests from different perspectives. Based on the simulation results, the LDSNS outperformed to other approaches based on energy efficiency and duty-cycles.

6.3.1 Duty Cycles

In Figure 6.9, the routing path is shown, which consists of 14 hops. LDSNS is compared with other well-known techniques of route discovery; Minimum Energy Relay Routing (MERR)[70],

![Figure 6.9: Consumed duty cycles versus number of hops Energy Consumption](image)

Figure 6.9: Consumed duty cycles versus number of hops Energy Consumption
Minimum energy accumulative routing (MEAR)[71] & asynchronous quorum-based wake up scheduling scheme (AQWSS)[72]. Based on the simulation results, we obtained very interesting results and observed that at the 1-hop destination, all of the techniques consumed 1.57% to 1.84% duty cycles. When the number of hops increase, then duty-cycles consumption rate decrease. However, LDSNS relatively uses fewer duty-cycles as compared with other competing techniques. It is observed that the number of hops are inversely proportional to number of duty cycles that is a new discovery.

![Figure 6.10: Consumption of energy VS variable size of packets](image)

*Figure 6.10: Consumption of energy VS variable size of packets*
In Figure 6.10, we show the energy consumption for each technique using variable packet size. LDSNS consumed less energy with variable size of packets. In the case of broken link, LDSNS uses alternate link to send data packets but other schemes do not have support for and alternate link to forward the data. Furthermore, LDSNS uses both proactive and reactive approaches.

When the nodes are stationary, then the nodes apply the proactive approach to letting the nodes either join or leave the network. If the node decides to leave or another node wants to join, then LDSNS uses reactive approach by obtaining the run time information according to the topological change .In Figure 6.11, we show energy consumption versus number of hops.

![Figure 6.11: Energy consumption at variable number of hops of WSN](image)

*Figure 6.11: Energy consumption at variable number of hops of WSN*
LDSNS consumes less energy than MERR, MEAR & AQWSS. The increase in the number of hops affects all competing techniques, but LDSNS is more energy-efficient. LDSNs is based with scalable mobility-aware PT and LMM models, whereas other mechanisms experience the problem of additional energy consumption due to limited mobility and scalability support.

In Figure 6.12, we show the effective duty cycle versus the number of neighboring nodes. Due to the increase in the number of neighbor nodes, LDSNS, MERR, MEAR, and AQWSS are affected. Meanwhile LDSNS is not highly affected. The semi-synchronous support of BN-MAC protocol causes the minimum duty-cycles. In all cases, LDSNS performs outperforms to competing routing discovery mechanisms.

![Figure 6.12: Effective duty cycles due to neighboring nodes](image-url)
6.3.2 Result Discussion of LDSNS Model

To validate the LDSNS model, we simulated LDSNS and compared its performance with other well-known path discovery mechanisms: MEAR, AQWSS, and MERR. Based on the simulation results, we demonstrate that LDSNS performed better than other mechanisms in terms of low duty-cycles, energy consumption, increasing the number of neighbor nodes and size of packets. LDSNS saved 24% to 62% energy resources and improved by 12% to 21% search at 1-hop neighboring nodes.

6.4 Lattice Mobility Model Evaluation

To validate the soundness of LMM, we did a simulation and obtained several results, but use the following metrics to demonstrate the performance of the LMM in the WSN.

6.4.1 Average Delay and Forwarding Range

In Figure 6.13 and 6.14, we show an average delay based on increased event range and forwarding range. The sensor node within an event area report to the boarder node in each region. The event area is centered at (300, 300) meters. The Figures show the simulation runs for the high moderate traffic rate. The mobility (mobile sensor nodes) is set to 50% , and an event range is 25 and 50 meters from the center in Figure 6.13 and 6.14 respectively. There are 20 sensor nodes, which participate in the event. We demonstrate that in the situation of high moderate traffic rate that is now common in wireless sensor networks due to the emergence of new mobility based applications, an end-to-end delay is of paramount significance for obtaining the improved throughput.
Thus, we validate that the end-to-end delay can be reduced by extending the forwarding range.

![Graph showing average delay versus forwarding range](image)

*Figure 6.13: Average delay versus forwarding range at 25 meters event distance with 50% mobility rates*[^12]

[^12]: Mobility rates: Number of sensor node, which are moving throughout simulation process.
This is the significant trade-off, which has not been investigated so far. In addition, we have validated through simulation that LMM outperforms to CMM, WMM and RWMM in the walking mobility patterns. Furthermore, RWMM performs poorly in reduced and extended forwarding range.

### 6.4.2 Average Delay and Forwarding Range

In Figure 6.15 and 6.16, we show an average power consumption using short and long event distances and forwarding ranges. The event area, the rate of traffic load, event ranges, forwarding ranges; number of participant nodes inside the event, traffic sources and mobility parameters are same as mentioned in Figure 6.15 and 6.16.
The simulation results demonstrate that extended forwarding range does not control power consumption, but the latency remains same. However, LMM consumes less power in short as well as extended forwarding ranges as compared to CMM, RWMM, and WMM. The RWMM also consumes more power than the other participants’ mobility models. We also validated based on simulation results that RWMM is not best choice for wireless sensor networks from latency and power consumption point of view.

Figure 6.15 Power consumption versus forwarding range at 25 meters event distance with 50% mobility
6.4.3 Time taken by sensor nodes to reach different locations

Here, we examine the compatibility of the LMM with sensor nodes. Based on the simulation results, we analyze the time taken by each moving node to reach different positions. We also compare the efficiency of the LMM with the CMM, WMM, and RWMM. Figure 6.17 presents the distance covered by the sensor nodes using the LMM and the other mobility models.

The LMM is more compatible with sensor nodes because it takes less time to change location than do the other mobility models.

The LMM collects information through several factors before letting the sensor nodes move to other locations. These factors include the moving location, the distance from the...
original location to the current location, and the distance from the current location to the
destination of the sensor nodes.

Figure 6.18 presents the moving times of the sensor nodes using the LMM and the
other mobility models at different velocities. The LMM outperforms the other mobility
models; it is scalable because the locations and the distance between the moving sensor
nodes are easily determined, and the motion increases the time required to change
position only marginally.

Figure 6.17: Times taken by the sensor node to reach different positions using the LMM, CMM, RWMM,
and WMM at a fixed velocity of 10 meters/second
Network congestion and a lack of network coverage are critical factors that affect the drop rate of packets. These two issues are directly or indirectly dependent on the performance of the mobility models. Congestion and coverage prevent packets from successfully arriving at the base station. The coverage problem includes monitoring a set of goals in the intended area. The sensor nodes collect the information from events within their communication range and forward to the base station.

The base station may not be able to receive transmitted packets due to such coverage problems. Figure 6.19 compares the packet drop rate of the LMM with those of the
CMM, RWMM, and WMM. The LMM outperforms the other mobility models in walking patterns; it loses a maximum of 0.7% of the packets, whereas the other mobility models have dropped rates as high as 2.45%. This result confirms the high potential of the LMM as a mobility model for walking patterns.

![Graph showing drop packets against mobility of nodes](image)

*Figure 6.19: Packet drop rates using the LMM, CMM, RWMM, and WMM at different velocities*

### 6.4.5 Residual energy of the BN after changing locations

The residual energy represents the remaining energy level of the sensor nodes when completing the task. Here, we discuss an average residual energy level of the sensor nodes after changing locations. Figures 6.20-6.22 compare the residual energy of LMM with those of the CMM, RWMM, and WMM at 10%, 25%, and 50% mobile sensor nodes. The sensor nodes have a higher residual energy with the LMM after changing the location seven times.
The residual energy of the LMM decreases from 0.12 to 0.38 joules at 10%, 25% and 50% mobility rates, which is a smaller reduction equivalent to 10.27% after completion of ninth cycles than for the other mobility models. The energy levels of the other mobility models decline from 0.28 to 0.756 joules after completing ten motion cycles (the completion of event monitoring), which is equivalent to 20.27%. It is almost a double energy consumption waste.

The state-of-art research in WSNs mostly depends on Energy consumption for maintaining QoS provisioning. This is also important trade-off, which has not been explored. The LMM has more residual energy because of the memory-less model, which supports the sensor nodes due to their lower battery power. In addition, there is also a marginal chance of breaking the links and MAC failure.
Figure 6.21. Residual energy after completion of ninth cycles at 25% mobility rates

Figure 6.22. Residual energy after completion of ninth cycles at 50% mobility rates
6.4.6 Result Discussion of Lattice Mobility Model

The simulation results show the lattice mobility model for walking patterns over wireless sensor networks. To validate the strength of the lattice mobility model; the realistic scenario of disaster discovery is simulated using. The LMM determines the motion of the nodes, accurately provides the node’s moving location, the distance from the original location of the sensor node to its current location, and the distance from its current location to its destination. We simulated the mobility scenarios and measured the performance in terms of QoS provisioning.

Based on the simulation results, we discovered that the latency can be reduced by increasing the forwarding range that is one of the important parameters for QoS provisioning. This is the significant trade-off that has not been investigated so far. The statistical data obtained through simulation is also a witness to the strength of LMM that outperformed the CMM, WMM, and RWMM in end-to-end delay, time taken by node to reach next locations, drop rate and residual energy at variable mobility rates.

The LMM decreases the time for the sensor node to change its location by 49-59%. In addition, the LMM has a drop rate of 0.7% as compared to the other mobility models, which have dropped rates as high as 2.45%. LMM decreases energy from 0.12 to 0.38 joules at 10%, 25% and 50% mobility rates that is 10.27%, energy consumption at ten complete motion cycles, whereas CMM, WMM, and RWMM decrease an energy from 0.28 to 0.756 joules that is 20.27%. These results demonstrate that LMM is an ideal choice for different kinds of walking patterns over wireless sensor networks.
6.5 Pheromone Termite Model Evaluation

We implemented the PT model for disaster recovery situation. The performance of PT model has been compared with two routing protocols: energy aware routing Protocol (EAP)[73], and Sensor protocols for information via negotiation (SPIN) [74],[75]. We also consider a sensor application module with a constant bit-rate source that maintains the quality of service (QoS) requirements. We obtained several results but use the following metrics to demonstrate the performance of the PT model BN-MAC:

6.5.1 Predicted pheromone rate at each link

We use four links to examine the trends of the arriving packets. The node always chooses the highest pheromone link to transfer data. Hence, it is important to choose suitable values for the pheromone generation ‘$\beta$’ and the pheromone sensitivity ‘$\rho$’

![Graph showing predicted pheromone rate at each link](image.png)

*Figure 6.23: Predicted pheromone on multiple links*
Figure 6.23 indicates that the node can use secondary, tertiary, and other paths if the primary path is broken or congested. This situation helps improve throughput on the network and reduces the packet drop rate. In Figure 6.23, the network transmits 24,010 data packets and only loses ten packets. Thus, approximately 99.96% of the packets are successfully delivered, which is an encouraging result.

The primary link shares 93.83% of the successfully delivered packets. Choosing the primary path while delivering additional packets helps reduce the energy consumption because the specific nodes on the path can collaborate to send the packets while the other nodes are in the sleeping state. These results confirm that PT provides higher throughput and reduced congestion. In case of broken links, PT provides the flexibility to choose alternate path that saves network from congestion. As a result, throughput remains stable.

### 6.5.2 Throughput of PT, EAP and SPIN

We evaluate the throughput efficiency based on PT and competing routing protocol depicted in Figure 6.24. PT appears to be compatible with BN-MAC. In Figure 6.24, we present the results of simulations using EAP, SPIN, and PT with O-MAC. To examine the robustness of these three routing protocols, we simulate combined mobility and static scenario. The static sensor nodes are fixed in the field, whereas the mobile sensor nodes are attached to objects. We analyze the throughput of the objects when they begin to move.

The speeds of the sensor nodes vary from 0 to 14 meters/second. The simulations demonstrate that PT with BN-MAC produces a stable throughput, whereas SPIN and
EAP with BN-MAC experience the slight problems due to motion. As a result, SPIN and EAP have decreased throughputs. The simulation results demonstrate that PT with BN-MAC is the superior choice for several WSN applications. BN-MAC-EAP and BN-MAC-SPIN result in low throughput because both lack mobility features.

![Graph showing throughput vs. mobility for different protocols](image)

*Figure 6.24: Throughput of BN-MAC-PT, BN-MAC-SPIN, and BN-MAC-EAP at different mobility rates*

### 6.5.3 End-to-end delay of packets using PT, EAP, and SPIN

The end-to-end delay is one of the most severe and critical issues for WSNs. Many WSN applications require an end-to-end delay for time-sensitive data. However, this delay is hard to bind for event-driven WSNs, where the sensor nodes produce and broadcast data only when an event of interest occurs. Thus, creating a variable traffic load, the end-to-end delay is also tightly linked to other factors, such as network capacity,
energy consumption, and the relative location of the sensors and sink nodes. In real-time applications, packets are dropped when they are transmitted with excessive delays.

Figure 6.25 presents the end-to-end delays of PT, SPIN, and EAP. PT produces a lower end-to-end delay than SPIN and EAP, and the end-to-end delay and node density are inversely proportional in the PT algorithm, which helps find alternative paths to the destination. PT also exhibits higher route maintenance than do SPIN and EAP due to the efficient use of alternative paths, which helps produce low end-to-end delays even with mobile nodes. $1 \times 10^{-2}$

![Figure 6.25: End-to-end delay for PT, SPIN, and EAP](image)

6.5.4 **Successful packet delivery rate and energy utilization efficiency**

In this section, we analyze and evaluate the performance of the PT model with SPIN
and EAP in a dynamic network. We created a mobility scenario and assumed that the BN moves at a given time. We monitor the event in the region of interest, but the nodes occasionally exceed the transmission range. Thus, they require the dynamic head node to reduce its energy consumption; in our case, we use the BN that is mobility-aware and dynamically elected.

![Graph](image)

Figure 6.26: Successful packet delivery rates of PT, SPIN, and EAP for different numbers of nodes

We simulate three routing protocols for long durations of time with varying node speeds. Figure 6.26 illustrates that PT outperforms the other routing protocols in terms of the successful delivery of packets in this scenario. PT has a higher packet delivery rate because of its efficient use of multiple paths. In addition, SPIN and EAP are designed for query-based communications, but their behavior is affected in the targeted region by sending a lot of control messages for inquiries.

The performance of PT was also analyzed in both less congested and more congested
networks. PT outperforms the other routing protocols in all cases[82]. The success rates of the competing protocols decrease with increasing network size. SPIN performs poorly due to the route request (RREQ) packets, which create unnecessary overhead in the network. Figure 6.27 illustrates that PT consumes less energy than the other routing protocols. The packet generation rate and pheromone sensitivity features of PT help forward the packets over single and multiple links smoothly, which lead to lower energy consumption and increased efficiency.

![Figure 6.27: Energy consumption of PT, SPIN, and EAP for different numbers of nodes](image)

6.5.5 Result Discussion of Pheromone Termite Model

The PT model supports single and multiple paths over WSNs. Two essential features of the PT model, the packet generation rate, and pheromone sensitivity, are analyzed and discussed. These features help in monitoring the rescue activities and maintaining the
faster recovery process. PT also identifies the survivor and victim location, rescuing the survivors and detecting the movement of survivors. The performance of PT with BN-MAC model is measured in terms of QoS parameters.

Based on the simulation results, we demonstrate the strengths of PT with BN-MAC model, which successfully delivered approximately 99.96% of the data packets, which is an encouraging result. Additionally, PT outperformed SPIN and EAP. Compared to SPIN and EAP, PT yielded a 15-22% higher throughput, 17.5-48% less end-to-end delay, and 13-18% lower energy consumption. These results demonstrate that PT with BN-MAC is an ideal choice for large-scale WSNs to handle disaster recovery process in terms of mobility.

6.6 Smart Queuing Model

Managing different types of traffic is highly significant that improves the QoS provisioning particularly throughput. Thus, throughput could be maximized by an adjustment of the different types of queues for non-real-time and real-time traffic. We measured and compared the reliable data delivery of Smart queuing model (SQM), Energy and QoS Aware Routing (EQSAR)[76], Energy efficient and QoS aware multipath routing (EQSR)[77], Multi-constraint Multi-path (MCMP)[78]. Based on the simulation results depicted in Figure 6.28, we observed that SQM produced the reliable data delivery as compared with competing queuing models. This result indicates that SQM is a good choice for dealing with the real-time and non-real-time traffic.
6.6.1 Result Discussion of Smart Queuing Model

We created 18 sessions simultaneously for SQM, EQSAR, EQSR and MCMP. The simulation process continues for 45 minutes. We finally observed that SQM persisted stable throughout the simulation process, whereas MCMP reduced the performance two times after 12.5 and 24.8 minutes. EQSAR and EQSR continued steady but reduced the performance after 29.9 and 20.1 minutes respectively. However, EQSAR and EQSR produced better throughput as compared with MCMP. As, SMQ remained stable during entire simulation process. This validates that SMQ possesses more stable queuing model as compared with other competing models.
6.7 Discussion and Analysis of the work

Energy has been a challenge and will also remain a future challenge for efficient deployment of WSNs because the advancement in battery technology has been slow compared with growth of processing power and communication data rates. We need particular emphasis on improvement of energy-efficient operation. To overcome this challenge, hybrid MAC protocols have been introduced to prolong network lifetime [79], [80], [81]. The hybrid MAC protocols get higher energy savings, flexibility, and better scalability. In this section, we discuss and compare the merits and demerits of BN-MAC and competing hybrid MAC protocols.

X-MAC is a hybrid low duty cycle protocol based on short preambles with a target address. An advantage of X-MAC is to minimize energy consumption and latency. Idle listening to the receiver side and overhearing at neighboring nodes can be reduced. However, the gaps between series of preamble packets is the problem that can be considered as idle listening by other nodes, and they start to send their preamble packets.

The mechanism of Z-MAC supports multi-hop topology, and nodes are fixed in their positions. The global time synchronization is used to synchronize the nodes, and slots are assigned to nodes but not fixed. The fixed nodes limit the scalability of WSNs. If new nodes are joined, that will be harder to set up the network phase. During the mobility, nodes with Z-MAC are unable to receive and send the data packets.

A-MAC, based on a collision-free and non-overhearing mechanism, is designed for surveillance and monitoring applications. The major advantage of A-MAC is to notify the
nodes in advance. However, A-MAC faces a little idle listening and a packet overhead problem. As a result, it consumes enough energy due to the advertisement.

MobiSense is a cross-layer MAC protocol that combines MAC and network layers to accomplish energy efficient data communication in the micro-mobility scenario. However, MobiSense experiences the problem due to managing the multi-channel and mobility in time that causes the collision. As a result, nodes reduce throughput and increase the latency.

ADC-SMAC improves two features of S-MAC: node utilization and sleeping delay. The advantage of ADC-SMAC is to introduce flexible duty cycles for nodes. However, ADC-SMAC is not suitable for controlling idle listening and overhead issues.

MS-MAC has introduced coordinated sleep/listen duty cycles and synchronizes the schedule of nodes periodically. MS-MAC enables each node to determine the mobility and its level within its neighborhood. However, nodes get confused to follow different schedules that could lead to congestion and waste of energy under a heavy traffic load.

The limitations of existing hybrid MAC protocols, create the platform for new hybrid MAC protocol to fulfill the remaining issues. Thus, BN-MAC protocol is introduced with features of a low duty cycle using the semi-synchronization approach. The beauty of the BN-MAC protocol is dynamic election of BN based on memory allocation, signal strength, and residual energy, making an improvement in the network lifetime.
The LDSNS model is used, adding extra energy saving based on a one-hop neighbor search. The LDSNS model finds the shortest efficient path that makes it more attractive. Thus, there is a trivial chance of failure of the one-hop path; if the one-hop path fails, then the second best one-hop path is chosen for intra-data communication using PT model.

BN-MAC possesses a promising time schedule because the assigned slot is not exceeded more than the one-hop neighborhood. BN-MAC performs localized time slot allocation without changing time slots of already existing nodes, reducing the latency and overhead with less chance of breaking the routes in WSN. The AAS and IDM are an energy efficient models that fully support reducing and energy consumption because the nodes automatically go to the sleep state after completing their monitoring process and setting their modes either in active or passive [83].

BN-MAC uses smart queuing model and AAIA for handling the real-time and non-real-time traffic and reducing the data redundancy. The optimized data frame format model based on CSMA improves the performance of BN-MAC in prolonging the network lifetime and QoS provisioning by incorporating rich features such as reduction in short preamble, anycasting addressing methodology, and automatic buffering capacity. The mobility and scalability have been handled using lattice mobility model.

These features make BN-MAC as a good candidate for multiple WSN application areas. Further, based on simulation, we have characterized the BN-MAC including supporting models given in Table 6.2 to show their improvement for different metrics.
Table 6.2: Showing an improvement of modular energy efficient protocols

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Improvement as compared with Existing Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PT Model</strong></td>
<td></td>
</tr>
<tr>
<td>Throughput</td>
<td>4.2% to 14.8%</td>
</tr>
<tr>
<td>Latency</td>
<td>15.12%</td>
</tr>
<tr>
<td>Energy Efficient</td>
<td>6.4 to 9.2%</td>
</tr>
<tr>
<td><strong>LMM</strong></td>
<td></td>
</tr>
<tr>
<td>Average Delay</td>
<td>34.2% to 52.8%</td>
</tr>
<tr>
<td>Average Power Consumption (Watt)</td>
<td>14.285%</td>
</tr>
<tr>
<td>Node Location finding capability</td>
<td>36.68%</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.99% to 1.72%</td>
</tr>
<tr>
<td><strong>SQ Model</strong></td>
<td></td>
</tr>
<tr>
<td>Reliable data delivery for Real-time and Non-real-time traffics</td>
<td>1.98%</td>
</tr>
<tr>
<td><strong>AAS Model</strong></td>
<td></td>
</tr>
<tr>
<td>Energy saved in Idle Listening</td>
<td>11.2%</td>
</tr>
<tr>
<td><strong>IDM Model</strong></td>
<td></td>
</tr>
<tr>
<td>Energy saved</td>
<td>13.4% to 32.2%</td>
</tr>
<tr>
<td>Network lifetime Extension</td>
<td>24% to 62%</td>
</tr>
<tr>
<td><strong>LDSNS Model</strong></td>
<td></td>
</tr>
<tr>
<td>Search timing</td>
<td>12% to 21%</td>
</tr>
<tr>
<td>Effective duty cycle at 1-Hop neighborhood</td>
<td>24% to 62%</td>
</tr>
<tr>
<td><strong>AAIA Model</strong></td>
<td></td>
</tr>
<tr>
<td>Time saving at different packet sizes</td>
<td>11.34%</td>
</tr>
<tr>
<td><strong>ODFF Model</strong></td>
<td></td>
</tr>
<tr>
<td>Chanel access time</td>
<td>18.91%</td>
</tr>
<tr>
<td>Data frame transfer time</td>
<td>2.25%</td>
</tr>
<tr>
<td>Transmission Timing for Acknowledgement</td>
<td>27.27%</td>
</tr>
<tr>
<td>Retry transmission time</td>
<td>11.11%</td>
</tr>
<tr>
<td>Total access channel, frame transfer and acknowledgment and turnaround time in an ideal scenario</td>
<td>8.92%</td>
</tr>
</tbody>
</table>
Total Access channel, frame transfer and acknowledgment and turnaround time in worst case scenario | 8.73%

### BN-MAC

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Improvement as compared with Existing Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time for sending short preamble</td>
<td>9.86%</td>
</tr>
<tr>
<td>Time for forwarding the data</td>
<td>15.776%</td>
</tr>
<tr>
<td>Throughput performance</td>
<td>8.6% 29.5%</td>
</tr>
<tr>
<td>Energy consumed for channel accessing</td>
<td>33.86%</td>
</tr>
<tr>
<td>Energy consumed for sending short preamble</td>
<td>36.177%</td>
</tr>
<tr>
<td>Energy consumed for forwarding data</td>
<td>15.88%</td>
</tr>
<tr>
<td>Coverage Efficiency with 25% mobile nodes</td>
<td>14.6% to 27.7%</td>
</tr>
<tr>
<td>Coverage Efficiency with 50% mobile nodes</td>
<td>19.7% to 30.2%</td>
</tr>
<tr>
<td>Latency with different node speed and 50% mobile nodes</td>
<td>4% to 183.33%</td>
</tr>
<tr>
<td>Latency with static nodes</td>
<td>6.25 % to 106.25%</td>
</tr>
</tbody>
</table>

### Dynamic BN

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Improvement as compared with Existing Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network lifetime</td>
<td>7.2% to 20.97%</td>
</tr>
</tbody>
</table>

### ISC

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Improvement as compared with Existing Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumed for channel accessing</td>
<td>5.4% to 8.2%</td>
</tr>
<tr>
<td>Energy consumed for sending short preamble</td>
<td>13.5% to 18.4%</td>
</tr>
<tr>
<td>Energy consumed for forwarding 5 MB data</td>
<td>3% to 4.2%</td>
</tr>
</tbody>
</table>
CHAPTER-7: CONCLUSION

This dissertation document introduces the modular energy efficient protocols at lower layers of wireless sensor networks. The contribution particularly focuses on the MAC layer and provides the cross-layering features with support for other models. The contribution aims to maintain QoS provisioning, reduces the energy consumption, handles the mobility, scalability, and data aggregation. In this document, BN-MAC protocol is presented with its robust contention and scheduled-based mechanisms for accessing the medium. BN-MAC incorporated optimized data frame format and automatic buffering models, which helped reduce channel access time, data transfer time and provisioning of low-duty-cycled. BN-MAC included short preamble, Anycasting addressing methodology and slotted contention window that improved the QoS provisioning.

BN-MAC involves intra-communication and dynamic boarder node selection process (DBNSP) mathematical models. These both models prolonged the network lifetime by determining the consumed energy for carrier sensing, synchronization, transmitter and receiver nodes prior to communication and also provided dynamic boarder node (Head node) selection.

The automatic active and sleep mathematical model was presented to reduce the critical problem of idle listening. As a result, we saved an additional energy waste during the transmission over the channel. Furthermore, saving the extra energy, an intelligence
decision-making model was introduced that automates the sensor nodes work either in passive or active mode of communication according to the nature of the environment.

Determining the exact location of the moving node including its speed and covered distance; the lattice mobility model was presented for walking patterns that involved the novel concept of supremum and an Infimum. Additionally, providing the cross-layering support, pheromone termite model and lattice mobility model require another model to establish a link between the MAC sublayer and the network layer to route the faster data packets. Thus, smart neighboring search model was created for achieving this goal.

We developed the Smart-queuing model that helps in classifying the real-time and non-real-time traffic. Furthermore, the traffic is also scheduled according to the capacity of each link of the network to avoid the congestion and ensure the in-order data delivery. Smart-queuing model requires the model to balance the network load on each link prior the congestion to happen; thus, pheromone termite model is included to maintain network load-balancing.

An adaptive application independent aggregation model is introduced for utilizing the communication channel efficiently, addressing the issue of energy limitation and low bandwidth inherited by sensor technology. This model aggregates between MAC sublayer and network layer to reduce the overhead experienced by acknowledgment and channel contention.

WSN applications such as earthquake disaster recovery and battlefield are tested, and their performance is evaluated based on several metrics. The several stationary and
mobility scenarios were tested. Finally, based on simulation results, comprehensive benchmark is created, and characterization of proposed modular energy efficient protocols and their improvements are illustrated. We believe that the proposed approach improved the QoS provisioning, energy efficiency, handled mobility, data aggregation and scalability over the large-scale wireless sensor networks. Furthermore, it could be used for multiple WSN applications areas.
CHAPTER-8: FUTURE WORK

These modular energy efficient protocols provide the scalability, mobility, QoS service provisioning, energy efficiency and data aggregation for wireless sensor networks. These incorporated features are of paramount significance, which can be used for multiple application areas. Additional features and modules can be easily added. Some of the areas that can significantly be benefited and use this work include:

1. These models could easily be deployed for several WSN applications particularly disaster recovery, health, military, observing the ocean, cool-mining process, oil-refinery system and animal behavior detection. However, these model require application and transport level support for new compatible models to operate entirely in the realistic environment.

2. The lattice mobility model proposed in this work is mainly designed for walking patterns, but it could be used for dynamic medium mobility patterns, and vehicular mobility patterns by focusing the orthogonality and incorporating couple of prototypes of three-dimensional from platonic solids and Kepler-pointsot polyhedral. The dynamic medium mobility patterns are used when the sensor nodes are in a medium (e.g., the wind, water, or other fluid). Vehicular mobility patterns support vehicles that are equipped with sensor nodes. The vehicles communicate with each other while using traffic conditions and exchanging information particularly underwater communication. These patterns are characterized by restricted speeds, a chaotic nature, and obstacle avoidance.
3. Pheromone termite, the smart queuing, and an adaptive application independent aggregation models handle a link capacity, packet generation rate, and dealing with the low-bandwidth, real-time, and non-real-time traffic. As a result, we maintain QoS provision over the lower layers, but the QoS provisioning relatively correlates at the lower layers and transport layer in the presence of mobility. Otherwise, sensor nodes experience the issues of emitting, increased latency, congestion, and jitter. Therefore, introduction of new transport layer with re-ordering the packet, guaranteeing the consistent pre-packet delivery for different packet types and also permissible for the faster recovery in case of packet loss and transport-level synchronization can control this problem.

4. This modular energy efficient approach is mainly designed for large-scale wireless sensor networks for handling the mobility, scalability, data aggregation, and energy-efficiency, but managing the aircraft automation system needs to extend the proposed automatic active and sleep model.

5. The automation mode of activating the sensors into passive and active has been a long standing problem. Using intelligence decision model to solve the problem of automation is very a promising avenue, as it can save the additional energy; this is not possible unless excitation control, analog filtering, and compensation exist.
BIBLIOGRAPHY


