Energy-efficient Routing and Secure Communication in Wireless Sensor Networks

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Abbreviations

Abbreviations	Descriptions
6LoWPAN	IPv6 over Low-power Wireless Personal Area Network
AAP	Anonymous Authentication Protocol
ADC	Analog-to-Digital Converter
AES	Advanced Encryption Standard
AIMD	Additive Increase and Multiplicative Decrease
ARQ	Automatic Repeat reQuest
BER	Bit Error Rate
CoAP	Constrained Application Protocol
CODA	COngestion Detection and Avoidance
DoS	Denial-of-Service
DTLS	Datagram Transport Layer Security
EFMP	Energy-efficient Fire Monitoring Protocol
ESRT	Event-to-Sink Reliable Transport
FCFS	First-Come-First-Served
FND	First Node Dies
HTTP	Hypertext Transfer Protocol
IANA	Internet Assigned Numbers Authority
ICE	Indisputable Code Execution
IETF	Internet Engineering Task Force

Abbreviations	Descriptions
IoE	Internet of Everything
IoT	Internet of Things
IP	Internet Protocol
LEACH	Low-Energy Adaptive Clustering Hierarchy
LEACH-C	Low-Energy Adaptive Clustering Hierarchy-Centralized
LLNs	Lower-power and Lossy Networks
LoS	Line-of-Sight
LND	Last Node Dies
MAC	Medium Access Control
MEMS	Micro-Electro-Mechanical Systems
MTU	Maximum Transmission Unit
NLoS	Non-Line-of-Sight
PASCCC	priority-based application-specific congestion control clustering
RAM	Random-access memory
REST	REpresentational State Transfer
RFC	Request For Comments
RFID	Radio Frequency IDentification
ROM	Read-only memory
RRM	Registration Request Message
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time

Abbreviations	Descriptions
SCUBA	Secure Code Update By Attestation
TCP	Transport Control Protocol
TDMA	Time Division Multiple Access
TLS	Transport Layer Security
UDP	User Datagram Protocol
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
WSN	Wireless Sensor Network
DEEC	Distributed Energy-efficient Clustering
HEED	Hybrid Energy-efficient Distributed

Abstract

Wireless Sensor Networks (WSNs) consist of miniature sensor nodes deployed to gather vital information about an area of interest. The ability of these networks to monitor remote and hostile locations has attracted a significant amount of research over the past decade. As a result of this research, WSNs have found their presence in a variety of applications such as industrial automation, habitat monitoring, healthcare, military surveillance and transportation. These networks have the ability to operate in human-inaccessible terrains and collect data on an unprecedented scale. However, they experience various technical challenges at the time of deployment as well as operation. Most of these challenges emerge from the resource limitations such as battery power, storage, computation, and transmission range, imposed on the sensor nodes.

Energy conservation is one of the key issues requiring proper consideration. The need for energy-efficient routing protocols to prolong the lifetime of these networks is very much required. Moreover, the operation of sensor nodes in an intimidating environment and the presence of error-prone communication links expose these networks to various security breaches. As a result, any designed routing protocol need to be robust and secure against one or more malicious attacks.

This thesis aims to provide an effective solution for minimizing the energy consumption of the nodes. The energy utilization is reduced by using efficient techniques for cluster head selection. To achieve this objective, two different cluster-based hierarchical routing protocols are proposed. The selection of an optimal percentage of cluster heads reduces the energy consumption, enhances the quality of delivered data and prolongs the lifetime of a network. Apart from an optimal cluster head selection, energy consumption can also be reduced using efficient congestion detection and mitigation schemes. We propose an application-specific priority-based congestion control protocol for this purpose. The proposed protocol integrates mobility and heterogeneity of the nodes to detect congestion. Our

proposed protocol uses a novel queue scheduling mechanism to achieve coverage fidelity, which ensures that the extra resources consumed by distant nodes are utilized effectively.

Apart from energy conservation issue, this thesis also aims to provide a robust solution for Sybil attack detection in WSN. In Sybil attack, one or more malicious nodes forge multiple identities at a given time to exhaust network resources. These nodes are detected prior to cluster formation to prevent their forged identities from participating in cluster head selection. Only legitimate nodes are elected as cluster heads to enhance utilization of the resources. The proposed scheme requires collaboration of any two high energy nodes to analyse received signal strengths of neighbouring nodes. Moreover, the proposed scheme is applied to a forest wildfire monitoring application. It is crucial to detect Sybil attack in a wildfire monitoring application because these forged identities have the ability to transmit high false-negative alerts to an end user. The objective of these alerts is to divert the attention of an end user from those geographical regions which are highly vulnerable to a wildfire.

Finally, we provide a lightweight and robust mutual authentication scheme for the real-world objects of an Internet of Thing. The presence of miniature sensor nodes at the core of each object literally means that lightweight, energy-efficient and highly secured schemes need to be designed for such objects. It is a payload-based encryption approach which uses a simple four way handshaking to verify the identities of the participating objects. Our scheme is computationally efficient, incurs less connection overhead and safeguard against various types of replay attacks.

List of Publications

Journal Papers

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Conference Papers

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2. Mian Ahmad Jan, Priyadarsi Nanda, Xiangjian He, Ren Ping Liu, Enhancing lifetime and quality of data in cluster-based hierarchical routing protocol for wireless sensor network, 10th International Conference on High Performance Computing and Communications & International Conference on Embedded and Ubiquitous Computing (**HPCC_EUC**), pp.1400-1407, 2013, IEEE. (Published-Tier **B**)
3. Mian Ahmad Jan, Priyadarsi Nanda, Xiangjian He, Ren Ping Liu, A robust authentication scheme for observing resources in the internet of things environment, 13th

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Chapter 1

Introduction

This thesis has three major objectives. First, the energy-efficient cluster-based hierarchical routing protocols of Wireless Sensor Networks are studied to improve the quality of delivered data, cluster head selection and network lifetime. Second, the distinguishing features of these protocols are exploited to improve the security of these networks. Finally, the application of sensor nodes in the context of Internet of Things is studied and a secure authentication scheme is designed for the interacting real-world physical objects. This chapter is organised as follows. In Section 1.1, we outline the background of the work presented in this thesis. In Section 1.2, we discuss the motivation for our work. The research objectives, contributions and novelty of the work are discussed in Section 1.3 followed by our research focus in Section 1.4. Finally, we conclude the chapter by providing the outline of the structure of remainder of the thesis in Section 1.5.

1.1 Background

Internet has revolutionized modern world by influencing every aspect of human life by providing seamless communication without geographical barriers. Gone are the days when communication was strictly limited to writing letters and waiting for postal services to deliver them. Technological advancements do not merely close the communication gap but

also influences various other sectors such as healthcare, industrial automation, agriculture, transportation and education. The advent of wireless communication has made network connectivity slightly more ethereal. The presence of innovative technological devices in the Internet has not only broadened its scope but also provides an interoperable wireless connectivity anytime, anywhere and on any device in the world. This is something impossible to happen in any traditional wired infrastructure.

The latest technological advances in Micro-Electro-Mechanical Systems (MEMS) have enabled the development of miniaturized sensor nodes [1]. These nodes are small in size, with limited computation and processing capabilities, and they operate on small batteries. Furthermore, they have limited storage and typically have a limitation on their transmission range. These tiny sensor nodes have brought a revolution in the world of wireless communication by operating in remote and human-inaccessible terrains. Wireless Sensor Network (WSN) is comprised of such tiny nodes which are deployed to monitor and gather data from the physical environment. The data is routed to a centralized base station for further processing to obtain valuable and meaningful information. WSNs possess some unique characteristics such as self-healing, self-organization, scalability and fault-tolerance [2]. These networks are considered as the next wave in computing as they are typically deployed in environments which cannot be monitored with wired networks. As a result, they have found their applications in various domains such as automated irrigation system [3], telemonitoring system for healthcare [4], forest fire monitoring [5] and air pollution monitoring system [6].

In WSNs, the nodes are either static or mobile depending on the nature of monitored application. Most applications rely on static deployment, which has several drawbacks [7]. First, static deployment cannot guarantee an optimal coverage of the sensor field. Even a large-scale deployment of nodes may not be sufficient to provide an optimal coverage. Static deployment may result in severe consequences if all the critical events occur outside the designated region of interest. Second, when static nodes die or malfunction, they create "holes" in the network which causes a communication gap among the sensor nodes. Thus,

the network connectivity is affected, causing packet loss and degradation of the network quality. Another major drawback of static deployment is the role of gateway nodes, which are one-hop away from the base station. These nodes consume a considerable amount of energy because the whole of network traffic is routed toward the base station via them. By contrast, mobile nodes move around the field to produce different sets of gateway nodes in the entire span of network lifetime. As a result, the energy load is uniformly distributed among all the nodes in the network to act as gateway nodes [8]. Mobile nodes ensure complete coverage by capturing events and transmitting them to the base station. Mobile WSNs improve the coverage, connectivity, energy consumption and other Quality of Service (QoS) metrics [9]. In many applications, the sensor nodes do not need to be mobile. However, they require data mules [10] to gather their data and transmit to the base station. Data mules not only carry the data to a base station but also maintain high connectivity to ensure a robust data flow.

In WSNs, the nodes are deployed and left unattended to monitor an application. These nodes need to operate with minimal human intervention. Furthermore, it is infeasible to replace their batteries especially when they are deployed in a hostile environment. Therefore, special considerations need to be in place in order to efficiently utilize the limited battery power of the nodes. In these networks, most of the energy is consumed in data transmission as compared to data processing. Therefore, energy-efficient routing protocols need to be carefully designed to maximize the lifetime of these networks. In these networks, routing is a challenging task because they possess several unique features which differentiate them from contemporary communication and wireless ad hoc networks [11]. First of all, it is very difficult to build a global addressing scheme due to the sheer number of deployed nodes. As a result, classical IP-based protocols are not suitable for such networks. Second, the source nodes in close vicinity capture identical data packets and as such, there is high redundancy in the gathered data. It is of utmost importance that such redundant data packets are eliminated by routing protocols to improve energy consumption, bandwidth utilization and quality of the data. Third, sensor nodes have strictly

limited resources and any routing protocol must abide by such limitations. Fourth, sensor nodes operate in harsh environment and as such, they are prone to failure. As a result, any routing protocol must be reconfigurable to find alternate paths for data transmission to a centralized base station. Moreover, the protocol must be adaptable to the frequency of happening events to ensure that highly prioritized events do not go unreported. Last but not the least, sensor nodes are deployed and left unattended to sense the environment. The absence of human intervention literally means that the routing paths need to be established automatically within the network. It is the job of a routing protocol to establish the routing tables dynamically within each node. Furthermore, the sleep-awake schedule of the nodes should not disrupt the quality and operation of a routing protocol. In this section, first we provide a generic overview of routing protocols with particular emphasis on cluster-based hierarchical routing protocols. Next, we describe the significance of WSNs in the emergence of Internet of Things (IoT) followed by the security considerations for cluster-based hierarchical routing protocols and the IoT.

1.1.1 Routing Protocols in WSN

In WSNs, the routing protocols are broadly classified into four categories, i.e., location-based, QoS-aware, data-centric and cluster-based hierarchical protocols [11]. Location-based routing protocols require the location information of nodes to establish network communication. Location information enables the nodes to calculate the distance among them which in turn estimates their energy consumption. In the absence of a global addressing scheme, location information is utilized for energy-efficient data routing in these protocols. If the region of interest is known, using particular location of the nodes, queries are directly transmitted to the region for data collection. Therefore, not only the energy consumption is minimized but the number of transmissions is also reduced significantly. Most of the location-based routing protocols were primarily designed for ad hoc networks and are suitable for static WSNs as well. However, these protocols are not suitable for those applications where mobile nodes are required. QoS-aware routing protocols con-

sider the end-to-end delay requirements among sensor nodes while establishing the paths for traffic flow. Most of these protocols emphasis on regulating the network traffic. All the nodes are assumed to have the same reporting rate, i.e., the number of packets transmitted per unit time is similar for all nodes. As a result, these protocols may not work efficiently for heterogeneous sensor nodes [12]. Also, some of them rely on traffic arrival time [13] and adjustment of packet service rate [14] which may increase energy consumption due to the delay associated with processing of packets. In data-centric routing protocols, the base station transmits queries to sensor nodes in certain geographical regions and waits for their responses. Query is a programming logic which has its own particular syntax and contains the specifications and requirements for data collection. Query-based data collection requires an attribute-based naming, i.e., the properties and features of data to be collected are specified. The use of queries significantly reduces the redundancy in captured data [15]. Data-centric routing forms a single-tier network which can overload a gateway node within a dense deployment. Overloading a gateway node increases latency, deterioration in QoS and loss of critical events. Moreover, single-gateway architecture is not scalable and may not be suitable for a large scale WSN. To address these deficiencies, cluster-based hierarchical routing protocols were developed. These protocols partition a network into small clusters and nominate one node in each cluster as a cluster head to collect data from member nodes. The role of a cluster head changes in each round and the nodes take turn to become cluster heads for a uniform distribution of energy load.

Among all the routing protocols, cluster-based hierarchical protocols are highly efficient in terms of data aggregation, energy consumption, collision avoidance, load balancing, fault-tolerance and network lifetime [16]. Unlike other protocols, a single cluster head node collects data from multiple nodes in order to eliminate redundancy in the gathered data. Data aggregation reduces the energy consumption of a network because the duplicate packets are eliminated. Each cluster head aggregates data within its cluster and transmits to a base station using a single-hop communication link. However, aggregating the data of member nodes is a resource-intensive operation. Therefore, the nodes take turn to become

cluster heads in different rounds to balance the resource consumption. In other routing protocols, the data is aggregated by each node on its way toward a base station. As a result, higher delay is incurred by the time the data reach a base station.

In cluster-based routing protocols, intra-cluster and inter-cluster communication techniques are used to reduce the number of sensor nodes which perform the task of long-haul transmission to a base station. In intra-cluster communication, a single cluster head is responsible to collect data which reduces the energy consumption within a cluster. In inter-cluster communication, one of the cluster heads is elected as a leader node which collects data from the remaining cluster heads, further aggregates it to improve its quality, and transmits to a base station. The use of intra-cluster and inter-cluster communication techniques for data aggregation and data transmission reduces collision to a greater extent. Each cluster head allocates Time Division Multiple Access (TDMA) slots to member nodes within its cluster. The member nodes remain in sleep mode and periodically wake up to transmit their data to a cluster head using their allocated slots. The use of TDMA slots ensures that there is either minimal or no collision among the data packets of member nodes [17]. Moreover, cluster heads are located at a distance far apart from each other which ensure that their transmissions have minimal chances of collision.

Low-cost sensor nodes deployed in remote and hostile environment are prone to frequent failure. Fault-tolerance is a major challenging task in which the key sensor nodes face a potential threat of losing high sensitive data [18]. In cluster-based hierarchical routing protocols, one or more cluster heads may relinquish their operations due to various reasons such as transmission error, malicious attack, energy depletion and hardware malfunctioning. In such cases, either a backup node may take over to perform the role of cluster head or re-clustering is initiated. However, re-clustering requires abandoning an on-going cluster operation, which may result in the loss of vital data. The assignment of backup cluster heads in a large scale WSN is one of the viable options as low-cost sensor nodes are deployed in large number for monitoring purposes. Furthermore, these protocols are highly scalable to topological changes, and in responding to occurring events within

the monitored region. These protocols are highly robust and flexible to various network changes such as node mobility, network connectivity and avoidance of energy holes. Unlike other routing protocols, cluster-based hierarchical protocols do not suffer from energy hole, a mechanism in which one-hop neighbours of a base station, i.e., gateway nodes consume high amount of energy [19]. The gateway nodes suffer excessive burden because not only they transmit their own data to a base station but from neighbouring nodes as well. As a result, they perform excessive computation, data aggregation and data transmission, which result in their early energy depletion. However, in cluster-based routing protocols, the role of cluster heads rotate in each round among all the available nodes.

1.1.2 Emergence of Internet of Things

Over the years, WSNs have experienced an unprecedented growth in terms of applications, interfacing, scalability, interoperability and data computation. These technological advances along with the innovations in Radio Frequency IDentification (RFID), wireless and cellular networks have laid a solid foundation for the Internet of Things (IoT). IoT is a novel paradigm which encompasses real-world physical objects by enabling them to interact with each other using unique addressing schemes [20]. It is estimated that around 50 billion such objects will be connected to the Internet by 2020[1]. These objects will be empowered to sense, process and control the physical world events and numerous phenomena of interest. This integration and interoperable communication will generate an enormous amount of data which needs to be stored, processed, analysed and transmitted in a very systematic manner [21]. Eventually, the IoT will lead us to the Internet of Everything (IoE), where the objects, data and processes will form integral parts of our lives. We are moving to an era where the Internet of embedded objects will become ubiquitous by integrating the virtual world of information with the physical world of objects. IoT is attracting a lot of research nowadays from academia and industry and has found its applications in various domains such as transport logistics [22], smart home [23], smart cities [24] and freight

[1] http://www.cisco.com/web/solutions/trends/iot/indepth.html

supervision [25].

To realize the above vision of IoT, the industry needs to adhere to a unified standard. Currently, each application has its own specifications and underlying software and hardware platforms. The objects require a scalable application layer for the interoperable communication. Also, a common programming model is required which will enable the developers to focus only on the application development rather than the hassle of worrying about the underlying platform [26]. The IoT objects comprise of energy-starved sensor nodes at its core which are equipped with relatively small amount of memory. The application code needs to run on the cloud and only the firmware and the network stack need to be nested at the core of each embedded device. Running applications on the cloud will serve two major purposes: the availability of ample memory space on the nodes and developing applications irrespective of the underlying hardware architecture.

1.1.3 Security Considerations

WSNs and IoT are resource-constrained networks and special considerations need to be in place at the time of security provisioning. The general perception about IoT objects is that they are resource-rich devices. However, this is not the case because the presence of miniature sensor nodes at the core of IoT objects classifies them as resource-constrained in nature. In any IoT paradigm, a physical object will not be able to communicate with the Internet or other objects in the absence of a sensor node. The presence of a sensor node and the assignment of an IP address or an RFID tag make an object smart enough to interact with the physical world. Therefore, any security consideration for an IoT object must take into account the resource-constrained nature of embedded sensor nodes. The presence of an embedded sensor node at the core of each object makes it compulsory to first understand the security challenges faced by WSNs before realizing the vision and goals of an IoT.

Most WSNs are deployed for mission-critical tasks for an unspecified duration of time [27]. Therefore, security considerations need to be in place at the time of net-

work design. The resource-constrained nature of these networks coupled with their unique characteristics such as dynamic topology, in-network processing, error-prone communication links and scalability makes security provisioning a challenging and complicated task. In addition, these networks are left unattended without human intervention and base station supervision. Instead, sensor-collected data is harvested intermittently by a base station [28]. Since data are retained on individual sensors, securing this data is both important and challenging. Sensor nodes operating in unattended environments face a higher risk of security breach. If any one of these nodes is compromised, its sensitive data and security parameters will be retrieved by an adversary to participate in malicious activities. The presence of wireless transmission medium and the broadcast nature of sensor nodes further complicate the security provisioning in these networks [29]. These networks are vulnerable to a wide range of attacks such as Sybil [30], wormhole [31], sinkhole [32], selective forwarding [33] and Denial-of-Service (DoS) [34].

The presence of embedded sensor nodes literally means that IoT is not only susceptible to the threats posed by these physical objects but also to the aforementioned vulnerabilities faced by the sensor nodes. Moreover, the integration of physical objects with the Internet requires various communication models. This requirement will likely to add various ingenious and innovative malicious models to the future Internet [35]. Security provisioning in an IoT framework is a challenging task because each physical object has its own distinguishing features. The identity of each person, object and system connected with the Internet needs to be verified. In the absence of identity verification, the intruders will gain access to the network and perform various malicious activities. The consequences of these activities are diverse in nature with applications ranging from disabling a home security system, conveying false health readings to practitioners to activating false fire alarms.

1.2 Motivation

The energy-efficient nature along with high scalability, data aggregation, collision avoidance, load balancing, and enhanced network lifetime of cluster-based hierarchical routing protocols motivate us to use them for our research. Broadly speaking, these protocols are classified into randomly distributed or centralized, depending on the cluster head selection technique. In randomly distributed cluster-based hierarchical protocols, each node chooses a random number between 0 and 1. If the chosen number is less than a threshold value (explained in Chapter 2), the node is elected as cluster head. These protocols emphasize on improving the threshold value for cluster head selection. However, improving the threshold value may not necessarily elect an optimal number of cluster heads. Based on the random number generation, it is highly probable that none of the nodes may be elected as cluster head or all the nodes may be elected as cluster heads. In the former case, all the nodes choose random numbers which are greater than the threshold value. In the latter case, all the nodes choose random numbers which are less than the threshold value. Both these circumstances result in high energy consumption, low quality of aggregated data and waste of allocated bandwidth.

The cluster head selection decision need not be made only on the basis of random number, but the residual energy of each node must be taken into account as well. In centralized cluster-based hierarchical routing protocols, the cluster heads are selected by a centralized entity, i.e., a base station. The residual energy and location information of each node are used as the deciding factors during cluster head selection. However, there is one major drawback of a centralized approach. The nodes need to transmit their location information and residual energy over a long distance to a base station in each round. This transmission incurs excessive burden and delay on part of each resource-starving sensor node. Like the randomly distributed cluster-based protocols, these protocols also cannot guarantee an optimal selection of cluster heads in each round. Therefore, not only the long-haul transmission to a base station need to be avoided but the optimal selection of the

cluster heads need to be improved as well.

In WSNs, the use of low-power lossy links and the broadcast nature of communication lead to network congestion. In these networks, two types of congestion arises [36]. The first type is node-level congestion which is caused by the buffer overflow of a sensor node. It may result in packet loss, increase in queuing delay and deterioration of network quality. The second type is link-level congestion which occurs when multiple sensors compete for the same transmission medium. It may result in collision which decreases network throughput, link utilization, and increases the packet service time and energy consumption of the nodes. In cluster-based hierarchical protocols, as the nodes move around the cluster field, it is highly probable that the number of nodes in a specific cluster may exceed the maximum threshold limit. It may lead to congestion, thereby resulting in packet loss, latency, blockage of new connections and QoS degradation. Time-critical applications experience severe setbacks due to congestion because time-stamped data need to be routed to a base station immediately. Minor delays in transmission will make the data useless and redundant. None of the previous studies have addressed congestion detection and mitigation in the context of cluster-based hierarchical protocols. As such, it becomes an important topic of research considering the application of cluster-based hierarchical protocols to a large-scale WSN which consists of a dense deployment of nodes.

Another factor which motivates us to use cluster-based hierarchical protocols is the application of WSN for a forest wildfire monitoring. The use of WSNs for a wildfire monitoring application is a well-studied research topic and there exists a significant amount of research in this context. However, all previous studies focused mainly on the improvement of QoS parameters of the collected data. Their main objective is to collect time-critical sensitive data and report them to a centralized base station without further delay. None of the previous studies focuses on the security aspects of the network in general and the data collected from the network in particular. Like any other application, security provisioning is a major challenging issue in wildfire monitoring application. The resource-constrained nature of WSN coupled with the remote and intimidating terrains of a forest

makes such provisioning become a daunting challenge. An adversary may capture critical alert packets, maliciously manipulates them and transmits to a base station. It may transmit false-negative alerts to a base station in order to mislead it about a particular geographical region. In doing so, attention of an end user is diverted to those regions which are less vulnerable to a possible wildfire. The application of data-centric, location-based and QoS-aware routing protocols may not achieve desirable results for security provisioning in wildfire terrains due to various factors such as implosion and overlapping [37] [38]. These factors consume a higher amount of energy and at the same time the network suffers from congestion, collision, packet loss and latency.

There has been a lot of speculations and future forecasts about the IoT products, however, most of them lack secure features and are vulnerable to a wide range of attacks. As a result, we are about to use products which are vulnerable to a wide range of security breaches. Rather than improving our lives, these products will lead us to a new era of cybercrimes. As a result, the IoT will more likely become the Internet of Vulnerabilities (IoV). Recently, Proofpoint Inc.[2] a leading security firm, uncovered a cyber-attack involving physical objects. This is considered as the first major security breach in the world of IoT. Over a period of less than two weeks, $750,000$ malicious emails were transmitted from more than $100,000$ devices. Interestingly, more than 25% of those devices were real-world objects including televisions, refrigerators and other house hold appliances. Therefore, it is necessary to design efficient algorithms to authenticate the identities of the interacting objects in order to provide secured IoT products to the customers.

1.3 Research Objectives and Contribution

In Section 1.2, we identified various research gaps which motivate us to address them. Based on those research gaps, this thesis set the following objectives and contributions. The novelty of each objective is explained as well.

[2] http://www.proofpoint.com/about-us/press-releases/01162014.php

1. A randomly distributed cluster-based hierarchical routing algorithm is proposed to improve the quality of data delivered at the base station and enhance the lifetime of the network. Unlike the existing randomly distributed cluster-based protocols, the proposed algorithm elects the cluster heads based on residual energy of each node.
2. A centralized cluster-based hierarchical routing algorithm is proposed which calculates the energy consumption of each node in various states, i.e., sensing, processing, and transmission. Based on the energy consumption in various states, a state-of-the-art energy evaluation model is developed. Unlike the existing centralized cluster-based protocols, our proposed algorithm does not take into account the long-haul transmission of location information and residual energy to a base station. Moreover, the cluster heads are no longer required to advertise themselves. Both these factors enhance the life of battery power for resource-starving sensor nodes.
3. A novel priority-based application-specific congestion control clustering (PASCCC) protocol is proposed, which integrates mobility and heterogeneity of the nodes to detect congestion in a network. PASCCC decreases the duty-cycle of each node by maintaining threshold levels for various applications. The transmitter of a node is triggered when the reading of a captured event exceeds a specific threshold value. Time-critical packets are prioritized during congestion in order to maintain their timeliness requirements. The cluster heads ensure coverage fidelity by prioritizing the packets of distant nodes over those of nearby nodes. A novel queue scheduling mechanism is proposed for cluster heads to achieve coverage fidelity, which ensures that the extra resources consumed by distant nodes are utilized effectively.
4. A lightweight Sybil attack detection scheme for a centralized cluster-based hierarchical network is proposed. In Sybil attack, an adversary forges multiple identities to the legitimate nodes. An adversary may either fabricate such identities or steal them from legitimate nodes by disabling them permanently. The existing Sybil attack detection techniques are designed primarily for data-centric routing protocols in which flooding technique is used to regulate traffic flow. Flooding allows inter-

mediate nodes to broadcast data and control packets on their way to a base station from source nodes. Duplicate packets keep circulating in the network which causes excessive energy consumption, delay, congestion, implosion and overlapping.

5. A two-tier Sybil attack detection scheme is proposed for a wildfire monitoring application. The proposed scheme operates at two levels. Initially, Sybil identities are detected by the high energy nodes at a lower level. However, due to the error-prone communication links within a forest, one or more identities of the Sybil nodes may sneak through the detection mechanism deployed at the high energy nodes. To detect such identities, two base stations are deployed which operate at a higher level. The ultimate objective of a two-tier detection scheme is to prevent the participation of Sybil nodes in cluster head selection. The proposed scheme uses a centralized cluster-based hierarchical algorithm to partition the forest into small geographical clusters. Spatial queries and on-demand queries are used to retrieve data from the sensor nodes within the forest terrains. Various environmental parameters such as temperature, relative humidity and wind speed are gathered which predicts the presence or absence of a wildfire. No previous studies to our knowledge have focused on Sybil attack detection for a wildfire monitoring application.

6. A lightweight payload-based encryption scheme for real-world physical objects in an IoT environment is proposed. It incurs a small connection overhead and is computationally simple and robust. The handshaking mechanism is used to authenticate the identities of clients and server interacting with each other. These clients and server are the real-world objects of everyday life. Our scheme restricts the malicious clients from establishing multiple connections with a server at a given time. Each client is allowed to establish only one connection with the server to fairly utilize the limited resources of the server. Authentication ensures that a legitimate server transmits the resource representation only to the legitimate clients.

1.4 Research Focus

Our research mainly focuses on energy-efficient routing and secured communication in WSNs using cluster-based hierarchical platforms. Furthermore, we take these concepts one step further by integrating sensor nodes in real-world physical objects to form an IoT and design a secured authentication scheme for the interacting objects. Irrespective of energy-efficient routing or secured communication, the ultimate goal of our research is to enhance the lifetime of the network. In Fig. 1.1, we show the importance of our research focus.

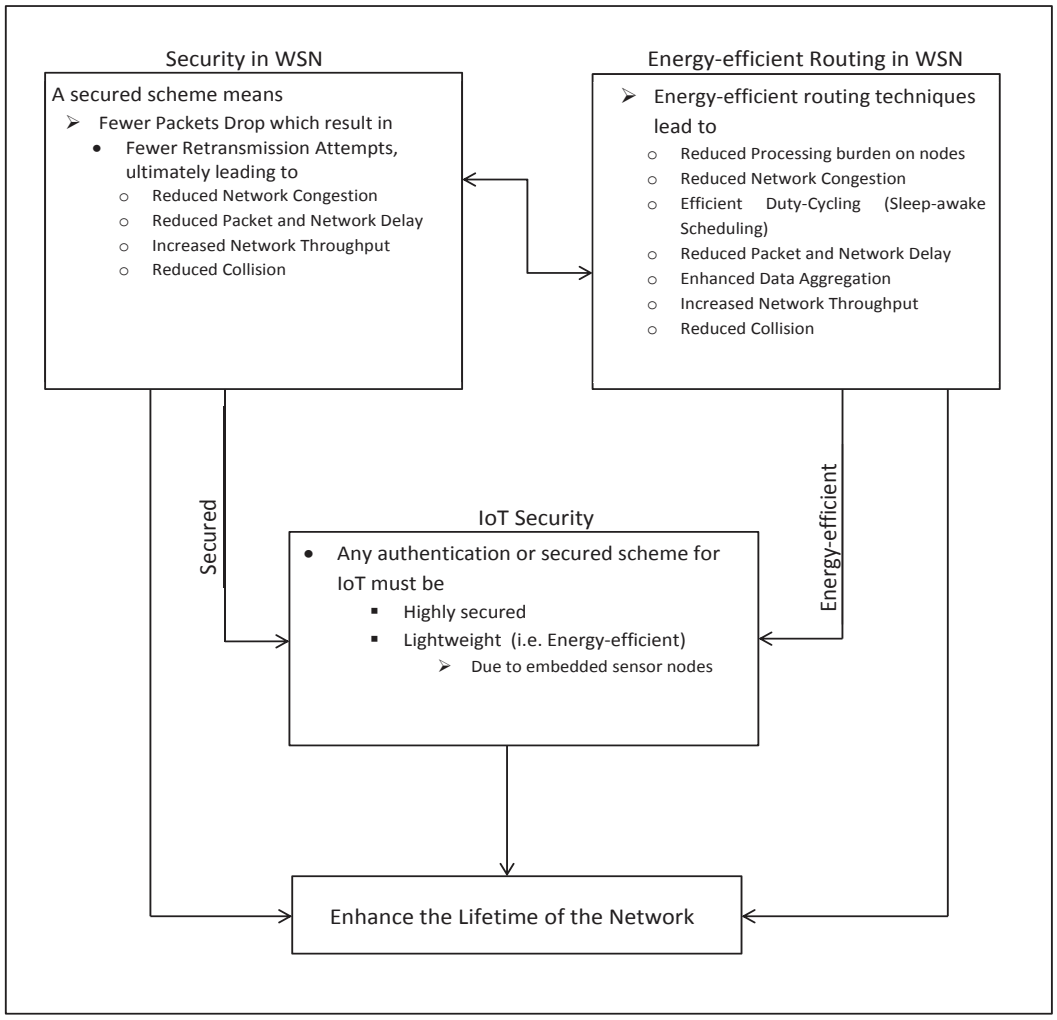


Figure 1.1: Research Focus

A network secured against one or more attacks drops fewer packets which reduces the number of retransmission attempts. Hence, energy consumption for such a network is much less compared to a network which does not have security measures in place. This also improves the overall performance. As a result, network congestion, packet and network delay, and collision are reduced, while the network throughput is increased. An energy-efficient routing technique reduces processing burden on each node, decreases network congestion through efficient duty-cycling, reduces collision and enhances the data aggregation capabilities of each node. All these factors increase the network throughput by reducing the delay incurred by the network in general and packets in-transit in particular. A secured network using an energy-efficient routing scheme as the underlying platform can benefit from its distinguishing features. This idea motivates us to design a robust and secured scheme for detecting Sybil attack using an underlying cluster-based hierarchical platform. Moreover, the presence of embedded sensor nodes at the core of each physical object requires extremely lightweight but highly secured authentication schemes in an IoT paradigm. These features can be acquired from WSNs if proper consideration is in place while profiling the energy-efficient routing techniques and secured algorithms of WSNs.

1.5 Structure of the Thesis

The rest of this thesis is organized as follows. A review of prior research works on cluster-based hierarchical routing protocols, IoT and Sybil attack is conducted in Chapter 2. Chapter 3 proposes an energy-efficient randomly distributed cluster-based hierarchical routing algorithm along with a centralized cluster-based hierarchical routing algorithm. The operational model of the centralized cluster-based algorithm is used to derive an energy evaluation model which computes the energy consumption of various type of nodes in different states. Chapter 4 proposes a novel priority-based application-specific congestion control clustering (PASCCC) protocol, which integrates mobility and heterogeneity of the nodes to detect congestion in a network. PASCCC uses randomly distributed cluster-based hi-

erarchical routing algorithm of Chapter 3 as the underlying platform for its operation. In Chapter 5, a lightweight Sybil attack detection scheme is proposed for a centralized cluster-based hierarchical network. The detection technique uses the signal strength of the received packets for the identification of Sybil nodes and their forged identities. In Chapter 6, a Sybil attack detection technique for a forest wildfire monitoring application is proposed. The geographical region of a forest is partitioned into small clusters by a centralized cluster-based hierarchical algorithm. The proposed technique uses two different types of queries to collect data from nodes within the network. In Chapter 7, a lightweight mutual authentication scheme is proposed for validating the identities of the interacting physical objects. These physical objects are part of a home automation system, which is an IoT application. Furthermore, replay attacks and their mitigation techniques are discussed for the same application. Finally, summary and future work are drawn together with the thesis conclusion in Chapter 8.

Chapter 2

Literature Review

There has been a wide spectrum of work during the last decade involving Wireless Sensor Networks (WSNs). The ability of these networks to operate in human-inaccessible terrains and hazardous locations have attracted a lot of research for addressing various challenges faced by these networks at different layers. There exists a wide range of applications which operate in a hostile environment. The presence of a hostile environment literally means that the operating devices fail quite frequently and it is practically infeasible to repair them. The frequent failure of devices means that these applications require low-cost replaceable devices. Furthermore, these applications do not support the wired mode of transmission and require a cost-effective multi-hop wireless communication. The data generated by these applications is mostly sporadic in nature. To reduce the cost of operation, the devices need to remain in sleep mode and wake up periodically to capture the data. To meet the above requirements, we need such devices which are of low-cost, replaceable, support multi-hop wireless transmission, and have the ability to operate in sleep and idle modes for energy conservation. Only, wireless sensor nodes have the ability to fulfil the above requirements of such applications.

This chapter presents a survey of related works that serve as a background to our research objectives. In Section 2.1, we provide a brief overview of WSN, its types and its

applications. In Section 2.2, various components of a sensor node are discussed. In Section 2.3, an overview of conventional routing protocols and their drawbacks is provided. In Section 2.4, we provide a detailed description of cluster-based hierarchical routing protocols in terms of their energy-efficient nature. Various congestion detection and mitigation protocols in WSNs are also discussed in this section which reflects our goals to develop an energy-efficient congestion detection protocol for a cluster-based hierarchical network. In Section 2.5, we discuss the existing Sybil attack detection techniques in WSNs which motivate us to apply such techniques to a cluster-based hierarchical network. We also discuss the need for a Sybil attack detection technique in a wildfire monitoring application in this section. We conclude this chapter with the discussion of Internet of Things (IoT) in Section 2.6.

2.1 Overview of Wireless Sensor Network

Wireless Sensor Network (WSN) consists of a number of miniature sensor nodes working together to monitor a geographical region and obtain data about the deployed environment [1]. The application of WSN in monitoring these regions enable us to quantify physical parameters such as humidity, temperature, pressure and movement in a rapidly changing dynamic environment. Based on the deployment of the nodes, WSNs can be further subdivided into two categories: unstructured and structured. An unstructured WSN consists of a dense deployment of nodes which are left unattended to collect the data. The nodes are deployed in an ad hoc[1] fashion into the sensor field. The major drawback of such deployment is the provisioning of network maintenance, failure detection and connectivity management. The presence of a large number of nodes makes these tasks rather complicated and difficult to provide. In a structured WSN, all or some of the nodes are deployed in a pre-planned manner and the number of nodes is relatively less as compared to an unstructured WSN. As a result, it is relatively easy to maintain such a network. Moreover, the

[1] In ad hoc deployment, sensor nodes are randomly placed into the field. One way of random deployment is by dropping sensor nodes from plane.

link or node failure can easily be detected and connectivity is managed with ease as well. The use of a structured or unstructured WSN depends on the requirements of a specific application.

A typical WSN deployed to collect data about an environment is shown in Fig. 2.1. The major components of this network are sensor nodes, a base station and a sensor field. The nodes monitor the sensor field for the happening events. An event or phenomena of interest is the data generated by a monitored application. For example, an event may be the temperature, relative humidity and wind speed alert packets generated during a wildfire monitoring application. The operation of each node depends on the nature of these events. Once an event is detected, it is reported to a base station using multi-hop transmission links. After further analysing the data, the base station makes it available on the Internet, which the users can access with their computers or handheld devices provided they have privileges to do so. The nodes which sensed the events are known as source nodes while the nodes which process the data during its transit to a base station are known as intermediate nodes.

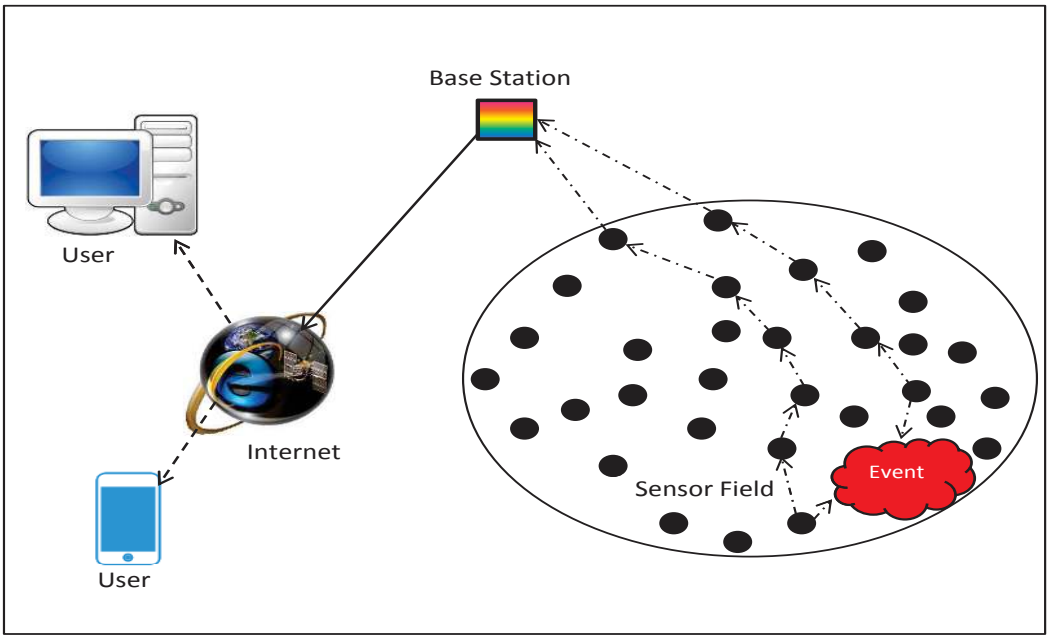


Figure 2.1: Wireless Sensor Network

In WSNs, multi-hop transmission links are used for communication because the nodes are not capable of long-haul transmission. The data traffic in these networks can be classified into three categories [39]: periodic, query-based and event-driven. In periodic traffic, the nodes transmit their measurements to a base station after a fixed time interval. In query-based traffic model, the sensor nodes sense and capture the data according to an end user or a base station's specific query. The base station specifies the required data and its attributes in the query. Attributes contain certain conditions which need to be fulfilled by each node before data transmission to the base station take place. In the event-driven model, the sensor nodes remain in sleep mode for most of their lifetime and wake up only when a specific event is detected. The occurrence of an event may take years to happen, for example, volcanic eruption [40].

Depending on the deployed environment, WSNs can be subdivided into five types [1]: underground WSN, underwater WSN, terrestrial WSN, mobile WSN and multi-media WSN. Terrestrial WSNs [41] typically consist of a dense deployment of nodes in a given geographical area. In a dense deployment, nodes are prone to frequent failure and they experience high level of network congestion. Moreover, dense deployment may result in high degree of retransmission attempt which may further delay the delivery of highly critical data to the base station. Underground WSNs [42] consists of sensor nodes deployed underground or in a cave or mine. Although, the sensor field is deployed underneath the ground, however, the base station is deployed above the ground. The presence of sensor nodes beneath the earth surface makes these networks expensive in terms of operation cost, maintenance and sensor nodes. Underwater WSNs [43] consist of sensor nodes deployed underwater to monitor the seabeds and similar applications. These networks use autonomous underwater vehicles to collect data from sensor nodes. Similar to underground WSNs, communication among the nodes in these networks is a challenging task due to limited available bandwidth, signal fading, node failure and propagation delay. Multi-media WSNs [44] support applications which demands high bandwidth, high data processing and compressing capabilities, high energy consumption and minimum transmission delay.

These networks are typically deployed to capture events such as audio, video and imaging. The sensor nodes in these networks are equipped with cameras and microphone. Mobile WSNs [45] are composed of sensor nodes which are capable of moving around the sensor field to sense an environment. The challenges faced by these networks are localization, deployment, navigation and control, coverage and self-organization. These networks are suitable for applications where the deployed environment is hostile and the occurrence of events is not confined to a specific geographical location.

There exist a wide range of applications of WSNs which can be subdivided into two categories: tracking [46] and monitoring [47]. Tracking applications pertain to locating the position of humans [48], animals [49], vehicles [50] and physical objects [51]. On the other hand, monitoring applications include agriculture monitoring [52], industrial automation [53], forest wildfire monitoring [5], smart city [54] etc. Some of the applications of WSNs are shown in Fig. 2.2.

2.2 Hardware Components of a Node

There are four basic components of any sensor node [55]: a sensor, a processor, a radio transceiver and a power unit. Apart from these essential components, each node may have additional components such as, a location finding unit, a mobilizer, a power generator, a storage unit and an analog-to-digital converter (ADC). The hardware architecture of a node is shown in Fig. 2.3.

The sensor unit is responsible to sense the deployed environment for capturing the data. Each node is equipped with one or more sensors depending on the need of an application and the type of generated data. The sensed data are the analog physical signals which need to be digitized. The ADC unit transforms these analog signals to digital form and sends to a processing unit which processes it and feeds into a radio transceiver for ultimate transmission to a neighbouring node. The radio transceiver is capable of simultaneous transmission and reception of data from the neighbouring nodes. The power unit is responsible for man-

Figure 2.2: Applications of WSN

aging the energy consumption of a node. Each node is equipped either with AA batteries or quartz cells which act as the power source. The location finding unit is the additional component which is used to find the location of a node. Various localization algorithms are used to program this module in order to find the exact location of the neighbouring nodes for accurate data delivery and updating routing tables. A mobilizer enables the node to move around the field to cover geographical regions and detect the happening events. The use of a mobilizer is application-specific and is mostly used in such applications in which the occurrence of the events is dynamic and location is hazardous. The storage unit is used

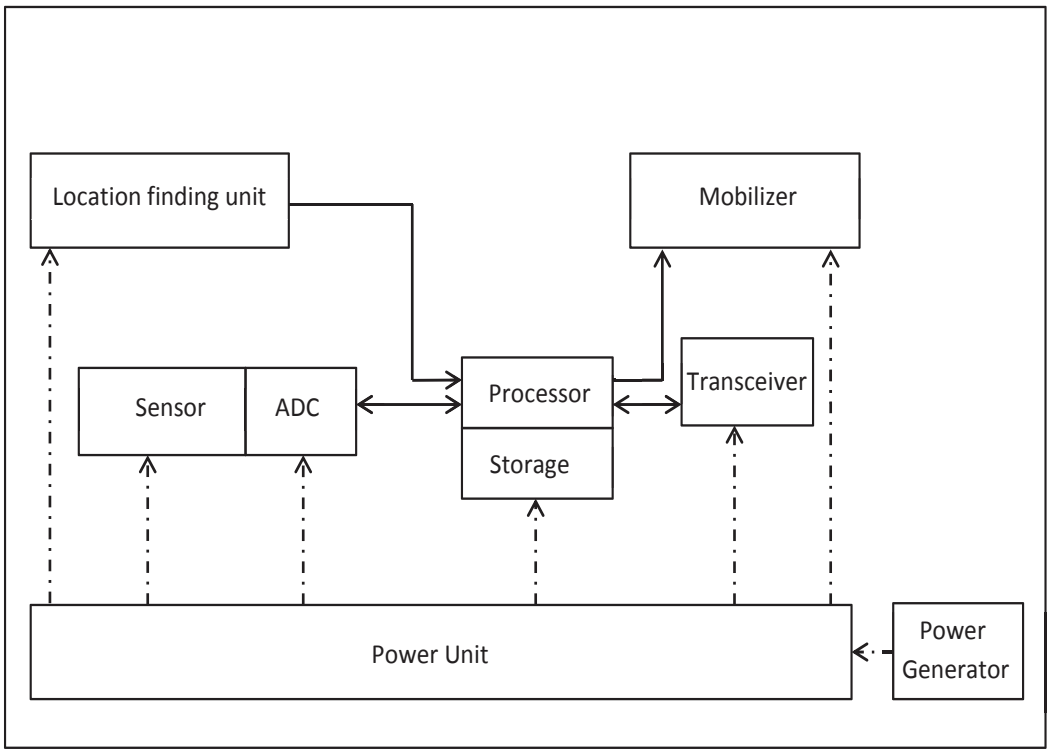


Figure 2.3: Hardware Architecture of a Node

for the temporary storage of the sensed data. The processing unit retrieves the data from the storage unit, processes it and transmits to the neighbouring nodes or a nearest base station. Nowadays, smart sensor nodes are available in the market which are equipped with relatively high amount of external flash memory (ROM) along with the primary storage unit (RAM). Many applications require the nodes to operate over a longer period of time. In these applications, the power unit may not be sufficient to sustain the nodes. To meet these requirements, a power generator is used to prolong the lifetime of each node. The power generator is provided in the form of a solar cell or energy scavenging technique [56].

The technological advancement in the field of WSN has brought small-sized, low-cost and highly intelligent sensors in the market. These sensors, also known as smart sensors are highly efficient in terms of processing, storage, transmission and energy consumption. They support high data rate at the expense of relatively smaller amount of energy consumption. Many people consider the node and sensor as the same device. They are not

the same because sensor is one of the components of a node. However, the terms can be used interchangeably for the sake of simplicity. In WSN, each sensor node hosts a protocol stack [57] which is used for various tasks such as, efficient routing, data aggregation and collaboration among the nodes. This stack consists of five layers, i.e., physical, data link, routing, transport and application layer. Furthermore, the stack also includes a power management plane, mobility management plane and a task management plane. The power management plane is used for the management of power unit of a node. This plane manages the power consumption during sensing, processing and transmission. The mobility management plane manages the mobility of a sensor node by keeping track of its trajectories. Moreover, this plane is responsible for establishing a route to the user and other neighbouring nodes. The task management plane is responsible for sensing and detecting events in a particular geographical region. The protocol stack of a WSN residing on each node is shown in Fig. 2.4.

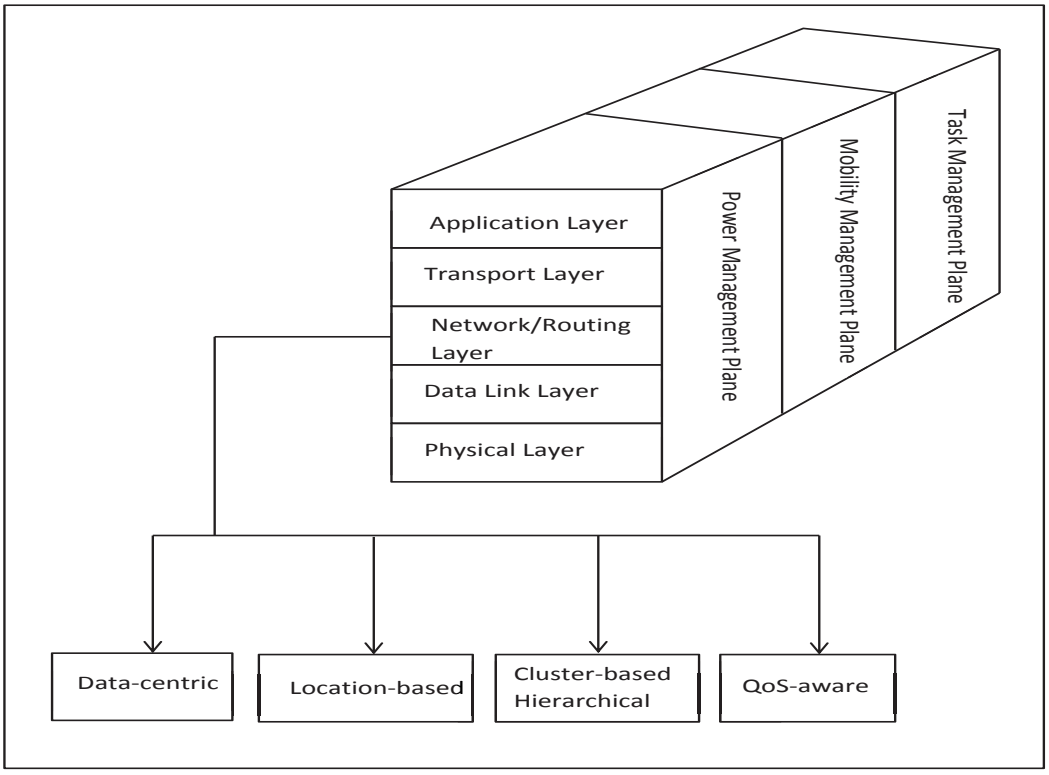
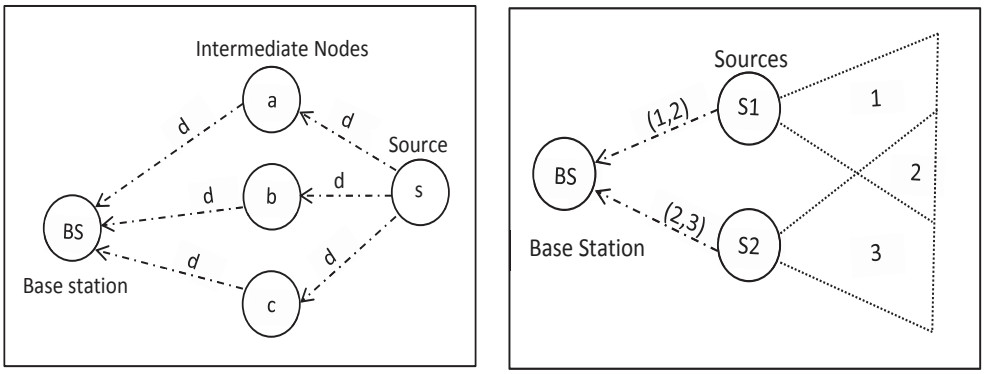


Figure 2.4: WSN Protocol Stack

Similar to the TCP/IP model [58], the lower layers support the upper layers in WSN. Each layer has specific protocols which carry out various tasks and functionalities pertaining to that layer. Our research is specifically related to the routing layers of a WSN. Therefore, only the routing protocols are shown in Fig. 2.4. Among these routing protocols, we will focus mainly on the cluster-based hierarchical protocols in view of their distinguishing features as discussed in Chapter 1.

2.3 WSN Routing Protocols

In Chapter 1, we explained some of the distinguishing features of cluster-based hierarchical routing protocols which make them an ideal choice for any WSN application. These features make them prominent among all other routing protocols used across WSN. Almost all of the routing protocols rely on flooding to some extent for routing the data towards the base station. Flooding has several drawbacks such as implosion and overlapping. The cluster-based hierarchical protocols also suffer from these drawbacks. However, they address them at the cluster head level which ensures that high quality data is delivered at the base station with little or no redundancy. The rest of the protocols, i.e., data-centric, location-based and QoS-aware suffer serious setbacks due to these drawbacks. The drawbacks of flooding are shown in Fig. 2.5 [59].



(a) Implosion (b) Overlapping

Figure 2.5: Drawbacks of Flooding

During implosion, a source node s broadcasts the sensed data packet d to all of its neighbouring nodes, also known as intermediate nodes as shown in Fig. 2.5(a). Each intermediate node further transmits the data resulting in multiple copies of the same data at the base station. In this figure, only three intermediate nodes are shown. The consequences may further worsen provided there are multiple source nodes and a large number of intermediate nodes. In overlapping, multiple source nodes sense the same geographical region. In Fig. 2.5(b), a source node $S1$ senses a geographical region, known as 2, which is also sensed by its neighbouring source node $S2$. A single region sensed by multiple source nodes is known as an overlapping region. The sensing of an overlapping region results in duplicate packets at the base station as shown in Fig. 2.5(b). Both implosion and overlapping consume a considerable amount of energy. They both lead to another drawback known as resource blindness [11] in which the nodes do not take into account their energy limitation while relaying the data to the base station.

To address the drawback of flooding, gossiping technique [60] was developed which randomly selects any one of the intermediate nodes. The problem with gossiping is that it is probable that the randomly selected intermediate node may be a malicious node or it may have relatively lower energy than the rest of the neighbouring nodes. Moreover, it is also possible that the randomly selected intermediate node may be far away as compared to others which may further increase the energy consumption. The random selection introduces too much latency during selection process which may not be a feasible option for most of the priority-based data transmission applications. Both flooding and gossiping have their own drawbacks such as data redundancy, energy consumption, and degradation in the QoS parameters such as delay, jitter and throughput. Moreover, excessive delay or latency may result in network congestion either at the nodes or at the links. Our next section on cluster-based hierarchical routing protocols is specifically designated to address these issues, i.e., high energy consumption and congestion in any WSN.

2.4 Cluster-based Hierarchical Routing Protocols

In a large-scale WSN, the data sensed by the source nodes experience excessive delay, retransmission attempts, high energy consumption, high redundancy and low throughput. Moreover, excessive delay and retransmission attempts lead to high network congestion while high redundancy leads to deterioration in the quality of delivered data at the base station. The cluster-based hierarchical routing protocols solve these problems by partitioning a large-scale WSN into small clusters and achieve better results as compared to data-centric, location-based and QoS-aware routing protocols. In this section, first we discuss the types of cluster-based hierarchical routing protocols with particular emphasis on their energy consumption because our main objective is to improve the lifetime and quality of data in these protocols. Next, we discuss the need for a congestion detection protocol in hierarchical networks formed by cluster-based hierarchical routing protocols.

2.4.1 Types of Cluster-based Hierarchical Routing Protocols

Broadly speaking, the cluster-based hierarchical routing protocols are of two types: randomly distributed (Self-organized) and centralized (Base Station Assisted). These two types are differentiated based on their cluster characteristics, cluster head selection technique and clustering process [16]. In this section, first we explain the randomly distributed cluster-based hierarchical routing protocols followed by the centralized cluster-based hierarchical routing protocols.

In randomly distributed cluster-based hierarchical routing protocols, each node decides on its own whether or not to become a cluster head. These protocols do not require any negotiation among the sensor nodes for cluster head selection. Low-Energy Adaptive Clustering Hierarchy (LEACH) [61] is designated as a pioneer protocol among the randomly distributed cluster-based hierarchical routing protocols. LEACH is a self-organizing, adaptive clustering protocol that uses randomization for the uniform distribution of energy load among the sensor nodes. The uniform distribution of energy load reduces the transmission

burden on any particular sensor node. LEACH partitions a sensor field into small geographical regions known as clusters. Each cluster has a cluster head node which collects and aggregates data from member nodes within the cluster and transmits to a base station. Thus, the task of transmitting data to a base station is restricted to only few nodes, i.e., the cluster heads. LEACH is iterative in nature and operates in rounds. Each round consists of two phases, a set-up phase and a steady-state phase. Moreover, the set-up phase consists of three sub-phases, i.e., cluster head selection, cluster formation and schedule creation. The decision of any node to become a cluster head is influenced by certain factors such as, the optimal percentage of cluster heads and the number of times a node has been elected as cluster head so far. The optimal percentage of cluster head depends on the network size and is decided at the time of network deployment. To elect itself as cluster head, each node n chooses a random number between 0 and 1. If this number is less than the threshold value $T(n)$ of Equation 2.1, the node is elected as a cluster head for the current round.

$$T(n) = \begin{cases} \frac{k_{opt}}{1-k_{opt}(rmod(\frac{1}{k_{opt}}))}, & if\ n \in G, \\ 0, & otherwise. \end{cases} \tag{2.1}$$

Here, k_{opt} is the optimal percentage of cluster heads in each round, r is the current round and G is the set of nodes that have not been elected as cluster heads in the past $\frac{1}{k_{opt}}$ rounds. The value of k_{opt} normally ranges from 5% to 10% depending on the size of a network. Using Equation 2.1, each node will get a chance to become a cluster head at some point within $\frac{1}{k_{opt}}$ rounds. During the first round, i.e., $r = 0$, each node has a probability k_{opt} of becoming a cluster head. The nodes which elect themselves as cluster heads in round 0 cannot become cluster heads for the next $\frac{1}{k_{opt}}$ rounds. As a result, the probability of the remaining nodes to become cluster heads increases for the next $\frac{1}{k_{opt}}$ rounds. After $\frac{1}{k_{opt}} - 1$ rounds, $T = 1$ for any node that has not yet been elected as cluster head. After $\frac{1}{k_{opt}}$ rounds, all the nodes are once again eligible to be elected as cluster heads. In Equation 2.1, if $n \notin G$, it means that n has already been elected as cluster head over the past $\frac{1}{k_{opt}}$ rounds.

Therefore, T=0 and n cannot be elected as cluster head for the current round.

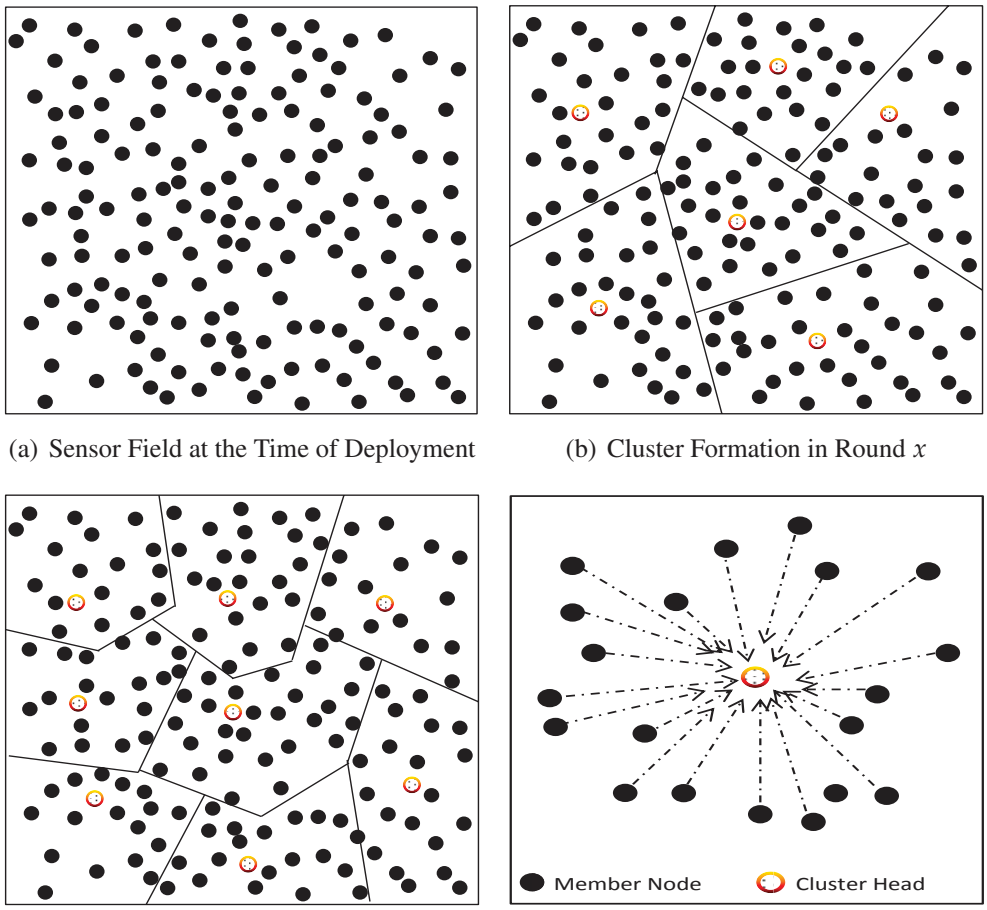
Each cluster head broadcasts an advertisement message containing its ID and location information. The neighbouring nodes keep their transmissions *on* to hear the advertisement messages from the elected cluster heads. They may receive multiple advertisement messages from the cluster heads located in their vicinity. However, each neighbouring node associates itself with a cluster head having the strongest signal strength. Once a neighbouring node decides to join a particular cluster head, it transmits a join-request message to that cluster head. The join-request messages show the willingness of neighbouring nodes in cluster formation and participation as member nodes in cluster communication. Each cluster head must keep its receiver *on* during the transmission of join-request messages. These join-request messages enable each cluster head to determine the size of its respective cluster, i.e., the number of member nodes in a cluster. Once each cluster head receives join-request messages, TDMA slots are assigned to the member nodes. The allocation of TDMA slots, also known as TDMA schedule, signals the end of cluster formation sub-phase and initiation of schedule creation sub-phase. After schedule creation, the nodes are ready to transmit the sensed data to their respective cluster heads. The assignment of TDMA slots reduces the contention for wireless medium among the member nodes and they can transmit their data using the allocated slots. The selection of cluster heads, the formation of clusters and the creation of TDMA schedule signals the end of set-up phase and initiation of steady-state phase. During the steady-state phase, each node remains in sleep mode and wakes up only on its allocated TDMA schedule to transmit the data to its designated cluster head. Each member node goes to sleep mode after the transmission of its data. However, each cluster head must keep its receiver *on* all the time during the steady-state phase. Once each cluster head receives data from its member nodes, it aggregates the data and transmits to a base station. It is highly probable that the neighbouring member nodes may have sensed similar data packets, hence, there will be redundancy in the data packets.

To reduce or eliminate the redundancy, each cluster head performs fusion by eliminat-

ing multiple copies of the same data. Each cluster head is capable to compress various data packets into a single composite signal. The tasks of each cluster head are resource-intensive because it performs data aggregation, fusion and long-haul transmission to a base station. Moreover, cluster head-advertisement along with keeping the receiver *on* during join-request messages are also resource-intensive tasks. All these tasks consume a considerable amount of energy. As a result, a new set of cluster heads are elected in each round for the uniform distribution of energy load on all the nodes in the network. Once the cluster heads transmit the aggregated data to a base station, the steady-state phase is completed. The completion of set-up phase and steady-state phase is coined as one complete round. A new round starts after the completion of steady-state phase and the same operations, i.e., set-up and steady-state phases are repeated in each round. The operations performed during set-up and steady-state phases is shown in Fig. 2.6.

In Fig. 2.6(a), the sensor field at the time of network deployment is shown. The nodes are yet to organize themselves into clusters. In Fig. 2.6(b), the cluster heads are elected and clusters are formed around them. Each cluster head collects data from member nodes and transmits to a base station which may be located inside or outside the sensor field depending on the need of an application. Once data is transmitted to a base station, a new set of cluster heads are elected in the subsequent round as shown in Fig. 2.6(c). Each cluster head creates a schedule for member nodes which enable them to transmit data on their turn. In Fig. 2.6(d), the internal operation within each cluster is shown. The member nodes remain in sleep mode, but wake up on their allocated schedule and transmit data to their respective cluster heads.

LEACH protocol has a single hierarchy, i.e., member nodes transmit their data to the cluster heads which in turn transmit to a base station. However, in many applications, there may be a dense deployment of nodes in a wide geographical region. In that case, the member nodes may need to transmit over a long distance to the base station. Moreover, the cluster heads may be located at a far distance from the base station. As a result, both the member nodes and cluster heads may deplete their energy much faster than expected.



(a) Sensor Field at the Time of Deployment

(b) Cluster Formation in Round x

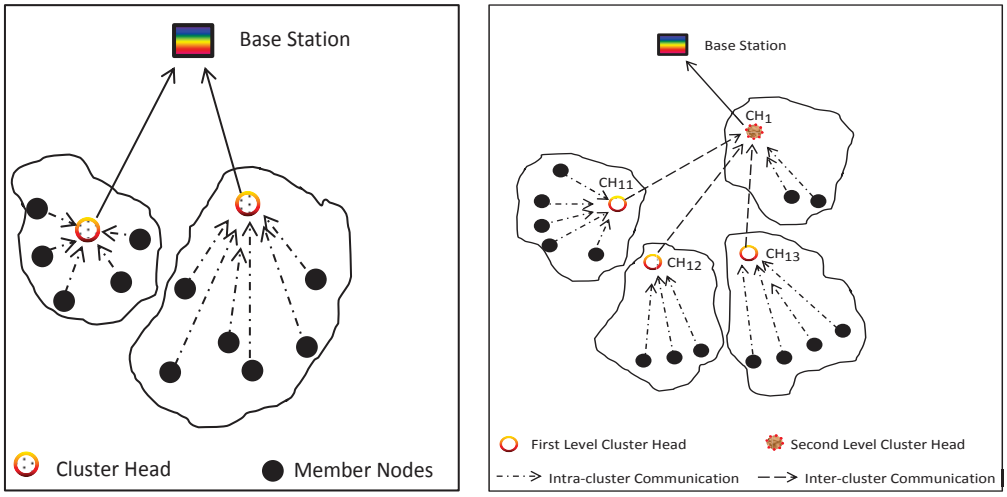
(c) Cluster Formation in Round x+1

(d) Communication at the Cluster Level

Figure 2.6: Randomly Distributed Cluster-based Hierarchical Routing

To solve the energy consumption problem, multi-level hierarchy was introduced in which the member nodes transmit data to their respective cluster heads which in turn transmit to the cluster heads one level above them. In Fig. 2.7, the different levels of a randomly distributed cluster-based hierarchical WSN architecture is shown.

The cluster heads at different levels in a multi-level hierarchical architecture are similar to each other in terms of operation. They have their own member nodes and they act as relay nodes for the lower-level cluster heads. Multi-level hierarchical architecture has its own benefits such as efficient data aggregation and fusion and lower energy consumption. However, the sensed data experience excessive delay at different levels during its



(a) Single-level Hierarchical WSN (b) Multi-level Hierarchical WSN

Figure 2.7: Different Levels of Hierarchy

transit. The cluster heads at each level perform data aggregation and fusion to improve the quality of data which in turn delay the transmission of data to the base station. As a result, multi-level hierarchical architecture may not be beneficial for applications where the timely delivery of data at the base station is of utmost importance. Irrespective of a single-level or multi-level hierarchical architecture, the randomly distributed cluster-based hierarchical routing protocols elect cluster heads using a random number generation technique. The probabilistic selection of cluster heads has a potential risk of low energy nodes being elected as cluster heads in subsequent rounds. Moreover, Equation 2.1 cannot guarantee an optimal number of cluster heads in each round. These protocols elect anything between 0 and 22 cluster heads in various rounds (explained in Chapter 3). If no cluster heads are elected in a particular round, it means that these protocols operate similar to the data-centric and location-based protocols as discussed in Chapter 1.

One way of solving the optimal selection problem is the inclusion of residual energy value of each node in Equation 2.1. The cluster heads need to be elected based on the residual energy of the nodes. There exist various schemes which elect the cluster heads based on the available resources of a node. For example, protocols such as LEACH-B [62], Energy-

LEACH [63], Distributed Energy-efficient Clustering protocol (DEEC) [64] and Hybrid Energy-efficient Distributed Clustering protocol (HEED) [65] elect the cluster heads based on the residual energy of the nodes, dissipated energy during the current round and average node energy. Another way of solving this problem is assigning the responsibility of selection to a central controller, i.e., a base station. In [66], the authors proposed LEACH-Centralized (LEACH-C) protocol which adopts a centralized approach for cluster head selection. The nodes having remaining energy greater than the average residual energy are elected as cluster heads in each round. However, it is highly probable that there will be a large number of such nodes in each round which will result in too many cluster heads. There are numerous protocols which are based on LEACH-C and rely on base station for cluster head selection. In [67], Base-Station Initiated Dynamic Routing Protocol (BIDRP) is proposed which is specifically used for heterogeneous sensor networks. In BIDRP, some nodes have higher energy in the network. These nodes are always elected by the base station as cluster heads in each round. In [68], the authors proposed a centralized scheme which elected an optimal percentage of cluster heads (5% of total nodes). Each round results in balanced clusters which enhance network stability, scalability and data aggregation. The main drawback of the centralized approach is the excessive delay experienced in cluster head selection. The base station consumes a considerable amount of time during selection process. Moreover, the selection process is complicated and requires extensive computation.

The main difference between the centralized approach and the randomly distributed approach is the cluster head selection methodology. In randomly distributed cluster-based hierarchical routing protocols, each node decide itself whether or not to become a cluster head. However, in centralized cluster-based hierarchical routing protocols, the base station is the main entity which elects the cluster heads. Moreover, the base station tries to form balanced clusters in which there is equal distribution of nodes. The rest of the operations, i.e., cluster formation, cluster head advertisement, schedule creation and data transmission are exactly similar in both these approaches. Furthermore, the concept of single-level and

multi-level hierarchical architecture is equally applicable to both these approaches.

2.4.2 Congestion Detection in Cluster-based Hierarchical Protocols

In WSNs, the protocols at transport layer are responsible for establishing an end-to-end connection to provide various services such as data flow, reliability, packet loss recovery and congestion detection and mitigation [69]. Moreover, these protocols manage bandwidth allocation and support heterogeneous application. Transport protocols such as User Datagram Protocol (UDP) [70] and Transport Control Protocol (TCP) [71] are not suitable for WSN applications due to their nature of operation. The UDP protocol does not offer flow control, reliability and congestion control. These are desirable features of any WSN application. In contrast, TCP protocol requires an end-to-end reliability and retransmission of lost packets. However in WSNs, the nodes are equipped with small batteries which cannot afford such expensive retransmission of data to the base station. These nodes support hop-by-hop communication for data delivery and the rate of flow on each hop is different. Therefore, it is very difficult to establish a reliable end-to-end connection from a source node to the base station for data delivery. In these networks, some hops have higher network traffic compared to others. On any hop, a node may fail or a link may be broken down, in which case, alternate paths need to be established.

The concept of hop-by-hop and end-to-end connection is shown in Fig. 2.8. In this figure, multiple end-to-end connections are shown. On one such connection, there are 8 hops between a source node and the base station. It is difficult to ensure the reliability of this connection between them. If the overloaded nodes fail or the hops on which they reside are broken down, the upstream traffic to the base station will be lost. These overloaded nodes and the hops on which they reside causes congestion during heavy traffic flow. In WSNs, congestion arises when the nodes are overloaded, i.e., the packet arrival rate is higher than the packet processing rate. Congestion also occurs when the rate of traffic on the links exceed than their available capacity. Congestion on the links mainly occurs due to interference, contention for wireless channel and blind mote problem [72].

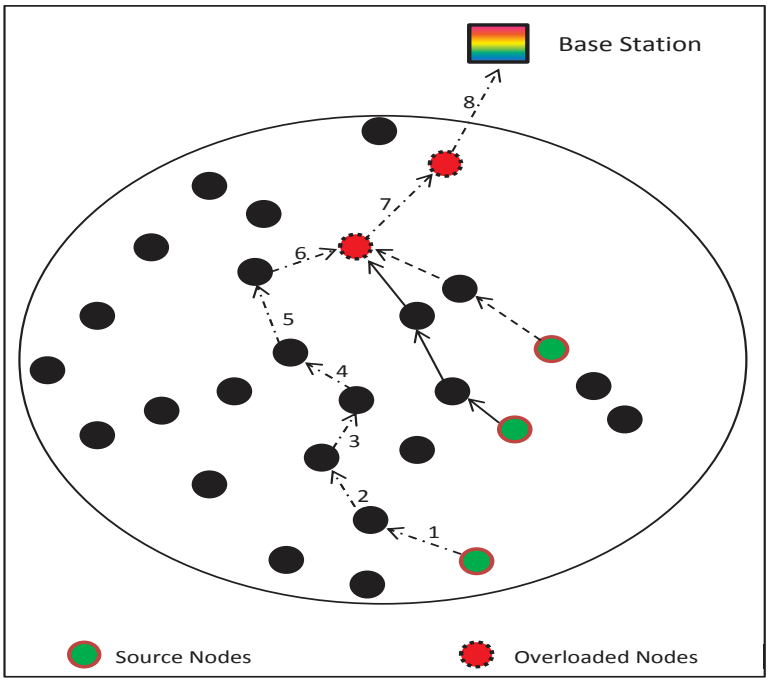


Figure 2.8: Hop-by-Hop Communication vs. End-to-End Communication

In WSNs, congestion causes packet loss, latency, degradation in network throughput, energy consumption and blockage of new connections. In literature, there exists various congestion detection and mitigation protocols at transport layer. In [73], the authors proposed an end-to-end, hop-by-hop congestion control protocol known as COngestion Detection and Avoidance (CODA). In CODA, the nodes near congested regions drop packets according to an Additive Increase and Multiplicative Decrease (AIMD) scheme [74] by monitoring and controlling the packet generation rate of each source node. CODA decreases the level of congestion but the retransmission of packets still remains high, which imposes an extra burden on energy-starved sensor nodes. In [75], the authors proposed the Fusion protocol for congestion detection based on static threshold levels. In Fusion, each node dynamically acquires a channel based on the occurrence of events, thereby making it difficult to pre-set a suitable threshold level. In [76], the Event-to-Sink Reliable Transport (ESRT) protocol was proposed. In ESRT, each node monitors its buffer occupancy for congestion detection. When the buffer is full, each node set a one bit congestion-notification

field in the header of each outgoing packet to inform the neighbouring nodes about the current status of its buffer. Each source node transmits data to the base station periodically at a predetermined rate. The drawback of ESRT is that the predetermined rate is applicable to each source node, which makes it unfair in terms of resource utilization. This is because the nodes in the congested regions are not capable of transmitting at the predetermined rate set by the base station. In [77], the authors investigated network congestion behaviour based on the optimal packet size using the Automatic Repeat reQuest (ARQ) protocol. The transmission of smaller packets with a high Bit Error Rate (BER) and larger packets with a low BER reduces the number of retransmission attempts and it effectively improves the network resource utilization. The proposed scheme determines the optimal packet size to reduce congestion with unpredictable BERs.

The existing congestion detection and mitigation protocols have certain drawbacks [78]. These protocols detect and mitigate congestion either through hop-by-hop or through end-to-end approaches. These protocols do not support an adaptive congestion control mechanism which has the ability to integrate both these approaches. Although, CODA uses both the approaches, however, it has no adaptive congestion control mechanism. As a result, CODA and other existing transport layer congestion detection and mitigation protocols are not applicable to a large scale WSN supporting diverse applications. The use of an adaptive mechanism is desirable because it reduces the energy consumption and simplifies the operation of sensor nodes. Another major drawback of the existing protocols is that they provide either application-level reliability or packet-level reliability, not both of them. If a sensor network supports two different applications such that, one of the application requires packet level reliability and another one requires application-level reliability, then the existing protocols may not produce optimal results. Moreover, the existing transport layer protocols for congestion detection and mitigation lack the support for cross-layer optimization. However, the lower layers, i.e., the network layer and data link layer provide various services to the transport layer. The services of these layers can be used to develop a robust congestion detection and mitigation protocol.

In view of the above discussion, our aim is to develop an energy-efficient cluster-based hierarchical routing protocol which detects congestion in a heterogeneous WSN supporting two different applications. Our proposed protocol partitions the network into small clusters. The presence of clusters in a network reduces the number of hops which eases the provisioning of end-to-end reliability as well. Furthermore, the number of hops directly affects the performance of any congestion detection and mitigation protocol. If a network has less hops, it mean that it is relatively easy to detect the nodes and links causing congestion in that network. Our proposed protocol is energy-efficient as well because it effectively schedules the duty-cycling of each node, i.e., the nodes remain in sleep mode and wake up only on their allocated time slots to transmit data. In our proposed protocol, one application has high priority while the second has low priority. At the time of congestion, the nodes drop low priority packets and transmit only the high priority packets to reduce the effect of congestion. The work in Chapter 4 is solely dedicated to this contribution.

2.5 Sybil Attack Detection

The word Sybil is named after the subject of a book titled Sybil, a case study of a woman diagnosed with dissociative identity disorder [79]. The name Sybil was suggested in or before 2002 by Brian Zill at Microsoft Research. First we discuss the existing literature on Sybil attack detection in WSN in Section 2.5.1 followed by the need for a Sybil attack detection scheme in a forest wildfire monitoring application in Section 2.5.2.

2.5.1 Detection of Sybil Attack in WSN

In WSNs, communication over an error-prone wireless channel exposes nodes to various types of malicious activities. Among them is Sybil attack where an adversary forges multiple identities at a given time to mislead legitimate nodes into believing that they are having many neighbours as shown in Fig. 2.9. An adversary may either fabricate such identities

or steal them from legitimate nodes by disabling them permanently. In doing so, the adversary may influence the outcome of data aggregation, fair resource allocation and voting on suspicious nodes [80].

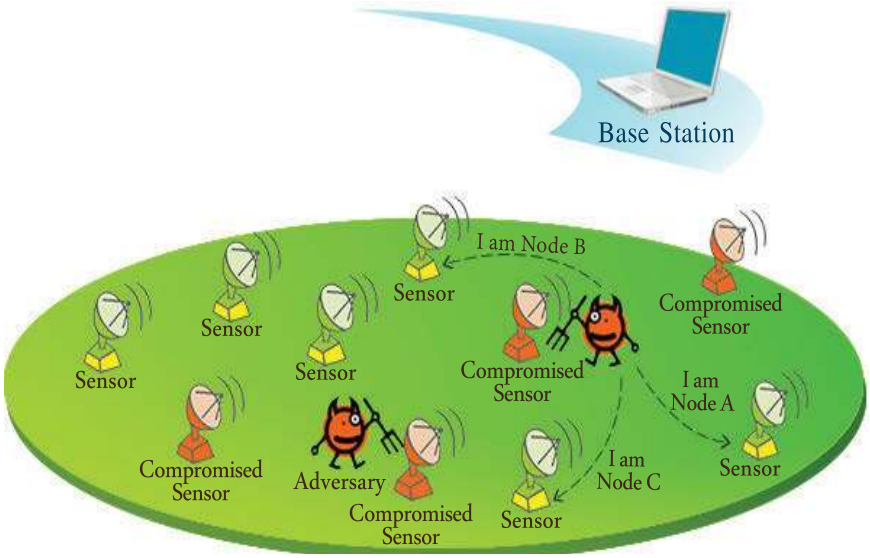


Figure 2.9: Sybil Attack in WSN

Data aggregation is an effective technique to conserve energy of the nodes. If a Sybil node resides on the path to a base station, it may maliciously modify the content of upstream traffic toward it. In doing so, a Sybil node may provide falsified readings to the base station to mislead it about the current status of the network. With sufficient forged identities, a Sybil node may even change the aggregated data of the whole network. A network may also suffer severe setbacks if the forged identities of a Sybil node seize multiple resources. This may cause scarcity of resources for legitimate nodes because a single malicious node is holding multiple resources. An unfair distribution of resources enables Sybil node to launch various other malicious activities as well. Sybil nodes can also influence the outcome of voting conducted by a base station. In voting, the base station determines if the identities of an attacker are legitimate or not. A Sybil node may use its forged identities to vouch for each other and change the outcome of voting. Instead, these identities may raise their concern over the authenticity of legitimate nodes. It happens when multiple forged

identities inform the base station that one or more legitimate nodes are misbehaving and are malicious in nature.

The unstructured and distributed environment along with broadcast nature of communication in WSNs suits well to Sybil attacks. Various protection mechanisms have been developed to protect the nodes against this type of attacks. A radio resource testing approach for detecting forged identities was proposed in [30]. It was assumed that a sensor node was incapable of simultaneous transmission or reception on a single radio. Moreover, a physical node may forge multiple identities but is incapable to use a single channel for these identities at a given time. Apart from radio resource testing, the authors also proposed a key validation approach for the random key pre-distribution. However, it requires excessive resources on part of each node and is computationally complex requiring ample amount of memory space. In [81], the authors proposed a scheme based on the assumption that probability of two nodes having exactly the same set of neighbours was extremely low provided that a network had a high node density. They argued that forged identities typically had the same set of neighbours because they were all associated with the same physical device. Therefore, the presence of a malicious node can easily be detected by checking the neighbourhood of a suspected victim of a Sybil attack. In [82], the authors proposed a Received Signal Strength Indicator (RSSI) based solution for a Sybil attack detection. They argued that even though an RSSI was a time-varying parameter and unreliable in nature, however, using RSSI ratio from multiple receivers might be used for Sybil attack detection. An identity-based detection scheme for Sybil and spoofing attacks in WSNs was proposed in [83]. The proposed approach uses a detector to identity malicious activities of the malevolent entities capable of adjusting their transmission power. The detector locates the positions of such entities and prevents them from network participation. In [84], the authors proposed Secure Code Update By Attestation (SCUBA) to detect and recover nodes compromised by an intruder. In SCUBA, public key is used for authentication between each sensor node and a base station. It is the job of a base station to determine the authenticity of each node. The node ID and the public key of a base station

is stored in Read only Memory (ROM) of each node. The node ID is used as an input for Indisputable Code Execution (ICE), a verification function which generates a specific checksum. SCUBA is a strong defence mechanism against Sybil attack and is beneficial in circumstances when a malicious node impersonates as a legitimate node. SCUBA uses the underlying principles of Code attestation, a technique to validate the code in the memory of each sensor node. The code of a malicious node differs from that of a legitimate node.

All of detection techniques mentioned above are designed for conventional routing protocols such as, data-centric in which flooding is exclusively or partially used to regulate traffic flow. Flooding allows intermediate nodes to broadcast data and control packets on their ways to base station from source nodes [37]. Duplicate packets keep circulating in the network which causes excessive energy consumption, delay, congestion, implosion and overlapping [38]. Our goal is to develop a lightweight Sybil attack detection scheme for a centralized cluster-based hierarchical network. Our proposed scheme for Sybil attack detection has two main objectives. First, we design a Sybil attack detection scheme which requires collaboration of only two nodes. Second, we implement our scheme for a centralized cluster-based hierarchical network to prevent Sybil nodes from participating in cluster head selection as these nodes are capable of forming multiple virtual clusters using their forged identities. Our proposed approach is lightweight in terms of number of nodes required to detect a Sybil attack. Moreover, it is efficient in terms of prolonging network lifetime, cluster head selection, energy consumption, packet loss rate and packet delivery ratio. The contribution of Chapter 5 is dedicated to this work.

2.5.2 Detection of Sybil attack in a Wildfire Monitoring Application

WSNs have widely been investigated for monitoring the forest environment for a possible outbreak of a wildfire. The existing research on wildfire monitoring application focus mainly on QoS parameters of the data collected from a forest environment. The main objective of the existing research is to gather time-critical, delay-sensitive data and report them to a base station without further delay. These studies do not focus on the security

aspects of the network in general and the data collected from the network in particular. However, if none of the previous studies have focused on security provisioning within a forest environment, it does not mean that communication in such an environment is free from security threats and vulnerabilities. Such applications are highly vulnerable to threats due to hostile environment of the forest and error-prone communication links over which the sensor nodes are communicating. Like any other application, security provisioning is a major challenging issue in wildfire monitoring application. In this section, first we provide the existing literature on the use of WSNs for monitoring a wildfire. We mainly focus on such studies in which cluster-based hierarchical networks are used as the underlying platforms. Next, we discuss the need for a Sybil attack detection scheme in a wildfire monitoring application.

In literature, there exist various works on wildfire monitoring using an underlying cluster-based hierarchical platform. In [85], the Energy-efficient Fire Monitoring Protocol (EFMP) was proposed which operates in three states namely, watch, slave and master. In a watch state, the nodes observe the detection of a possible wildfire. Among all the cluster heads, the one which first detects a fire, known as master head, transforms itself into master state. The master head informs all other cluster heads which transform themselves to slave state in order to act as slave heads within the network. In this fashion, a layered hierarchical architectural model is formed. Irrespective of master or slave head, all the cluster heads collect data within their clusters. However, only a master head is eligible to transmit the data to a base station. All slave heads transmit their data to a master head which aggregates the data and transmits to a base station. EFMP reduces energy consumption because of master and slave head concepts. In [86], the authors proposed a simulation framework to monitor and detect a possible forest fire. When the environmental conditions are normal, the nodes remain in low-duty cycle to conserve energy. However, during a possible fire threat, the nodes become aggressive and coordinate with each other at a much faster rate to ensure that critical alert packets are reported instantly to a base station.

The operation of the nodes depends on terrain, current weather forecasts and season of the year. Upon network deployment, the sensor nodes associate themselves with their nearest cluster heads. Each cluster head assigns transmission slots to member nodes which enable them to avoid contention for transmission on a wireless link. Furthermore, each cluster head has the ability to transform the member nodes into sleep mode in a Round Robin fashion to minimize their energy consumption. In the event of a fire detection, the nodes in close vicinity of a fire alter their normal transmission patterns and react more aggressively. If a fire ignites near a cluster head, it needs to immediately elect the most suitable member node as a replacement cluster head. A cluster-based hierarchical WSN to detect a possible wildfire was proposed in [87]. Sensor nodes were deployed to measure relative humidity and temperature readings within a forest. The cluster heads collect alarm packets from member nodes and transmit to a gateway node which ultimately delivers it to a centralized monitoring computer. In [88], the authors proposed a reliable wildfire monitoring system for a sparsely deployed WSN. The proposed scheme is reactive [38] in nature because the nodes remain in sleep mode and wake up only when an event is detected. While awake, each node remains in normal or in an alert mode for transmission of captured data without further delay. Moreover, the authors proposed separate routing paths for normal data and delay-sensitive data. In [89], the behaviour of nodes within a forest was studied. The authors proposed a mobility constraint model for providing adequate coverage to such events. They argued that the risk factors of a possible wildfire ignition characterise the coverage density of the nodes. Those areas which are more vulnerable to a possible wildfire occurrence require higher coverage densities. To provide accurate readings of the happening events, the nodes need to move toward hotspots to ensure complete network coverage.

The existing wildfire monitoring techniques do not address any security challenges incurred within a forest which motivate us to fill the research gap by proposing a Sybil attack detection scheme for a wildfire monitoring application. We propose two different detection techniques for a possible Sybil attack. Different types of threshold-based queries

are used to collect data within a forest environment. Furthermore, mobility is provided by the two coordinating base stations to enhance network coverage and avoid any hotspot issues. The contribution of Chapter 6 is dedicated to this work.

2.6 Internet of Things

The term Internet of Things (IoT) was first coined by Kevin Ashton in 1999 in the context of supply chain management [90]. However, today the IoT expands to a vast majority of fields such as healthcare, transportation logistics, industrial automation and agriculture [91]. Today's Internet has been rapidly moving from traditional computing platforms such as computers and laptops, to multiple miniature devices capable of executing a variety of applications. Miniature sensors and RFID tags embedded in physical objects have enabled the emergence of smart objects in recent years. Any physical object is smart as long as it possess three distinguishing features, i.e., awareness, representation and interaction [92]. Awareness is the ability of an object to understand, i.e., sensing, interpreting and reacting to the events occuring within an environment. Representation refers to the application and programming model of an object. Interaction is the ability of an object to communicate and negotiate with a user in terms of input, output, control and feedback. Embedded sensors and RFID tags in objects such as refrigerators, washing machines, cars, and personal gadgets have enabled them to collaborate with each other and share valuable information about the physical world. Advances in wireless technologies and increased number of physical objects integrating with the Internet are enabling the transition of Internet into a service-oriented future Internet, such as the IoT [93]. This transition enables our environment to be more interactive and informative. In 2011, the number of physical objects connected with the Internet has surpassed the human population. Currently, there are around 9 billion objects connected with the Internet. It is estimated that around 50 billion such objects will be integrated within the Internet by 2020 [94]. This integration and interoperable communication will generate an enormous amount of data which need

to be stored, processed, analysed and transmitted in a very systematic manner.

This interaction with the physical world is not a straight forward process and requires certain norms and regulations which need to be obeyed. First, the presence of embedded sensors and RFID tags make these objects constrained on various resources such as available storage, data rate, computation, and battery power. A physical object itself is not resource-starving but the sensor or an RFID tag embedded in it is resource-constrained in nature. Such physical objects can communicate with each other in the presence of an embedded sensor or RFID tag attach to them. This is because, each object requires an ID such as IP address, for network communication. In case of an embedded sensor, the IP address is assigned to the sensor node. If the object uses RFID tag instead of a sensor node, then it communicates with other objects using its tag. To provide IP addresses to 50 billion objects is not an easy task and IPv4 is clearly not sufficient to facilitate such a sheer volume of objects. The addressing space of IPv6 is sufficient to provide unique addresses to each object currently connected or will be connecting to the Internet in future. IPv6 can provide up to 3.4×10^{38} addresses to computers, routers and other real-world objects [95]. At first glance, it seems that IPv6 has solved all the problems, i.e., connecting objects to the Internet. However, the provisioning of IPv6 in physical objects is not that simple. The embedded sensor in each object may be powered by an 8-bit, 16-bit or 32-bit microcontroller with 64Kbytes or more of flash memory. The sensor nodes use IEEE 802.15.4 standard which supports only 127 bytes of packet size [96]. Therefore, each IPv6 packet needs to be in a simple format, i.e., removing its high-level complexity and redundancy, to make usable for physical objects. The integration of physical objects with the traditional Internet is shown in Fig. 2.10.

In Fig. 2.10, the traditional Internet is on one side of the network while an IPv6 over Low-power Wireless Personal Area Network (6LoWPAN) is on the other side of the network. The 6LoWPAN is based on the idea that "IP address could and should be applicable even to the smallest devices [97]" and "the low-power objects having limited storage, processing capabilities, battery power and other available resources should be able to partici-

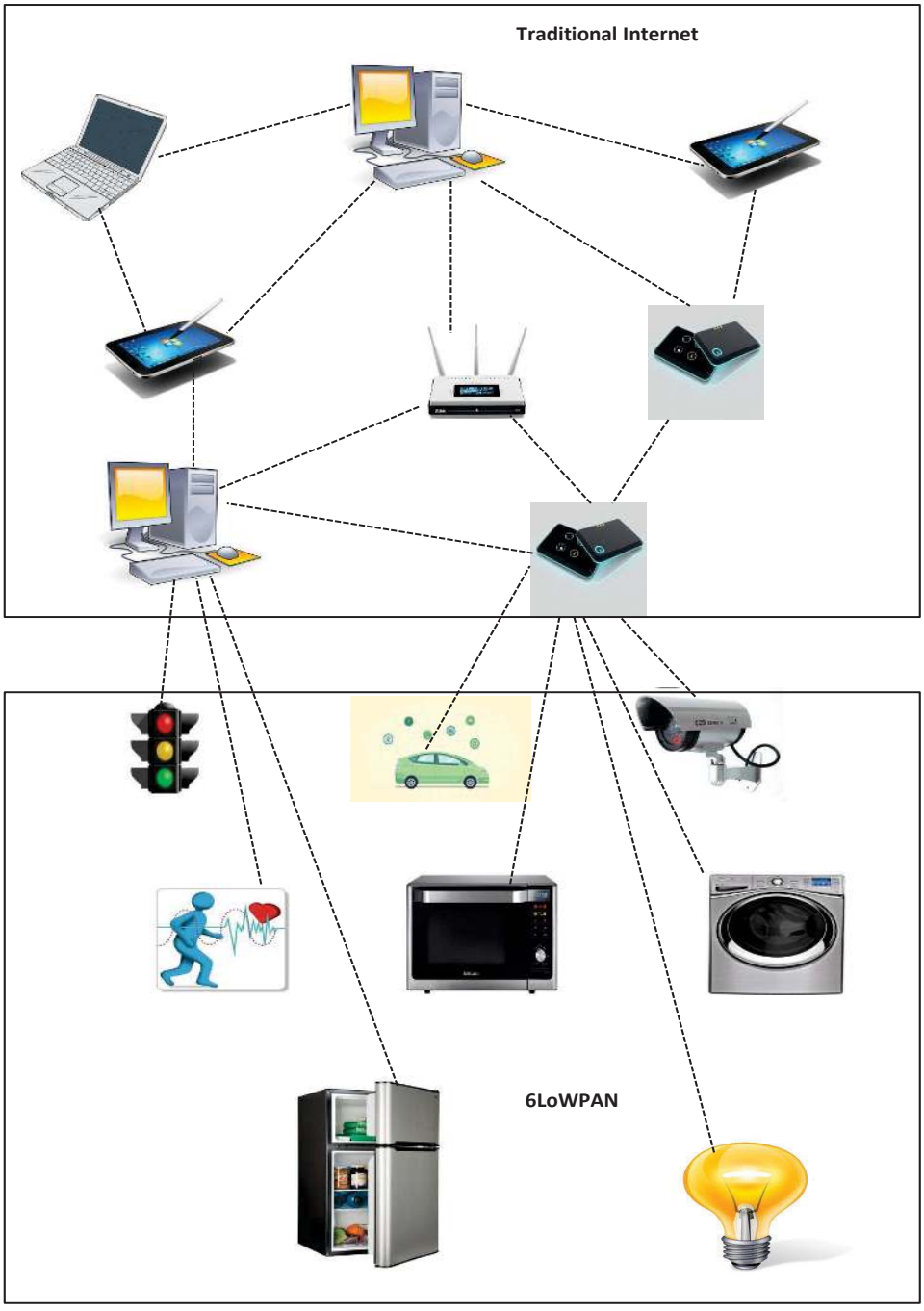


Figure 2.10: Integration of Physical Objects with Internet-IoT

pate in the IoT [98]". The 6LoWPAN working group has defined various encapsulation and header compression techniques so that IPv6 packets can be transmitted and received over low-power networks such as IEEE 802.15.4. In Fig. 2.10, the 6LoWPAN specifications manage the traffic flow from traditional Internet toward the objects and vice-versa. The 6LoWPAN uses encapsulation and header compression techniques to strip down highly-complex IPv6 packets incoming from traditional Internet. As a result, the packets become lightweight and do not possess the headers and complexity imposed by the upper layers. Likewise, the 6LoWPAN specifications configure smaller packets, i.e., those packets which are flowing from 6LoWPAN to the traditional Internet. In that case, the header and high-level complexity are added to each packet before its delivery to traditional Internet. The protocol stack at the nodes in these two networks is shown in Fig. 2.11.

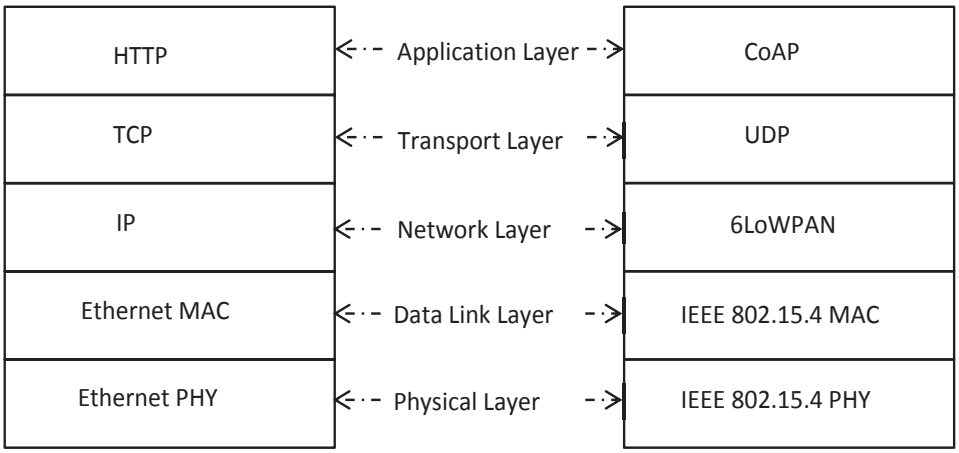


Figure 2.11: Protocol Stack at the Nodes

The nodes[2] in the traditional Internet of Fig. 2.10 use the TCP/IP model. On the other hand, the nodes in 6LoWPAN use a lightweight protocol stack which meets the requirements of these low-powered and resource-starving objects. The use of Hypertext Transfer Protocol (HTTP) in 6LoWPAN or any IoT is not an optimal choice because HTTP requires abundant of network resources and the request-response interaction model of HTTP does not match the event-driven nature of applications in WSNs [99]. To support and de-

[2]A node does not necessarily mean a sensor node. Any device capable of sending and receiving data is a node such as laptop, desktop, refrigerator and mobile phone.

velop applications in any IoT, the Internet Engineering Task Force (IETF)[3] came up with a "lightweight HTTP ", known as Constrained Application Protocol (CoAP).

2.6.1 Constrained Application Protocol

CoAP [100] is an application layer protocol which is designed to allow the exchange of messages between resource-constrained objects over the resource-constrained networks. Given its simplicity, it is also easier to implement CoAP-based systems on small embedded hardware. The protocol inherits the lightweight features of HTTP and the conversion between the two protocols is relatively easy. CoAP provides an HTTP-like request and response interaction paradigm, where the objects can interact by sending a request and receiving a response. Similar to web services, objects are addressed using IP addresses and port number. Resources are accessed by each object via Restful [101] URIs[4], i.e., objects in the form of clients and server communicates with each other in such a way that a resource resides over a server and each client access it by using the Uniform Resource Locator (URL) of the resource. CoAP supports the discovery of various resources hosted by a server. A CoAP client needs to learn about the services offered by a CoAP server [102]. Each client learns about the server via a URI that refers to a resource in the namespace of the server. Alternatively, a client can use "Multicast CoAP" and "All CoAP Nodes" multicast address to find a CoAP server. CoAP is based on the UDP protocol, hence, the packets may arrive out of order, missing and/or corrupted. The protocol supports four types of messages: CON, NON, ACK and RST as shown in Table 2.1. To provide reliability, each client transmits confirmable (CON) messages to the server which need to be acknowledged (ACK) in a pre-specified duration. A request can carry either a confirmable or non-confirmable message. A non-confirmable (NON) request is used for unreliable transmissions such as, a request for sensor measurements recorded periodically by a server. Even if one or more values of sensor measurements are missing, there is not

[3] http://www.ietf.org/

[4] REST stands for Representational State Transfer while URI stands for Uniform Resource Identifier

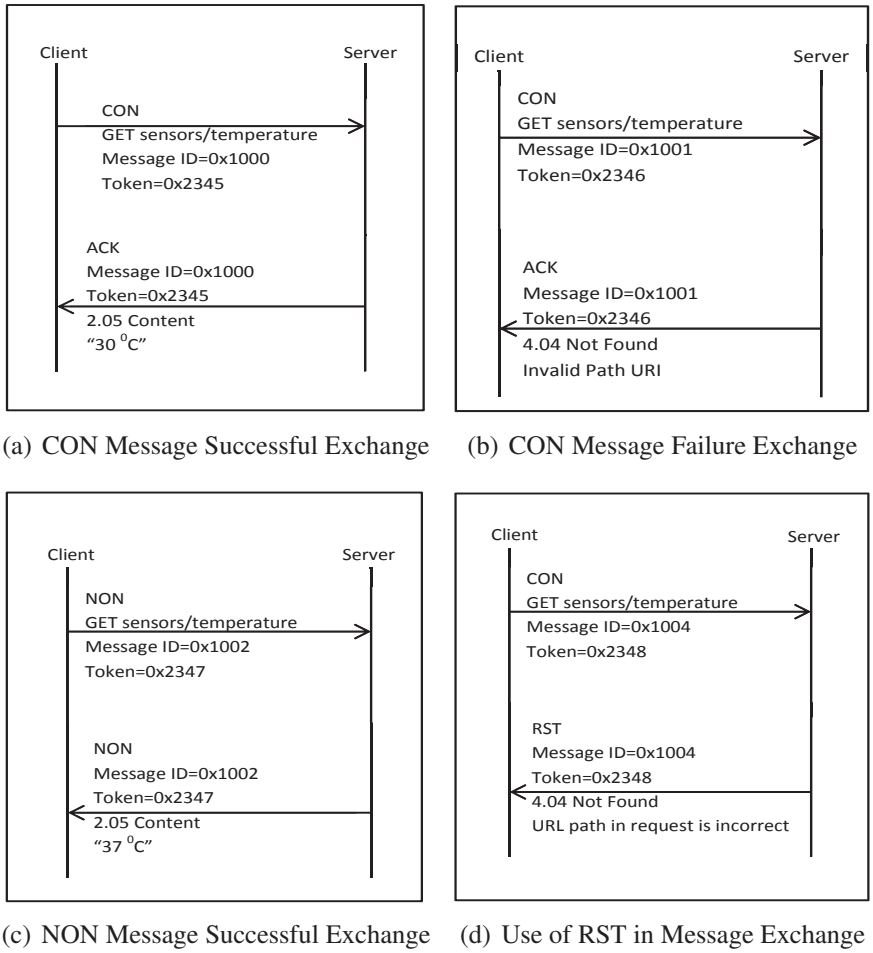
much impact on the overall system performance. Generally speaking, NON messages are not acknowledged. The response can either be separate or piggybacked in an ACK message. Empty messages are used to check the liveliness of the nodes. One such message is "CoAP ping" [102] which is a CON message and requires an ACK from the recipient to verify its current status (dead or alive). The reset message (RST) is used only when a recipient has rebooted and unable to process the messages due to missing context, i.e., some kind of failure such as, the server is unable to parse the received message.

Table 2.1: Usage of CoAP Messages

Action	CON	NON	ACK	RST
Request	Yes	Yes	No	No
Response	Yes	Yes	Yes	No
Empty	Yes*	No	Yes	Yes

In Fig. 2.12, the use of different CoAP messages is shown. The successful exchange of a CoAP message is shown in Fig. 2.12(a). In this figure, a client sends a CON request message to a server. To retrieve a temperature resource, the client uses GET method in the request and provide a URL path "sensors/temperature". The message ID is a 16-bit number which is used for unique identification of the request message. Furthermore, the message ID enables the server to detect duplicate message. Token is used to correlate CoAP messages at the client and server ends, i.e., matching a response with the corresponding request. It also prevents the intruders from malicious manipulation of transmitted data. Token is a variable-length value; anything between 0 and 8 bytes long. Once the server receives the message, it measures the temperature and returns an ACK response message which contains the same message ID and token present in the request message. Along with ACK, the message also contains the temperature data and the response code, "2.05 Content" in this case. The response code is an indication that the request was successfully received and processed. In Fig. 2.12(b), an unsuccessful exchange of CoAP message is shown. The request message is of type CON with a specific message ID and token. The response is transmitted in an ACK message, i.e., a piggyback response. In this figure, the

server is unable to process the request, so it transmits the response with a response code "4.04 Not Found " with a description that the URI path in the request is invalid.



(a) CON Message Successful Exchange (b) CON Message Failure Exchange

(c) NON Message Successful Exchange (d) Use of RST in Message Exchange

Figure 2.12: Exchange of CoAP Messages

In Fig. 2.12(c), the successful exchange of NON message is shown. The client sends the request in a NON message, which literally means that there is no guarantee that the client will receive a response from the server. The server transmits the response in a NON message having a specific token, message ID and the requested data. If the response message is lost, the client needs to send a request again. The use of RST in a response message is shown in Fig. 2.12(d). The client sends a CON request which the server is unable to interpret and replies back with a RST message. The response code is "4.04 Not Found"

with a description that the URL path in the request is incorrect. One more thing to add here is that apart from GET method, CoAP requests may also contain POST, PUT and DELETE methods. These methods are used to create a resource on the server (POST), update a resource (PUT) and delete a resource (DELETE) [103].

CoAP has a fixed-length binary header of only 4 bytes, hence, fewer resources are consumed. In [104], a series of request/response transactions were carried out to compare CoAP against HTTP for the resource-constrained networks. It was observed that the number of bytes consumed per transaction in CoAP is much smaller than HTTP. As a result, when using CoAP in WSN, the power consumption is much lower, which directly affects the lifetime as well. The comparison between the two protocols is shown in Table 2.2.

Table 2.2: CoAP vs. HTTP

	Bytes-per-Transaction	Power (in mW)	Lifetime (days)
CoAP	154	0.744	151
HTTP	1541	1.333	184

The cost-effective provisioning of RESTful services in Low-power Lossy Networks (LLNs) coupled with low complexity in terms of protocol header, message parsing, asynchronous transaction model and build-in resource discovery makes CoAP an ideal choice for the IoT deployment. As a result of these distinguishing features, CoAP is proposed to replace the existing IoT protocols such as MQTT-S [105] and XMPP [106]. Currently, CoAP is deployed in many applications such as transport logistics [107], home automation [108] and freight supervision [25] are some to mention here. After providing a detailed description of CoAP protocol, we discuss below the security challenges faced by the objects in an IoT environment.

2.6.2 Security Challenges in IoT

Trust, privacy and security provisioning are challenging tasks in any communication network. However in the IoT, designing secure solutions are more difficult and complex due to the peculiar nature of the objects. Moreover, sensors are deployed at the core of the com-

munication system, which makes it even more difficult to design computationally complex but secure and robust algorithms. In the Internet of today, various types of attacks and their defence mechanisms are well studied. However in the IoT domain, threats posed by various objects are unknown until they are deployed in the network. Therefore, their dimension, scope and nature are yet to be observed.

Fig. 2.13 depicts an IoT environment, which is vulnerable to a wide range of attacks. Here, an intruder poses threats to various type of objects and information at a given time. An Internet, a sensor network and a smart phone are susceptible to this type of attack. Any data coming from the attached objects will also be affected. As a result, a single intruder is capable to conduct a large scale attack. The intruder may intercept the sensor data, manipulates it and replays the malicious data in other parts of the network. Also, it may inject fabricated data of its own. In this figure, various types of objects are connected with the Internet. Therefore, large amount of data is at risk which may result in malfunctioning of the whole network. Off course, the severity of this attack depends on the intruder's battery-power, storage, computation and other features. Like any other legitimate object, a malicious object also requires an ID to participate in an IoT communication. Each participating object needs to be validated and authenticated in order to establish its true identity in the network. In absence of ID validation and authentication, an attacker will always be able to conduct a wide range of malicious activities. An intruder may establish multiple connections with the gateway node of the sensor network. This is by far the simplest of the attacks where multiple network resources will be seized by the intruder. This results in denial of services to the legitimate sensor nodes and ultimately causes scarcity of resources in the network [34]. Wireless medium is shared among the network devices. The intruder may block access to the network resource by continuously emitting signals to interfere with the legitimate transmissions. This act is known as jamming [109] and its consequences are severe in an IoT environment as compared to traditional networks because, physical objects differ significantly from each other in terms of various resources.

The identity validation approach restricts the objects from establishing multiple simul-

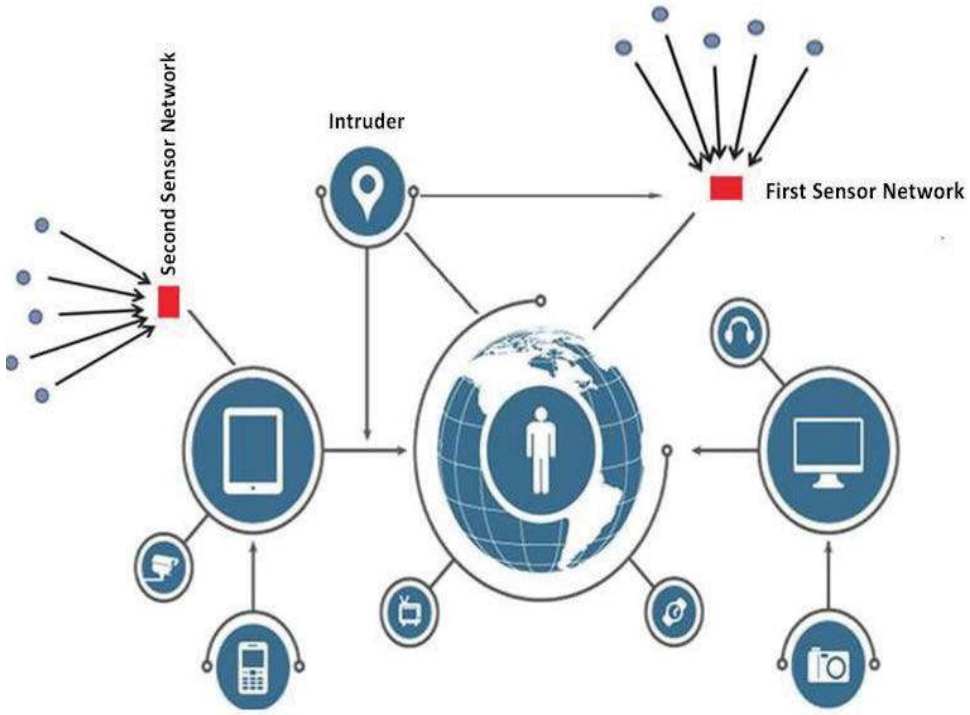


Figure 2.13: A Vulnerable IoT Architecture

taneous connections with a given server. A CoAP-based interaction model requires that each client object is restricted to a single connection with a given server. This objective serves two purposes. First, CoAP is specifically designed for energy-constrained objects. Therefore, energy of each object needs to be utilized in an efficient manner. Second, the magnitude of any security breach has a direct relationship with the number of established connections. However, connection restriction alone is not sufficient to achieve a robust secure solution. Each connection needs to be authenticated using some lightweight encryption scheme. Off course, ID validation and authentication techniques cannot combat all types of threats in any communication network. But, they are still capable to tackle a subset of malicious threats. Another challenging task in an IoT communication is the resource observation at the server. Each application has its own requirements in terms of data acquisition and resource observation. Some applications require periodic transmission while other requires continuous data flow. Yet, there are other applications which observe abrupt and sudden changes in the resource state. Therefore, the IoT needs to be config-

ured in such a way that the requirements of each application are fulfilled. The conditional resource observation is well-suited to the energy-constrained objects of an IoT environment. Each client specifies certain conditions in the request message. Once the condition is fulfilled at the server end, it notifies the client about the current state of the resource. This reduces the number of transmitted packets which in turn enhances the lifetime of the network, throughput and at the same time reduces congestion.

There exists various works in literature which tackles security challenges in an IoT. In [110], the authors highlighted various security challenges faced by these networks. In an IoT, the error-prone communication links coupled with the resource-constrained nature of objects restrict the use of Transport Layer Security (TLS) [111]. In addition, the packets may arrive out of order, and may be missing and/or corrupted. Therefore, the Datagram Transport Layer Security (DTLS) is an obvious choice for securing the communication [112]. The handshake and the record layers of DTLS incur 25 bytes of overhead in each datagram header. IEEE.802.15.4 specifies a physical layer Maximum Transmission Unit (MTU) of only 127 bytes. As a result, only 60-75 bytes are left for the payload after the addition of DTLS, MAC and upper layers headers [113]. Therefore, DTLS needs to be profiled to make it more friendly toward the resource-constrained networks [114]. In [115], the authors proposed a lightweight authentication scheme to establish a unicast communication channel. Their scheme is based on symmetric encryption algorithm to reduce the energy consumption and computation. The authors claimed that DTLS can be configured to develop an energy efficient authentication scheme. In [116], the authors have proposed the DTLS implementation for smart phones (INDIGO) using CoAP. INDIGO uses extensive resource consuming cryptographic cipher suites and its use is therefore restricted only to smart phones. In [117], the authors proposed a bootstrapping protocol for improving the system security in the IoT. The protocol is based on the mother-duckling relationship [118]. A duckling node searches for the mother node by sending a POST command using CoAP. Once a mother node is identified in the network, it imprints a shared secret on the duckling. Upon successful imprinting of the shared secret, an encrypted

channel is established between them. However, the protocol lacks any information on the communication range between the mother and the duckling along with the imprinting cost. In [119], the authors have proposed a lightweight authentication scheme for resource observation. However, they have not provided sufficient experimental results to justify their claim.

In view of the discussion in this section, we propose a lightweight and mutual authentication scheme for IoT objects using CoAP in Chapter 7. The proposed scheme authenticates the identities of clients and the server communicating with each other. Various scenarios for the replay attack and their mitigation techniques are briefly explained. Our scheme can be a lightweight yet robust and secure alternative to the DTLS scheme. Various concepts of Chapter 7 heavily rely on the discussion in this section. Therefore, it is necessary to have a thorough understanding of this section.

2.7 Summary

This thesis aims to address energy-efficient routing and secure communication issues among sensor nodes in WSNs. The resource-constrained nature of sensor nodes requires protocols which consume less energy in data aggregation, transmission and sensing. WSNs are differentiated from traditional networks based on various distinguishing features, as explained in this chapter. Among these features, operation of sensor nodes in a hostile environment not only broadens the scope of the network but also exposes it to various vulnerabilities. As a result, this thesis also aims to address security challenges faced by the sensor nodes. Furthermore, sensor nodes are embedded in real-world objects of an IoT. The presence of objects in the network exposes it to new security challenges which are different than the ones faced by traditional Internet. The presence of embedded sensor nodes at the core of each object requires lightweight but robust security schemes. This thesis aims to address such issues and proposes a lightweight authentication scheme to validate the identities of objects communicating in an IoT paradigm. Next, in Chapter 3, we propose two differ-

ent routing schemes which conserve the energy of the nodes and prolong the lifetime of WSNs.

Chapter 3

Energy-efficient Communication in Cluster-based Hierarchical Networks

This thesis so far has discussed many of the distinguishing features of cluster-based hierarchical routing protocols and based on our discussion, in this chapter we explore further on our research. The energy-efficient communication provided by these protocols make them an ideal choice for various WSN applications. In this chapter, an energy-efficient routing algorithm along with an energy evaluation model is proposed for cluster-based hierarchical WSNs. The proposed routing algorithm uses the randomly distributed cluster-based hierarchical architecture as the underlying platform while the energy evaluation model is designed for a centralized cluster-based hierarchical network. The routing algorithm discussed in Section 3.1 is based on our work published in [120] while the energy evaluation model discussed in Section 3.2 is based on our work published in [68].

3.1 Energy-efficient Cluster-based Routing Algorithm

In WSNs, the neighbouring nodes gather events which may have identical data patterns [121]. The transmission of such events to a base station may have an adverse impact on the lifetime, storage and processing capabilities of each node. In WSNs, an end user is

mainly interested in the quality of transmitted data. An end user wants a brief description of events happening within a sensor field rather than huge collection of redundant data. The objective of our proposed routing algorithm is to enhance the lifetime of a WSN and improve the quality of data delivered at the base station. First, we explain the network architectural model of our proposed routing algorithm followed by its operational model.

3.1.1 Network Architectural Model

In our proposed scheme, the sensor nodes are deployed in a (100×100) square meter geographical region. All nodes are static and are randomly deployed. We make the following assumptions about the architectural model of our proposed scheme.

- Base station is immobile and located outside a sensor field.
- All nodes have the same initial residual energy at the time of deployment.
- Nodes have the ability to adjust their transmission power.
- Nodes sense the environment at a fixed rate and always have data to transmit.

In WSNs, the lifetime of sensor nodes depend on their communication patterns. In these networks, the energy consumption in communication is much higher than data processing and data sensing [57]. The distance among the neighbouring nodes determines the type of communication model to be used. If the distance between a transmitter node and a receiver node is less than crossover distance (d_c), free-space propagation model (*fs*) is used, otherwise, multipath ground propagation model (*mp*) is used [122]. In a free-space model, there is a line-of-sight connection between a transmitter and a receiver node. In a multipath model, a radio signal travels through multiple paths due to reflection, refraction and deflection through various obstacles. Irrespective of the type of model, the crossover distance between a transmitter and a receiver node is calculated using Equation 3.1.

$$d_c = \frac{4\pi h_t h_r \sqrt{L}}{\lambda}. \tag{3.1}$$

Here, h_t, h_r are the heights of transmitter and receiver antennas, L is the system loss factor and λ is the wavelength of a radio signal. In general, $L > 1$, but if there is no loss in system hardware, then L=1 [123].

In our scheme, the radio model of the transmitter and receiver node is similar to *first-order* radio model [61]. The electronic component of a node is responsible for processing the data while the amplifier component performs the transmission of data over low-power lossy links of WSNs. The radio communication among any transmitter node and a receiver node is shown in Fig. 3.1. A transmitter node processes a k-bits packet and transmits to a receiver over a distance d. The value of d determines the type of model to be used between any two sensor nodes. If $d < d_c$, free-space propagation model is used, otherwise, multipath ground propagation model is used.

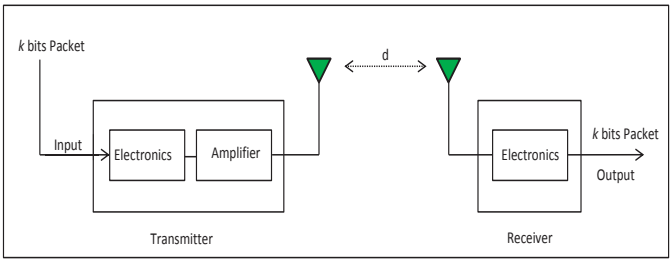


Figure 3.1: Radio Communication Model

The amount of energy consumed by a transmitter node (E_{Tx}) in transmitting a k-bits packet over a distance d in a free-space model is calculated using Equation 3.2.

$$E_{Tx}(k,d) = kE_{elec} + k\epsilon_{fs}d^2, \qquad d < d_c. \tag{3.2}$$

Here, E_{elec} and ϵ_{fs} are the energy consumptions of the electronic and amplifier components of a transmitter node. The free-space assumption is being used to allow comparison with existing work which does use this assumption. For a multipath ground propagation model,

the energy consumption of a transmitter node is calculated using Equation 3.3.

$$E_{Tx}(k,d) = kE_{elec} + k\epsilon_{mp}d^4, \qquad d \geq d_c. \tag{3.3}$$

Here, ϵ_{mp} is the energy consumption of the amplifier component in a multipath model. Irrespective of the type of model, the energy consumption of a receiver node (E_{Rx}) stays the same and is calculated using Equation 3.4.

$$E_{Rx}(k,d) = kE_{elec}. \tag{3.4}$$

3.1.2 Network Operational Model

Here, we provide a brief overview of the underlying operational model of our proposed routing algorithm. The main objective is to improve the network lifetime and quality of the data delivered at the base station.

Upon network deployment, each node n chooses a random number between 0 and 1 in each round. If the random number is less than threshold value ($T(n)_{proposed}$) of Equation 3.5, the node is elected as cluster head for the current round. Unlike LEACH protocol [61], our proposed algorithm elects the cluster heads based on the consumed energy (E_{con}) of each node.

$$T(n)_{proposed} = \begin{cases} \frac{k_{opt}}{1-k_{opt}\left(r \bmod (\frac{1}{k_{opt}})\right)} \times E_{con}, & n \in G, \\ 0, & \text{Otherwise.} \end{cases} \tag{3.5}$$

The inclusion of E_{con} in Equation 3.5 reduces the likelihood of lower energy nodes being elected as cluster heads in each round. The unit of E_{con} is joule. Our proposed cluster-based routing algorithm has significant improvement over LEACH protocol in terms of cluster head selection. However, the probabilistic nature of Equation 3.5 cannot completely

rule out the possibility of lower energy nodes being elected as cluster heads. The use of a random number generation approach in LEACH protocol elects x nodes as cluster heads for a network of n nodes in each round, where $x \ll n$. However, the inclusion of E_{con} further reduces the number of cluster heads to y nodes, where $y < x \wedge y \ll n$.

Using Boston University source code[1], LEACH protocol generates anything between 0 and 22 cluster heads in various rounds. When there are no cluster heads in a particular round, it means that LEACH protocol operates similar to data-centric and address-centric protocols [124]. In that case, the sensor nodes require long-haul, multi-hop transmissions to a base station. As a result, the protocol suffers from implosion and flooding issues similar to data-centric and address-centric protocols. In our proposed scheme, the number of elected cluster heads remains stable between 3 and 8 when the network has sufficient number of alive nodes. However, the percentage of elected cluster heads decreases towards the end of network lifetime which is logical as there are not sufficient nodes to form optimal number of clusters. The election of a near-optimal percentage of cluster heads in various rounds prolong the network lifetime. Unlike LEACH protocol, our proposed routing algorithm always elects cluster heads in each round. It means multiple clusters (anything from 3 to 8) are formed in each round which enables the nodes to avoid long-haul transmission to a base station. The only exception is toward the end of network lifetime when there are not sufficient nodes to form clusters and they transmit their data directly to a base station. The election of near-optimal percentage of cluster heads coupled with the avoidance of long-haul transmission to a base station enhances the lifetime of our proposed algorithm over LEACH protocol.

Once a near-optimal percentage of cluster heads are elected, they advertise themselves to the nearest neighbouring nodes to form clusters. Similar to LEACH protocol, each cluster head allocates TDMA slots within its cluster for data transmission. The neighbouring nodes within a cluster may sense and transmit highly redundant events containing similar data patterns as shown in Fig. 3.2. In this figure, multiple nodes capture a single event

[1] http://csr.bu.edu/sep/

containing data observed by these nodes. The transmission of multiple copies of a single event to a base station depletes the battery of each node. Furthermore, the delivery of duplicate copies at the base station deteriorates the QoS of the network as well.

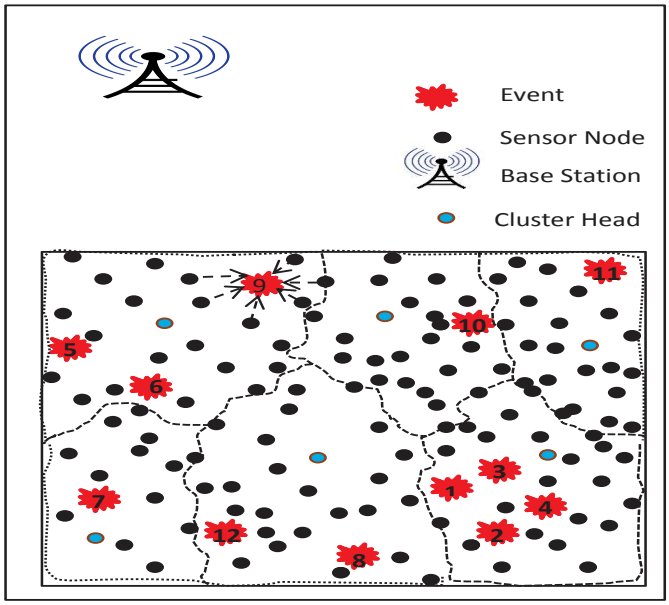


Figure 3.2: Sensing Similar Events

It is important to eliminate or at least reduce the transmission of such redundant data patterns. Each cluster head eliminates multiple copies of an event gathered from neighbouring nodes, aggregates with other events to further reduce data size and transmits to a base station. The elimination of redundant data packets ensures that high quality data is delivered to a base station. Moreover, reducing the number of transmitted events and the elimination of multiple copies enhances the lifetime of the network as well.

3.1.3 Experimental Results and Analysis

We compared our algorithm with LEACH and DEEC protocols in terms of various performance metrics. In our experiments, we use E_{elec}=50nJ/bit, n=100, ϵ_{fs}=10pJ/bit/m^2, ϵ_{mp}=0.0013pJ/bit/m^4, d_c=87m, k=500bytes and r=10000. The maximum packet size is 500 bytes, out of which 25 bytes are reserved for control information. We have used

Matlab 2011a for creating simulation environment in a 100×100 square meter area under Windows 7 platform. A detailed analysis of various performance metrics such as network lifetime, data aggregation, and quality of the aggregated data is presented here.

3.1.3.1 Lifetime of the Network

Lifetime of a network is measured in terms of stability period and instability region. Stability period is the point in time when the first node dies in the network. Instability region is the point in time when the last node dies in the network. In [125], it was assumed that the instability region is reached after 97% of the nodes die, because it becomes very difficult to form clusters as insufficient nodes remain in the network. In Fig. 3.3, we compare our proposed routing algorithm with LEACH and DEEC protocols in terms of stability period and instability region.

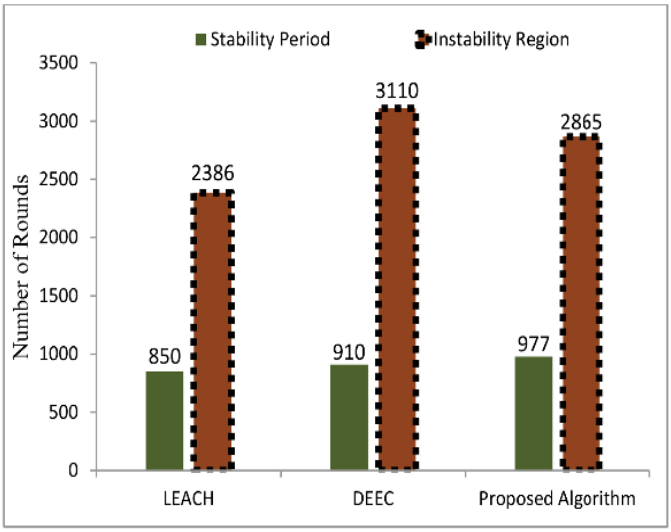


Figure 3.3: Lifetime of the Network

In our proposed scheme, the inclusion of E_{con} in Equation 3.5 prohibits lower energy nodes from being elected as cluster heads. The residual energy of each node plays a vital role in the cluster head selection and nodes having higher residual energy take preference over low energy nodes during cluster head selection. In our proposed scheme, a near-optimal percentage of cluster heads in each round restricts the resource-intensive tasks

to fewer nodes which in turns influence the overall network lifetime. On the other hand, LEACH protocol randomly elects cluster heads irrespective of their residual energy values. Unlike LEACH and our proposed scheme, DEEC protocol is a heterogeneous cluster-based hierarchical routing protocol in which 20% of the nodes have higher residual energy at the time of network deployment. As a result, the network operates for a longer duration in DEEC protocol which prolongs the instability region.

3.1.3.2 Data Aggregation

In cluster-based hierarchical networks, local data aggregation and fusion is performed by each cluster head to avoid the transmission of redundant data. The total amount of data aggregated by each cluster head and the base station over the span of network lifetime is shown in Fig. 3.4.

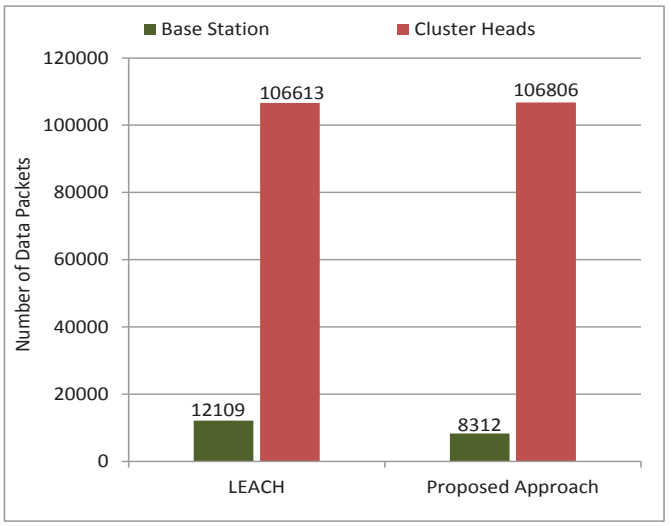


Figure 3.4: Data Aggregation

The performance of any data aggregation technique can be judged by the number of packets received at the cluster head and a base station. During the course of network lifetime, the cluster heads in our proposed scheme receive 106806 packets in comparison to 106613 packets in LEACH protocol. After data aggregation, fusion and elimination of redundant data packets, the data is further transmitted to a base station. In our approach,

there are 8312 data packets received at the base station in comparison to 12109 data packets in LEACH protocol. In comparison to LEACH protocol, our proposed algorithm transmits much lower number of packets to the base station. This is because the duplicate packets are refrained from transmission to a base station by each cluster head. The use of an efficient data aggregation technique at the cluster heads not only eliminates or reduces the transmission of duplicate packets but also reduces the energy consumption of the nodes which further prolongs the lifetime of a network.

3.1.3.3 Quality of Data

Quality of data is a percentage value which depends on data aggregation. It is calculated as sum of packets delivered at the base station to the sum of packets received at the cluster heads over the span of network lifetime. In Fig. 3.5, quality of data of our proposed scheme is compared with LEACH protocol using different energy values for sensor nodes.

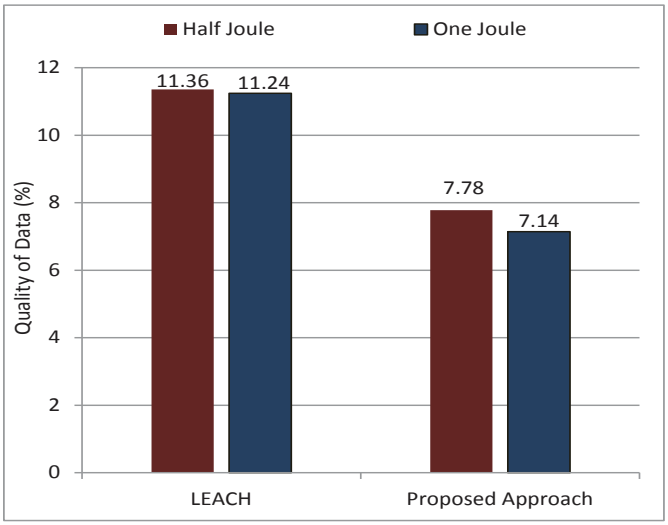


Figure 3.5: Quality of Data

For a network of 100 nodes, where each node has half joule of energy, quality of data is 7.78% for our scheme and 11.36% for LEACH protocol. It means that for every 100 packets, only 7.78 packets on average are transmitted by each cluster head to a base station in our proposed scheme and 11.36 packets in LEACH protocol. For a similar network size

with one joule of nodes, quality of data is 11.24% for LEACH protocol and 7.14% for our proposed scheme. The quality of data improves with the increase of residual energy of the nodes. Lower the percentage value, higher will be the quality of data and efficient will be data aggregation at cluster heads. Moreover, low percentage values prolong network lifetime because less number of packets are transmitted to a base station which reduces the energy consumption, data processing and communication bandwidth.

3.2 A Centralized Energy Evaluation Model

In Section 3.1, we briefly explained our randomly distributed cluster-based hierarchical routing algorithm. Although, our proposed scheme is capable to enhance network lifetime and quality of data, however, it does not guarantee an optimal percentage of cluster heads in each round. It is a best-effort algorithm which tries to elect a near-optimal percentage of cluster heads in each round. In other words, the average percentage of cluster heads elected over a certain number of rounds remains optimal, but in each round, an optimal percentage is not guaranteed. This is because the threshold Equation 3.5 for cluster head selection is probabilistic in nature and depends on a random number generation as explained earlier.

To guarantee an optimal percentage of cluster heads in each round, a centralized selection mechanism is required. A central entity such as a base station elects cluster heads for each round. Nodes are no longer required to generate random numbers and the probabilistic threshold value of Equation 3.5 has no further influence in the cluster head selection. Base station uses the residual energy and location information of each node to elect cluster heads. In the existing centralized cluster-based hierarchical routing protocols [126] [67] [127] [66], each node is required to transmit its location information and residual energy to a base station at the beginning of each round. Although, the existing protocols result in a near-optimal election of cluster heads but these protocols are not energy-efficient on part of each node. The transmission of residual energy and location information in each round is a burden on resource-starved sensor nodes. Furthermore, these

protocols use simulated annealing algorithm [128] for solving NP-hard problem of finding *k*-optimal clusters [129]. However, they do not provide any detail on using simulated annealing algorithm for obtaining optimal clusters. These protocols incur high overhead in cluster head selection and advertisement, cluster formation and data transmission to a base station [130].

In this section, we introduce a novel energy evaluation model for a centralized cluster-based hierarchical network. Our model takes into account the energy consumption of various types of nodes involved during set-up and steady-state phases. Unlike the existing centralized cluster-based routing protocols, the underlying clustering technique of our proposed scheme eliminates the cluster head advertisement, i.e., cluster heads are no longer required to advertise themselves which further enhances the network lifetime. To reduce the overhead and transmission delay, the underlying clustering technique does not require simulated annealing for cluster head selection. Each node is either a normal node or a high energy node. The normal nodes are equipped with 2 joule while high energy nodes have 5 joule of residual energy. High energy nodes are only 5 percent of the normal nodes to balance network cost. They are uniformly distributed within the geographical region to enable energy-efficient access for normal nodes. In our scheme, high energy nodes perform multiple resource-intensive operations such as, assisting the base station in cluster head selection and relay back vital information to the base station. It is for this reason that high energy nodes refrain from participation in cluster head selection and only normal nodes are permitted to do so. In this section, first we explain the network operational model of our proposed scheme followed by a novel energy evaluation model which computes the energy consumption of sensor nodes during various phases.

3.2.1 Network Operational Model

Our centralized cluster-based hierarchical routing algorithm operates in two phases, a set-up phase and a steady-state phase. The set-up phase can be further subdivided into four sub-phases.

- Status
- Cluster Head Selection
- Cluster Formation
- Schedule Creation

During status sub-phase, each normal node transmits a status message to it's nearest high energy node before the start of each round. This message contains an 8-bit source ID, 8-bit destination ID and a variable-length residual energy field. The source ID is the identity of the transmitter node whereas destination ID is the identity of a nearest high energy node. The frame format of a status message is shown in Fig. 3.6

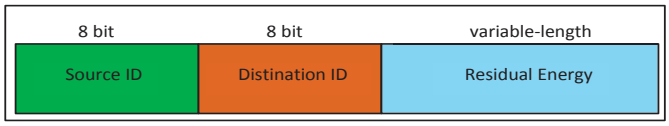


Figure 3.6: Frame Format of a Status Message

Each high energy node aggregates status messages from its neighbouring normal nodes and transmits to a base station. Upon transmission to a base station, each high energy node goes to sleep mode until the beginning of next round. The base station retrieves the source ID and residual energy from each status message and stores locally within a queue. It then calculates the average residual energy (E_{avg}) using Equation 3.6

$$E_{avg} = \sum_{i=1}^{i=n} (\frac{E_i}{n}). \tag{3.6}$$

where, E_i is the residual energy of a normal node and n is the total number of such nodes. In our proposed scheme, n is equal to 100.

During cluster head selection sub-phase, an optimal percentage of cluster heads are elected by the base station. The base station maintains a queue as shown in Fig. 3.7. Any node having E_i greater than E_{avg} is eligible for cluster head selection. In Fig. 3.7, the

value of E_{avg} is equal to 1.5 joule for the current round. It is highly probable that there will be a large number of nodes for which E_i is greater than E_{avg} in each round. All such nodes are nominated as the possible candidates for cluster heads. If two or more candidates are located in the same geographical region, they are evaluated according to their residual energy values and their election as cluster heads in the past $\frac{1}{k_{opt}}$ rounds. In our network, the optimal percentage of cluster heads is 4% to 6% in each round for a network of n nodes.

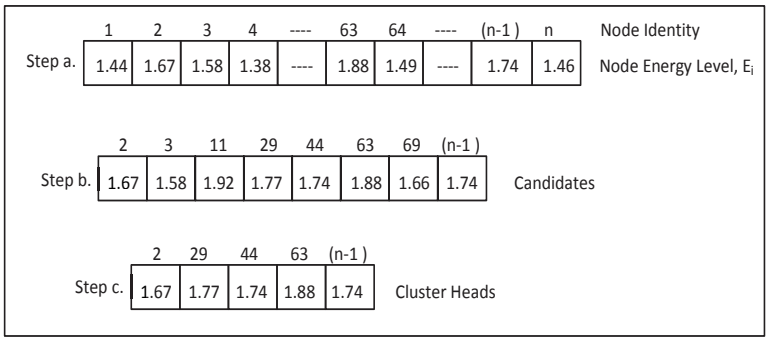


Figure 3.7: Candidate Nodes and Cluster Heads

Among the candidates of Fig. 3.7, nodes 2, 3 and 11 reside in one cluster whereas nodes 63 and 69 reside in another cluster as shown in Fig. 3.8. Only one candidate in each cluster is allowed to be elected as cluster head. Among nodes 2, 3 and 11, node 11 has the highest E_i, however, this node has previously been elected as cluster head in the past $\frac{1}{k_{opt}}$ rounds which makes it ineligible for the current round. The elimination of node 11 from cluster head selection paves the way for node 2 and 3 as the possible nominees for cluster head in the current round. Node 2 takes preference over node 3 for cluster head selection because the former has higher E_i and has not been elected as cluster head in the past $\frac{1}{k_{opt}}$ rounds. In the second cluster, the election procedure is rather straightforward. Node 63 has a higher E_i than node 69. Furthermore, it has not been elected previously over the past $\frac{1}{k_{opt}}$ rounds.

We used the term *cluster* while referring to Fig. 3.7 and Fig. 3.8 for clarity and simplification purposes. In reality, there is no such thing like cluster at the time of evaluating E_i by the base station. Once a base station evaluates the residual energy of each node, only

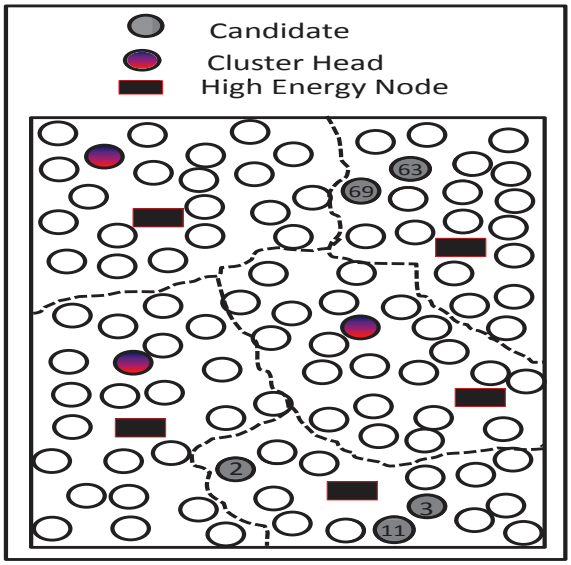


Figure 3.8: Cluster Head Selection

then the cluster heads are selected and clusters are formed. In the beginning, all normal nodes reside within a *region* inside a sensor field.

The cluster head selection sub-phase is a complex resource-intensive task which incurs high processing overhead and network delay. During this phase, the normal nodes and high energy nodes remain in sleep mode to conserve their battery powers. Once an optimal percentage of cluster heads are selected for the current round, the base station transmits a message to each normal node. This message contains ID of each normal node and ID of its respective cluster head. At this point of time, there are two types of normal nodes within the network: non-cluster head nodes and cluster head nodes. Non-cluster head nodes are those normal nodes that participated in cluster head selection but were unable to satisfy the criteria for selection. The base station assigns a cluster head to each non-cluster head in order to form a cluster. The non-cluster heads become member nodes of a cluster head within each cluster. The formation of a cluster around each cluster head signals the end of cluster formation sub-phase. The direct association of a member node with its respective cluster head enhances network lifetime because a cluster head is no longer required to advertise itself. Furthermore, each member node avoids the transmission of join-request

messages to its cluster head.

The completion of cluster formation sub-phase is initiated by schedule creation sub-phase. During this sub-phase, each cluster head assigns TDMA slots to its member nodes which allow them to transmit their data using these slots. Furthermore, the creation of schedule allows the nodes to remain in sleep mode and wake up only on their allocated time slots.

The completion of status, cluster head selection, cluster formation and schedule creation sub-phases signal the end of set-up phase and initiation of a steady-state phase. During steady-state phase, each member node collects data according to a predefined condition and transmits to its cluster head using the allocated TDMA slots. When all the member nodes within each cluster have transmitted their data, the cluster heads perform necessary signal processing to eliminate redundant data packets. Because multiple cluster heads are involved during this process, it would be a resource-consuming task if all these nodes transmit their aggregated data directly to a base station. To reduce their energy consumption, one of the cluster head is elected as a leader node which collects data from other cluster heads as shown in Fig. 3.9.

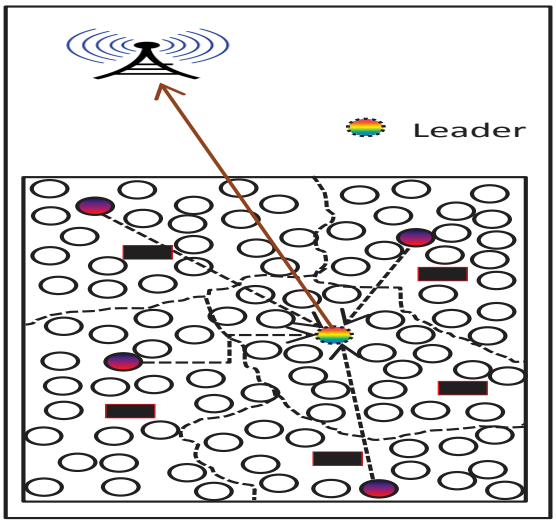


Figure 3.9: Data Transmission to a Base Station

The leader node further aggregates the incoming data from the remaining cluster heads and transmits to a base station. The task performed by a leader node is resource-consuming and as a result the cluster heads take turn to become a leader node in each round. Among the cluster heads, the one having the largest residual energy in a particular round is elected as a leader node. The completion of set-up phase and steady-state phase is coined as one complete round as previously discussed. After the completion of steady-state phase, status messages are transmitted again and a new round starts. The complete set of operations performed during each round is shown in the flowchart of Fig. 3.10.

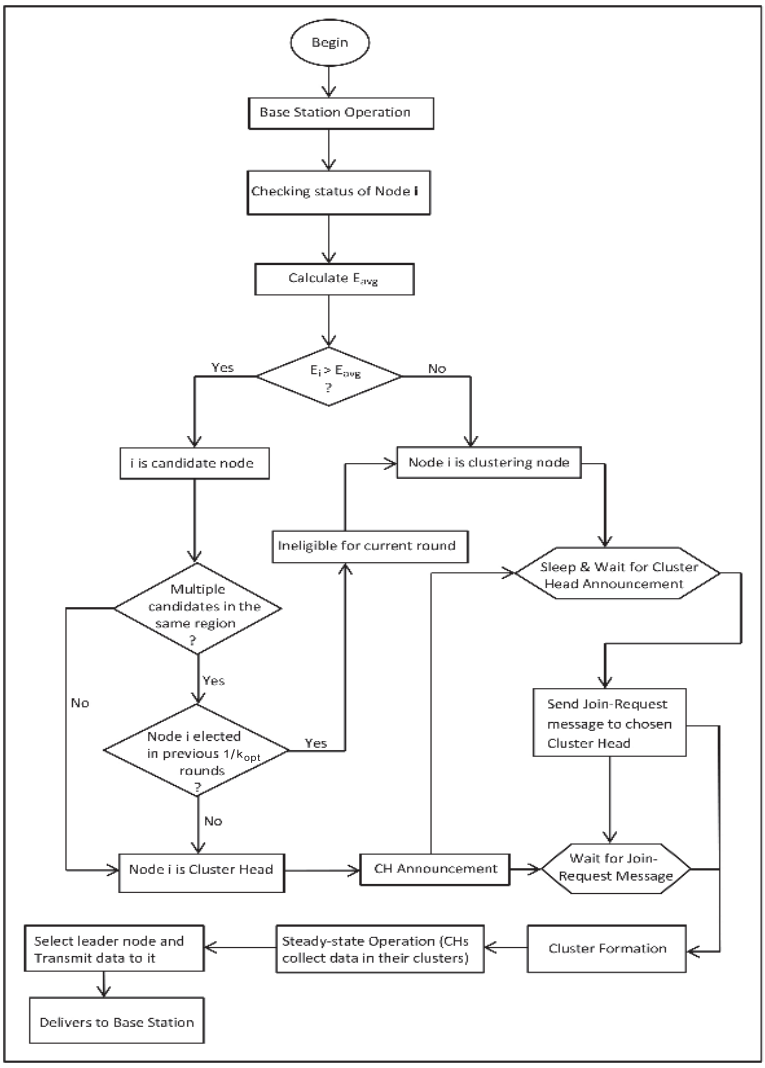


Figure 3.10: Flowchart of Set-up and Steady-state Phases

3.2.2 Energy Evaluation Model

During set-up phase and steady-state phase, a series of operations are performed and each one consumes a considerable amount of energy. The energy consumption of a node depends on the operation it performs at a particular time. A single node may perform one or more operations in each round. The type of operation along with the distance metric determine the energy consumption of a node.

During status sub-phase, each normal node transmits its location information and residual energy to a nearest high energy node. The amount of energy consumed by a normal node (E_{status}) during this sub-phase is calculated using Equation 3.7.

$$E_{status}(m,d) = mE_{elec} + m\epsilon_{fs}d^2_{HEN}, \qquad d_{HEN} < d_c. \tag{3.7}$$

Here, m is the size of message and d_{HEN} is the distance between a normal node and the nearest high energy node. Because, our network model uses a (100×100) square meter area, it is most likely that a normal node is within the free-space range of a high energy node.

Each high energy node receives status messages from multiple neighbouring normal nodes and transmits to a base station. The amount of energy consumed by a high energy node (E_{HEN}) during status sub-phase is calculated using Equation 3.8.

$$E_{HEN}(m,d) = \begin{cases} mE_{elec}x + m\epsilon_{fs}\, d^2_{BS}, & d_{BS} < d_c, \\ mE_{elec}x + m\epsilon_{mp}\, d^4_{BS}, & d_{BS} \geq d_c. \end{cases} \tag{3.8}$$

Here, x is a subset of normal nodes communicating with a particular high energy node, $\forall$ $x \in n \wedge x < n$ and d_{BS} is the distance between a high energy node and the base station. If the base station is located at a distance less than d_c, free-space propagation model is used, otherwise, multipath ground propagation model is used.

When the base station selects an optimal percentage of cluster heads, it advertises them to all the normal nodes. Each cluster head collects data within its cluster and transmits to the base station using a two-hop communication link. The energy consumed by a cluster head (E_{CH}) is calculated using Equation 3.9.

$$E_{CH}(m,d) = \begin{cases} mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + m\epsilon_{fs}d_{LN}^2, & d_{LN} < d_c, \\ mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + m\epsilon_{mp}d_{LN}^4, & d_{LN} \geq d_c. \end{cases} \tag{3.9}$$

Here, k_{opt} is the optimal number of clusters which is always equal to the number of cluster heads because, there is one cluster head per cluster and d_{LN} is the distance between a cluster head and a leader node.

We used balanced-clustering technique [131] to establish nearly equal-sized clusters. The base station knows the location of each node and always tries to select cluster heads which are easily accessible to member nodes provided that such cluster heads satisfy the selection criteria. The base station tries its best to distribute equal load in each cluster, i.e., 20 nodes per cluster for a network of 100 nodes. Using these calculations, the value of k_{opt} is 5 for a network of 100 nodes. The use of balanced-clustering technique enables our proposed algorithm to elect an optimal number of clusters and cluster heads in most of the round over the span of network lifetime. Each cluster head consumes energy in data processing (E_{elec}), data aggregation within its cluster (E_{DA}) and transmission to a leader node (d_{LN}).

In Equation 3.9, the cluster heads only perform data processing, data aggregation and transmission to a leader node. They were not assumed to sense data within their respective clusters, a role similar to the member nodes. However in case, if the cluster heads sense the data as well, their energy consumption is much higher. This is due to the fact that each cluster head not only collects and transmits data from member nodes but also senses its neighbourhood for data collection. Furthermore, each cluster head aggregates its own data with the data of member nodes. The energy consumption of each sensing cluster head is

computed using Equation 3.10.

$$E_{Sensing-CH}(m,d) = \begin{cases} \alpha I + mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + \\ m\epsilon_{fs}d_{LN}^2, & d_{LN} < d_c, \\ \alpha I + mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + \\ m\epsilon_{mp}d_{LN}^4, & d_{LN} \geq d_c. \end{cases} \tag{3.10}$$

where, α is the amount of energy consumed by a cluster head in sensing a single bit and I is the total number of bits in the sensed message.

The amount of energy consumed by a member node (E_{member}) within its cluster is computed using Equation 3.11.

$$E_{member} = \alpha I + mE_{elec} + m\epsilon_{fs}d_{CH}^2, \qquad d_{CH} < d_c. \tag{3.11}$$

Here, d_{CH} is the distance between a member node and its cluster head. The member node is in close neighbourhood of a cluster head, therefore, free-space propagation model is an obvious choice. Once each cluster head collects data from its member nodes, a leader node is elected by them to transmit their data to a base station. The amount of energy consumed by a leader node (E_{LN}) is computed using Equation 3.12.

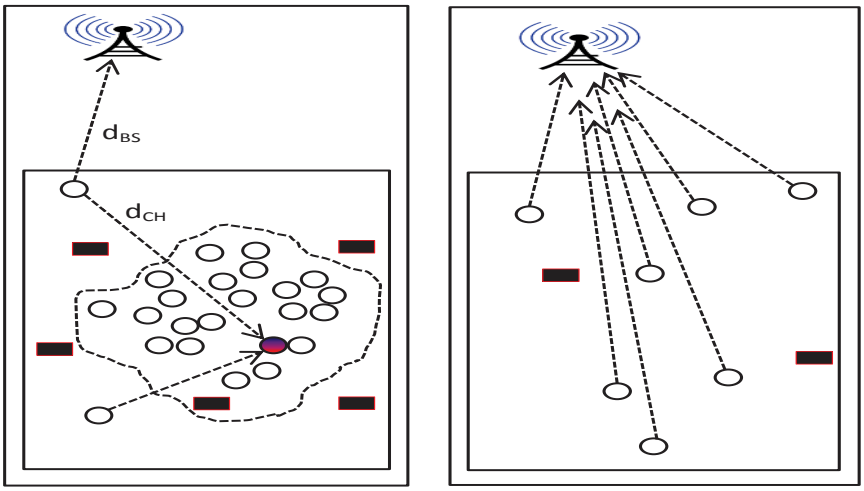
$$E_{LN}(m,d) = \begin{cases} mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + \\ mE_{DA}(\sum_{i=1}^{k_{opt}-1} CH_i) + m\epsilon_{fs}d_{BS}^2, & d_{BS} < d_c, \\ \\ mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + \\ mE_{DA}(\sum_{i=1}^{k_{opt}-1} CH_i) + m\epsilon_{mp}d_{BS}^4, & d_{BS} \geq d_c. \end{cases} \tag{3.12}$$

Here, d_{BS} is the distance between a leader node and the base station. Each leader node consumes energy in data processing and data aggregation within its cluster. Furthermore, it consumes energy in aggregating data from other cluster heads (CH_i) and in data transmission to the base station.

During a particular round, one or more normal nodes may be faraway from their nearest cluster heads and may refrain themselves of joining them. Instead, it may be more energy-efficient if such nodes transmit their data directly to the base station as shown in Fig. 3.11(a). We call such nodes as isolated nodes and the amount of energy consumed by an isolated node ($E_{isolated}$) is calculated using Equation 3.13.

$$E_{isolated}(m,d) = \begin{cases} mE_{elec} + m\epsilon_{fs}d_{BS}^2, & d_{BS} < d_c < d_{CH}, \\ mE_{elec} + m\epsilon_{mp}d_{BS}^4, & d_{BS} < d_{CH} \wedge d_{BS} \geq d_c. \end{cases} \tag{3.13}$$

Here, d_{BS} is the distance between an isolated node and the base station and d_{CH} is the distance between an isolated node and the nearest cluster head. For an isolated node to transmit its data directly to a base station, d_{BS} must always be less than d_{CH}.



(a) Isolated Nodes (b) Insufficient Nodes To Form Clusters

Figure 3.11: Energy Consumption in different Scenarios

In WSNs, there are not sufficient nodes toward the end of network lifetime. Therefore,

it may not be possible to form one or more clusters. In that case, each normal node transmits its data directly to the base station as shown in Fig. 3.11(b). The amount of energy consumed by each node (E_{end}) is calculated using Equation 3.14.

$$E_{end}(m,d) = \begin{cases} mE_{elec} + m\epsilon_{fs}d_{BS}^2, & d_{BS} < d_c, \\ mE_{elec} + m\epsilon_{mp}d_{BS}^4, & d_{BS} \geq d_c. \end{cases} \tag{3.14}$$

The amount of energy consumed in any particular round (E_{round}) is calculated using Equation 3.15.

$$E_{round} = E_{status} + E_{HEN} + E_{CH} + E_{member} + E_{LN} + E_{isolated} \tag{3.15}$$

Finally, the total amount of energy (E_{Total}) consumed over the span of network lifetime is computed using Equation 3.16.

$$E_{Total} = \sum_{i=1}^{i=r} E_{round} + \sum_{i=1}^{i=r} E_{end} \tag{3.16}$$

Here, r is the total number of rounds over which a network operates. When there are one or more clusters within a network, E_{round} is the end product. However, towards the end of network lifetime, there are not sufficient nodes to form one or more clusters in any round and the end result is E_{end}. The sum of E_{round} and E_{end} result in the total amount of energy consumed over the span of network lifetime.

3.3 Summary

This chapter has two major objectives. First, a randomly distributed cluster-based hierarchical algorithm was proposed to elect a near-optimal percentage of cluster heads. The proposed routing algorithm elects cluster heads based on their residual energy consumption. The goal of the routing algorithm was to enhance network lifetime and quality of data

delivered at the base station. Secondly, a centralized cluster-based hierarchical algorithm was proposed in which the base station elects an optimal percentage of cluster heads in each round. Unlike the existing centralized approaches, our algorithm does not require cluster head advertisement and join-request message transmissions. Once a centralized selection of cluster heads is performed, an energy evaluation model is developed which takes into account the energy consumption of the nodes during various phases and sub-phases.

Chapter 4

Energy-efficient Cluster-based Congestion Control Algorithm

In WSNs, the data generated by heterogeneous applications differ from each other in terms of data rate, transmission priority, bandwidth requirement, delay-tolerance and acceptable packet loss [132]. It is necessary to meet the individual requirements of each data type. In a cluster-based hierarchical WSN, as the nodes move across the cluster field, it is highly probable that the number of nodes in a particular cluster may exceed the maximum threshold limit for that cluster. Unbalanced clusters cause congestion, thereby resulting in packet loss, latency, blockage of new connections and QoS degradation. Congestion affects both static and mobile WSNs. Time-critical applications experience severe setbacks due to congestion because time-stamped data need to be routed to a base station immediately. Minor delays in transmission will make the data useless and redundant. Network congestion is mitigated by increasing the capacity of the links or by controlling the data rate of each node [133]. In this chapter, a novel priority-based application-specific congestion control clustering (PASCCC) protocol is proposed, which integrates mobility and heterogeneity of the nodes to detect congestion in a network. PASCCC decreases the duty-cycle of each node by maintaining threshold levels for various applications. The transmitter of a sensor

node is triggered when the reading of a captured event exceeds a specific threshold value. Time-critical packets are prioritized during congestion in order to maintain their timeliness requirements. The cluster heads ensure coverage fidelity by prioritizing the packets of distant nodes over those of nearby nodes. A novel queue scheduling mechanism is proposed for cluster heads to achieve coverage fidelity, which ensures that the extra resources consumed by distant nodes are utilized effectively. PASCCC uses the randomly distributed cluster-based hierarchical algorithm as the underlying platform for its operation. PASCCC is based on our work published in [134] and operates on the network layer of WSN stack. The rest of the chapter is organized as follows. In Section 4.1, various features of the deployed nodes are discussed. In Section 4.2, the framework of PASCCC is presented followed by its operational mechanism in Section 4.3. Finally, we conclude the chapter by providing experimental results in Section 4.4.

4.1 The PASCCC Protocol

In this section, we provide a brief description of the nodes used by our energy-efficient PASCCC protocol. To the best of our knowledge, PASCCC is the first protocol of its kind to consider mobility, heterogeneity, congestion detection and mitigation using a cluster hierarchy. We make the following assumptions about the operational capabilities of the nodes.

- Nodes are deployed randomly in the field with a different set of energy values.
- Nodes are capable of adjusting their transmission power in order to reach a far distant cluster head during a specific round.
- A small percentage of advanced nodes are used to provide network stability towards the end of network lifetime. These nodes have higher energy as compared to normal nodes and are more frequently elected as cluster heads.
- The location of a base station is not fixed and it can be either within or outside the sensor field.

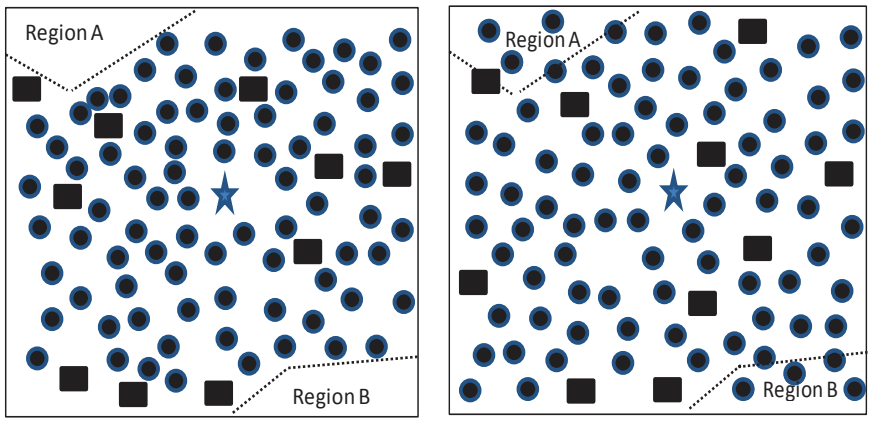
- Nodes are capable of moving around the sensor field to cover vacant regions using the random waypoint mobility model [135] with a speed V, where the value of V ranges between V_{min} and V_{max}.

The framework of our proposed protocol is discussed in Section 4.2 followed by its operational mechanism in Section 4.3.

4.2 Framework of PASCCC

In static WSNs, the nodes are confined to specific geographical locations for monitoring various applications. To balance the network cost, the nodes cover only a subset of sensor field which results in uncovered regions. In these networks, the dynamic nature of happening events may cause one or more events to go unreported provided they occur in uncovered regions. Fig. 4.1(a) presents the generic topology of a static WSN where all the nodes are static, which results in uncovered regions such as region A and region B. If critical events occur in these regions, they will go unreported, thereby causing important data loss and degradation of the network quality. Mobile nodes solve this problem by moving around the field to provide the necessary coverage and connectivity using PASCCC as shown in Fig. 4.1(b). The nodes are capable of moving around the field if required in order to cover vacant regions. Mobility ensures complete coverage and connectivity at all times. Hence, it is less likely that the generated events will go unreported. In PASCCC, 10% of the nodes are advanced. These nodes have higher energy levels as compared to normal nodes. Normal nodes are represented by "circle", advanced nodes are represented by "square" and the base station is represented by "star" as shown in Fig. 4.1(b).

PASCCC is an application-specific protocol. In our scheme, we consider two application parameters using PASCCC: temperature and humidity. PASCCC acts as a reactive protocol for temperature monitoring and as a proactive protocol for humidity monitoring. In reactive routing protocols, the nodes react immediately to sudden and drastic changes in the values of sensed events [136]. As a result, these protocols are suitable for time-critical



(a) Topology of Static WSN (b) Topology of PASCCC

Figure 4.1: Framework of the Proposed Protocol

applications. In proactive routing protocols [61], the nodes switch on their transmitters, sense the environment and report the sensed data periodically to a base station. These protocols are suitable for applications that require periodic data transmission.

4.3 PASCCC Operational Mechanism

A detailed description of PASCCC is provided here in terms of application support, congestion detection and mitigation and the underlying queuing model.

4.3.1 PASCCC: An Application-specific Protocol

PASCCC supports two different types of application, thus different sets of priorities and timeliness requirements are maintained for the packets. Each node is equipped with two sensors to monitor the temperature and humidity packets. Our protocol operates under the following assumptions.

- The nodes sense and capture humidity packets continuously and transmit them to their respective cluster heads.
- During congestion, humidity packets are dropped to reduce the level of congestion.
- Nodes turn on their transmitters and start sensing temperature events after a certain

threshold value is reached.

In terms of priority, humidity packets have a lower priority and they can tolerate some delay, packet loss and degradation in their QoS. By contrast, temperature packets have a higher priority and they need to be reported immediately to a base station. These packets are time-stamped. Even a minor delay in their transmission will make them useless and redundant. During congestion, the temperature packets are prioritized over humidity packets. To capture temperature packets, the nodes turn on their temperature sensors only when the hard threshold (H_T) is reached [136]. We set the value of H_T to 50 ^{0}C. In our proposed scheme, H_T is the minimum temperature reading at which the sensors operate by capturing the packets. Any value less than H_T will not be able to trigger the temperature sensors. This value is stored in a local variable inside the memory of each node, which we call the sensed value (SV). If a node has to transmit data to its cluster head more than once in the current round, it can only do so if its sensed value is greater than or equal to the soft threshold (S_T). S_T represents a small change in the value of the sensed data, which triggers the transmitter of each temperature sensor to capture the packets and report them to their respective cluster heads. In PASCCC, the value of S_T is 2 ^{0}C. Thus, each temperature sensor will trigger for the first time at 50 ^{0}C. On the next occasion, it will only trigger when the temperature reading is at least 52 ^{0}C in the current round. This new value is then stored in SV. The reason for using the soft threshold is to reduce data redundancy in the current round because an end user is only interested in disjoint sets of data patterns collected from sensor field. In the absence of S_T, the nodes will transmit similar data packets, which will then impose an extra burden on energy-starved sensor nodes.

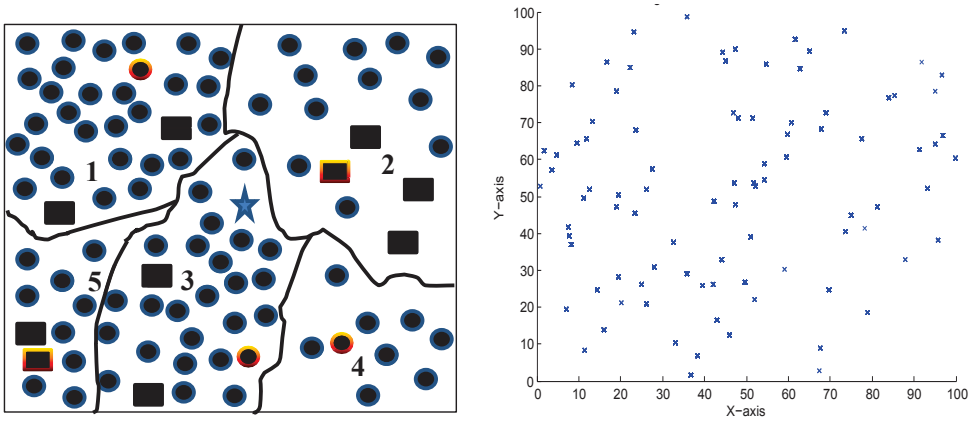
It should be noted that PASCCC is designed to operate in a temperature range of 50 ^{0}C to 100 ^{0}C. Humidity, on the other hand, has a lower priority and is measured as the amount of moisture content in the air. Humidity is a percentage value. H_T and S_T are not applicable to humidity packets and they are transmitted immediately upon detection during normal network load. However, during network congestion, they are dropped to pave the way for highly-prioritized temperature packets. Because it depends on a threshold value, PASCCC

is suitable for bush fire monitoring [85] and similar applications where temperature is the main parameter used to measure critical events. When the temperature in the bush rises above a certain threshold value, the nodes turn on their transmitters and report the captured events to a base station. These events are prioritized in order to prevent any catastrophic consequences.

4.3.2 PASCCC: Congestion Detection and Mitigation

PASCCC uses the balanced clustering technique [131] to ensure that each round results in an equal number of nodes in each cluster. This technique is a rather idealistic approach to cluster formation because it tries its best to achieve its goal, but balanced clusters cannot be guaranteed in each round. In addition, PASCCC inherits mobility features to cover the vacant regions. Mobility ensures complete coverage and connectivity at all times, but it also yields unbalanced clusters in various rounds throughout the network lifetime. This problem is common in static clustering protocols as well such as LEACH and its variants, which imposes an extra burden on the cluster heads in terms of communication, computation, and data aggregation. Congestion arises in these circumstances, thereby causing packet loss, delay, blocking of new connections and degradation of the QoS.

During congestion, highly-prioritized temperature packets are routed to the base station to maintain the integrity of their time-stamps while humidity packets are dropped to reduce the level of congestion. Congested clusters are shown in Fig. 4.2(a), where clusters 1 and 3 are overcrowded, thereby causing extra resource utilization. Thus, nodes are prevented from capturing humidity packets in these clusters. PASCCC reduces congestion by a considerable degree because the temperature packets are only captured when a specific threshold is met and the humidity packets are dropped during congestion. Fig. 4.2(b) shows the location of congested regions, which are represented by the x and y coordinates in the sensor field. In PASCCC protocol, the duty-cycling of each node depends on the congested regions and predefined threshold limits.



(a) Congestion at the Cluster Level (b) Congested Region Locations

Figure 4.2: Congestion Detection and Mitigation

We programmed the nodes by modifying the balanced clustering technique which assumes that all clusters are supposed to have an equal number of member nodes. This technique depends on the value of optimal percentage of cluster heads (k_{opt}). In PASCCC, the nodes are capable of moving around the field to cover vacant regions to prevent valuable data losses. However, the mobility of the nodes may result in unbalanced clusters in which some clusters will have more member nodes as compared to other. In addition, the nodes move from one cluster to another during various rounds of operation, which may result in overcrowded clusters. During the set-up phase, each cluster head allocates TDMA slots to its member nodes. The number of assigned slots within each cluster depends on the total number of join-request messages sent by the member nodes. If these request messages exceed the threshold limit for a specific cluster, the cluster head piggybacks one bit field in each time slot for its member nodes. After receiving the piggybacked time slots, the nodes in that specific cluster turn off their humidity sensors. The piggybacked time slots are used to prevent congestion in this manner. These time slots are used only when each member node receives indications from its specific cluster head about the degree of congestion within its cluster.

Congestion and unbalanced clustering lead to sparse distributions of nodes in other clusters. Hence, the network resources are not fully utilized, thereby causing poor data ag-

gregation and low quality of data transmission to the base station. Congestion is associated directly with the queuing model of each node. The queuing model of a normal node differs from that of a cluster head. Next, we present a brief description of the internal queuing model of our proposed protocol.

4.3.3 PASCCC: Queuing Model

Under a normal network load, the queue of a normal node is modelled using a First-Come-First-Served (FCFS) algorithm [137]. However, the behaviour of the queue changes during congestion and it is prioritized for temperature packets in order to route them immediately to a base station. Source nodes detect events and assign them priorities based on the type of data. One bit in each packet header is reserved for the priority assignment. If the bit is 1, the packet contains temperature data, whereas it contains humidity data otherwise. Priorities are assigned based on the type of data rather than the locations of the nodes because event occurrences are not restricted to a particular location [138]. Priority assignment prevents the dropping of critical packets during congestion. The queuing model under a normal network load and at the time of congestion is shown in Fig. 4.3, where P_L and P_H represent lower and higher priority packets, respectively, whereas Q_{TL} and Q_{TH} are the lower and higher threshold limits. The queue at each node maintains the following rules.

- $0 \leq P \leq Q_{TL}$: Buffer both types of incoming packets under a normal network load at time t. Here, P is equal to the sum of all P_L and P_H packets.
- $Q_{TL} < P < Q_{TH}$: Start dropping lower priority packets while buffering higher priority packets. At this point of time t+t_0, congestion starts to arise.
- $Q_{TH} \leq P \leq Q$: Drop all lower priority packets while "randomly" or "selectively" dropping higher priority packets, depending on the type of node.

In non-cluster heads, also known as member nodes, the lower priority humidity packets begin to drop when the threshold exceeds Q_{TL}. If the threshold exceeds Q_{TH}, higher priority temperature packets are dropped randomly. Random dropping is used at the node

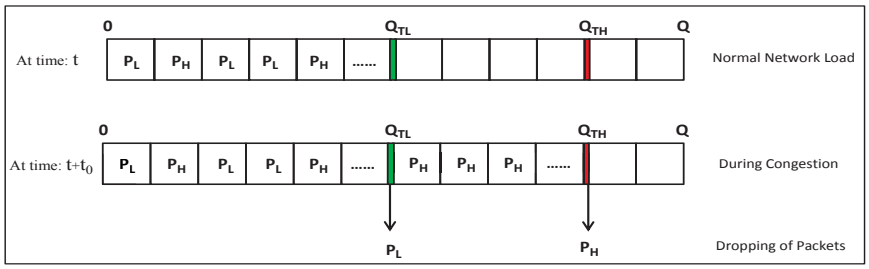


Figure 4.3: Queuing Model of a Sensor Node

level because each member node senses and captures packets in its neighbourhood, which is highly redundant and contains very similar data. When Q is reached, all the packets are dropped at this point because the queue is full. The flowchart of queuing operation is shown in Fig. 4.4.

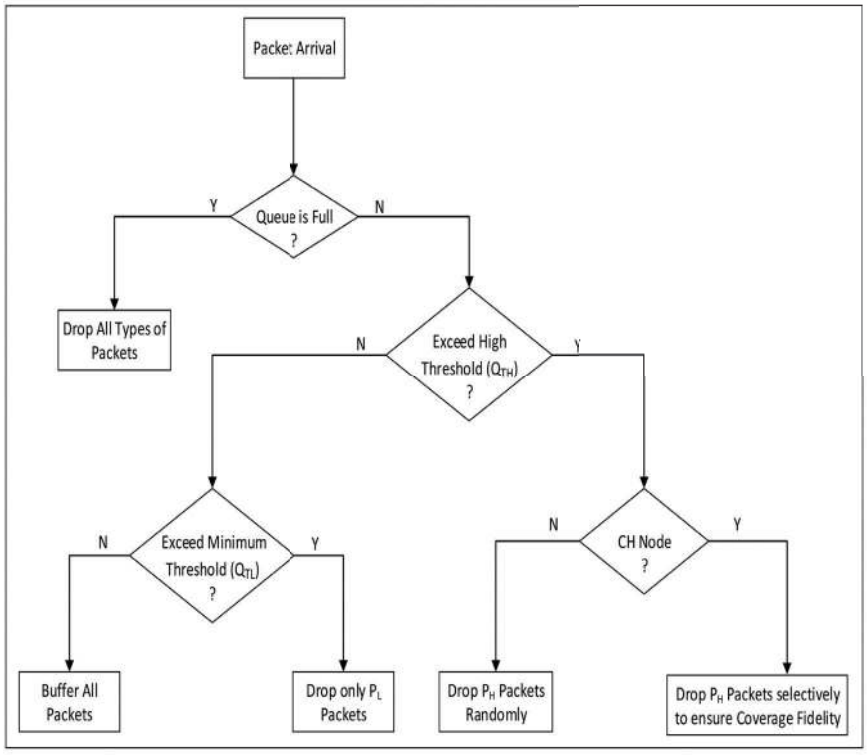


Figure 4.4: Flowchart for the Queuing Operation

In contrast to member nodes, the packets at each cluster head are selectively dropped when the threshold exceeds Q_{TH}. The cluster heads maintain the coverage fidelity in

sensor field [139]. Distant nodes in each cluster consume more energy to transmit their data to their respective cluster heads. Thus, the prioritized packets of these nodes are routed immediately due to the time elapsed in their time-stamps, which will expire earlier compared with the nearby nodes. Therefore, the distance of a node from the cluster head plays an important role in queue scheduling of that node. In WSNs, distant nodes at remote locations capture highly sensitive data compared with nearby nodes. Thus, each cluster head evaluates critical temperature packets based on the distance of the source nodes from itself. Packets of remote nodes are forwarded to the base station, whereas those of nearby nodes are dropped when the threshold exceeds Q_{TH}. The temperature readings of incoming packets from remote nodes and nearby nodes must be in close proximity of each other, otherwise, the above condition cannot be applied. Priority assignment is applied due to the application-specific nature of PASCCC, but the data delivery timeliness and QoS requirements vary among applications. More specifically, applications have a different quality of information [140].

4.4 Experimental Results and Analysis

In this section, we make comparison between PASCCC protocol and other routing protocols in terms of various performance metrics. We performed our evaluation and analysis using the same parameters of the randomly distributed cluster-based hierarchical algorithm of Chapter 3. Therefore, comparisons were made between PASCCC and existing cluster-based hierarchical routing protocols in terms of network lifetime, energy consumption, data transmission and quality of data. In addition, a probabilistic approach was used to detect congestion, which was then validated based on the simulation results. Matlab R2011a was used as the simulation tool under Windows 7 platform. The nodes were deployed in a 100×100 square meter area with sensor nodes randomly distributed.

4.4.1 Lifetime of the Network

The lifetime of a network is measured in terms of stability period and instability region. We calculated the stability period and instability region as shown in Fig. 4.5.

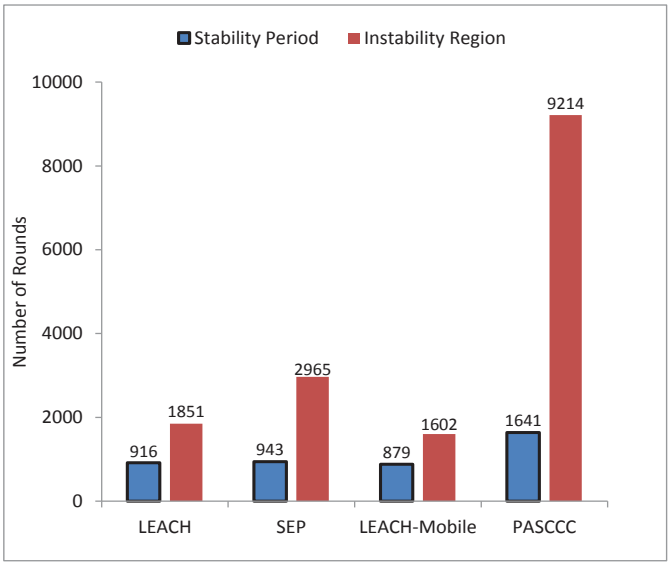


Figure 4.5: Lifetime of the Network

In terms of stability period and instability region, PASCCC performs much better as compared to other protocols because of its application-specific nature, which reduces the duty-cycling of each node. On the other hand, SEP [141] has a better performance as compared to LEACH [61] and LEACH-Mobile [142] because of its heterogeneous collection of nodes, which extends the lifetime of the network. LEACH-Mobile handles constantly moving nodes, which consume more energy and the lifetime of the network is significantly reduced. Unlike LEACH-Mobile, our proposed protocol provides mobility on-demand basis to cover vacant regions left behind by the dying nodes.

4.4.2 Residual Energy

Energy consumption of the nodes influences the lifetime of a network. Higher the residual energy consumption, shorter will be the lifetime of a network. In Fig. 4.6, we compare

PASCCC protocol with LEACH and its variants in terms of residual energy consumption. In PASCCC, the temperature sensors remain in the sleep mode until specific thresholds trigger their transmitters. Humidity sensors also enter the sleep mode after congestion is detected. In other protocols, the nodes have higher duty-cycles and they consume higher amount of energy during processing and communication. PASCCC and SEP protocols contain normal nodes and advanced nodes. The normal nodes are equipped with 0.5 joule while the advanced nodes are equipped with 1 joule of energy. PASCCC utilizes limited energy of the nodes efficiently compared with LEACH, SEP and LEACH-Mobile protocols. The energy consumption of the existing protocols exhibits an overlapping trend, although SEP produces a slight improvement in the instability region.

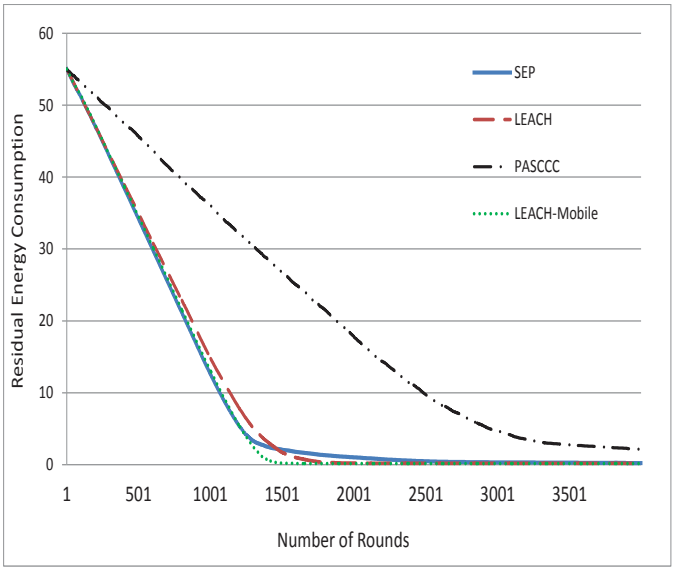


Figure 4.6: Residual Energy Consumption (in Joules)

4.4.3 Data Transmission

The number of transmitted packets affects the energy consumption and network congestion. Higher volume of data traffic increases the possibility of congestion which can ultimately lead to network failure. Hence, in this thesis, our aim is to limit redundant data transmission to the base station. Fig. 4.7 shows the total number of data packets delivered

at the cluster heads and base station over the span of network lifetime. PASCCC has a lower duty-cycle compared with the existing cluster-based routing protocols. As a result, the total amount of transmitted data is significantly lower. For temperature monitoring, PASCCC captures the data only when H_T and S_T are met. For humidity monitoring, it drops humidity packets when congestion is detected and keeps the humidity sensor of a node in sleep mode which reduces the amount of captured data. The use of H_T, S_T and keeping the humidity sensors in sleep mode not only reduces the amount of transmitted data but also enhances the network lifetime. In Fig. 4.7, PASCCC delivers 148232 packets to the cluster heads and 3922 packets to the base station. In comparison, LEACH, SEP and LEACH-Mobile deliver much higher number of packets to the cluster heads and the base station.

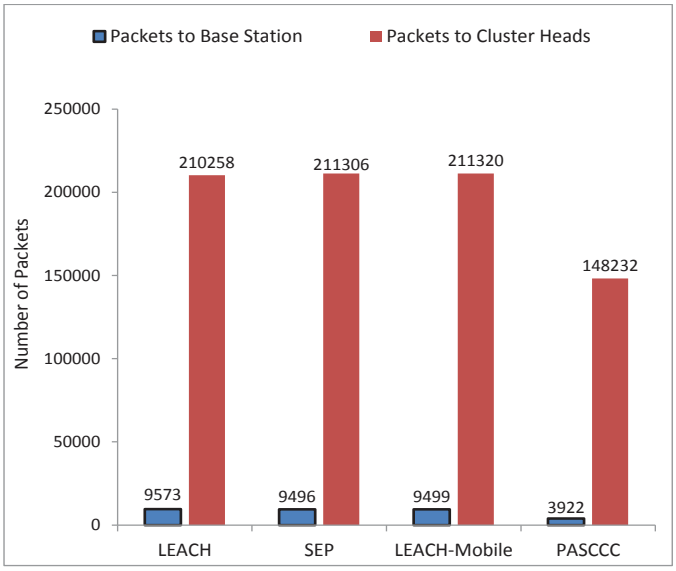


Figure 4.7: Data Transmission to Cluster Heads and Base Station

Using Fig. 4.7, we computed the quality of data for these protocols. Recall that the quality of data is a percentage value and is calculated as the sum of packets delivered at the base station to the sum of packets delivered at the cluster heads. The quality of data for PASCCC is 2.64, LEACH-Mobile is 4.49, SEP is 4.49 and LEACH is 4.55 respectively. These values indicate that PASCCC performs much better as compared to existing

protocols due to its efficient duty-cycling and threshold-based operational mechanism.

4.4.4 Causes of Congestion

Based on our simulation results, we identified the nodes that caused congestion. Mobility of the nodes results in an unequal distribution of nodes in one or more clusters which causes network congestion. In a cluster-based hierarchical protocol, each node must be elected as cluster head once every $\frac{1}{k_{opt}}$ rounds [122]. In addition, each cluster has exactly one cluster head so the number of clusters is always equal to the number of cluster heads in each round. If there are $\mathbb{N}$ nodes in the network and the optimal number of clusters is k_{opt}, then the number of nodes in each cluster is calculated using Equation 4.1.

$$C_n = \frac{\mathbb{N}}{k_{opt}}. \tag{4.1}$$

The probability of a node X to be elected as cluster head throughout the network lifetime is calculated using Equation 4.2.

$$X_{CH} = k_{opt} \times r_{total}. \tag{4.2}$$

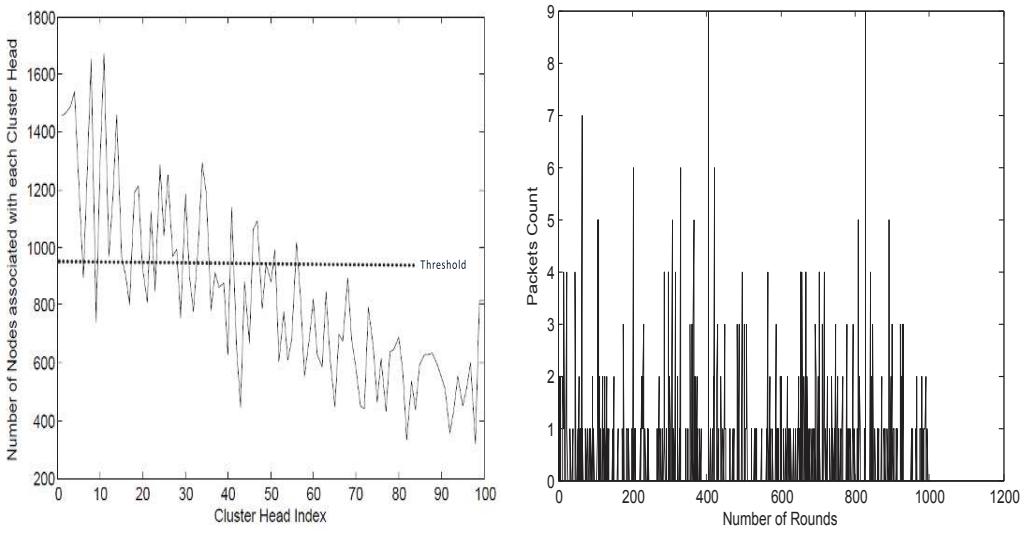
Here, X_{CH} is the number of times X is elected as a cluster head during its lifetime and r_{total} is the total number of rounds during which X_{CH} is calculated.

Based on Equations 4.1 and 4.2, the number of nodes associated with any cluster head during its lifetime is calculated using Equation 4.3.

$$\sum_{n=1}^{n=\mathbb{N}} CH_n = (\frac{\mathbb{N}}{k_{opt}} - 1) \times X_{CH}. \tag{4.3}$$

Here, n is any node that wants to become a cluster head. According to the balanced clustering technique [131], each cluster has an equal number of nodes, $\frac{\mathbb{N}}{k_{opt}}$. Any value greater than that obtained using Equation 4.1 will result in congestion at the cluster level.

We evaluated Equations [4.1-4.3] using $\mathbb{N}$=100, r_{total}=1000, and k_{opt}=5. Based on these parameters, any cluster head associated with more than 950 nodes (threshold level) throughout the network lifetime will cause congestion, as shown in Fig. 4.8(a). The number of humidity packets dropped during congestion in the first 1000 rounds is shown in Fig. 4.8(b).



(a) Nodes Associated with Each Cluster Head (b) Dropping of Humidity Packets

Figure 4.8: Congestion Detection and Mitigation

4.5 Summary

In this chapter, we used the randomly distributed cluster-based hierarchical algorithm of Chapter 3 to design a novel congestion detection and mitigation protocol for cluster-based hierarchical WSNs. The proposed PASCCC protocol has the following distinctive features.

1. PASCCC provides an on-demand network mobility to cover vacant regions within a sensor field.
2. PASCCC is an application-specific and priority-driven protocol which treats two different monitoring applications based on their levels of assigned priorities.
3. At the time of network congestion, higher priority temperature packets are routed

from congested clusters to the base station while lower priority humidity packets are instantly dropped to mitigate the level of congestion.

4. A novel queuing model is designed which drops the packets based on the assigned priority levels, threshold levels and types of nodes.

PASCCC protocol uses threshold parameters to efficiently schedule the duty-cycling of each node. The threshold-specific nature of PASCCC reduces the energy consumption of the nodes in various network operations. As a result, PASCCC is suitable for monitoring a wide range of threshold-specific applications such as forest wildfire, volcanic eruption, air pollution and habitat monitoring.

In this chapter, we focused on designing an efficient clustering mechanism to detect and mitigate congestion in a cluster-based hierarchical network. Efficient congestion detection and mitigation techniques conserve the energy of sensor nodes and enhance the lifetime of a network. In Chapter 5, we present a Sybil attack detection scheme in a centralized cluster-based hierarchical network. The proposed detection technique is highly efficient in term of detection rate, energy consumption and network lifetime. An efficient detection technique against Sybil attack reduces the number of packets being dropped which literally means that the number of retransmission attempts are reduced. Ultimately, the energy consumption is reduced which enhances the lifetime of a network. Moreover, safeguarding against various threats such as malicious data transmission, alteration of packet sequencing and fabricated data transmission, also reduces the energy consumption of the nodes.

Chapter 5

Sybil Attack Detection Scheme for a Cluster-based Hierarchical Network

The presence of low-power lossy links and a hostile deployed environment exposes WSNs to a wide range of security threats at different layers. Sybil attack is one such threat which targets the routing layer of WSN. The cluster-based hierarchical protocols operate at the routing layer which makes them a favourable target for an adversary to launch a Sybil attack. In this chapter, we propose a lightweight Sybil attack detection scheme for a centralized cluster-based hierarchical network. The proposed scheme requires coordination of any two high energy nodes and performs its detection task using signal strength of the received packets. The goal of our proposed scheme is to prevent Sybil nodes from participation in cluster head selection. A single Sybil node can wreak havoc in the network by forming multiple clusters using its forged identities as separate cluster heads. In Section 5.1, we discuss some network assumptions for the proposed scheme. In Section 5.2, we provide a detailed explanation of our Sybil attack detection scheme which is followed by the formation of a centralized cluster-based hierarchical network in Section 5.3. This chapter is based on our work published in [143].

5.1 Network Assumptions

In our proposed scheme, the sensor nodes are classified according to their energy levels at the time of network deployment. Each node is either an ordinary sensing node or a high energy node. The ordinary sensing nodes are equipped with 2 joules while high energy nodes are having 5 joules of energy. High energy nodes are uniformly distributed within the geographical region to enable energy-efficient access for ordinary sensing nodes. Moreover, they are only 5 percent of ordinary sensing nodes to balance the network cost. They assist the base station in Sybil attack detection and in relaying back vital information.

To minimize the occurrence of a malicious activity, Sybil nodes are barred from cluster head selection. In doing so, network stability, efficiency and energy consumption are enhanced. In WSNs, each node has the ability of adjusting its transmission power to reach a far distant node [144]. A Sybil node may vary its transmission power to deceive the neighbouring nodes and far distant nodes into believing that it is the potential cluster head because of its maximum signal strength. Recall that in cluster-based hierarchical protocols, a neighbouring node associates itself with a potential cluster head having the strongest signal strength among all the cluster heads. A Sybil node which forges five different identities to the sensor nodes in its vicinity is elected as cluster head in Fig. 5.1. It means that all the forged identities of a Sybil node are the potential cluster heads as well. In WSNs, each node is an entity which has an identity of its own. An entity is elected as cluster head but it is the identity which is used for network communication. It is for this reason that each identity of a Sybil entity is a potential cluster head. Each ordinary sensing node has a single identity and as a result it can form only one cluster provided that it is elected as cluster head. However, a Sybil node is capable to form multiple clusters by assigning each one of its identity as a separate cluster head. A single Sybil node is capable to engulf most of the legitimate nodes within the sensor field.

The consequences of this attack may further worsen provided that there is more than one Sybil node in the network. The election of Sybil identities as separate cluster heads

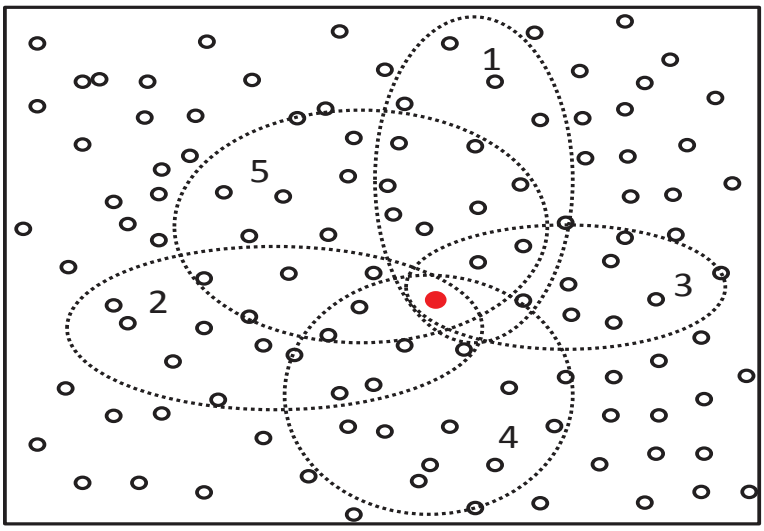


Figure 5.1: A Single Sybil Node Forming Multiple Clusters

has an adverse impact on various parameters such as network lifetime, packet loss rate, throughput and latency. Furthermore, there is a trade-off between the number of forged identities and their energy consumption. The energy consumption increases with an increase in the number of forged identities which ultimately decrease the lifetime of each Sybil node. However, energy-constraint factor does not restrict Sybil nodes from conducting their malicious activities. Unlike ordinary sensing nodes and high energy nodes, Sybil nodes do not care much about their residual energy consumption. Their ultimate goal is to harm the network as much as possible. They are short-lived as they achieve their goal at the expense of higher energy consumption.

In randomly distributed cluster-based hierarchical protocols, the base station has little control over cluster formation and cluster head selection. Each node (including Sybil nodes) can elect itself as cluster head based on a generated random number. As a result, these protocols are highly vulnerable to a Sybil attack. Each self-elected Sybil node can form multiple clusters, maliciously manipulating and aggregating data and transmitting to a base station. An error-prone redundant data may be delivered to the base station at the expense of actual data [134]. High energy nodes have a vital role in Sybil attack detection and these nodes are constantly monitored by a base station.

In view of the above discussion, we propose a novel Sybil attack detection scheme for a centralized cluster-based hierarchical network. Initially, high energy nodes identify Sybil nodes and report them to a base station to avoid their participation in cluster head selection. It ensures that only legitimate nodes can be elected as cluster heads in each round. Next, the base station elects an optimal number of cluster heads in each round based on an average residual energy value.

5.2 Sybil Attack Detection

We use the concept of Received Signal Strength Indicator (RSSI) for detection of Sybil attack. A variable number of Sybil nodes with multiple forged identities are injected before the start of each round. Each Sybil node has 2 joules of energy. Both normal nodes and Sybil nodes are isomorphic in nature, i.e., having similar capabilities in terms of sensing, processing, communication and broadcasting. The objective of our scheme is to prevent their participation in cluster head selection. The normal nodes and Sybil nodes transmit control packets to their two nearest high energy nodes as shown in Fig. 5.2. Each packet contains the identity and residual energy of the transmitter node. Theorem 5 in [145] argued that if at least four sensor nodes monitor radio signals from a neighbouring node, it will not be able to hide its location. However, for a resource-constrained WSN, it is a computationally complex task which requires abundant of network resources. To reduce the processing complexity, we propose a lightweight scheme for Sybil attack detection which requires the coordination of any two high energy nodes.

Suppose that, high energy nodes, $hen1$ and $hen2$, receive control packets from node i at time t_1. If the identity of node i in control packets is x, then the RSSI (R^x_{hen1}) is calculated by $hen1$ using Equation 5.1.

$$R^x_{hen1} = \frac{P_t k}{d^\alpha_{hen1}}. \tag{5.1}$$

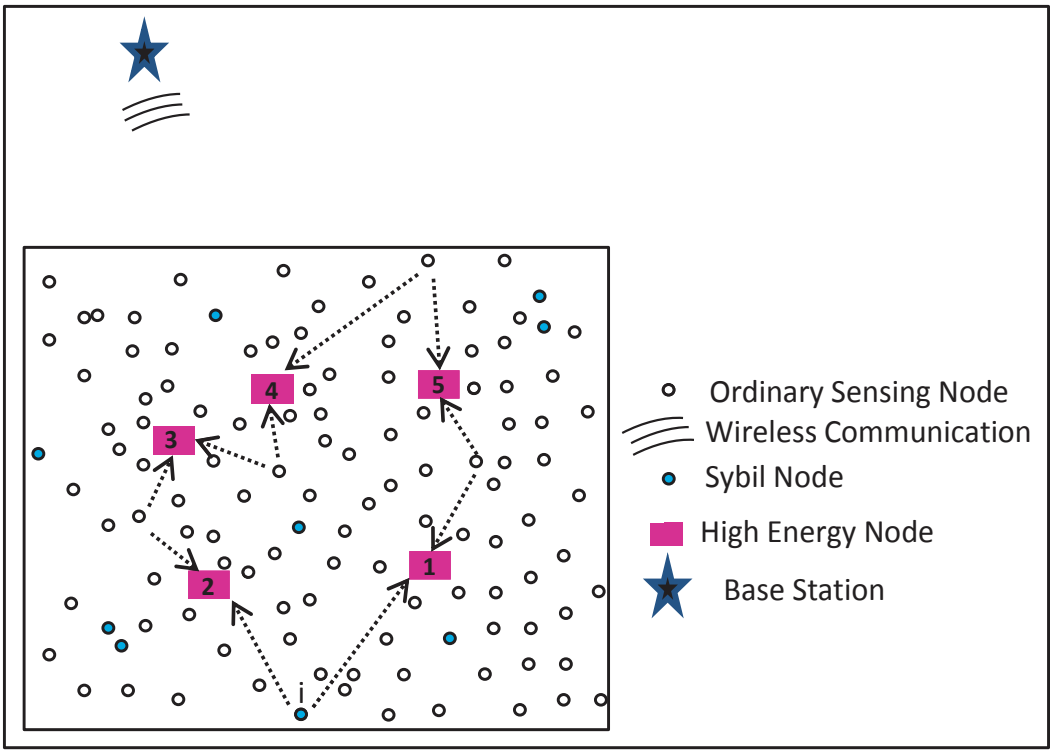


Figure 5.2: High Energy Nodes Collaboration for Sybil Attack Detection

In Equation 5.1, P_t is the transmitted power, k is constant, d_{hen1} is the Euclidean distance between node i and $hen1$ while α is the path-loss exponent. The value of α depends on the deployed environment. For free-space, its value is 2, for buildings with line-of-sight connection is 1.6 to 1.8 and for buildings with obstructions is 4 to 6 respectively [146]. The value of α for a free-space environment is computed using Equation 5.2 [147]. Let λ_c be the wavelength of a radio signal and be equal to 3×10^8 m/s. Then,

$$\alpha = (\frac{4\pi d_{hen1}}{\lambda_c})^2. \tag{5.2}$$

The transmitted power (P_t) is related to received power (P_r) as shown in Equation 5.3.

$$P_t = \frac{P_r}{(1/d_{hen1})^{\alpha}}. \tag{5.3}$$

The location of node i with respect to $hen1$ can be computed by solving the Euclidean

distance of Equation 5.4. Euclidean distance enables an ordinary sensing node to locate its two nearest high energy nodes.

$$d_{hen1} = \sqrt{(x_{hen1} - x_i)^2 - (y_{hen1} - y_i)^2}. \tag{5.4}$$

Solving Equations [5.2-5.4] and substituting their values in Equation 5.1 enable $hen1$ to calculate R^x_{hen1}. At this point, $hen1$ creates its own control packet and appends the value of R^x_{hen1} in it and transmits to its nearest high energy node, $hen2$. Recall that $hen2$ has received a similar control packet from node i at time t_1 and has calculated the value of R^x_{hen2} using a similar procedure as $hen1$. Next, $hen2$ calculates the radio signal strength ratio as shown in Equation 5.5.

$$\frac{R^x_{hen2}}{R^x_{hen1}} = (\frac{P_t k}{d^\alpha_{hen2}}) / (\frac{P_t k}{d^\alpha_{hen1}}). \tag{5.5}$$

Further evaluation results in

$$\frac{R^x_{hen2}}{R^x_{hen1}} = (\frac{d_{hen1}}{d_{hen2}})^\alpha \quad and \qquad t = t_1. \tag{5.6}$$

At time, $t_1 + t_0$, node i again broadcasts control packets with a different identity, y. High energy nodes, $hen1$ and $hen2$ perform similar operations as before and coordinate with each other to calculate the radio signal strength ratio at $hen2$ as shown in Equation 5.7.

$$\frac{R^y_{hen2}}{R^y_{hen1}} = (\frac{d_{hen1}}{d_{hen2}})^\alpha \quad and \qquad t = t_1 + t_0. \tag{5.7}$$

At this point of time, $hen2$ compares the ratios obtained at time t_1 and $t_1 + t_0$. If the difference between these ratios is very close to zero as indicated in Equation 5.8, then $hen2$ concludes that a Sybil attack has occurred.

$$\frac{R^x_{hen2}}{R^x_{hen1}} - \frac{R^y_{hen2}}{R^y_{hen1}} \approx 0. \tag{5.8}$$

A single physical node, i has forged two identities, x and y, to its nearest high energy nodes at different time intervals. As the radio signal strength ratios are equal, location is in fact the same for alleged multiple identities. The complete process of Sybil attack detection is shown in Algorithm 1.

Algorithm 1 Detection of Sybil Attack

Input: E_i, n, ID_N, s, m, α, k ▷ ID_N includes the identities of normal nodes (n) and Sybil nodes (s), $\forall\, n \in N \wedge s \in N$.
Output: {Sybil *or* non-Sybil}
`syb=round(rand(1)*s)+1;` ▷ Sybil generation
`id=round(rand(1)*m);` ▷ Generate m identities
▷ Next, each node is associated with high energy nodes
for $i = 1$ `to` N **do** ▷ N=n+s
  for $b = 1$ `to` 5 **do** ▷ Five high energy nodes
    Calculate Euclidean distance (d_i^b) between i and b
    Sort d_i in ascending order to get two nearest high energy nodes, b' and b'', where b', $b'' \in b$
    At time, t_1
    `SEND` $(E_i,\ ID_i), \forall\, i \in N$ ▷ Each node sends its control packets to b' and b''
    `Calculate` $R_{b'}$ ▷ Check identity of i
    `Calculate` $R_{b''}$ ▷ Check identity of i
    ▷ $R_{b'}$, $R_{b''}$ are the received signal strengths at b' and b''
    b' `transmits` $R_{b'}$ `to` b''
    `Calculate` $R_{b''}/R_{b'}$ ▷ Calculated at b''
    At time, $t_1 + t_0$
    `Repeat step 9-13` ▷ Check identity of i
    `Compare ratios` ▷ Obtained at time, t_1 and $t_1 + t_0$
    if *Ratios are equal* ***and*** *having similar identities for* i **then**
    Node i is **Sybil**
    else
    Node i is **non-Sybil**
    end if
  end for
end for

5.3 Centralized Cluster-based Hierarchical Network

In Fig. 5.2, each high energy node monitors its nearest neighbouring nodes for a possible Sybil attack. Upon detection, Sybil nodes are reported to a base station located outside a

sensor field. Each high energy node creates a control packet containing residual energy and identities of ordinary sensing nodes along with forged identities of detected Sybil nodes. These packets are transmitted to a base station which makes the final decision on cluster head selection. The base station maintains two queues, one for blacklisted Sybil nodes and one for ordinary sensing nodes. It monitors the status of both queues at regular intervals. The procedure of Sybil attack detection is repeated at the start of each round before cluster formation and cluster head selection. Once a Sybil node is detected, it is blacklisted to withhold its participation in cluster head selection. Clearly, there is a trade-off between the cost of Sybil attack detection and energy consumption of high energy nodes. High energy nodes remain active before the start of each round to detect new Sybil nodes. Furthermore, they avoid communication with already blacklisted Sybil nodes to preserve their residual energy levels.

The base station evaluates the residual energy (E_i) of ordinary sensing nodes to derive an average energy threshold (E_{avg}). The procedure for deriving E_{avg} is similar to the one discussed in Section 3.2 in Chapter 3. Any ordinary sensing node having E_i greater than E_{avg} is eligible for cluster head selection. However, it is highly probable that there will be a large number of such nodes in each round. These nodes are potential candidates for cluster heads in a particular round. It is the job of base station to elect a desire percentage of cluster heads among candidate nodes. The criteria for electing the cluster heads among the candidates is similar to the one discussed in Section 3.2 in Chapter 3. In our proposed scheme, the optimal percentage of cluster heads is 5% for a network of 100 nodes. An optimal percentage of such nodes is one major factor that influences the performance of cluster-based hierarchical WSNs. A cluster head consumes more energy in aggregating data and relaying vital information to a base station and performs general route maintenance and some other similar tasks [148]. If a small set of cluster heads are elected, network lifetime will degrade because these nodes will spend extra energy in data aggregation and long-haul transmission to a base station. On the other hand, the selection of more cluster heads will make a cluster-based network rather inefficient and ineffective.

Unlike the centralized cluster-based hierarchical algorithm of Chapter 3, the proposed approach for cluster formation is slightly different in this chapter. In the centralized cluster-based hierarchical algorithm of Chapter 3, the base station was responsible for broadcasting the cluster head-nomination packets to each node in order to inform them about their nearest cluster heads. However, the proposed approach of cluster head nomination is different in this chapter. The base station elects an optimal percentage of cluster heads, creates nomination packets and appends only the identities of elected cluster heads. As a result, these packets are received only by the elected cluster heads. Upon reception of nomination packets, each cluster head advertises itself to the nearest neighbouring nodes in order to form clusters. Recall that Sybil nodes are blacklisted and they are not allowed to participate any further in network communication. Each non-cluster head transmits a join-request message to a potential cluster head having the strongest signal strength in order to form cluster. After cluster formation, each non-cluster head becomes a member node within the cluster of its associated cluster head as shown in Fig. 5.3.

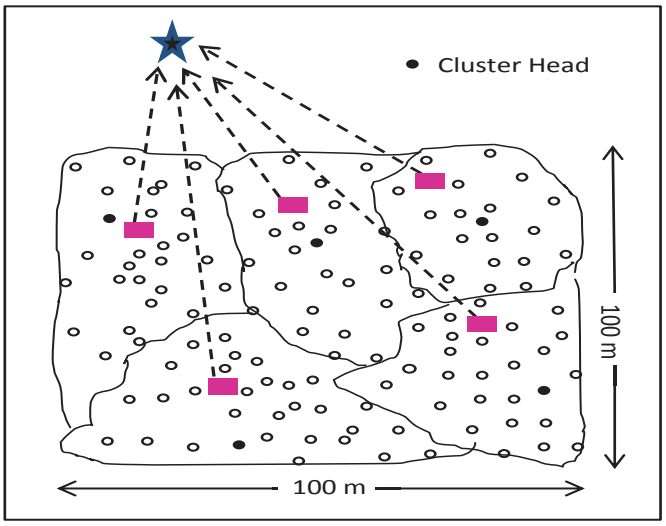


Figure 5.3: Cluster formation and Data Transmission

Unlike the centralized cluster-based hierarchical routing algorithm of Chapter 3, the cluster heads in Fig. 5.3 do not transmit their aggregated data directly to the base station. Each cluster head collects data within its cluster in a particular round and transmits to the

nearest high energy node which in turns transmit to the base station. The transmission of data to a nearest high energy node reduces the energy consumption of each cluster head as they are no longer required to use long-haul transmission links to a base station. Using two-hop communication links not only reduces the energy consumption of each cluster head but also enhances the quality of delivered data. Each high energy node performs data aggregation to further improve the quality of data before delivering it to the base station.

Next, we calculate the energy consumption of various type of nodes during set-up and steady-state phases. The energy consumption of an ordinary sensing node in a particular cluster depends on its distance (d_{CH}) from its respective cluster head and is computed using Equation 5.9. Each ordinary sensing node is a member node within its cluster.

$$E_{member} = \begin{cases} kE_{elec} + k\epsilon_{fs}d_{CH}^2, & d_{CH} < d_c, \\ kE_{elec} + k\epsilon_{mp}d_{CH}^4, & d_{CH} \geq d_c. \end{cases} \tag{5.9}$$

Once a cluster head receives data from all member nodes, it aggregates the data to reduce its size without compromising its quality. The aggregated data is further transmitted to a nearest high energy node for ultimate transmission to a base station. The energy consumption of a cluster head is significantly higher than a member node and is computed using Equation 5.10.

$$E_{CH} = \begin{cases} kE_{elec}\frac{n}{k_{opt}} + kE_{DA}\frac{n}{k_{opt}} + k\epsilon_{fs}d_{HEN}^2, & d_{HEN} < d_c, \\ \\ kE_{elec}\frac{n}{k_{opt}} + kE_{DA}\frac{n}{k_{opt}} + k\epsilon_{mp}d_{HEN}^4, & d_{HEN} \geq d_c. \end{cases} \tag{5.10}$$

where, E_{DA} is the energy consumption in data aggregation, k is the message size, k_{opt} is the optimal number of cluster heads and d_{HEN} is the distance between a cluster head and its nearest high energy node. Our proposed scheme is based on the idea of balanced-clustering technique in which the number of cluster heads is equal to the number of clusters [149].

Optimal number of cluster heads ensures that each round will have balanced clusters in which there will be one cluster head per cluster.

The energy consumption of high energy nodes differ from each other. Before the start of each round, ordinary sensing nodes and Sybil nodes transmit their control packets to their two nearest high energy nodes at two different time intervals. Recall that all five high energy nodes were involved in computationally complex task of RSSI-based Sybil attack detection. In Fig. 5.2, *hen1* calculates only the RSSI of incoming control packets. However, the actual decision about the type (Sybil or non-Sybil) of a node is taken by *hen2*. Clearly, *hen2* consumes more energy because of the additional task of finding the type of a node. Therefore, each high energy node is classified as either a received signal strength calculator (*rssc*) or a Sybil detector (*sd*). In view of the above discussion, *hen1* is an *rssc* while *hen2* is an *sd* for node i. It is important to mention here that an *sd* node performs dual functionality of signal strength calculation (RSSI) and Sybil detection. The energy consumption of an *rssc* node is calculated using Equation 5.11.

$$E_{rssc} = \begin{cases} E_{elec} \times 2\sum_{i=1}^{x} ctr_i + \epsilon_{fs}\sum_{i=1}^{x} ctrpk_i\, d_{nHEN}^2 \\ +k\epsilon_{fs}d_{HEN}^2 + k\epsilon_{fs}d_{BS}^2, \qquad d_{nHEN} < d_c, \\ \\ E_{elec} \times 2\sum_{i=1}^{x} ctr_i + \epsilon_{mp}\sum_{i=1}^{x} ctrpk_i\, d_{nHEN}^4 \\ +k\epsilon_{mp}d_{HEN}^4 + k\epsilon_{mp}d_{BS}^4, \qquad d_{nHEN} \geq d_c. \end{cases} \tag{5.11}$$

where, ctr is a control packet sent by each node (x), d_{nHEN} is the distance between the *rssc* and its nearest *sd*, and d_{HEN} is the distance between the cluster head and its nearest high energy node. Recall that each cluster head transmits its data to the nearest high energy node for ultimate transmission to the base station. Each node transmits two control packets to its two nearest high energy nodes to determine its type. Furthermore, each *rssc* transmits a control packet to its nearest *sd* which contains the received signal strength value. The size of the control packet (ctr) is much smaller than the data packet

(k). The energy consumption of an sd node is calculated using Equation 5.12.

$$E_{sd} = \begin{cases} E_{elec} \times 2\sum_{i=1}^{x} ctr_i + E_{elec}\sum_{i=1}^{x} ctr_i + \epsilon_{fs}\sum_{i=1}^{i=x} \\ ctr_i d_{BS}^2 + k\epsilon_{fs} d_{HEN}^2 + k\epsilon_{fs} d_{BS}^2, \quad d_{BS} < d_c, \\ \\ E_{elec} \times 2\sum_{i=1}^{x} ctr_i + E_{elec}\sum_{i=1}^{x} ctr_i + \epsilon_{mp}\sum_{i=1}^{i=x} \\ ctr_i d_{BS}^4 + k\epsilon_{mp} d_{HEN}^4 + k\epsilon_{mp} d_{BS}^4, \quad d_{BS} \geq d_c. \end{cases} \tag{5.12}$$

The extra energy consumed by the sd node is due to the received control packets from its counterpart $rssc$ node. Furthermore, an sd node also consumes energy in transmitting control packets containing the identities and energy levels of ordinary sensing nodes along with the forged identities of detected Sybil nodes.

5.4 Experimental Results and Analysis

In this section, we provide a series of simulation results for our proposed scheme. Our network comprises of n ordinary sensing nodes in a 100×100 square meter area. A variable number (denoted by s) of Sybil nodes with multiple identities are injected in each round. We evaluate our scheme in terms of number of detected Sybil nodes, total number of candidates and optimal selection of cluster heads, network lifetime, energy consumption, packet loss rate and packet acceptance ratio. We use Matlab R2011a as the simulation tool under Windows 7 platform.

5.4.1 Detection of Sybil Nodes

In our proposed scheme, a random number of Sybil nodes having a variable number of forged identities are injected in the network before the start of each round. It is the job of high energy nodes to refrain Sybil nodes from participation in cluster head selection. The total number of Sybil nodes and their average number of forged identities detected in each

round are shown in Fig. 5.4.

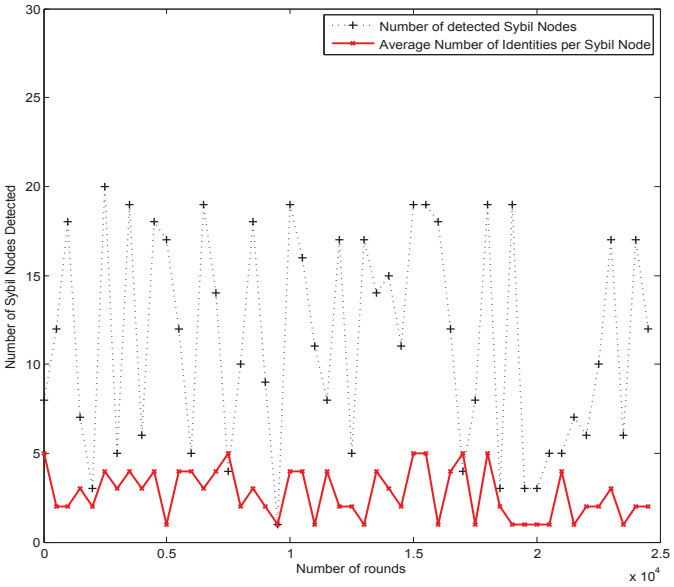


Figure 5.4: Detection of Sybil Nodes and their Forged Identities

The number of Sybil nodes are as high as 20 and the average number of their forged identities have reached upto 5 in certain rounds over the course of network lifetime. It would have an adverse impact on the outcome of voting, data aggregation and fair resource utilization if these nodes had gone undetected and were elected as cluster heads.

5.4.2 Total Number of Candidates and Cluster Heads

Our proposed scheme prevents Sybil nodes from participation in cluster head selection. If the detection scheme is not in place, Sybil nodes may elect themselves as potential candidates for cluster heads as shown in Fig. 5.5. The majority of Sybil nodes are capable to nominate themselves as potential candidates for cluster heads in various rounds. However, our detection scheme prevents their participation in cluster head selection. The performance of base station is highly precise and accurate because it elects only 5% of cluster heads in each round until the network has insufficient number of alive nodes toward the end. The optimal selection of cluster heads and the prevention of Sybil nodes from participation in cluster head selection efficiently utilize the limited energy of ordinary sensing

nodes and enhance network lifetime.

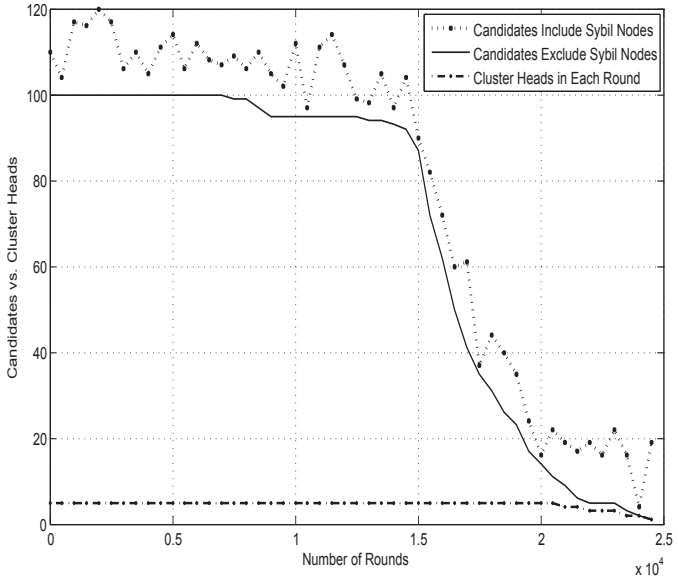


Figure 5.5: Candidates vs. Cluster Heads

5.4.3 Network Lifetime

The lifetime of a network is defined in terms of number of rounds it remains functional. In Fig. 5.6, we compare the lifetime of our proposed scheme with LEACH and SEP protocols. Both LEACH and SEP randomly elect cluster heads using probabilistic threshold values and result in an excessive number of cluster heads in various rounds. The distributed nature of these protocols results in unbalanced clusters which depletes network energy and ultimately decreases network lifetime. The centralized approach of our proposed scheme elects an optimal number of cluster heads which restricts the network load to only few nodes. In Fig. 5.6, we define the lifetime of the cluster-based hierarchical networks in terms of two threshold values, i.e., 90% and 10% of alive nodes. For 90% alive nodes, the lifetime of our scheme is 6989 rounds while LEACH and SEP have a lifetime of 3633 and 4599 rounds respectively. For 10% alive nodes, our network lifetime is 10822 rounds while LEACH and SEP have a lifetime of 5363 and 5902 rounds respectively. Our simulation results show that our proposed scheme significantly improves the network lifetime

as compared to LEACH and SEP.

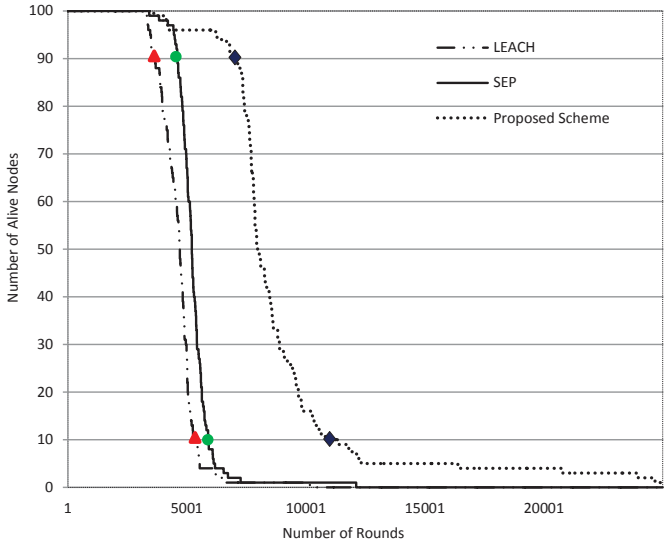


Figure 5.6: Lifetime of the Network

5.4.4 Energy Consumption with Sybil Nodes

Total energy consumption of our scheme varies with the number of Sybil nodes and their forged identities in each round. In Fig. 5.7, we calculate the average amount of energy consumed in each round in presence and absence of Sybil nodes.

The increase in energy consumption is contributed much toward the control packets transmitted by Sybil nodes. When the number of control packets increases, energy consumption of high energy nodes also increases. Furthermore, locations of ordinary sensing nodes and Sybil nodes with respect to high energy nodes and base station have a direct impact on energy consumption of the network. The energy consumed by any high energy node varies with the number of identities forged by a Sybil node. Higher the number of forged identities, greater will be the energy consumption of a network and lower will be its lifetime.

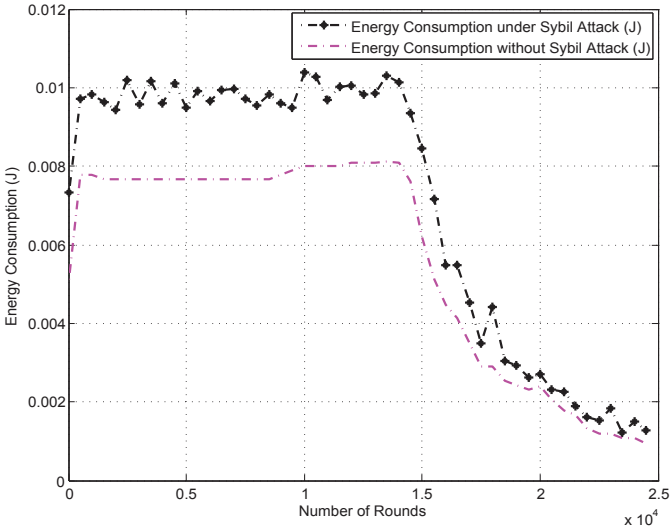


Figure 5.7: Energy Consumption in Presence of Sybil Nodes

5.4.5 Packet Loss Rate

The traffic flow of our network is distributed in nature which allows us to use a random uniform model [150] to compute wireless transmission losses due to noise, interference and other channel impairments. The packet loss rate is the percentage of packets lost in the network over a specified number of rounds (duration).

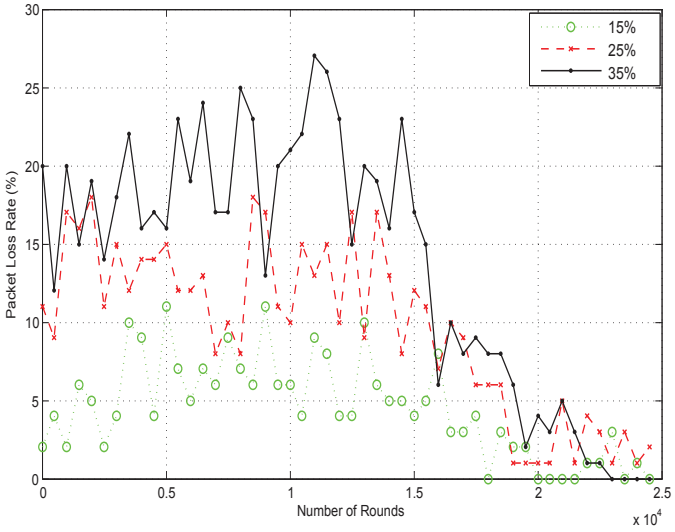


Figure 5.8: Packet Loss Rate

The random uniform model shown in [150] calculates the probability of distributed packet losses with a mean value (p). Therefore, we plot the packet loss rate for different values of p in Fig. 5.8. From this figure, it is clear that the percentage of packet loss is higher at 35%. The mean value of p determines the quality of a network. In case of our network, the packet loss rate does not reach the threshold levels (15%, 25% and 35%) in most of the rounds which means that the network is sustainable and delivers most of the data required for decision-making at the base station.

5.4.6 Packet Acceptance Ratio

The packet acceptance ratio is defined as the number of packets successfully received at a base station to the number of transmitted packets. The packet acceptance ratio for our proposed network model is shown in Fig. 5.9. The packet acceptance ratio varies with the quality of communication links. The better the quality of links is, the higher the acceptance ratio is. Furthermore, it also depends on numerous other factors such as queuing capacity of cluster heads and high energy nodes, upstream traffic flow, data rate and interference.

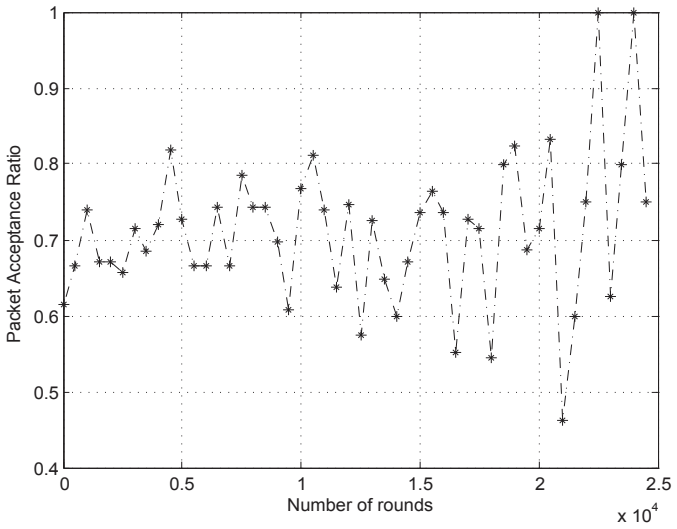


Figure 5.9: Packet Acceptance Ratio

In Fig. 5.9, the packet acceptance ratio increases after 2×10^4 rounds because as the

number of nodes dies due to energy depletion, the probability of packet collision during upstream traffic flow also decreases. As a result, packets have higher probability to reach the base station.

5.5 Summary

In this chapter, we present a novel scheme for Sybil attack detection within a centralized cluster-based hierarchical network. This chapter has two major objectives. First, Sybil nodes are detected and blacklisted to prevent them from network communication. Based on the ratio of signal strength of the received packets, our detection technique is designed. The collaboration of any two nearest high energy nodes is required to determine the origin of each control packet. High energy nodes assist the base station in Sybil nodes detection and enable it to prevent such nodes from participation in cluster head selection. Next, the candidate nodes for cluster heads are evaluated based on their residual energy values, geographical locations and previous history of selection. In each round, an optimal percentage of cluster heads are selected which enhances the network lifetime and other QoS parameters. Each cluster head collects data from member nodes, aggregates it and transmits to a nearest high energy node which ultimately delivers it to a base station. The use of two-hop communication links reduces the transmission burden on each cluster head.

In Chapter 6, we discuss the application of Sybil attack detection scheme to a wildfire monitoring environment. The hostile environment within a forest provides an ideal platform for an intruder to launch a Sybil attack. An intruder can easily impersonate to the neighbouring nodes by forging multiple illicit identities. The absence of human intervention within a forest makes it quite easy for the intruder to disable one or more legitimate nodes and stole their identities. The stolen identities can also be used by the intruder to establish multiple connections with legitimate nodes to maliciously manipulate their data.

Chapter 6

Detection of Sybil Attack in a Wildfire Monitoring Application

In Chapter 5, a Sybil attack detection technique for a centralized cluster-based hierarchical network was proposed. The proposed technique assumed that the nodes have a line-of-sight connection among them and the free-space propagation model is used for communication. Sybil nodes and their forged identities were permanently blocked in order to prevent their participation in cluster head selection and cluster formation. In WSN, it is probable that the identity of a sensor node may be known only to a base station but it may not be known to other sensor nodes. The only exception is, when all the sensor nodes in a network know the identities of each other. However, knowing the identity of each sensor node is both resource-intensive and time-consuming. When one or more Sybil nodes are detected by a base station, they are prevented from participation in cluster head selection. However, any normal node in the field is unaware about the type (sybil/normal) of another node. Each normal node assumes that all other nodes in the network are genuine, similar to it. As a result, Sybil nodes can communicate with any normal node. Sybil nodes cannot participate in cluster head selection but they can communicate with normal nodes during cluster formation for transmission of their data to the cluster heads. This chapter

is based on the above concept. In this chapter, Sybil attack is detected in a forest wildfire monitoring application. The geographical region of a forest is divided into small clusters using a centralized cluster formation approach. Various environmental parameters such as temperature, relative humidity and wind speed are monitored. The anomalies among the readings of the environmental parameters determine the presence or absence of Sybil nodes and a possible wildfire as well. First, we discuss the design considerations for a wildfire monitoring application followed by the actual detection mechanism for a possible Sybil attack.

6.1 Design Considerations

In this section, we provide a brief overview of various considerations which need to be in place at the time of designing an efficient wildfire monitoring application. First, we provide a description of various environmental parameters which influence the behaviour and characteristics of a wildfire in Section 6.1.1. Various network parameters and design considerations which govern the data collection capabilities of the sensor nodes are explained in Section 6.1.2.

6.1.1 Characteristics of Burning Wildfire Scenario

The behaviour of a wildfire is characterized by the following factors [151].

1. Fuels
2. Weather Conditions
3. Topography

These three factors determine how quickly a wildfire can spread or turn into a raging blaze which may scorches thousands of acres of land in a short period of time. The fuels include grass, dry leaves, twigs, shrubs and branches of the trees. Small pieces of fuels burn quickly, particularly when they are large in quantity, dry and loosely arranged. The weather also plays a crucial role in igniting and spreading a wildfire. On a hot and windy

day, fuels are at their driest which increases the risk of a wildfire. The three weather ingredients, i.e., temperature, relative humidity and wind speed have the ability to ignite and spread a wildfire to engulf a vast region. Temperature has a direct impact on fire ignition because the fuels are closer to their ignition points at a very high temperature. Each fuel has a *flash point*, a temperature reading at which it bursts into flames. The typical flash point for various types of dried fuels is 300 ^{0}C[1]. At flash point, the fuels release hydrocarbon gases that mixes with oxygen in the air and causes wildfire due to combustion. Relative humidity is the percentage of moisture in the air. It has an adverse impact on the intensity and flammability of a wildfire. During hot summer days and dry conditions, humidity is relatively low which adds to the possibility of a wildfire as the fuels do not have sufficient moisture in the air to absorb. The possibility of a wildfire increases when the relative humidity drops below 30% (*critical point*) in the air. Wind supplies oxygen which further dries the fuels and spreads the fire across a wide geographical region. The stronger the wind blows, the faster a wildfire will spread. The *threshold* wind speed of 12-15 km/h has a significant impact on the behaviour of a wildfire. Low relative humidity coupled with strong winds and high temperature readings rapidly spread a wildfire. Topography or the slope of a land also influences the behaviour of a wildfire. Topography can either aid or hinder the progression of a wildfire because a fire spreads quickly and much faster up a slope and slow down as it goes down a slope. Among these three factors, weather condition is highly crucial in igniting and spreading a wildfire. It is for this reason that we have formulated our network model based on the flash point, critical point and threshold values of the three weather ingredients. Temperature and relative humidity ignite a wildfire while the speed of wind facilitates in spreading it.

6.1.2 Network Parameters and Design Consideration

In WSNs, the source nodes located in close vicinity of each other capture somewhat identical data packets [152]. If such data is transmitted to a base station, it may flood the whole

[1] http://science.howstuffworks.com/nature/natural-disasters/wildfire.htm

network with multiple copies of the same data. To avoid data redundancy, an end user specifies various conditions for data transmission. In a wildfire monitoring application, an end user is mainly interested in threshold values of certain environmental parameters. Threshold values enable an end user in taking swift actions according to the environmental conditions within a forest.

In our proposed scheme, each normal node is equipped with three sensors for monitoring temperature, relative humidity and wind speed. Each node remains in sleep mode and wakes up only when the threshold conditions are satisfied by the captured data. The sleep-awake scheduling of sensor nodes in our proposed approach enhances the network lifetime by reducing the energy consumption. Upon capturing the events of interest, they are locally processed and relayed back to a nearest base station. Similar to PASCCC protocol [134], the operation of these nodes is governed by hard threshold (H_T) and soft threshold (H_T). A sensor node remains idle or in sleep mode until H_T is reached. For our proposed network model, H_T is set to 100^0C for temperature reading, 40% for relative humidity and 8 km/h for wind speed. These values of H_T are stored locally in each node as a base value. Recall that the temperature's flash point is 300^0C, relative humidity's critical point is below 30% and wind speed's threshold is 12-15 km/h. These values are the maximum threshold readings for environmental parameters at which a wildfire ignites and spread across the forest. An end user needs to be informed well before these maximum threshold readings. It is for this reason that we have set the values of H_T for temperature, relative humidity and wind speed to inform an end user well before any emergency situation. Each node sends an alert packet to a nearest base station when H_T is reached for these parameters. The alert packets are constantly transmitted to keep an end user up-to-date about the current status of a forest.

In a wildfire monitoring application, an end user is not interested in an incoming alert packet for which the H_T reading is similar to the previous one. To ensure that the incoming alert packet has a different reading than the previous ones, we set soft threshold (S_T) for each parameter. In our proposed approach, S_T is set to 40^0C for temperature, 2% for

relative humidity and 1 km/h for wind speed. Thus, the transmitter of each sensor will trigger for the first time when H_T is 100^0C for temperature, 40% for relative humidity and 8 km/h for wind speed. In the second time, it will trigger when H_T is 140^0C for temperature, 38% for relative humidity and 9 km/h for wind speed. In the third time, it will trigger when H_T is 180^0C for temperature, 36% for relative humidity and 10 km/h for wind speed. This process of adjusting the values of H_T continues and alert packets are transmitted to a nearest base station on regular intervals. The value of S_T is added to the previous H_T value in order to obtain a new H_T value for the current round. The threshold values of H_T and S_T provide sufficient time for an end user to take precautionary measures in an emergency situation within a forest.

6.2 Sybil Attack Detection in a Forest Wildfire

In this section, we provide a detailed explanation of our proposed scheme. First, the architectural model of our network is presented in Section 6.2.1 followed by its deployment model in Section 6.2.2. Next, two different approaches for Sybil attack detection are presented in Section 6.2.3. The first approach is based on the signal strength of received packets, similar to the one presented in Chapter 5. The second approach is based on the residual energy of each node. Both these approaches detect Sybil nodes prior to cluster formation and cluster head selection to ensure that only legitimate nodes are elected as cluster heads. Once Sybil nodes are barred from cluster head selection, a cluster-based hierarchical network is formed. Section 6.2.4 presents our scheme to obtain environmental data based on the conditions specified by an end user.

6.2.1 Network Architectural Model

The network architectural model of the proposed scheme is shown in Fig. 6.1. The Sybil attack detection techniques and cluster-based hierarchical algorithm are supported at the network layer. During routing, the forged identities of Sybil nodes are detected to prevent

their participation in cluster head selection. The three environmental parameters such as, temperature, relative humidity and wind speed are supported at the application layer.

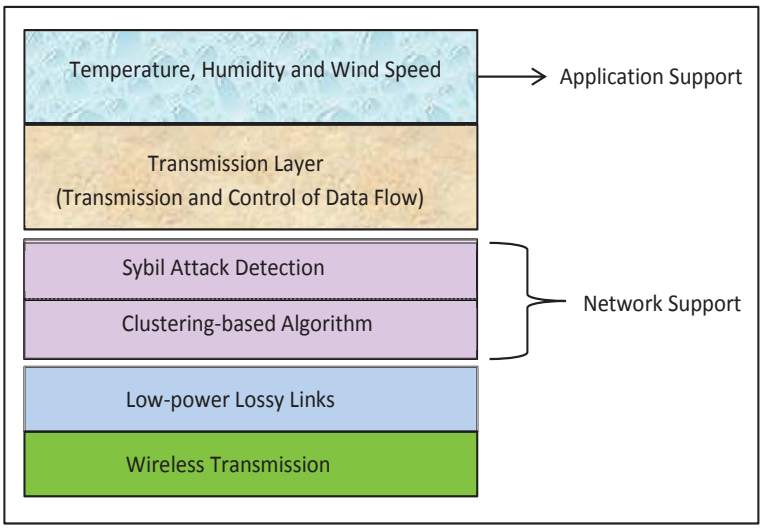


Figure 6.1: Network Architectural Model

The goal of Sybil nodes is to sneak into the network and provide false-negative alert readings of the environmental parameters to an end user. Furthermore, the presence of lossy links and a hostile environment pose a potential threat that some of these Sybil nodes may sneak through the detection process due to varying signal strength at different time intervals. The escaped Sybil nodes are ultimately detected by the base stations to prevent their participation in cluster head selection. However, the escaped Sybil nodes are still eligible to participate in the network as *legitimate* non-cluster head nodes. This is because the normal nodes in the network have no idea about the identities of other normal nodes or Sybil nodes. However, the malicious data of Sybil nodes is ultimately discarded by the base stations to prevent its usage during critical decision-making.

6.2.2 Network Deployment Model

Our proposed network model consists of 200 normal nodes and 20 high energy nodes deployed in a wide geographical region of (100×100) square meter area. The normal nodes are equipped with 2 joules while high energy nodes are having 5 joules of residual

energy. High energy nodes assist the base stations in Sybil attack detection and relay back vital information. We use joint-sink mobility [153] in which two base stations are used to avoid hotspot problems within the geographical region. Both these base stations support to-and-fro motion to cover a subset of the nodes. Base station 1 moves horizontally between the coordinates (25, 25) and (75, 25), while base station 2 moves horizontally between coordinates (25, 75) and (75, 75) as shown in Fig. 6.2.

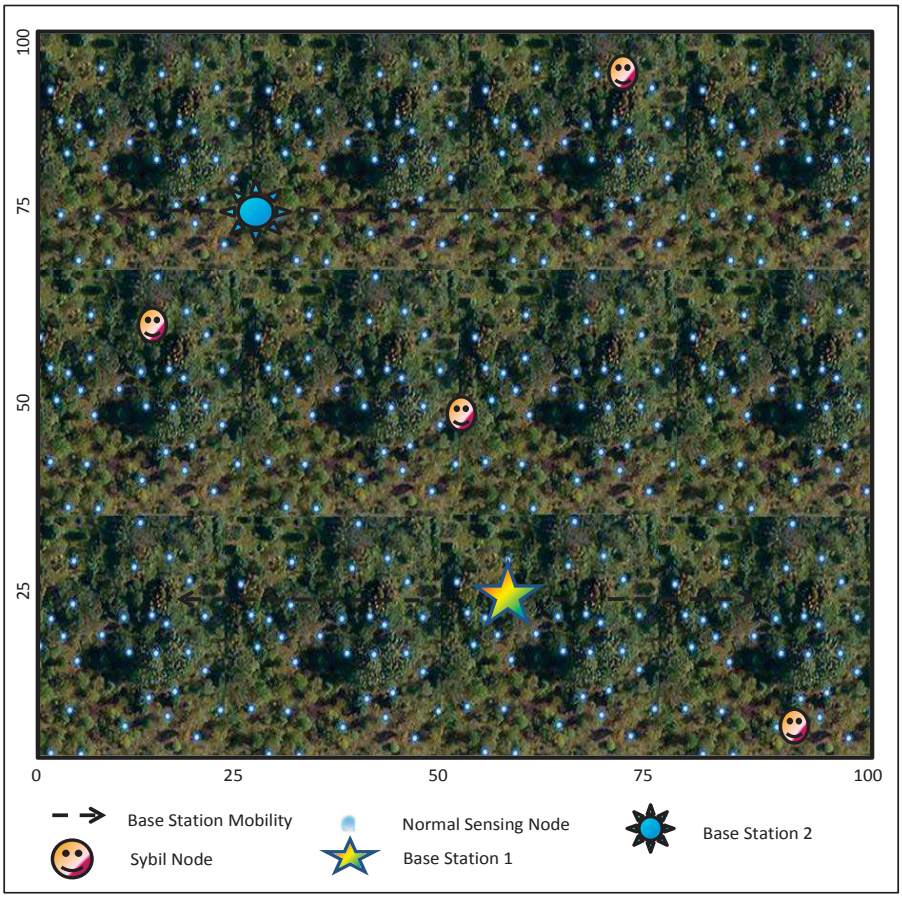


Figure 6.2: Base Station Mobility

Unlike a random waypoint mobility model [135] which suits mobile nodes, we are more interested in the sink mobility, also known as base station mobility. Our model does not support mobile nodes as it will bring too much fluctuation in the RSSI values of the received signals which will ultimately affect the detection process at the high energy nodes.

Both base stations provide sufficient coverage to the nodes by dividing the geographical region equally between themselves. To-and-fro motion ensures that the source nodes no longer require long-haul transmission to the base stations.

In a wildfire monitoring and many other delay-sensitive applications, a single base station may not be sufficient to provide a complete network coverage in a wide geographical region. In these applications, the source nodes generate critical events which need to be reported immediately to a base station. To avoid hotspot problem [154], a single base station may require constant movement with a predefined velocity to ensure that critical events are not lost. In our scheme, a series of critical events are detected based on the H_T and S_T values of the environmental parameters. Missing one or more events may result in a wrong interpretation of the forest environment which may result in catastrophic circumstances. Furthermore, precautionary measures need to be taken against external adversaries such as Sybil nodes, which are capable to manipulate the readings of captured events.

6.2.3 Detection of Sybil Attack

Before environmental monitoring to proceed, each node needs to authenticate itself to ensure that only legitimate nodes are elected as cluster heads. In a wildfire monitoring application, Sybil identities may result in catastrophic circumstances by constantly providing misleading results to an end user. If such identities are elected as cluster heads, they may discard time-critical and decision-making data of member nodes within each cluster. Instead, they may either fabricate their own data or transmit data from those member nodes which is less critical and may not be useful for an end user to take precautionary measures within a forest. If there is a high probability of wildfire in a particular geographical region, they may mislead an end user into believing that there is no such possibility of wildfire in that specific region. Furthermore, they may divert its attention to those areas which are less vulnerable to a wildfire. In view of the above discussion, we propose two different techniques for Sybil attack detection in a forest wildfire monitoring application. Our first approach is based on RSSI of the transmitter node while the second approach is based on

the residual energy of the nodes. The objective of both these approaches is to prevent Sybil nodes from electing themselves as cluster heads as they may wreak havoc in the forest.

6.2.3.1 RSSI-based Sybil Attack Detection

The RSSI-based Sybil attack detection scheme within a forest is somewhat identical to the one explained in Chapter 5. The only difference is the presence of a harsh transmission medium within a forest. The RSSI-based detection technique of Chapter 5 was designed for a free-space propagation model while the one proposed in this chapter is designed for a multipath ground propagation model. Recall that the RSSI-based scheme detects Sybil nodes based on the received signal strength at high energy nodes. In a typical forest environment, the value of signal strength is influenced by various factors such as reflection, refraction, physical obstacles, channel impairment, transmitter power, antenna type, and distance between a transmitter and a receiver node. Furthermore, the strength of signal also depends on Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) radio transmissions. The NLoS transmission along with channel impairment causes significant reflection and refraction of radio signals through various obstacles which results in highly fluctuating RSSI values. As a result, the quality of a signal strength is quite poor which may enable one or more Sybil nodes to sneak through the detection process. The fluctuating values of the received signal strengths at time, t_1, and time, $t_1 + t_0$, may result in varying RSSI ratios. The differences in these ratios are sufficient to convince nearby high energy nodes into believing that a transmitter is not a Sybil node. In this fashion, one or more identities of Sybil nodes go undetected and are reported to a nearest base station as *normal* nodes.

High energy nodes have a fair detection policy which is equally applicable to both normal nodes and Sybil nodes. High energy nodes have no prior knowledge if a node is normal or Sybil. For high energy nodes, undetected Sybil nodes are also normal nodes. Furthermore, undetected Sybil nodes try to participate in cluster head selection as well. To prevent them from electing themselves as cluster heads, we implement a two-tier detection process: one at high energy nodes and another one at the two base stations. The Sybil nodes

may sneak through the detection process at high energy nodes due to the fluctuating RSSI values within a forest. However, it is highly improbable for such nodes to sneak through the detection process at the two base stations. Unlike high energy nodes, each base station maintains the identities of the normal nodes locally within a database. In case of Sybil nodes, there will be a mismatch of identities and they will be barred from participation in cluster head selection. The RSSI-based Sybil attack detection scheme within a forest is shown in Fig. 6.3.

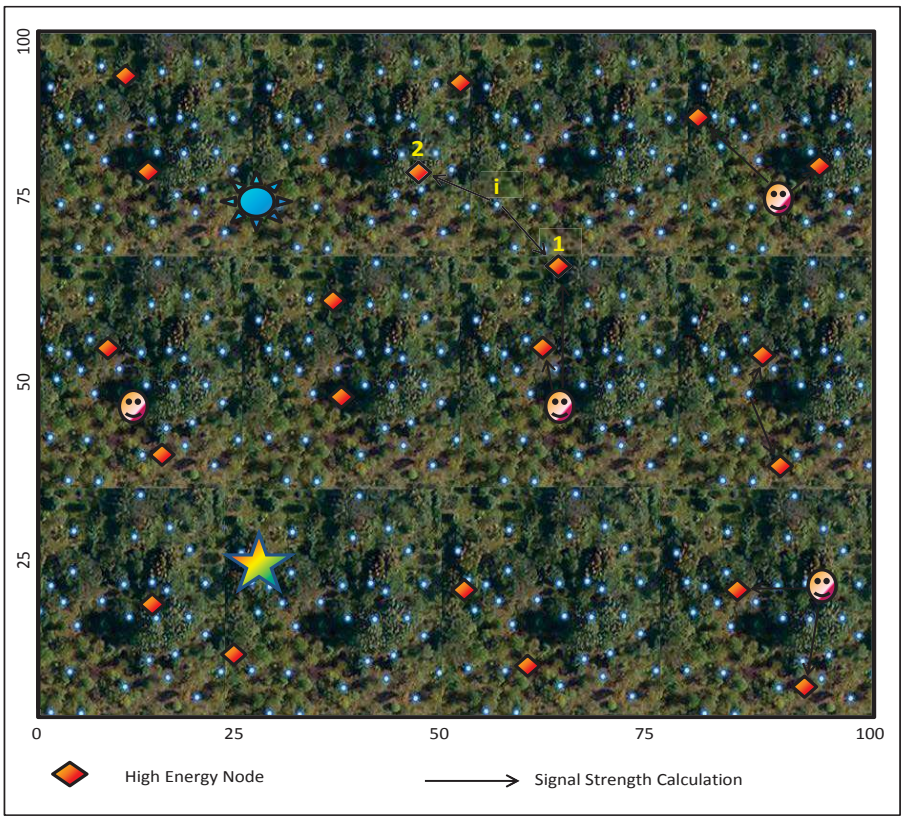
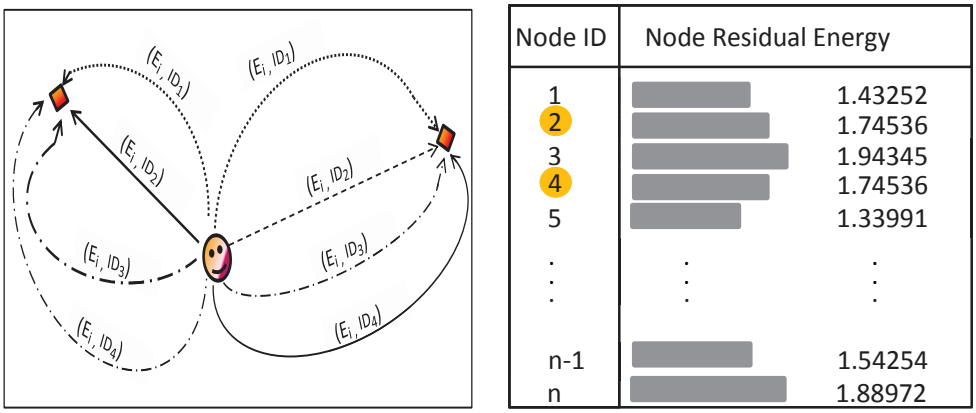


Figure 6.3: RSSI-based Sybil Attack Detection in a Forest

6.2.3.2 Residual Energy-based Sybil Attack Detection

In this section, we propose another scheme for Sybil attack detection based on the residual energy of each node. Unlike a normal node, each Sybil node requires multiple transmissions of control packets to validate its forged identities. A single Sybil node forges four

different identities to its nearest high energy nodes as shown in Fig. 6.4(a). Recall that all the forged identities of a Sybil node reside in a single physical location. To authenticate its illegitimate identities, a Sybil node transmits two control packets for each one of these identities. It requires four such different transmissions and in each transmission, it appends one of its illicit identity. Each control packet contains residual energy (E_i) and forged identity of a Sybil node. All identities of a Sybil node consume an equal amount of energy irrespective of the presence or absence of an obstacle between a Sybil node and the two nearest high energy nodes. This is due to the fact that the presence or absence of an obstacle is the same for each identity because they all reside in a single physical location. It means that the energy consumed by one identity in transmission of its control packets is similar for another identity as well.



(a) Energy Consumption in Transmission (b) Queue of a High Energy Node

Figure 6.4: Residual Energy-based Sybil Attack Detection

Upon reception of control packets, each high energy node retrieves the identity (node ID) and residual energy from them and stores locally within a queue as shown in Fig. 6.4(b). The Sybil node has launched an attack by transmitting four different pairs of control packets for its forged identities. High energy node can detect such an attack by examining the residual energy field of each control packet. If there is a match between residual energy fields of two or more control packets and a mismatch between their identities, it means that a Sybil attack has occurred. In that case, the forged identities are reported to a nearest base

station. It is possible that there may be a match between residual energy field of a normal node and that of a forged identity of a Sybil node. To rule out such possibility, we calculate the precision of the residual energy field upto 5 decimal digits. This value ensures that it is highly unlikely that there will be a match between residual energy of a normal node and forged identities of a Sybil node.

In this scheme, we have implemented our logic using two high energy nodes, though it can be accomplished with only one such node as well. The use of two high energy nodes assure that both nodes agree upon the detected forged identities. Upon detection, both nodes share the forged identities to confirm that they have achieved the same results.

6.2.4 Cluster-based Hierarchical Network

After Sybil attack detection, a cluster-based hierarchical network is formed which consists of two phases; a set-up phase and a steady-state phase. During set-up phase, cluster heads are selected, spatial queries are distributed and clusters are formed. The completion of set-up phase is initiated by steady-state phase during which each cluster head collects data as specified in each query with H_T and S_T values for the three environmental parameters. Each base station has the ability to modify or discard H_T or S_T at any time and transmits new queries according to an end user requirements. Furthermore, the base station may request data from specific nodes using on-demand queries which have different format and are more complex as compared to spatial queries. First, we explain the set-up phase followed by the steady-state phase.

6.2.4.1 Set-up Phase

Upon detection, Sybil nodes are reported to a nearest base station. Those Sybil nodes that sneak through the detection process are reported as *normal* nodes. From high energy nodes perspective, normal nodes along with undetected Sybil nodes are eligible to participate in cluster head selection. However, this is not the case at the two base stations because they know the identity of each normal node within the network. Based on the identity

verification at the two base stations, undetected Sybil nodes are barred from participation. Although, they are not allowed to participate in cluster head selection, undetected Sybil nodes can still communicate with their respective cluster heads because they are considered as normal nodes. The two base stations coordinate with each other on regular intervals to elect an optimal percentage of cluster heads. These base stations are resource-rich entities and are fully synchronized with each other to elect a single set of cluster heads in each round. They elect an optimal percentage of cluster heads using a similar criteria to the one discussed in Chapter 5.

Both base stations elect an optimal percentage of cluster heads for a particular round and broadcasts nomination packets containing their identities and end user spatial queries. Within each spatial query, an end user specifies certain conditions for collecting critical events from the source nodes within a geographical region [155]. For example, a spatial query may be "temperature readings from the nodes in a geographical region *x*" or "relative humidity below 35% in region *y*". These are just two simple examples of spatial queries but in reality, they can be highly complex containing various combination of these environmental parameters. Initially, each cluster head is assigned a very simple query containing H_T values for temperature, relative humidity and wind speed. Each cluster head advertises itself to the nearest neighbouring nodes in order to form clusters. Each advertisement message contains the identity of a specific cluster head and the end user's spatial query. Upon cluster formation, each member node must abide by the conditions associated with the advertised query. An end user may modify or discard a transmitted query at any point of time. This is because an end user only wants the data of interest which enables it in making critical decisions. The assignment of spatial queries is restricted to cluster heads only. Such queries cannot be assigned to member nodes within a cluster. These queries are useful to collect user-specific data from the nodes within a geographical region.

In a forest wildfire monitoring application, one or more member nodes may be reporting time-critical, delay-sensitive alert packets. An end user is more interested in the individual readings of such nodes. Rather than waiting for a cluster head to collect such

alert packets, the nearest base station gathers it and relay back to an end user. Each cluster head consumes a considerable amount of time in data aggregation, in-network processing and relaying back the data to a base station. To avoid delay and maintain the integrity of time-stamp of each alert packet, the nearest base station performs data gathering. For this purpose, on-demand queries are transmitted to such nodes which store them and report alert packets on a regular interval based on the specified conditions.

In Fig. 6.5, the use of spatial and on-demand queries is shown. Two different spatial queries are shown in Fig. 6.5(a). One such query is used to collect temperature readings between 189 ^{0}C and 230 ^{0}C, while the second one is used to collect temperature readings greater than 219 ^{0}C and relative humidity less than 35%. In Fig. 6.5(b), two rather complex on-demand queries are shown. In the first such query, an end user requests packet generation rate and readings of the three environmental parameters from a sensor node with ID 19. In the second query, a subset of nodes are requested to report packet generation rate, and readings of the three environmental parameters having values above the threshold, H_T. Furthermore, they are requested to provide H_T values with timestamps.

Cluster Head ID	Spatial Query	Latitude	Longitude
4	189 ^{0}C < Temp < 230 ^{0}C	47.252298	-138.446387

(a)

Node ID	On-demand End User specific's Query	Latitude	Longitude
19	Packet Generation Rate (Temp>220 ^{0}C && R.H<32 && W.S >10km/h)	112.345543	-66.346642

(c)

Cluster Head ID	Spatial Query	Latitude	Longitude
7	Temp >219 ^{0}C R.H < 0.35	69.545563	-19.985542

(b)

Node ID	On-demand End User specific's Query	Geo Location
87 to 92	(Time Stamp && Report above specific thresholds && Packet generation rate)	Region x

(d)

(a) Spatial Queries (b) On-demand Queries

Figure 6.5: Types of Queries

The selection of cluster heads, distribution of queries and formation of clusters signal the end of set-up phase and initiation of steady-state phase. It is important to mention here that the distribution of spatial queries is part of the set-up phase, however, on-demand

queries distribution may or may not be part of it. They are distributed according to an end user requirements and importance of the reported data. Irrespective of the set-up phase or steady-state phase, an end user may transmit on-demand queries at any point of time.

6.2.4.2 Steady-state Phase

During this phase, each cluster head allocates TDMA slots within its cluster for sharing the transmission medium. In our proposed scheme, the member nodes within a cluster are either normal nodes or undetected Sybil nodes. Recall that those Sybil nodes which sneak through the detection process at high energy nodes are also eligible to participate in data transmission within a network. These nodes may transmit quite a large amount of false-negative alerts to an end user. Within each cluster, a cluster head collects and aggregates data from member nodes and transmits to the nearest base station using a two-hop transmission link. The only exception is the presence of a nearby base station. In that case, the cluster head directly delivers data to it. Both base stations aggregate data from the network and transmit to an end user. Based on the aggregated data, an end user decides the next step. If a subset of neighbouring nodes is reporting sensitive alert packets on a regular interval, the end user informs a rescue team in order to take precautionary measures within a forest. An end user evaluates the aggregated data from each perspective before declaring an emergency situation within a forest. The process of data collection within a forest is shown in Fig. 6.6. Our proposed cluster-based hierarchical network is iterative in nature which operates in rounds to collect data.

During steady-state phase, each cluster head collects data within its cluster based on the conditions specified in a distributed spatial query. This data may be highly malicious as the forged identities of undetected Sybil nodes may have provided a large amount of false-negative time-critical and delay-sensitive alert packets. For a cluster head, it is impossible to determine the nature of this data. It forwards the data to a nearby high energy node for ultimate transmission to a base station. Upon reception at a base station, the identity, geographical location and sensitivity of an alert packet are examined. A mismatch of

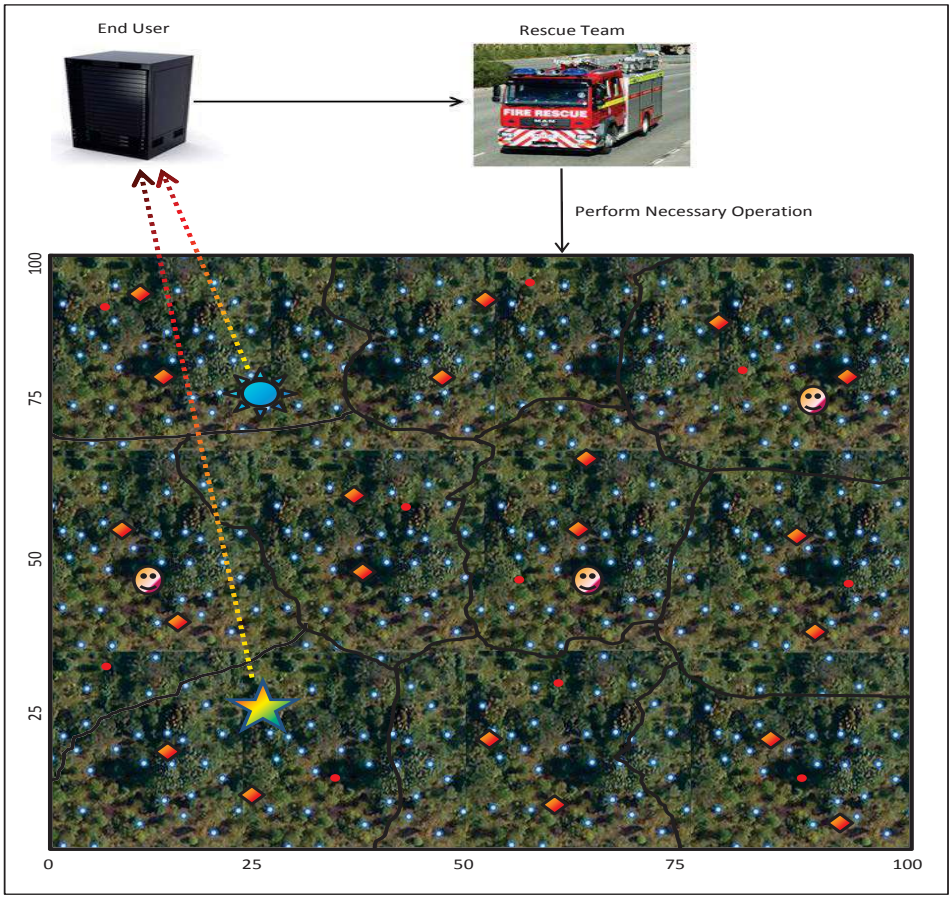


Figure 6.6: Data Collection within a Forest

identities between an incoming alert packet and those stored with a base station enables it to discard such packet. This comparison enables each base station to weed out malicious and false-negative alert packets of Sybil nodes.

In Algorithm 2, the generation, transmission and outcome of a simple spatial query is shown. The base stations elect an optimal percentage of cluster heads (opt_{CH}) and append H_T values of temperature, relative humidity and wind speed in control packet (ctr_i) for each cluster head (CH_i). Here, opt_{CH} = $\{CH_1, CH_2,....,CH_{opt}\}$, $\forall$ opt$_{CH} \in n$. The base stations also append the identity, latitude (LatT) and longitude (LongT) of CH_i in ctr_i. Next, ctr_i is sent to a neighbouring high energy node (hen_i) for ultimate transmission to CH_i. Each CH_i gathers alert packets from member nodes based on the specifications in

ctr_i and transmits to a nearby base station which evaluates the nature of these incoming alert packets. If the identity of a member node ($N\text{-}CH_x$) does not match with the identities stored in the database ($Database_{BS}$) of each base station, the incoming alert packets of $N\text{-}CH_x$ are discarded and this node is considered as a Sybil node. Each base station prevents data from $N\text{-}CH_x$ to reach an end user. However, a match of identities would mean that $N\text{-}CH_x$ is a legitimate node and its alert packets are further evaluated for the possibility of assigning an on-demand query to this node.

Algorithm 2 Generation, Transmission and Outcome of Spatial Query

procedure SPATIAL QUERY
    for each identity of a cluster head, $CH_i \in opt_{CH}$ **do**
Creates a control packet, ctr_i
Appends H_T along with LatT, LongT of CH_i in ctr_i
SEND ctr_i to hen_i
    end for
    if $N\text{-}CH_x \notin Database_{BS}$ **then**
Discard the incoming alert packets from N-CH_x
    else
Further Evaluation of alert packets
    end if
end procedure

Once data is collected from each cluster head, the two base stations further analyse this data. The dynamic nature of happening events (wildfire in this case) is not restricted to a particular geographical location. Moreover, the data collected from various geographical regions may have different temperature, relative humidity and wind speed readings. Both the base stations carefully examine the data before delivering to an end user. During this process, the nodes which have highly sensitive data are analysed and assigned on-demand queries. In Algorithm 3, a subset of nodes are assigned an on-demand query. This query probes a total of 6 nodes to obtain specific values for temperature, relative humidity and wind speed. Furthermore, each incoming alert packet must have a time-stamp otherwise

it will be discarded. The allocation of on-demand queries is restricted to legitimate nodes only because the base stations have already discarded alert packets of undetected (sneaked) Sybil nodes in Algorithm 2.

Algorithm 3 Generation and Outcome of an On-demand Query

1: **procedure** ON-DEMAND QUERY
2: SELECT *Temp*, *R.H*, *W.S*, *Timestamp* FROM Nodes
3: WHERE (Node ID = 2 TO 7) $\wedge$ (*Temp*$>=$ 219, *R.H*$<$ 0.34, *W.S*$>$ 10)
4: **if** *Collected data* is *Time stamped* **then**
5: End user checks data pattern collected from nodes in the above range
6: **else**
7: Discard data of the nodes without Time stamps
8: **end if**
9: **end procedure**

According to Algorithm 3, if some nodes i.e., legitimate nodes, in a particular region are occupied by the attack, the alerts will still be transmitted by the remaining nodes to the end user. However, if all the nodes in a particular region are occupied by the attack, alerts will not be transmitted to the end user. When all the legitimate nodes in a particular region are occupied by an attack, only fake alerts will be transmitted. These fake alerts will be from the undetected Sybil nodes. However, these fake alerts are blocked from reaching the end user by the two operating base stations. If the nodes in a particular region are powered off, such nodes will not transmit alerts to the base station.

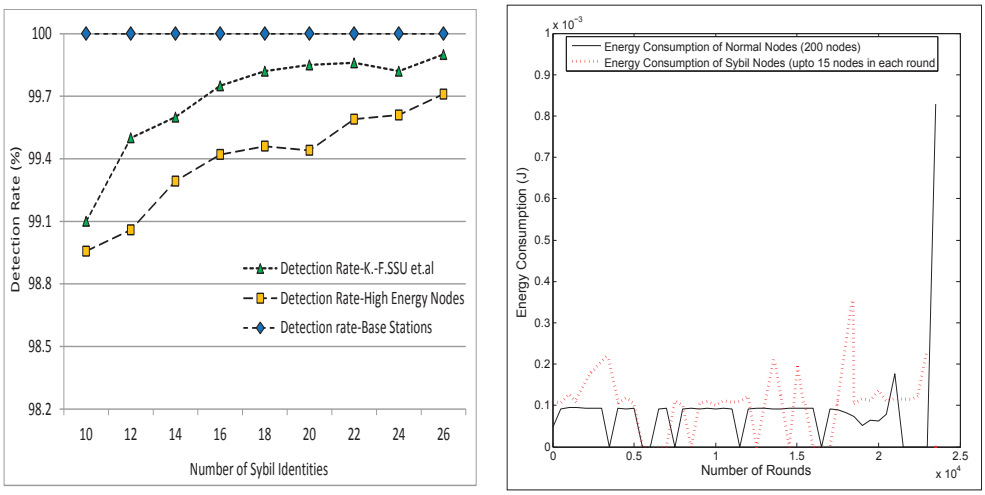
6.3 Experimental Results and Analysis

In this section, we provide a series of simulation results for our proposed scheme. A (100×100) square meter geographical area is used for the network deployment. We use the first-order radio model [68] to minimize the energy consumption of nodes by efficiently scheduling their duty-cycles. We evaluate our scheme in terms of detection rate, accuracy of the application, network lifetime and average size of the clusters. These parameters are

calculated over a period of up to 30000 rounds.

6.3.1 Detection of Sybil Attack

Fig. 6.7(a) illustrates the effect of s Sybil nodes and their m forged identities on the detection rate for a network of s=20 and n=300. The value of m varies between 10 and 26. The detection rate increases with the increase in the value of m. In comparison with [81], the detection rate of our approach is slightly lower at high energy nodes. However, we have a better detection rate at the two base stations. Unlike their detection scheme, our proposed scheme operates in a hostile environment within a forest which causes high fluctuation in RSSI values. As a result, one or more identities of Sybil nodes sneak through the detection process at high energy nodes in various rounds resulting in a lower detection rate. However, our proposed scheme has a 100% detection rate at the two base stations and all previously sneaked identities are detected at this stage. It is the ultimate goal of our proposed approach that all Sybil nodes and their forged identities are prevented from participation in cluster head selection and a 100% detection rate achieves that objective.



(a) RSSI-based Detection (b) Energy Consumption-based Detection

Figure 6.7: Detection of Sybil Attack

In Fig. 6.7(b), Sybil nodes are detected based on their residual energy consumption.

The comparison is made for a network of 200 normal nodes and upto 15 Sybil nodes. In most of the rounds, Sybil nodes consume more energy as compared to normal nodes because each Sybil node forges *m* identities. The energy consumption varies with *m* identities forged by each Sybil node over the course of network lifetime.

6.3.2 Accuracy of Wildfire Monitoring Application

The accuracy of the proposed wildfire application ($\phi_{wildfire}$) is a percentage value which is calculated as the number of genuine alerts denoted by N to the number of total alerts denoted by T as shown in Equation 6.1.

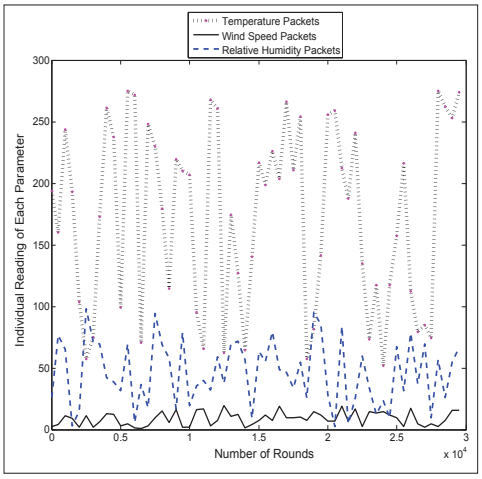
$$\phi_{wildfire} = \frac{N}{T} \times 100, \tag{6.1}$$

In Equation 6.1, we calculate the accuracy of our wildfire monitoring application in presence of up to 20 Sybil nodes. Each Sybil node is capable of forging up to 10 identities.

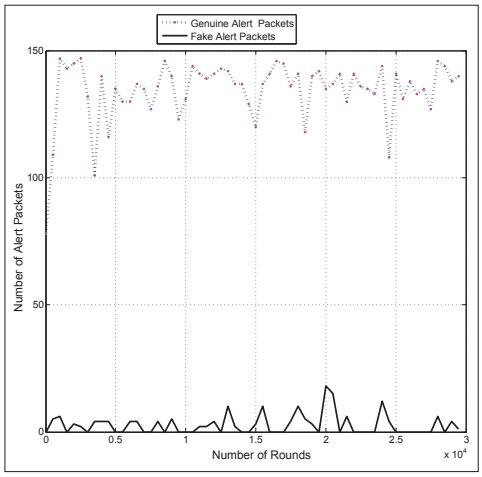
In Fig. 6.8(a), the data packets carrying information on three environmental parameters captured over the span of network lifetime are shown. These packets are generated by the normal nodes and Sybil nodes. Furthermore, these packets may or may not be alert packets. Each data packet is an alert packet if it satisfies the H_T and S_T conditions specified for an environmental parameter. Let Temp represent the temperature reading, RH represent the relative humidity reading and WS represent the wind speed reading sensed by a member node. This node will transmits an alert packet to its respective cluster head only when Equation 6.2 is satisfied.

$$(Temp \geq H_{Temp}) \wedge ((RH \geq H_{RH}) \vee (WS \geq H_{WS})) = True, \tag{6.2}$$

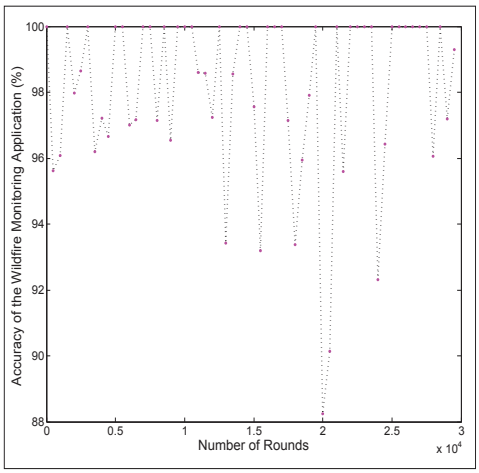
Here, H_{Temp}, H_{RH} and H_{WS} are the hard thresholds for temperature, relative humidity and wind speed. An alert is generated and transmitted only when H_{Temp} is reached **and** either of H_{RH} **or** H_{WS} is reached. Equation 6.2 is application-specific and may be modified ac-



(a) Readings of Environmental Parameters



(b) Genuine Alerts vs. Fake Alerts



(c) Percentage Accuracy

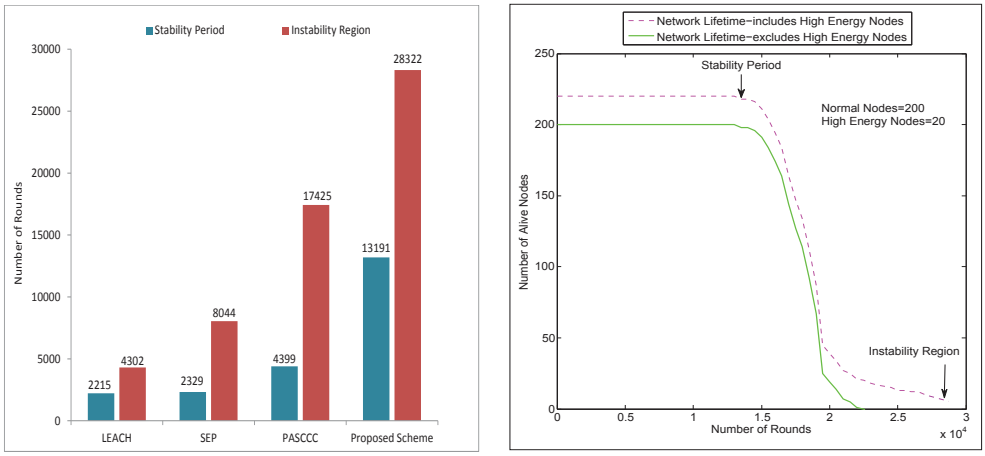
Figure 6.8: Accuracy of the Wildfire Monitoring Application

cording to the demands of an end user. This is because an on-demand query has different conditions for an alert transmission as compared to a spatial query. As previously discussed, an on-demand query is highly generalized and assigned to a member node based on the outcome of a spatial query. For example, an end user may require only temperature alerts of above 200 ^{0}C from a specific geographical region and may not be interested in relative humidity and wind speed alerts within the same region. In that case, Equation 6.2 will change accordingly. The alerts include both genuine and fake readings as shown in Fig. 6.8(b). Fake alerts belong to the forged identities of one or more Sybil nodes while the

genuine alerts belong to the normal node. In Fig. 6.8(b), there are as many as 147 genuine alerts and upto 20 fake alerts in various rounds. In Fig. 6.8(c), the percentage accuracy of our wildfire monitoring application is obtained using genuine and fake alerts of Fig. 6.8(b) and substituting their values in Equation 6.2.

6.3.3 Lifetime of the Network

The lifetime of a network is defined in terms of stability period and instability region. Recall that the stability period is the point in time when the first node dies while instability region is the point in time when there are not sufficient nodes to form balanced clusters. In [134], the authors argued that a network is unable to sustain balanced clusters when 97% of its nodes die. Using their argument, we have compared our proposed approach with LEACH, SEP and PASCCC protocols in Fig. 6.9(a).



(a) Stability Period and Instability Region (b) Prolonged Network Lifetime

Figure 6.9: Lifetime of the Network

Unlike LEACH and SEP protocols, the sensor nodes in our approach wake up only when H_T is reached for each environmental parameter. The use of H_T and S_T within the spatial and on-demand queries efficiently manages the sleep-awake scheduling of the nodes. On the other hand, PASCCC protocol uses H_T and S_T parameters. However, the selection of cluster heads is similar to LEACH and SEP which enables each node

to elect itself as cluster head irrespective of its residual energy. The threshold-based event detection along with a centralized cluster head selection significantly improves the stability period and instability region of our scheme. In our proposed scheme, the instability region reaches in round 28322 and has a 62% improvement over the nearest reading, i.e., PASCCC protocol. In terms of stability period, our proposed scheme has almost 3 times better performance as compared to PASCCC protocol. In Fig. 6.9(b), we calculate the network lifetime of our proposed approach in the presence and absence of high energy nodes. The presence of only 20 high energy nodes may have less impact on the lifetime of the network, however, they perform vital tasks of Sybil attack detection and relaying critical data to the base stations.

6.3.4 Average Size of the Clusters

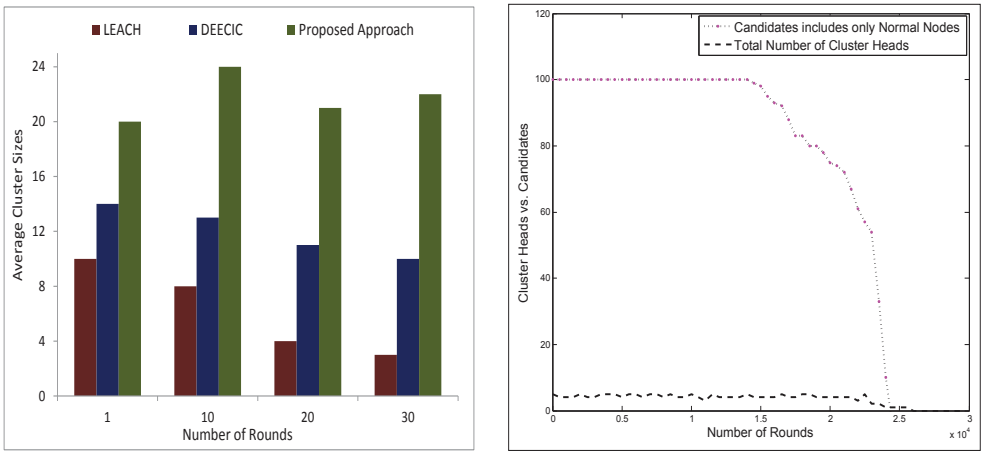
This parameter determines the efficiency of an algorithm in terms of data aggregation and geographical coverage [156]. The average size of a cluster ($C_{average}$) is defined as the ratio of number of alive nodes to the number of clusters within a network and is calculated using Equation 6.3.

$$C_{average} = \frac{count(n_{alive} \mid E_i(n_{alive}) > 0, \forall\, n_{alive} \in n)}{count(CH)}, \tag{6.3}$$

Here, n_{alive} denotes the number of alive nodes participating in cluster formation and CH denotes the number of clusters. In cluster-based hierarchical routing protocols, there is one cluster head per cluster and both these parameters are always equal. The average size of a cluster expresses the efficiency of an algorithm in terms of data aggregation, data fusion and the minimum number of cluster heads required to cluster a large geographical network.

In Fig. 6.10(a), the average cluster size of our proposed scheme is compared with LEACH and DEECIC protocols. Our proposed scheme has a significantly higher $C_{average}$ as compared to DEECIC and LEACH protocols. Our algorithm is centralized in nature and elects an optimal percentage of cluster heads in each round. On the other hand, DEECIC

and LEACH are randomly distributed in nature and cannot guarantee an optimal percentage of cluster heads in each round. The selection of an optimal percentage of cluster heads means a uniform distribution of network load, better coverage, high throughput, better data aggregation and low delay within each cluster [157]. In LEACH and DEECIC protocols, each node elects itself as cluster head based on a generated random number [61]. As a result, either too many or very few cluster heads are elected in each round which results in unbalanced clusters. Too many member nodes within a cluster increase the load on a cluster head and very few member nodes make the concept of clustering rather inefficient and ineffective. In Fig. 6.10(b), the total number of cluster heads elected in each round are shown for a network of 100 normal nodes. Irrespective of the candidate nodes, each round results in 4 or 5 cluster heads as long as the network is stable. As we are using a centralized approach, the two base stations elect an optimal percentage of cluster heads among the candidate nodes.



(a) Average Cluster Size (b) Cluster Heads in each Round

Figure 6.10: Coverage of a Geographical Region

Fig. 6.10(a) is derived based on the statistics of Fig. 6.10(b). As discussed earlier, $C_{average}$ is the ratio of number of alive nodes (candidates nodes of Fig. 6.10(b)) to the total number of clusters in each round. Recall that the number of clusters is always equal to the number of cluster heads. In Fig. 6.10(b), cluster heads vs. candidates decreases after

2×10^4 rounds because there are not sufficient alive nodes to form balanced cluster. As a result, the number of cluster heads in the network also decreases.

6.4 Summary

This chapter talks about the detection of Sybil attack in a wildfire monitoring application within a forest. Two different detection techniques for Sybil attack are discussed. The RSSI-based detection technique relies on the signal strength of control packets and is somewhat similar to the one discussed in Chapter 5. The residual energy-based detection technique identifies Sybil nodes based on the remaining energy of the transmitter nodes. In both these techniques, high energy nodes play a pivotal role in the detection process. In Chapter 5, the RSSI-based detection technique was designed for WSNs in which there is a Line-of-Sight connection among the nodes. This technique relies on the free-space propagation model for communication. However, the RSSI-based detection technique in this chapter is designed for a hostile forest environment in which multipath ground propagation model is a norm. The Non-Line-of-Sight connection within a forest enables one or more Sybil nodes to sneak through the detection process deployed at the high energy nodes. These Sybil nodes are blocked from participation in cluster head selection, however, they are still eligible to participate in the network communication. The two base stations elect an optimal percentage of cluster heads and distribute spatial queries among them. Each cluster head broadcasts an advertisement message to the neighbouring nodes which contains its ID and the assigned spatial query. The neighbouring nodes are either the undetected Sybil nodes or those normal nodes which failed to be elected as cluster heads. In order to form clusters, both Sybil nodes and normal nodes associate themselves with the cluster heads having the strongest signal strengths. Moreover, the member nodes within each cluster must abide by the conditions specified within the spatial queries. These queries contain the H_T and S_T values of the three environmental parameters, i.e., temperature, relative humidity and wind speed. Each cluster head collects and aggregates data from

member nodes and transmits to a nearest base station using a two-hop communication link. At this point, the two base stations discard the data of Sybil nodes by comparing the identities of the source nodes with their respective databases. Once Sybil nodes are weeded out, the two base stations carefully examines the readings (alert packets) of the three environmental parameters. Those nodes which are reporting highly critical alert packets are assigned on-demand queries and the two base stations remain highly vigilant to ensure that the alert packets generated due to on-demand queries are not lost. The base stations examine these alert packets and inform an end user if critical events continuously happen in any of the geographical region. To declare an emergency situation within a forest, it is mandatory that the nodes (assigned with on-demand queries) are consistent in alert packets, i.e., they need to continuously provide highly alert packets containing the three parameters.

Chapter 7

A Lightweight Authentication Scheme for the Internet of Things Objects

Chapters [3-6] focused mainly on energy-efficient routing techniques and Sybil attack mitigation strategies within the cluster-based hierarchical WSNs. The aim was to provide network stability by avoiding the transmission of maliciously manipulated data. Recent technological advances in the fields of RFID, wireless, cellular and sensor networks have enabled the interaction among real-world physical objects. In this chapter, we make use of these recent developments by embedding sensor nodes in real-world objects. This integration of sensor nodes and the physical world will empower objects to sense, process and control occurring events and phenomena of interest. The network of physical objects, also known as IoT, is the next wave in the era of computing outside the realm of traditional desktop [21]. The presence of embedded sensor nodes and the assignment of IP addresses make the physical objects smart enough to interact and share data. Unlike the Internet, the presence of physical objects in the IoT generate data on an unprecedented scale which need to be processed, stored and presented in a seamless, efficient and simple interpretable form. Similar to Internet, the data generated by various physical objects need to be protected against various type of attacks. Moreover, the presence of resource-starving

miniature sensor nodes at the core of physical objects requires extremely lightweight but secured and robust authentication protocols.

In this chapter, we present a lightweight payload-based mutual authentication scheme for the IoT objects. The proposed scheme uses CoAP [102] as the underlying application layer protocol to meet the requirements of the resource-starving sensor nodes. The lightweight features of CoAP such as low header overhead, parsing complexity, caching and simple subscription for a resource are ideal choices in our scheme. In the IoT, the participating objects can be easily compromised to act as potential intruders in order to manipulate network resources. The proposed scheme authenticates the identities of clients and the server communicating with each other. Various scenarios for the replay attack and their mitigation are briefly explained. Our scheme can be a lightweight yet robust and secure alternative to the DTLS protocol [158] for the IoT objects. In Section 7.1, the problem at hand is identified which builds the foundation for our proposed scheme. In Section 7.2, the payload-based mutual authentication scheme is discussed followed by the detection of replay attacks and their mitigation in Section 7.3. The payload-based mutual authentication scheme is based on our works in [119] and [159].

7.1 Problem Statement

The IoT incorporates physical objects which differ from each other in terms of various resources and operational behaviours. The sensor nodes and actuators are embedded in them to provide seamless and interoperable communication. These miniature sensors give a unique ID to each participating object in the IoT paradigm. Any physical object is *smart* as long as it can identify itself to the participating objects in the network. A small scale IoT communication model consisting of various physical objects is shown in Fig. 7.1. The client objects communicate with a NetDuino[1] server for the observation of a temperature resource. The server monitors the environmental temperature and provides its readings to

[1] http://netduino.com/

the clients. Each client may specify certain conditions for the notification of temperature readings. The electric heater, the refrigerator and the rest of the objects (clients) will not be able to communicate with the NetDuino server in absence of an IP address. The presence of an IP address enables an object to perform various RESTful operations in a resource-constrained network.

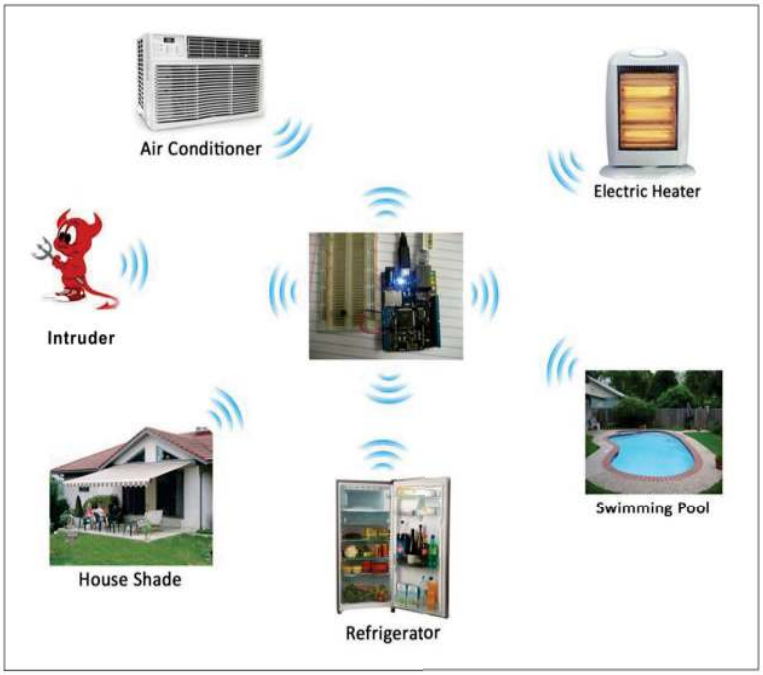


Figure 7.1: A Vulnerable Internet of Things Connected Environment

The IoT objects presented in Fig. 7.1 are susceptible to a wide range of malicious activities. An intruder may intercept the refrigerator data, manipulate it and replay in other parts of the network. It is also possible that the attacker may inject fabricated data of its own in the network. Therefore, a huge amount of data is at risk which may result in the malfunctioning of the whole network. Similar to a legitimate device, a malicious object also requires an ID to participate in a network communication. Each participating object needs to be authenticated to establish its true identity in the network. In absence of an ID validation and authentication scheme, an attacker will always be able to conduct a wide range of malicious activities. An intruder may establish multiple connections with a server

at a given time so that multiple network resources will be seized by the malicious object. This results in the denial of services to the legitimate objects and ultimately causes scarcity of resources in the network [34]. As wireless medium is shared among various objects, the intruder may block access to the network resources by continuously emitting jamming signals to interfere with legitimate transmissions [109]. The presence of wireless medium can easily expose objects to eavesdropping as well.

To detect and mitigate various types of attacks in a network, extremely lightweight but secure protocols need to be designed in view of the limited resources of sensor nodes. In today's Internet, considerable efforts have been spent on securing the existing standard authentication and authorization protocols such as TLS [111], Anonymous Authentication Protocol (AAP) [160] and Kerberos [161] among others. It indeed saves a lot of efforts if these protocols are customized to be feasible for resource-constrained networks. However, these protocols were not designed with the constrained resources in mind, which is one of the most important limitations with WSN. Therefore, profiling of an existing authentication protocol may not result in an optimal solution. Another major concern is that the existing authentication protocols may not necessarily comply with their original design objectives if they are used outside their intended domains of applications [162]. Almost all of the authentication and encryption schemes in constrained networks are based on DTLS protocol. However, DTLS includes computationally complex and resource consuming cipher-suites and hence provides an expensive secure solution to these networks. Most of the DTLS-based encryption schemes emphasize on the use of DTLS without stateless cookies. With the absence of stateless cookies, however, a server will be exposed to replay attacks [163].

In view of the above discussion, our objective is to develop a lightweight CoAP-based authentication scheme for the objects in an IoT paradigm. An important question which arises is "How lightweight does a protocol need to be?" A protocol is sufficiently lightweight if there are ample resources available to other tasks after its deployment. Therefore, the aim of our proposed approach is to develop an authentication scheme which meets the above requirements. We have developed an authentication algorithm us-

ing the basic principles of the CoAP for RESTful interactions. It is a lightweight mutual authentication scheme for any client wishing to interact with a server to establish a secure communication channel. Upon mutual authentication, the clients communicate with the server for the resource observation. Only the authenticated clients are allowed to observe the resources.

7.2 Payload-based Mutual Authentication

CoAP and our authentication scheme are not two separate protocols. For the authentication, we have added security features into CoAP to make it more robust, efficient and secure against various malicious activities. Like any communication network, preserving resources in an IoT domain is of utmost importance. Both the client and the server have equal chances to be compromised in the network. Therefore, it is important to authenticate the identities and integrity of the communicating parties in order to prevent the transmission of malicious data within the network.

In our scheme, the clients and the server challenge each other for the authentication process. Four handshake messages are used to complete the authentication and in each message the payload does not exceed 256 bits. We use the payload of each message to secure the integrity of clients and the server. Encryption and decryption techniques are applied to the payload at the sender and receiver end in order to authenticate each other. The Advanced Encryption Standard 128-bit (AES-128) algorithm is used for payload encryption. We believe that the 128-bit encryption is sufficient for most of the resource-constrained objects in an IoT paradigm. Highly secured authentication schemes such as, AES-192 and AES-256 involve excessive computational and time-consuming tasks which require sophisticated hardware and software platforms. However, the majority of resource-constrained objects of an IoT environment do not have such provisioning of sophisticated hardware and software platforms. The proposed authentication scheme is completed using the following four phases.

1. Session/Connection initiation
2. Server challenge
3. Client response and challenge
4. Server response

The session initiation is preceded by the provisioning phase. It is a prerequisite offline phase during which the clients share a 128-bit pre-shared secret (λ_i) with the server. Each pre-shared secret is known only to the server and the client to whom it belongs. The server maintains a table of such secrets, each one belonging to a particular client as shown in Table. 7.1. Each client has a unique ID which enables the server to perform a table look-up for the identity verification of the object. Upon successful verification, both parties communicate with each other for exchanging the session key. It is assumed that the end-devices are tamper-safe to avoid compromising the security primitives in accordance with the Internet Threat Model [164].

Table 7.1: Pre-Shared Secrets Table

Object ID (i)	1	2	3	4	5	6	.....	n
Pre-Shared Secret (λ_i)	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	.....	λ_n

- In the session initiation phase, each client sends a request message to the server similar to a *Hello Client* message as shown in Fig. 7.2. It is a confirmable request for the creation of a session as a resource at the server. The request is sent to the server's URI, */.well-known/authorize*. Each message has a specific token for correlating the request with a matching response. The object ID is transmitted in the message payload. Two options, *Auth* and *Auth-Msg-Type*, are included in the request whose values indicate the type of operation performed on a resource at the server. Upon successful verification of the client ID, the resource *authorize* will be created at the server. The combination of *Auth*=true and *Auth-Msg-Type*=0 indicates a session initiation request to the server.

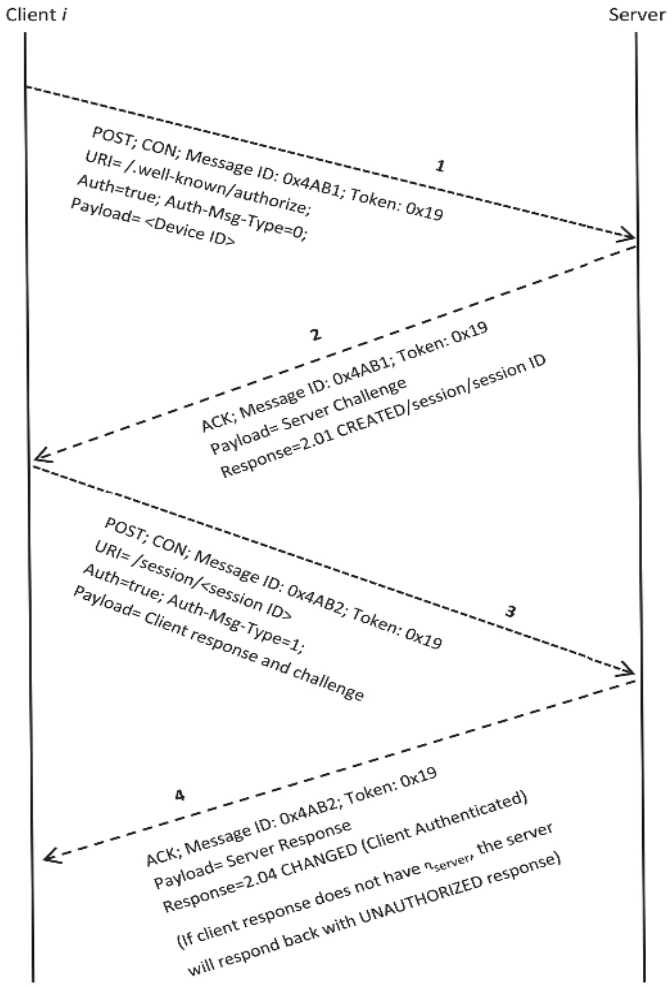


Figure 7.2: Four-way Authentication Handshake

- During the server challenge phase, the server retrieves the object ID from the payload of a session initiation request. Using this ID, the server performs a table look-up for a matching λ_i. If a match is found, the server responds back with an encrypted payload using the AES algorithm. As a new session is created for the client, a response code of 2.01 (*Created*) is included in the message. If the server is unable to find a matching λ_i, it will send a 4.01 (*Unauthorized*) response code. Moreover, the server needs to include the same message ID and the token which were present in the session initiation request. It can do so by simply copying them into the server challenge response. This enables the client to correlate a confirmable request with

the corresponding response message. To create the challenge, the server generates a pseudorandom nounce (η_{server}) and a potential session key (μ_{key}) of 128 bits each. Nonce is a temporary number used only once by an object in the entire cryptographic communication. At this stage, an encrypted payload is generated. First, an Exclusive OR operation is performed on λ_i and μ_{key} using Equation 7.1.

$$\psi_{resultant} = \lambda_i \oplus \mu_{key}. \tag{7.1}$$

Next, the 128-bit resultant ($\psi_{resultant}$) is appended to η_{server} and encrypted with λ_i to generate an encrypted payload of 256-bit using Equation 7.2. This encrypted payload is transmitted to the client as a challenge.

$$\gamma_{server\text{-}payload} = AES\{\lambda_i, (\psi_{resultant}|\eta_{server})\}. \tag{7.2}$$

- In the client response and challenge phase, the client needs to decipher $\gamma_{server\text{-}payload}$ to retrieve the potential session key (μ_{key}). If the client is successful to do so, it will have the correct η_{server} and μ_{key}. The η_{server} and the μ_{key} are known only to the server while λ_i belongs to a specific client. Only a legitimate client can decipher this challenge. An intruder can only eavesdrop on the η_{server} and the μ_{key}, but not on the λ_i in accordance with the Internet Threat model [164]. The client uses its λ_i to decipher the payload. Upon successful deciphering, the client has authenticated itself. As mutual authentication requires both parties to be verified, the server also needs to authenticate itself [165]. The client generates a new encrypted payload similar to the server. First, an Exclusive OR is performed on η_{server} and λ_i using Equation 7.3.

$$\psi_{resultant} = \eta_{server} \oplus \lambda_i. \tag{7.3}$$

Next, the 128-bit $\psi_{resultant}$ is appended with η_{client} and encrypted with μ_{key} as shown in Equation 7.4. The client-encrypted payload ($\gamma_{client\text{-}payload}$) is transmitted to the

server as a challenge.

$$\gamma_{client\text{-}payload} = AES\{\mu_{key}, (\psi_{resultant}|\eta_{client})\}. \tag{7.4}$$

- Finally, in the server response phase, the server deciphers $\gamma_{client\text{-}payload}$ of the client challenge to observe the η_{server} in it. If present, the server realizes that the client has successfully authenticated itself. The server retrieves the η_{client} and creates an encrypted payload of its own by appending the η_{client} to μ_{key} and encrypting with λ_i as shown in Equation 7.5. Next, the 256-bit encrypted payload ($\gamma_{server\text{-}payload}$) is transmitted in response to the client challenge.

$$\gamma_{server\text{-}payload} = AES\{\lambda_i, (\eta_{client}|\mu_{key})\}. \tag{7.5}$$

  At this point of time, the status of the resource changes to $Authenticated$ at the server as both parties are mutually authenticated. However, the client has yet to verify the authenticity of the server, so it decrypts the $\gamma_{server\text{-}payload}$ and observe η_{client} in it. As the client is the one which generated the η_{client}, the client comprehends that the response is from a legitimate server. At this stage, both the client and the server have agreed upon a common session key (μ_{key}) for the mutual authentication and are authorized to use the key for exchanging the data packets (β_{data}) as shown in Equation 7.6.

$$\kappa_{client\text{-}server} = AES\{\mu_{key}, \beta_{data}\}. \tag{7.6}$$

Each client and a server uses μ_{key} for encrypting/decrypting β_{data}. The value of μ_{key} varies from one client to another because each one has a different λ_i. The complete pseudo-code for the payload-based four-way handshaking authentication is shown in Algorithm 4. For guaranteed responses from the server, CON messages are used by clients in the transmitted requests. The responses from the server are also provided in CON messages. The use of various response codes such as 2.01, 2.04 and 4.01 were discussed in Chapter 2.

Algorithm 4 Lightweight Payload-based Mutual Authentication

Input: C_i : Client ID, $\lambda_i : \{0,1\}^{128}$, where $i = 1, 2, \ldots, n$

▷ λ_i is 128-bit

Output: {Access Granted *or* Access Denied}

Initialization:

(a) Each Client i is provided with a unique C_i and λ_i

(b) A server S is provided with all C_i and λ_i

Four-way Handshaking Proceeds:

1. Session Initiation: The Client i sends a CON message of payload C_i to S

2. Server Challenge: S retrieves C_i to find a matching λ_i

if C_i matches λ_i **then**

Session Created 2.01

Next, S responds with an encrypted payload, AES $\{\lambda_i, (\lambda_i \oplus \mu_{key} | \eta_{server})\}$, where $\mu_{key}, \eta_{server} = \{0,1\}^{128}$ and *message size*=$\{0,1\}^{256}$

else

C_i Unauthorized 4.01

end if

3. Client Response & Challenge: The Client i deciphers challenge and responds with an encrypted payload, AES $\{\mu_{key}, (\eta_{server} \oplus \lambda_i | \eta_{client})\}$, where $\eta_{client} = \{0,1\}^{128}$, *message size*=$\{0,1\}^{256}$

4. Server Response: S checks the η_{server} in the client challenge by comparing against the η_{server} generated in the server challenge

if Both matches **then**

Access Granted- C_i Authenticated 2.04

▷ As client is authorized, so the resource at the server changes from session creation *2.01* to successful authentication *2.04*.

S responds as AES $\{\lambda_i, (\eta_{client} | \mu_{key})\}$, $messagesize = \{0,1\}^{256}$

else

Access Denied-C_i Unauthenticated 4.01 ▷ Unsuccessful Authorization

end if

Data Transmission: Mutual data exchange between S and C_i using AES $\{\mu_{key}, (\beta_{data})\}$, where $\beta_{data} = \{0,1\}^n$, n is the varying payload size in bytes

In our authentication scheme, the *Auth* and the *Auth-Msg-Type* options play an important role. Both of these options are critical and unsafe-to-forward. A critical or elective option is related to the endpoint while the safe or unsafe-to-forward is used in the proxy context. If an endpoint is unable to understand a request message having a critical option, it must return a 4.02 *Bad Option* response to the sender. These options do not have any default values unlike the core options such as *Max-Age*, *Block*, *Uri-Path* and *Uri-Authority* [102]. Each of these options is to be assigned a number by the Internet Assigned Numbers Authority (IANA)[2]. The *Auth* has a length of 0 byte because if the message header indicates that this option is present, it is *true* and thus there is no need to occupy a byte. For the lightweight authentication schemes, it is important to have a simple message format with extremely lightweight options and related fields. The formats of these two options are shown in Table 7.2.

Number	C	U	N	Name	Format	Length	Default
TBD	Yes	Yes	No	Auth	empty	0	(none)
TBD	Yes	Yes	No	Auth-Msg-Type	uint	1	(none)

*C=Critical, *U= Unsafe-to-Forward, *N=NoCacheKey, *Length is in Bytes

Table 7.2: Format of the Authentication Options

Table 7.2 shows that both options are critical, unsafe-to-forward and do not have NoCacheKey. An option is a NoCacheKey if and only if, bits 3-5 of the least significant byte are all set to 1 [166]. NoCacheKey indicates that a server does not store the latest representation of a resource and has to prepare a fresh reading each time a client makes a request for the previous readings. In other word, cache is disabled for a server which resides a particular resource. As NoCacheKey is not present in the two options, it means that the server has the ability to cache the latest representation of a resource to serve a client more quickly. In our payload-based mutual authentication scheme, the presence of the *Auth* option indicates that the *POST* method carries an authentication payload in the request message. The *Auth-Msg-Type* is always used in combination with the *Auth* and its

[2]https://www.iana.org/

value indicates the type of authentication request by the client. If its value is 0, it indicates a session initiation request and if its value is 1, it indicates a client response and challenge.

7.3 Detection of Replay Attacks and their Mitigation

In Section 7.1, we have identified various possibilities for a replay attack in a typical IoT environment. In this section, we provide a list of solutions to combat them. The identity validation approach of our authentication scheme can eliminate most of such attacks at the first instance. However, the intruder always tries to gain access to a network by different means. If an intruder manages to infiltrate in a communication network, it can capture data packets and replay them to the clients as shown in Fig. 7.3. An intruder A eavesdrops on a full-duplex wireless link between the server S and a client C1. It captures the data packets and replay them to C1, C2 and C4 along the way.

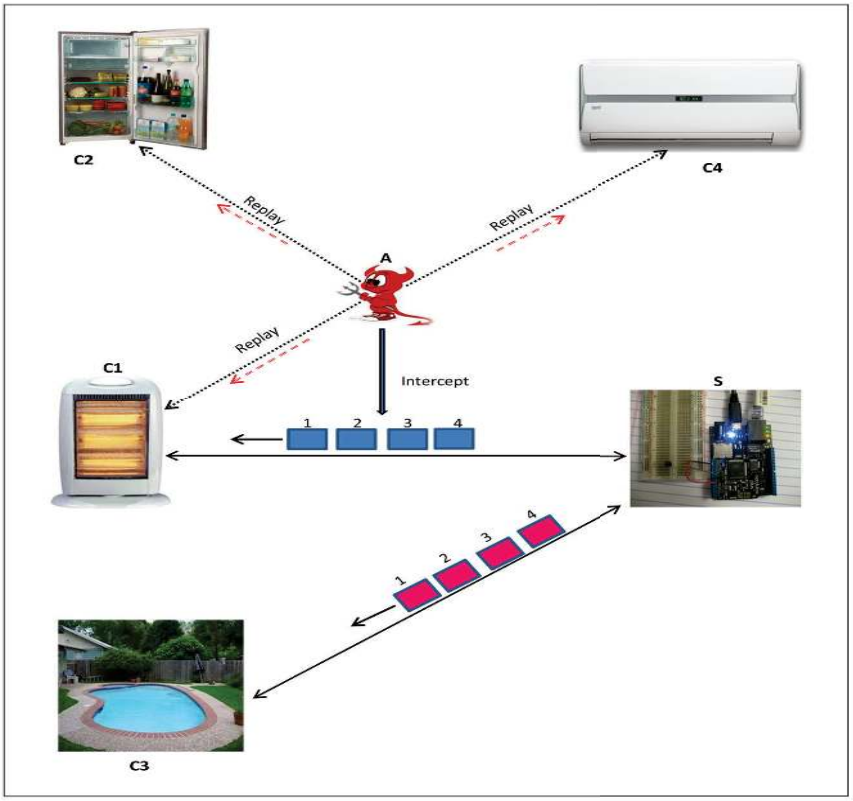


Figure 7.3: The Replay Attack in an IoT Environment

In our proposed scheme, the clients register themselves with a server upon successful authentication for resource observation. The registration request message (RRM) has an *observe* option, which has a 24-bit sequentially incremental sequence number. When the server realizes the presence of an *observe* option in an RRM, it registers the client and notifies it upon each state change of a resource. The client has the option to specify certain conditions for notification updates. Each client stores the RRM in its queue which has a unique token and a message ID for correlating the response notifications. Each of the incoming notifications from the server will have an incremental sequence number, a token and a message ID similar to an RRM. Potentially, a single RRM can generate an enormous amount of notification updates. In Fig. 7.3, the clients may not be interested in each notification update and may be more interested in those updates when the state of a resource changes and the criteria specified for the notification updates are fulfilled. This reduces the number of notification updates and at the same time minimizes the computational cost and energy consumption of a client. In each notification response, the server appends an *observe* option to enable the clients for keeping track of incoming notifications.

To detect a replay attack, each client compares the message ID and token of an incoming notification against the similar parameters of an RRM. If these parameters match, the client checks the sequence number of the incoming notification. To do so, the client can make use of a simple logic by comparing the incoming notification with the previously received notification from a server as shown in Equation 7.7.

$$\Omega_{freshness} = fresh \qquad when[(V_i < V_j) \wedge (V_j - V_i < 2^{23})] \vee [(V_i > V_j) \wedge (V_i - V_j > 2^{23})], \quad (7.7)$$

Here, we have used the freshness of the notification responses ($\Omega_{freshness}$) from a server as a measure to detect a replay attack. In this equation, V_j and V_i are the 24-bit sequence numbers of an *observe* option in an incoming (latest) notification and a previously received notification. A notification is fresh and latest if V_j is greater than V_i and their difference is

less than 2^{23}. Moreover, an incoming notification is fresh if V_j is smaller than V_i and their difference is greater than 2^{23}. This is the case when the value of V_j rolls over [167]. The entire mechanism for detection of a replay attack is shown in the flowchart of Fig. 7.4.

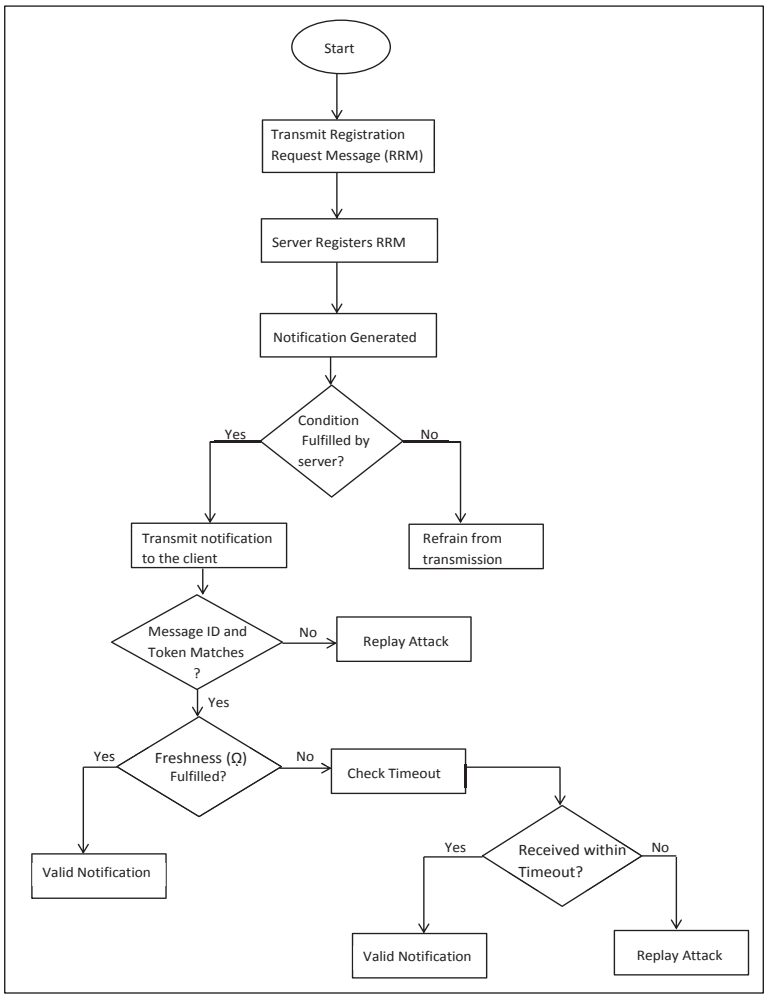


Figure 7.4: Flowchart for the Replay Attack Detection

In Fig. 7.3, the clients C1, C2 and C4 are vulnerable to a replay attack. The intruder may or may not alter the sequence numbers of the incoming notifications from a server. Irrespective of the alteration, the clients C2 and C4 can easily detect a replay attack because these incoming notifications are intended for C1 only. There will be a mismatch between the token and message ID of an RRM and those of the incoming notifications at C2 and C4 respectively. If the sequence numbers of the notifications are altered, C1 will easily

detect it by comparing the notifications with the previous one. However, if the intruder replays the notifications without any modification, it becomes a tricky situation as C1 is indeed waiting for such notifications from the server. There will be a match of the tokens and message IDs between an RRM and incoming notifications. Moreover, the sequence numbers are also in the same order as expected by this client.

To solve this puzzle, the clients can use a time stamp field in a registration request and a notification response [168]. Alternatively, each client may store in a queue the notifications previously received from a server within an acknowledgement timeout (*Ack timeout*). As the incoming notifications to a client C1 are replayed by an intruder, their timeout values play a crucial role. At this point of time, the client does not know whether the incoming notifications are replayed or not. Therefore, it checks the sequence number of these notifications against the previously received notifications in a sequential order. For example, the incoming notification (V_n) is checked against V_{n-1} to determine if it was received within an *Ack timeout* after the successful reception of V_{n-1}.

The above scenarios are linked to an intruder which somehow manages to sneak through the authentication phase and performs replay and other malicious activities during the communication phase. In our authentication scheme, η_{server} and η_{client} are generated by a pseudorandom number (R_i) which is appended to a timer (T_i). This combination of R_i and T_i assures that an intruder will find it even more difficult to replay messages. Here, T_i is to guarantee that η_{server} and η_{client} are non-reproducible. At the same time, T_i is to ensure that η_{server} and η_{client} are non-predictable.

As our scheme is specifically designed for Lower-power and Lossy Networks (LLNs), the intruder can easily eavesdrop on the communication in transit. In doing so, it can even capture a server challenge payload and retrieve η_{server} and μ_{key} from it. Using these parameters, it can generate an encrypted payload and transmit to the server. However, an intruder requires λ_i for encrypting the payload. The lack of an authentic λ_i will generate a suspicious payload for a server to decrypt and will be immediately ignored by it.

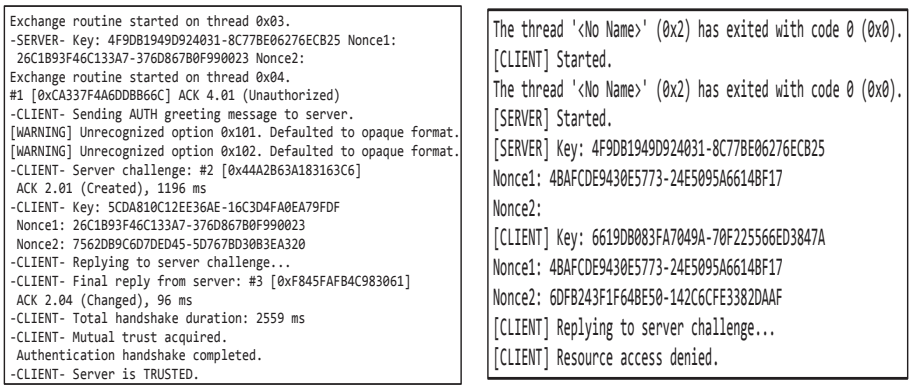
7.4 Experimental Results and Analysis

In this section, we provide the experimental results for our proposed scheme. We have used the NetDuino Plus 2 boards for the client and server interaction model. First, we perform our experimental works on the build-in emulator provided within the .NET Micro Framework for the Netduino Plus 2 boards. Next, we implement the code on the boards for the real-world environment of Fig. 7.1. The NetDuino server uses a DS18B20 temperature sensor to obtain the temperature readings. Upon successful authentication, the clients are allowed to observe the temperature resource. We use the CoAPSharp[3] library which provides a very basic communication model for resource exchanges. For the authentication provisioning, we have created our own library, CoAPMicro which runs on top of the CoAPSharp and uses its basic communication model. The library is efficient and robust, and consumes relatively less amount of resources. To justify our claim, a detailed comparison against various existing schemes is presented here.

7.4.1 Authentication

Each client needs to authenticate itself for observation of the resources. In Fig. 7.5(a), the successful handshake between a client and the server is shown. The *Auth* and the *Auth-Msg-Type* are the extended options used only for our authentication purpose. They are yet to be assigned numbers by IANA, so they appear as unrecognized. We use temporary numbers $0x101(257)$ and $0x102(258)$ for these options in our library using the *option registry* mechanism. The client and the server have successfully agreed upon a common session key and the handshake duration along with the round-trip response time is obtained. In Fig. 7.5(b), the client is unable to decipher the server challenge as it does not possess the required secret (λ_i). The outcome is an incorrect session key which causes the denial of access to the resource. In both cases, the presence or absence of the secret determines the outcome of the authentication.

[3] http://www.coapsharp.com/



(a) Resource Access Granted (b) Resource Access Denied

Figure 7.5: The Authentication Process

7.4.2 Handshake Duration

The handshake duration is computed as the sum of two round-trip messages, namely, the session initiation request and the client response & challenge. The client's session initiation request is acknowledged through a server challenge whereas the client response & challenge is acknowledged through a server response. The handshake duration is computed at the client-end using Equation 7.8.

$$\tau_{handshake} = RTT_{session} + RTT_{challenge} + \delta_{proc}. \tag{7.8}$$

In this equation, $RTT_{session}$ is the session initiation request, $RTT_{challenge}$ is the client response & challenge and the δ_{proc} is the processing time taken by the client. The processing time at the server is part of the *RTT* messages.

To compute the handshake duration, we performed 20 random handshakes between the clients and the server. To determine the variability and accuracy among the readings, we compute the standard deviation using Equation 7.9.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}. \tag{7.9}$$

Here, σ is the standard deviation, N is the total number of readings, μ is the mean value and x_i is the actual handshake duration of each individual reading.

In Fig. 7.6, we have compared our scheme with the CoAP-based DTLS implementation (INDIGO) for smartphones [116]. DTLS* represents the handshake between a smartphone and a standard computer. In this case, the smartphone acts as a client whereas the standard computer as a server. DTLS$^+$ represents the smartphone as a server and the computer as a client. Both these implementations use DTLS on the client and the server. The creation of stateless cookie at the server and the exchange of computationally complex certificates and raw-public keys contribute to a higher handshake duration for DTLS* and DTLS$^+$ respectively. Moreover, the simultaneous execution of multiple processes inside an android device contributes to a higher standard deviation for these schemes.

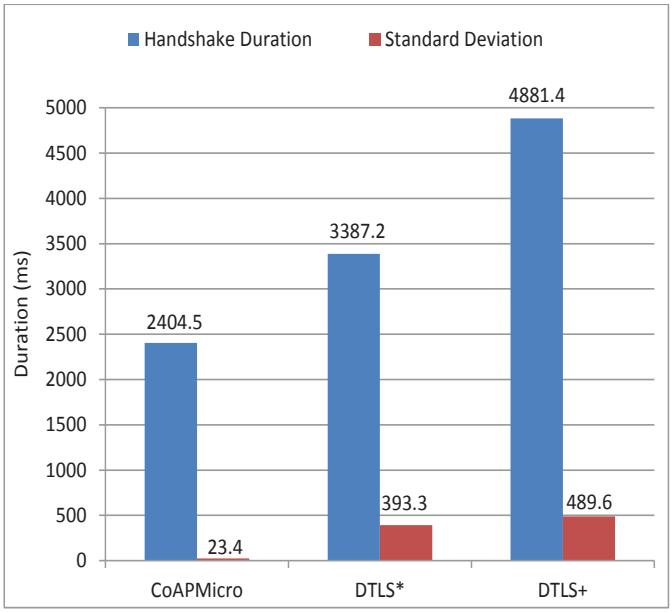


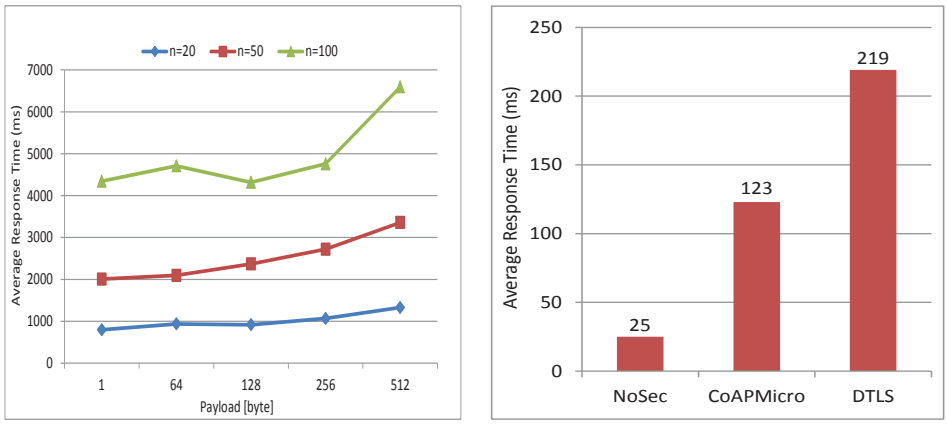
Figure 7.6: The Handshake Duration

Our CoAPMicro library has only 23.4ms of average standard deviation in comparison to 393.3ms for DTLS* and 489.6ms for DTLS$^+$. Moreover, the average handshake duration is 2404.5ms for our library which is considerably smaller as compared to 3387.2ms for DTLS* and 4881.4ms for DTLS$^+$.

7.4.3 Average Response Time

In our scheme, the CoAP messages are exchanged asynchronously over the UDP sockets. Each client maintains the record of the transmitted CON request messages to keep track of their transit through the network. When a matching acknowledgement or a reset response is received for such messages, the exchange is considered as successful.

In Fig. 7.7(a), the average response time for each message is computed for a server handling multiple requests at a given time. The response time increases with the increase of simultaneously transmitted messages. When the number of such requests (n) is 100, the response time is significantly higher which can ultimately cause congestion and scarcity of resources to the clients in the network. The response time is considerably lower when n is 20 or 50. Furthermore, the payload size has little impact on the average response time for these values of n. In Fig. 7.7(b), the average response time for a single confirmable message of 1 byte is compared with those of the DTLS and the CoAP protocol with no security. As explained previously, the presence of certificates, raw-public keys and expensive flight-based authentication makes DTLS as an expensive choice for the interacting objects in an IoT platform.

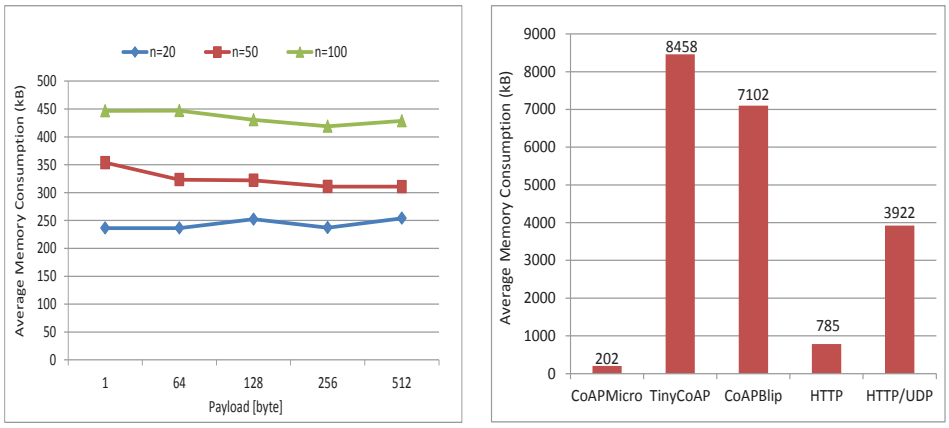


(a) Simultaneous Transmissions (b) Response Time at 1 Byte Payload

Figure 7.7: The Average Response Time

7.4.4 Average Memory Consumption

The average memory consumption of a message at the compile time is obtained by using the Debug.GC() method of the Microsoft.SPOT.Native assembly within the .NET Micro Framework. In Fig. 7.8(a), the average memory consumption is computed for varying payload sizes. The number of request messages has a significant impact on the memory consumption whereas the payload of each message has a minor impact. This is due to the fact that the server allocates memory on per message basis rather than per byte basis.



(a) Simultaneous Transmissions (b) Consumption at 500 Byte Payload

Figure 7.8: The Average Memory Consumption

In Fig. 7.8(b), we compare our approach with the existing schemes for a confirmable message of 500 bytes. CoapBlip [107] and its variant TinyCoAP [169] allocate a substantial amount of memory to the messages at the compile time. CoapBlip is an adaptation of the standard C libraries which require TinyOS[4] component for its installation on a sensor node. The use of C libraries is too complex for the resource constrained sensors embedded in a physical object. On the other hand, HTTP/UDP has a low memory footprint as it does not provide a reliability mechanism or a request/response matching. Our scheme ensures that sufficient memory is available to other tasks at the compile time. The allocated memory is immediately released upon a successful message exchange.

[4]http://www.tinyos.net/

7.4.5 Detection of Replay Attacks

As an application layer protocol, CoAP is exposed to various denial-of-service (DoS) attacks. Even in the presence of an authentication scheme, intruders always try to sneak into a network to conduct malicious activities. The number of such activities increases with the increase in the number of intruders in the network. In Table 7.3, the number of replay attacks is computed over a period of 60 seconds.

Time (sec)	Intruder A	Intruder B
0-10	3	5
11-20	6	2
21-30	3	4
31-40	4	0
41-50	1	2
51-60	7	6

Table 7.3: Number of Detected Replay Attacks

Here, intruder A conducts 24 attacks whereas intruder B conducts 19 such attempts over the same period of time. The detection of replay attacks is based on the freshness of the notification messages as discussed in Section 7.3.

7.5 Summary

Advances in WSN, RFID, wireless and cellular networks have enabled real-world objects to generate data on an unprecedented scale. This chapter takes sensor nodes one step further by integrating them in real-world physical objects to form an Internet of Things (IoT). The presence of a sensor node and an IP address make an object smart enough to interact in the real-world. The data generated by various physical objects is susceptible to a wide range of security threats at different layers. The presence of sensor nodes at the core of each physical object requires lightweight but robust authentication and security protocols. The scope of this chapter is twofold. First, a payload-based authentication scheme is proposed to verify the identities of the communicating clients and server in the network. It

uses a simple handshake procedure to exchange the session key for the resource observation. The proposed approach uses pre-shared keys for the identity verification of objects. These keys are known only to legitimate objects and cannot be obtained illicitly in view of the Internet Threat Model. Second, this chapter talks about the application of the proposed scheme for detection of replay attack, eavesdropping and resource exhaustion of a server. The lightweight features of CoAP protocol are used to provide an efficient exchange of resources while secure features of MicroCoAP validates the identities of participating clients and server.

Chapter 8

Conclusion and Future Work

Wireless Sensor Networks (WSNs) have the ability to operate in remote and hazardous locations which cannot be monitored with traditional Internet. The use of these networks for monitoring the state of physical environment is promising yet challenging. WSNs comprise of resource-starving sensor nodes which provide an interface between the physical world events and the virtual world of information. The nodes face various challenges at different layers and such challenges are addressed in this thesis. In sensor networks, minimization of energy consumption of sensor nodes has attracted a lot of research. Such approaches effectively enhance the lifetime of these networks. In this thesis, we focused on designing efficient routing protocols. This thesis also investigated and proposed secure schemes to conserve the energy of nodes. Efficient routing protocols reduce the energy consumption by various means such as reducing the number of transmission hops, efficient data aggregation, scheduling the duty-cycling of nodes and collision avoidance. On the other hand, secure and robust schemes also reduce energy consumption because safeguarding the nodes or networks from malicious attacks literally mean to enhance the network lifetime. For example, in Sybil attack, the forged identities inject malicious data in the network which increases the energy consumption of legitimate nodes in data processing, aggregation and transmission. Similarly in replay attack, an adversary replay

out-dated data which again affects the energy consumption of legitimate nodes. The use of sophisticated protection schemes not only protect the networks from malicious activities but also enhance their lifetime. Moreover, these sensor nodes are used as part of Internet of Things (IoT) by embedding them in everyday physical world objects for data collection. The IoT has the ability to collect a huge stream of data which may poses further challenges for the cloud computing and Big data. Therefore, robust and secure solutions are required to address such challenges.

To achieve the aforementioned objectives, we have conducted in-depth research on energy-efficient cluster-based hierarchical routing protocols and robust secure solutions in this thesis. A summary of the research conducted for this thesis is provided in this section followed by potential future works. We provide a summary of all the chapters and their findings.

In Chapter 2, a detailed description of Wireless Sensor Network (WSNs) and their applications has been presented. The drawbacks of conventional routing protocols in WSNs were highlighted which motivate us to use cluster-based hierarchical routing protocols for our research. A brief overview of various congestion detection and mitigation techniques in WSNs was presented and their shortcomings were highlighted. The existing research on various Sybil attack detection schemes was presented which refines our objective to develop such a scheme for a centralized cluster-based hierarchical network. Chapter 2 also presents scenario for forest wildfire monitoring application and the need for a Sybil attack detection scheme in such applications. We conclude this chapter with a detailed discussion on the Internet of Things (IoT), it's fascinating applications, CoAP and the existing works on various security schemes to protect the object in an IoT paradigm.

Chapter 3 proposed two different routing algorithms for cluster-based hierarchical WSNs. The first algorithm uses a randomly distributed approach for cluster head selection and aims at improving network lifetime and quality of data. In a randomly distributed approach, each node autonomously elects itself as a cluster head based on a probabilistic

threshold value. Our proposed approach considers the residual energy of each node as the main criteria for cluster head selection. As a result, nodes having higher residual energy values are frequently elected as cluster heads which enhance the lifetime of the network as compared to LEACH protocol. Moreover, the proposed algorithm achieves better data aggregation results as compared to LEACH protocol, which in turn affect the quality of delivered data at the base station. The second algorithm uses a centralized approach in which the base station decides an optimal percentage of cluster heads for each round. Unlike the existing centralized approaches, our approach does not require cluster heads to advertise themselves. Moreover, the transmission of join-request messages is eliminated. Once a cluster-based hierarchical network is formed, an energy evaluation model is developed which takes into account the energy consumption of nodes during various phases and sub-phases.

Chapter 4 proposed PASCCC protocol which uses randomly distributed cluster-based hierarchical algorithm presented in Chapter 3. This scheme has been used to detect congestion in cluster-based hierarchical WSNs. PASCCC is an application-specific and priority-driven protocol which monitors two different applications, i.e., temperature and humidity, based on their assigned levels of priorities. The protocol provides an on-demand mobility to cover vacant regions left behind by the energy-starved depleted nodes. The use of on-demand mobility ensures that time-critical and delay-sensitive events are not lost. During congestion, higher priority temperature packets are routed from congested clusters to the base station without further delay. Moreover, lower priority humidity packets are instantly dropped to reduce the level of congestion. PASCCC uses a novel queuing model which drops the packets based on the assigned priority levels, threshold values and type of nodes, i.e., queuing model of a member node is different from the cluster head. The use of threshold values efficiently schedule the duty-cycling of each node which enhances the network lifetime as compared to the existing protocols. PASCCC is an optimal choice for monitoring various threshold-dependent applications.

Chapter 5 proposed a lightweight scheme for Sybil attack detection and its application

to a centralized cluster-based hierarchical network. The proposed scheme detects Sybil nodes based on the RSSI of received control packets. A small percentage of high energy nodes are assigned the task of detection. They assist the base station in Sybil attack detection and enable it to prevent such nodes from participation in cluster head selection. Each candidate node for a cluster head is evaluated based on its residual energy, geographical location and previous history of selection. The use of a centralized approach ensures that an optimal percentage of cluster heads are elected in each round. The optimal selection of cluster heads enhances network lifetime, packet loss rate and packet acceptance ratio. Moreover, the proposed scheme detects the number of Sybil nodes and their forged identities which give a rough estimation of the average number of identities forged by each Sybil node in each round.

In Chapter 6, two different detection techniques, i.e., two-tier and residual energy-based schemes, for Sybil attack within a forest wildfire monitoring application were studied. The two-tier detection technique uses high energy nodes operating at a lower level to detect forged identities of Sybil nodes. However, due to the hostile environment in a forest, one or more identities may sneak through the detection process. These identities are ultimately detected by the two base stations operating at a higher level. A residual energy-based detection technique uses the residual energy of each node to detect a possible Sybil attack at the high energy nodes. If two or more incoming control packets have the same residual energy but different identities, it means that a Sybil attack has been launched by an adversary. After Sybil attack detection, an optimal percentage of cluster heads are selected by the base stations using a centralized approach. Each cluster head is assigned a spatial query to collect data about the environmental parameters within a forest. The data collected from member nodes may either belong to normal nodes or sneaked identities of Sybil nodes. To deceive an end user, the sneaked Sybil identities may broadcast high volume of false-negative alerts. The two base stations remain vigilant to prevent any such alerts from reaching an end user. Only incoming genuine alerts from normal nodes are analysed and if any of them are of significant importance, the base stations assign on-

demand queries to the origin of those alerts, i.e. the source nodes. The proposed techniques have a better network lifetime, detection rate, accuracy, data aggregation, data fusion and coverage as compared to the existing schemes.

In Chapter 7, a payload-based authentication scheme was proposed which verifies the identities of the objects in an IoT environment. The objects in the roles of clients and server, communicate with each other for exchanging the resources. The identity is provided to each object by a miniature sensor node embedded in it. However, the presence of embedded sensor nodes requires lightweight communication protocols to optimize the usage of resources. As a result, our proposed scheme uses a simple handshake procedure to exchange the session key for the resource observation. The proposed approach uses pre-shared keys for the identity verification of the objects. These keys are known only to legitimate objects and cannot be obtained illicitly in view of the Internet Threat Model. The proposed scheme is feasible to detect various types of attacks such as, replay, eavesdropping and resource exhaustion. Our scheme is extremely lightweight and incurs less overhead and exhibits much lower handshake duration. Moreover, the average memory consumption and average response time is much lower than the existing schemes which are currently used for securing the objects in an IoT paradigm.

8.1 Future Work

Wireless Sensor Networks (WSNs) possess some unique characteristics such as self-healing, self-organizing, fault-tolerance, low duty-cycling, dynamic network topology, energy harvesting and operation in human-inaccessible terrains. These unique characteristics have broadened the scope of these networks. As a result, they have found their presence in a wide range of applications. In WSNs, the nodes are low on various resources such as battery power, storage, computation, data rate and transmission range. These networks face various challenges during operation due to the presence of these miniature sensor nodes. To address these challenges, WSNs have attracted a significant amount of research from

academia and industry. In fact, researchers are continuously working on addressing a myriad of challenges that have spawned from the resource limitation imposed on the sensor nodes. At first glance, it seems that cluster-based hierarchical routing protocols are the solution for addressing all the limitations of WSNs. However, these protocols also have their own limitations which need to be further investigated.

Regardless of randomly distributed or centralized approaches, almost all of the cluster-based hierarchical routing protocols are designed for conceptual WSNs, i.e., these protocols do not address any real-time application. These protocols have the potential to optimize the usage of various resources but they need to be implemented with real-time applications, such as battlefield surveillance, agriculture monitoring, industrial automation and healthcare monitoring. Almost all, these real-time applications use conventional routing techniques in which hop-by-hop and end-to-end communication is used for data delivery to a base station. QoS provisioning is a challenging task in these applications and the use of cluster-based hierarchical routing protocols for these applications will have a significant impact on their performance if proper care on resource management is not taken with due care. However, these protocols need to satisfy the QoS requirements of these applications. The distinguishing features of these protocols, i.e., load balancing, fault-tolerance, power optimization, data aggregation, collision avoidance and prolonging network lifetime, will facilitate these applications in long run. Our contributions in Chapter 4 and Chapter 6 used cluster-based hierarchical routing protocols as the underlying platforms for monitoring a real-time application, i.e., forest wildfire monitoring. Although, these chapters addressed congestion and security challenges in a real-time application but, the ultimate goal was to optimize the usage of resources. In other words, both these chapters enhanced QoS parameters such as network lifetime, energy consumption, delay, congestion and throughput. To this end, cluster-based hierarchical routing protocols were applied to a real-world application and various QoS parameters were enhanced. However, both these chapters have their own shortcomings. In Chapter 4, the queuing model of PASCCC protocol was developed for a single time-critical application. It would be interesting to see the behaviour of the

queue in presence of more than one time-critical application. Moreover, the behaviour of the queue needs to be analysed in presence of leaky bucket algorithm which maintains the flow of data and ensures that the available bandwidth is utilized efficiently. Furthermore, the nature of the traffic arrival process exhibits a bursty and correlated behaviour, which degrades the network performance. All these factors, i.e., queue scheduling, number of queues, queuing threshold, traffic arrival rate and network performance contribute toward the QoS of any real-time application. In Chapter 6, a Sybil attack detection technique was designed for a forest wildfire monitoring application. Although, the main objective was to address the security challenges faced by the nodes within a forest, however, our proposed scheme achieved better QoS metrics as well. In fact, it is the aim of any design scheme for a WSN, that it must be secure, robust and efficient in term of resource usage. Our proposed scheme enhances the optimization of resources and at the same time, is highly efficient in terms of detection of Sybil nodes. However, the selection of cluster heads is computationally complex and a large overhead is involved which may be improved further using a rather simple logic. These performance metrics involving computational complexity and delay incurred in cluster head selection may be enhanced through future research investigation.

The Internet of Things (IoT) represents the next generation of the Internet by taking a huge leap to gather, analyse and distribute data about the physical world which can be transformed into information, knowledge and ultimately wisdom. This evolution involves interconnecting the physical objects from everyday life. Each object requires an identity to bridge the gap between the virtual world of information and the physical world of objects. However, the presence of objects in the Internet poses new challenges which were not known in the past. The addition of such objects is not a straightforward process. Each object has its own attributes and requirements for network communication. As a result, interoperability is a major challenging task which needs to be addressed. Despite all the speculations about the IoT applications and interconnected objects, fewer efforts have been made to secure IoT products reaching the market. Most of these products lack secure fea-

tures. As objects are having different attributes and specifications, hence, secure solutions available for the conventional Internet are not feasible for these objects. Although, sensor nodes are involved at the core of communication system in these objects, however, secure solutions for WSNs are not feasible for these physical objects. The underlying hardware and software platforms of these objects are incompatible with the sensor nodes. In Chapter 7, we proposed a payload-based authentication scheme which is efficient against various attacks such as, replay, eavesdropping and resource exhaustion. However, it is yet to be determined how efficient and robust the scheme is against other types of attacks such as Sybil, sink-hole, wormhole and black hole. Furthermore, the proposed approach allocates pre-shared keys at the provisioning phase, hence, it is a suitable choice for a static deployment. If the pre-shared key of an incoming mobile client is not present in the server lookup table, the client will not be able to communicate with the server. For this type of scenario, a dynamic key allocation scheme may be a more optimal choice. This is specifically the case with a large scale deployment of IoT objects in real life situations. The scalability and mobility of the nodes may further improve the proposed scheme and broaden its future scope of application.

Currently, we are focusing on the integration of LEACH protocol with CoAP for the objects communicating in an IoT environment. Presently, most of the CoAP-based objects in an IoT paradigm rely on 6LoWPAN at network layer and IEEE 802.15.4 standard at data link (MAC) and physical (PHY) layers. We aim to implement a protocol stack which uses CoAP at application layer and LEACH at network layer. We will compare the performance of the scheme against the existing schemes. Furthermore, we also aim to eliminate the use of IEEE 802.15.4 standard at MAC and PHY layers. LEACH has the ability to provide standalone services which literally means that all the services required at MAC and PHY layers may be provided by LEACH as well. Another fascinating area for future research work is congestion detection within a forest wildfire monitoring application using a cluster-based hierarchical routing protocol. Our PASCCC protocol reduces congestion in overcrowded clusters by using threshold levels at the nodes, i.e., nodes drop humidity

packets and route time-critical, delay sensitive temperature packets at the time of congestion. The proposed scheme can be improved further if the cluster heads in the congested clusters borrow communication channels from those clusters where density of the nodes is low. The cluster heads in uncongested clusters have ample of communication channels available which can be provided to cluster heads in congested clusters.

This thesis first addressed energy conservation issues faced by sensor nodes in WSN followed by designing secured schemes to tackle Sybil attack. Both these objectives aim to prolong the lifetime of a network. Designing energy-efficient routing techniques conserve the energy of sensor nodes in sensing, transmission and data aggregation. On the other hand, robust security schemes protect the network from malicious activities of an attacker. In a secured network, packet drop ratio is low which means that the nodes require fewer retransmission attempts. Each retransmission attempt consumes the energy of sensor nodes in transmission, in-network processing at the intermediate nodes, and data aggregation. Moreover, the number of retransmission attempts increases the possibility of congestion in the network which ultimately leads to higher delay and low network throughput. The presence of sensor nodes at the core of each real-world physical object imposes the resource-limitations on these objects. The existing energy-efficient and security schemes of Internet cannot be applied to IoT because each object has its own distinguishing attributes and characteristics. As a result, new authentication and security schemes need to be designed for the interacting objects in an IoT environment.

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