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Efficient and secured rekeying based key distribution in wireless sensor architecture with Arduino and XBee

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EFFICIENT AND SECURED REKEYING BASED KEY DISTRIBUTION IN WIRELESS SENSOR ARCHITECTURE WITH ARDUINO AND XBEE

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Dedication

To my parents and wife.

Abstract

Since the time of their introduction, Wireless Sensor Networks (WSN) have been catching the interest of researchers. WSN have a wide range of applications, some even involving sensitive and secret information, thereby raising security concerns. Nevertheless, WSN have some constraints like limited memory, energy and computational capability, which pose an obstacle for the addition of proper security in sensor nodes. This thesis introduces a new rekeying design for WSN security framework whose implementation would dispense effective security in the sensor nodes. This proposed security framework is endowed with the capacity to address security issues, such as message integrity, confidentiality, authenticity and freshness based on symmetric key cryptography. In addition, this design does not allow the storage of any key except the initial master key in the sensor nodes prior to network deployment. This thesis also investigates reconfigurable sensor nodes in terms of execution time, memory, power consumption, and cost while running the security framework. Finally, the findings of this thesis are compared with previous studies conducted in this interesting field.

Acknowledgments

First and foremost, I would like to render my utmost thanks and gratitude to my supervisor, Dr. Hua Li, for his continuous guidance, support and cooperation throughout the journey of my MSc program. His direction, valuable opinion and effort have led me on the path of my thesis.

I wish to express my thanks to Dr. Robert Benkoczi for his encouragement and insightful advice which certainly has helped me to ascertain my research objective. He took the time to review my thesis and his valuable feedback has helped me in the successful completion of my thesis. My sincere thanks also to Dr. Gongbing Shan for his thoughtful advice and invaluable feedback regarding my thesis work.

I am very thankful to all my fellow graduate students, family members and lab members whose cooperation has made this path easier for me. Special thanks go to my wife for her tremendous support, encouragement and help throughout my master's program.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Wireless sensor networks are cost effective, convenient to use and have gained immense importance in a variety of fields including home automation, traffic control, military surveillance, health monitoring, agriculture, and more.

In 1991, Marc Weiser proposed invisible and ubiquitous computing [49] which initiated the idea of wireless sensor networks. This thought inspired the Smart Dust Team [30] of the University of California, Berkley, in 1999, who then worked on extremely tiny sensor nodes. With the passage of time, the Smart Dust project at the University of California led to the development of wireless sensor network technology where the sensor nodes are the basic building block.

In this era of globalization, information is easily accessible and, therefore, unsecured. A sensor network processes data and transmits a signal between the sensor nodes and the receiver such as a smart phone. Therefore, information can be intercepted by unauthorized users. This is the reason that security concerns in WSN are now becoming a topic of further research. There are many open problems and shortcomings in the existing security methods. These have inspired me to pursue further research on this sensitive issue to propose a more convenient and efficient framework for ensuring the security of WSN.

1.1 Motivation

Wireless sensor networks are gaining popularity day by day because of their lower cost and convenient use in remote places. They are used in several important applications like

military, health and agriculture monitoring. As WSN are an evolution from research to practical implementation, it is high time for researchers to consider the sensor nodes as reprogrammable and to validate the code running on the nodes. When proceeding with the research in this field, it is observed that most of the research is based on simulation and proposal with very few practical implementations. The limited experimental applications of previous work have inspired me to pursue further research in this field. One of the focuses of my thesis is to choose the appropriate device to implement WSN. After several analyses, I have selected Arduino UNO for this purpose. It is the reconfigurable property of this device that d has inspired me to choose this gadget. In addition, the chosen device is cost effective as well as less power consuming. In my proposed design, the session between sender and receiver starts from the sensor nodes. To create the Wireless DigiMesh, XBee has been used as a transceiver as it is a low cost, reconfigurable and low power consumption device. There are other products available on the market to build the wireless sensor network; however, the major benefits of the selected device over the others are better flexibility and configurable property. For other devices, a fixed predefined library is needed to implement the network.

In WSN, data pass through the wireless medium and, hence, are sensitive to external attacks. In addition, WSN has been deployed in different process control environments like water, gas or oil usages, in monitoring and billing. In these infrastructures, secret information is being passed over the network. Scientists are proposing different cryptographic solutions for efficient network security. Key management is one of the pivotal issues regarding the security of WSN. This motivates me to introduce a new symmetric rekeying mechanism.

Previous research shows that few numbers of asymmetric and symmetric key based solutions exist [18] [22] [24] where a cryptographic key is preloaded to the sensor nodes prior to network deployment. This approach has certain advantages like less memory and message overhead; however, a single compromised node leads to the destruction of the whole network [43]. This shortcomings of key management has led me to design a Wireless Sen-

sor Network based on rekeying. As the sensor nodes operate for a longer period of time, rekeying is very important after a certain period. Rekeying is proposed by [26] [37] [27] which are based on a combination of public key and symmetric key, among which two are practically implemented. The empirical performance of the proposed architecture based on rekeying is compared with their works. The other details of the background research are discussed in chapter 3. Moreover, this design also considers the cost and limited computational and energy resources.

1.2 Main contribution

The major contribution of this thesis is to design and develop a framework incorporating security measures in WSN. The new rekeying method, based upon symmetric keys as well as data transfer security has been discussed with authentication and verification. To the best of my knowledge, Arduino is the first platform where rekeying based authentication is designed and developed. The whole approach, from hardware design to software implementation of the program, has been practically implemented in the live DigiMesh network which is a ZigBee based WSN and tested with real life sensors. Furthermore, for the sensor nodes, a particular device has been used which is economic but powerful and easily programmable. Extensive assessment of the designed framework on the sensor nodes, in terms of execution time, cost, energy, throughput and data transfer has been considered. Finally, the outcome and performance of the framework has been compared with previously implemented practical versions.

1.3 Thesis organization

The rest of this thesis is organized in the following order. In Chapter 2, the background information related to the sensor network is discussed. The chapter covers applications of wireless sensor network and attacks in the network. It also summarizes the security requirements for a secured wireless sensor network, which is followed by a narration of

symmetric key cryptography and hash.

In Chapter 3, the related research is discussed. Chapter 4 describes the proposed framework design. It also covers how the proposed system achieves security and prevents against known attacks in the wireless sensor network.

The implementation detail of the system starts in Chapter 5. This chapter describes hardware which are used in the experiment. The detailed implementation steps of rekeying and data transmission over a DigiMesh network are deliberated in Chapter 6.

The performance analysis and testing of the proposed system is shown in Chapter 7. This chapter also covers the comparison of my work with previous results. Finally, the thesis is concluded and future plans are proposed in Chapter 8.

Chapter 2

Background Study

2.1 Wireless Sensor Networks

Wireless Sensor Networks are a combination of tiny sensor nodes having a microprocessor, memory, radio and an energy source. WSN can combine a variety of sensors to measure diverse environmental properties and is usually used in remote places. A radio is introduced in the network for sending data into a receiver such as a laptop or smart phone device. The network can get power from different sources, such as a battery or solar panel, but the battery is the most common. A feature of WSN is that they can rest in sleeping mode most of the time and work when necessary, thus preserving power. The sensor nodes are deployed in monitoring fields like healthcare, military and agriculture. A sample WSN is depicted in figure 2.1.

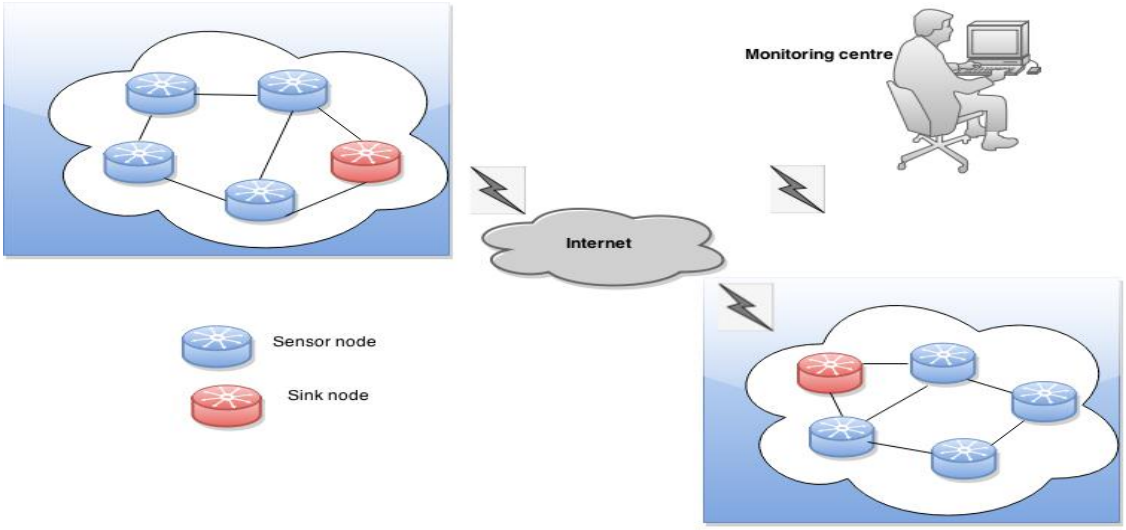


Figure 2.1: Wireless Sensor Network

2.2 Applications of Wireless Sensor Networks

The wide area of utilization of WSN is sorted into tracking and monitoring functions [51]. When considering the tracking function, it can be applicable to military department for searching the opponents or intrusions, in traffic inspection, for locating a specific animal and so on. Moreover, it also aids in business and industrial production by finding the appropriate person [51]. As mentioned above, WSN have huge prospects regarding surveillance and monitoring. This is evident in military fields, as it is used for observing the potential for biological or chemical attacks which forms an essential part of security monitoring. WSN can be deployed in the agricultural field for quoting weather, temperature or pressure. For disaster forecasting, assuming volcanic eruption, they also have immense utilization. Moreover, WSN have gained popularity for factory, equipment and inventory monitoring. In healthcare and the biomedical field, patient alarms are greatly improved with the availability of WSN. Currently, WSN have both residential and industrial uses. Automatic light switching and temperature sensing are examples of the household benefits of WSN. Out of the huge range of applications for WSN, only a few of the most used fields are mentioned here. In practical terms, WSN have great potential to be used in many other sectors [51].

2.3 Attacks on WSN

WSN are prone to many kinds of attacks. Based upon security requirements, the threats are characterized as [47]:

2.3.1 Attacks on secrecy and authentication

The existing cryptographic protocol can prevent these sorts of attacks [47]. The asymmetric key, symmetric key or cryptographic hash protects sensor nodes from known attacks such as reply attacks, contents modification and deceiving data packets.

2.3.2 Attacks on network availability

This is a more common WSN denial of service attack. This attack is very vulnerable and may occur in any of the network layers of WSN.

2.3.3 Stealthy attack

Stealthy attack denotes inserting false data into the node and tring to validate the false data in the network. The main goal of the intruders is to validate an outsider node as a trustworthy node.

2.3.4 Physical layer attacks

The physical layer deals with the generation and selection of frequencies as well as data encryption. It is susceptible to the following attacks:

(a) Jamming attack: Jamming can be defined as a potential threat that disrupts a network's radio frequency. A powerful jamming source can shut down the entire network while a weaker one can affect a smaller portion of the network concerned. There are two possible protective measures against jamming, namely frequency hopping and code spreading. In WSN, for cost effectiveness and low power requirement, the sensor nodes commonly use a single frequency which is easily liable to jamming attacks.

(b) Tampering: Tampering is a direct physical attack on the sensor nodes to obtain delicate information like asymmetric or symmetric keys from the nodes. To avoid this attack, the sensor nodes can be made tamper resistant. However, most of the nodes are not equipped with this package, thereby necessitating a security protocol for physically compromised nodes.

2.3.5 Data link layer attacks

The Data link layer confirms trustworthy communication between point to point and point to multipoint connections in the network model. Common attacks in this layer are discussed below:

(a) Collision: The sensor nodes use the same frequency for commutation, resulting in collisions of data packets. As a result, some data packets are lost. The intruders can deliberately cause collisions towards important data packets such as session initialization. There is no existing protection against such attacks. The only solution is the error correction code which is applicable for low collision data.

(b) Exhaustion: Excessive collision in the network exhausts the sensor nodes. For example, if a sensor node is constantly sending a particular data packet, it may lose its power, resulting in a suddenly broken sensor node. The solution for this attack is to limit the request for delivering the same data. This technique helps to drain the energy of sensor nodes.

(c) Unfairness: Unfairness is initiated by the previously discussed attacks of collision and exhaustion. The remedy for this attack is to use a small packet size, because a small packet size does not dwell in a channel for a long period of time.

2.3.6 Network layer attacks

The Network layer is designed for routing and addressing. The attacks targeting this layer are discussed below.

(a) Spoofed or replay routing information: This is the most common routing protocol attack. The intruder deceives or alters routing information to create an interruption which creats a routing loop or increased end to end latency in the network. The countermeasure for this attack is to add a signature to every packet with hash operation. As a result, the receivers can regenerate the signature in their site to verify that signature.

(b) Sinkhole attack: In this attack, the eavesdroppers compromise a node, misleading other nodes to transmit their routing information through the compromised node. As a result, the eavesdroppers can capture all the routing information passing through that node.

(c) Sybil attack: Sybil attack refers to stealing the ID of other nodes in the network. In this attack, the compromised node has more than one identity. Direct or indirect validation

of the node is the suitable preventive mechanism for this attack.

(d) Acknowledgement spoofing: In the WSN, routing information is acknowledged to the neighboring nodes. The intruder takes advantage of this routing property by spoofing the acknowledgement information. For example, an attacker acknowledges on behalf of a node which is actually wrecked.

2.3.7 Transport layer attacks

End to end communication is achieved by the transport layer. Just like other layers, this layer is also susceptible to different attacks.

(a) Flooding: The flooding denotes to the exhaustion of memory or energy of sensor nodes by continuously opening a connection between them. The attackers linger this attack as long as the nodes reach their maximum capacity to make connection. The nodes may prevent this attack by avoiding unnecessary connections.

(b) Desynchronization: This attack refers to the interruption of existing connections between the sensor nodes. The attackers try to fool the nodes by injecting wrong sequence numbers into the packet. As a result, the receiver assumes that the intended packet is lost, so again requests for the same data entering a loop. Thereby, sensor nodes lose their energy and expire. Authentication can be used to avoid this attack.

2.3.8 Application layer attacks

According to Xing *et al.* [50] the application layer attacks are divisible as below:

(a) Data aggregation distortion: Data aggregation is the modification or alteration of final data before being sent to the receiver. For example, a patient's wrong blood pressure reading may lead a physician to take incorrect action. Encryption and signature verification can be used to prevent this attack.

(b) Clock skew: Some of the sensor nodes use a real time clock to manage the communication between themshelves. The sensor nodes generate timestamps using this real time clock to verify data. In this attack, the intruders skew the clock to distrupt the timestamps.

As a result the whole network may become asynchronous [50].

2.4 Performance Requirements in WSN

WSN consist of many battery powered tiny sensor nodes. As a result, performance issues need special consideration. According to Qian *et al.* [42], performance and design issues which need to be addressed in WSN are discussed below:

2.4.1 Energy efficiency:

Many of WSN applications work in remote environments. The main energy source available to distant locations is battery; therefore, battery power is a vital factor in network operation. At the time of imposing security, the energy issue needs to be addressed. Sensor nodes are normally very tiny. Before proposing any algorithm or framework, the energy requirement of the nodes should be measured. In addition, at the time of deployment, sleeping functionality is integrated to the node to save as much energy as possible. In sleeping mode, the sensor nodes only work when required. The nodes wake up because of some interruption or during a particular period of the day.

2.4.2 Memory requirement and execution time:

Normally, the sensor nodes have low memory and low computation capability. Handling the security in WSN requires calculation of computational time and memory. Cryptographic operations place a high demand on computation and memory resources. Therefore, a framework and algorithm with less execution time and memory consumption should be considered for inclusion in the sensor nodes.

2.5 Security Requirements in WSN

The wireless sensor network transmits crucial information and therefore is susceptible to various attacks. The following are the security attributes of WSN [47]:

2.5.1 Confidentiality:

Data confidentiality refers to the attribute that data is only understandable to the receiver for whom it is meant. The objective is to keep important sensor data secured and confidential. The norm for keeping data confidential is to use an encryption technique between the sender and the receiver. A major hazard for attaining data confidentiality is compromised nodes, which causes hacking of the cryptographic keys stored in the sensor nodes.

2.5.2 Integrity:

Data integrity is concerned with the fact that no messages between the sender and the receiver are altered by an eavesdropper. When dealing with critical data like healthcare, contents must not be changed. Therefore, data in an unsafe network are greatly threatened by vulnerable fields as they can cause disastrous outcomes. As a result, data integrity is highly important when processing vital sensor data.

2.5.3 Authentication:

Data authentication is a characteristic of WSN where the source node for data can be verified as legitimate. Therefore, the authentication system is based on verification and distinguishing of the original sender from the trespassers. It is fundamental for a network to safeguard against adversary nodes sending fallacious data and to assure that the received data has been sent from a reliable sender node. For example, in the process control environment, it is to be ensured that a water metre bill is recorded and sent from the intended nodes. Otherwise, there may be a chance of erroneous and disastrous results.

Data authentication is achieved by producing a one time Hash Message Authentication Code (HMAC), using a symmetric key shared between the two devices. However, data integrity along with authentication can be attained by using a symmetric key on the two devices at the same time. Furthermore, for reliable communication, there should be a mechanism that ensures data integrity and authenticity when sending important sensor data.

2.5.4 Authorization:

Authorization denotes that only authorized sensor nodes are involved in the activities between the sender and the receiver.

2.5.5 Current Data:

In the sensor network, the transmitted data should be up to date. The inclusion of nonce (number sequence) with every message ensures data freshness and prevents reply attacks with old messages.

2.5.6 Forward and backward secrecy:

When designing WSN, this is one of the criteria for conferring network security. Forward secrecy ensures that gaining access to the current key does not allow any attacker to read future messages. On the other hand, backward secrecy assures that the attacker does not get access to previous messages.

2.6 Symmetric Encryption

The symmetric encryption protocol is a cryptographic algorithm using the same key for conferring network security. It is comprised of five components [44]: plaintext, encryption algorithm, secret key, cipher text, and decryption algorithm.

Plaintext: This is the data which is used in the algorithm as input.

Encryption algorithm: This is used for alteration and substitution of the plaintext, for example, AES, DES, RC4, and XTEA.

Secret key: The secret key acts as an input to the encryption algorithm but does not depend on plaintext or algorithm. The output is different depending upon the various keys used. Substitution and alteration are achieved by the algorithm.

Ciphertext: The ciphertext can be referred to as the output, which is a somewhat random set of data and is incoherent. It is based on plaintext and secret key. For any given data, a separate key a separate ciphetext.

Decryption algorithm: This is the opposite of the algorithm used for encryption. With the help of ciphertext and secret key, it can extract the original plaintext input.

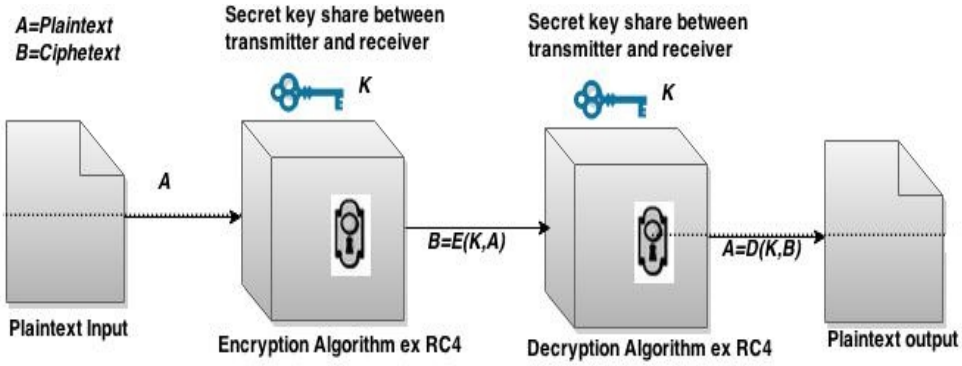


Figure 2.2: Symmetric encryption model [44]

For any given message A and key K , the encryption algorithm produces the ciphertext B= [B1,B2,.,BN] which is written as $B=E\ (K,A)$. On the other hand, the receiver extracts the plaintext back with the help of a decryption algorithm, by using the formula $A=D\ (K,\ B)$ [44].

To make the encryption technique secured:

1. The encryption algorithm has to be so strong that any eavesdropper knowing the algorithm and possessing the cipher text will not be capable of deciphering the ciphertext or finding out the key in a certain amount of time. The third party must not be able to decrypt ciphertext, even by gaining access to the cipher text with the plaintext that produced it.

2. As it is possible to discover the communication by gaining access to the keys and algorithm, the main prerequisite for security is that both the sender and the receiver obtain the keys in a secured fashion.

2.6.1 Cryptographic dimension:

Operations for transforming plaintext to ciphertext: There are two basic operations for encryption algorithm. The first one is substitution signifying that every component in the plaintext is mapped into another component. The other is transposition which means

the rearrangement of the plaintext components. The fundamental constraint is that no data should be lost. Most of the encryption algorithm involves multiple stages of substitution and transposition [44].

Key numbers: A system where the sender and the receiver are using the same key is called symmetric or secret key encryption. On the other hand, if different keys are used, the system is deemed asymmetric or as having public key encryption [44].

Plaintext processing: There are two techniques for plaintext processing: in a block cipher, the input block produces an output block for each input block at a time; however, the stream cipher processes input continuously to produce a one element output at a time [44].

2.7 RC4

RC4 is a stream cipher based cryptography designed by Ron Rivest. The algorithm is generated by true random permutation and the key size of the algorithm is variable. The same key is used for both encryption and decryption.

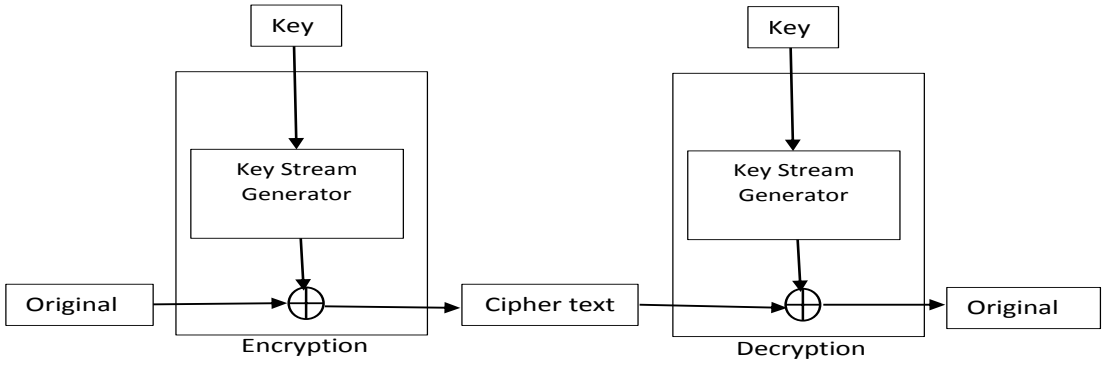


Figure 2.3: RC4 operation [44]

The operation of this algorithm is divided into two parts: one is the key stream generator phase and the other is the true pseudorandom number generator (PRNG) phase. These two phases always perform operations for every new key issued in the system [45].

The operation starts with the initialization of state vecotor S box. The initialization is

ensued in ascending order.

*/*Initialization*/*

for $i \leftarrow 0,255$ **do**

$S[i] \leftarrow i$

end for

The randomized S box is created using the pseudocode below

*/*Randomizes S box*/*

for $i, j \leftarrow 0,255$ **do**

$j \leftarrow (j + key[i \pmod{keylen}] + S[i]) mod 256$

$Swap(S[i], S[j])$

end for

After the initialization of the S box, a stream generator is used instead of an input key, followed by the cycling operation involving all the elements of S[i]. Finally, encryption or decryption is attained through execution of an XOR operation of the pseudorandom number outcome (ks) by the plaintext or ciphertext correspondingly. The detail is outlined in the following code

*/*PRNG*/*

$i, j \leftarrow 0$

while (true) **do**

$i \leftarrow (i+1) \pmod{256}$

$j \leftarrow (j + S[i]) \pmod{256}$

$Swap(S[i], S[j])$

$ks \leftarrow (S[i] + S[j]) \pmod{256}$

end while

$output[i-1] \leftarrow S[ks] \oplus (input[i-1])$

2.8 Hash Functions

The hash function accepts a variable length of data and produces the fixed size of output [44]. A good hash function always produces evenly distributed and random output for a variable size of input. The hash function ensures data integrity, and any alteration to any bits causes a variation in the hash code. The algorithm in the hash function has a one way property, where a message sketches a predetermined hash result and the collision free property confers that the two messages sketch the same hash result. These features specify whether or not the data has been transformed. [44].

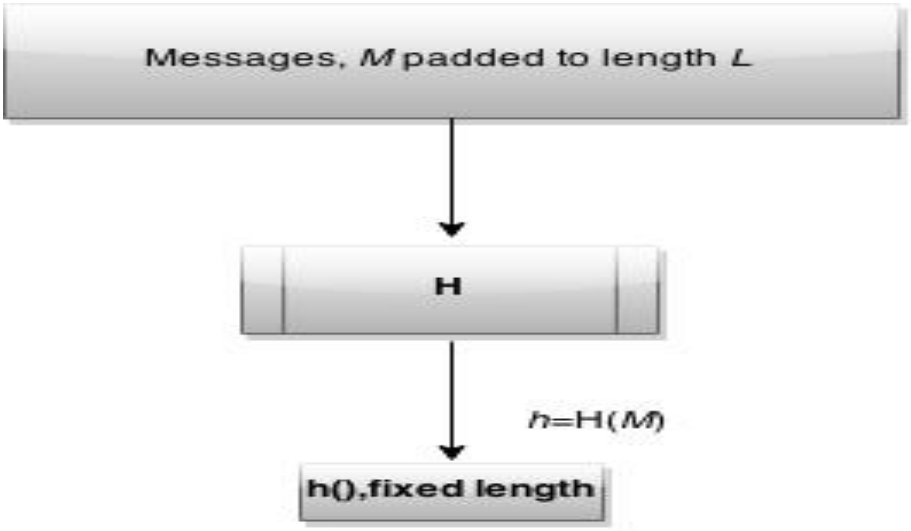


Figure 2.4: Cryptographic Hash function [44]

2.8.1 Properties of Hash value:

In a cryptographic hash function, there are some unique properties. Among these, the first is accommodating variable input size which means it can be applied to any size of block of data. The hash function also allows fixed output size. In a cryptographic hash function *H, H(a)* is easier to compute for any given data *a* which contributes to the efficiency of the hash function [44].

The other property is preimage resistant or the one way property. In a hash function, hash value can be produced from a given input but the input cannot be revived from the

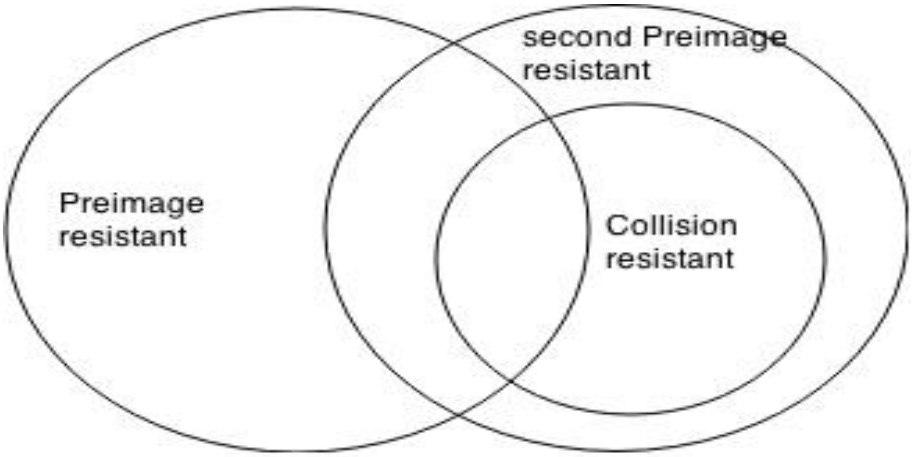


Figure 2.5: Relationship among the Hash function properties [44]

hash value. This means it is computationally infeasible to find *(b)* for any *H (b)=h.* [44].

A successful cryptographic hash function requires second preimage resistant which can be also called weak collision resistant. When using the same message as input, it is never possible to find an altered hash output. For any given message 'a', it is computationally impractical to be $b \neq a$. with *H(b)= H (a).* This property safeguards against fake information when any encrypted hash code is used [44].

Any hash function that possesses the above mentioned properties is deemed a weak hash function. To qualify as a strong hash function, a property, collision resistant, is to be acquired. When the sender generates a message for the receiver to sign, the strong hash function should have the ability to protect against any interfering attack. It can be noted that, it is practically impossible to find any pair *(a,b)* such that *H (a) = H (b)* [44].

Last but not the least is the pseudo randomness which denotes a random output. Any given hash function creates a pseudo random output and satisfies the criteria and standard tests for pseudo randomness [44].

2.9 Secure Hash Algorithm (SHA-1)

SHA-1 is the most extensively used hash function around the world [44]. SHA-1 was developed by the National Institute of Standard and Technology (NIST), in 1993. SHA-1

design very closely resembles MD4 design which is another hash function used in practice. SHA-1 uses five 32 bits registers to produce 160 bits output of hash value. However, the output is shown in a Hexadecimal number which is 40 digits long. SHA-1 involves 4 main iterative rounds where each round contains 20 steps. To execute SHA-1, 2^{69} operations are needed [44]. Table 2.1 demonstrates the important facts of SHA-1.

Table 2.1: Facts regarding SHA-1

Message Digest Size	160 bits
Message Size	$<2^{64}$
Block Size	512
Word Size	32
Number of Steps	80
Initialization Variables	5
Collision Complexity	2^{80}

2.10 IEEE 802.15.4 Protocol

IEEE 802.15.4 is a communication protocol based on low data rate and low power consumption that enables connection of devices through radio communication in personal area networks. This standard is applicable to WSN. It includes only two layers: the medium access control (MAC), which is sub layer of the Data link layer and the Physical layer (PHY) [23]. These are used to build different networks like star and mesh. The other higher layers of open system interconnection (OSI) are not discussed in this protocol.

2.11 ZigBee

ZigBee is a network protocol based upon IEEE 802.15.4 standards. It is affiliated with a coalition of companies working to build ZigBee. ZigBee delivers low cost and low power connectivity to devices which do not require high data rates. The range of ZigBee based devices is 10-75 meters. However, wireless mesh networks are implemented using ZigBee to expand the range of ZigBee based networks. It operates globally on a 2.4 GHz band

where the data transfer rate is 250 kbps [23].

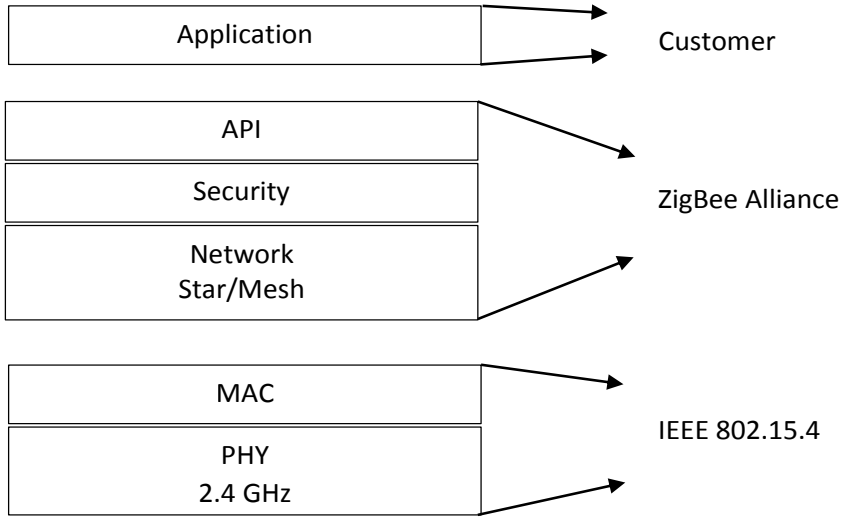


Figure 2.6: The ZigBee network architecture [35]

The ZigBee protocol is comprised of a coordinator, router and an end node. All these three types of nodes have individual functions.

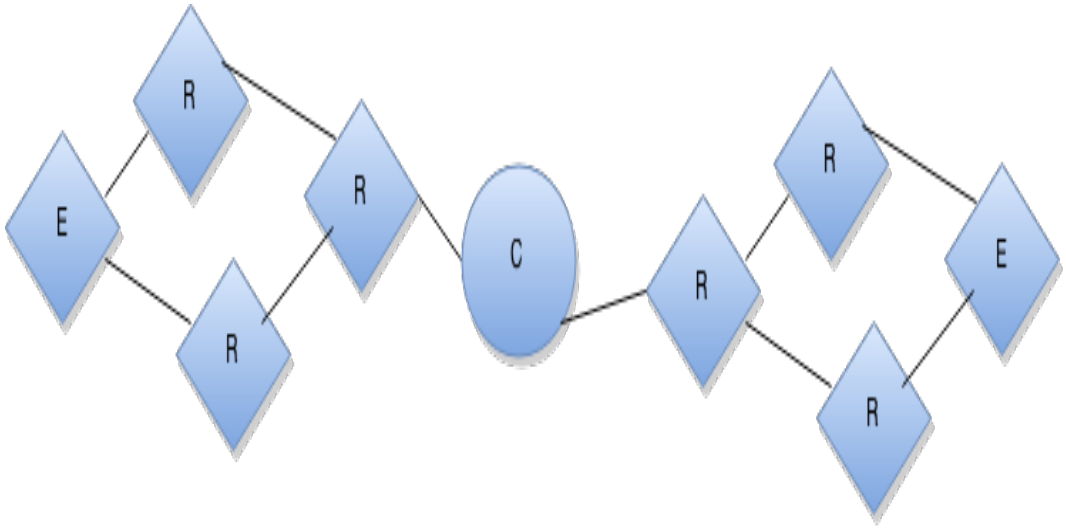


Figure 2.7: The ZigBe network [10]

The coordinator is the prime type of node in the network, with the ability to store information and keys. Its main function is to manage the network; each network requires only one coordinator. The router acts as an intermediate node in the pathway of data transmis-

sion. The end device communicates with the parent devices, like router and coordinator, and it is unable to relay data from other devices. It is low powered and low cost equipment.

2.12 DigiMesh Network

DigiMesh is a homogenous network of sensor nodes which are battery powered, interchangeable and capable of acting as a router. The DigiMesh offers the advantage of simple, reliable and flexible networking. At the same time, it supports easy expansion of a network and convenient replacement of the acting routers when they are damaged [10].

To minimize power requirements, a node is allowed to sleep when its functioning is not required. In ZigBee network, only the end devices are permitted to sleep, whereas the introduction of DigiMesh allows all the nodes to sleep. Therefore, the DigiMesh is more power effective as compared to the ZigBee.

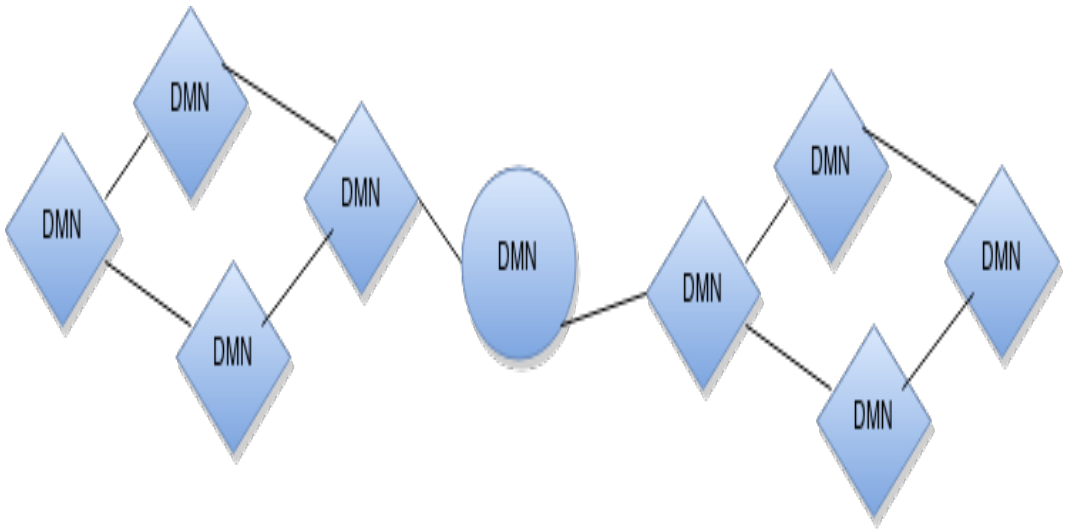


Figure 2.8: The DigiMesh network [10]

Chapter 3

Related Contributions and Motivation

This chapter provides the objective and motivation behind this research. There are a number of research studies going on in the field of security of WSN. However, some of the important research, which acts as the motivation and guidance behind my thesis is described in the following section.

According to Lian *et al.* [33], the ZigBee network is noise free which has allowed ZigBee to be established as the best wireless network technology for low power consumping applications. It is one of the reasons for an increase research in the field of WSN based on ZigBee technology. In this field the researchers use two approaches towards research: one is simulation and the other is practical implementation. During practical implementation, researchers use different sensor nodes to test their results. In previous studies [17] [40] [20], the authors showed and compared their work on TelosB and MICAz sensor motes. A sensor mote can be defined as a sensor node capable of processing and gathering sensor information. TelosB and MICAz are very popular sensor motes for deploying WSN. However, they lack the reconfigurability property.

Lian *et al.* [33] did their experiment on Arduino to deploy hand written word based authentication for ZigBee. They presented a novel idea which incorporates ZigBee and Wi-Fi to overcome the shortcomings of existing network technology. In their research, they did not highlight security measures and the scrawled signature possessed some difficulties in the verification of indentity. Baraka *et al.* [16] proposed a framework to remotely control a home automation system. They used Arduino as a hardware to implement the design. They

claimed their design was cost effective as well as energy efficient. A study of sensor cloud system is outlined by Chandra *et al.* [19]. They also showed inclusion of an Arduino based sensor network to read the cloud data. However, security consideration was absent in these two frameworks [16] [19]. An experiment was done on Arduino [14] to test the outcome of cryptographic function hash MD5 on an 8 bit microcontroller with 100% accuracy. Another experiment was done on Arduino [13] to test public key cryptography RSA. Qasem *et al.* [13] proposed and designed a microcontroller based RSA. They tested their design with 32 bit key size. Both these works [14] [13] implemented the algorithm on hardware. However, they did not deal with real life data. In this section, it is observed that not many real life implementations of WSN are done with Arduino.

The next section focuses on the security deployed in a WSN, and the problems and threats associated with the existing proposals. During the time of deploying expensive security measures, the fact of resource-constrained nodes demands consideration.

RSA and elliptic curve cryptography are widely used in public key cryptography. According to some researchers, due to the limitations of the sensor nodes, these two techniques may place a heavy burden on the network. In spite of this, Gura *et al.* [25] and Watro *et al.* [48] tested public key cryptography in resource constrained WSN. Gura *et al.* [25] depicted that, when ECC and RSA are compared they both are capable of working on an 8 bit CPU. However, the performance of ECC was better than RSA when small devices were considered. Watro *et al.* [48] suggested TinyPK, a public key cryptography for incorporating security in WSN. This approach tested one MICA2 sensor node in the TinyOS environment. The authentication and key agreement between two sensor networks is permitted in this protocol without allowing any rekeying among the nodes.

Minisec [36] was implemented on a Telos mote platform. It provides high level security while consuming less energy. An encryption key is stored in the sensor node in Minisec but the actual technique for this has not yet been revealed. There is still an opportunity to upgrade Minisec by improving the key management strategy.

Karlof *et al.* [31] implemented an efficient link layer encryption protocol for WSN called TinySec which is less energy and memory consuming. In this design a network key was loaded before the network formation. One of the major drawbacks is, it does not prevent reply attacks. They mentioned in their design that adding a counter to monitor data packets might impose heavy burden on the sensor nodes memory. Therefore, they did not include reply attack prevention in their design.

Liu *et al.* [34] presented a faster and more energy efficient public key cryptography algorithm for WSN, named TinyECC, but some factors concerned with the patent have limited its use.

SPINS [38], was developed by Perrig *et al.* which is a combination of two protocols, SNEP and Tesla. A master key shared with the base station is the mainstay of security in this protocol. Nevertheless, by compromising that master key, the intruders could decrypt all information.

Though public key cryptography is an option for network security, it is costlier to implement. In a study [47], Wang *et al.* studied and found that this public key cryptography takes longer time to perform encryption and decryption which opens the door for the attackers to execute denial of service attacks on the node. Furthermore, they discovered that this technique consumes more energy in providing effective security. On the other hand, they tested the symmetric cryptography algorithm on an Atmel ATmega128 processor and revealed that this algorithm is much faster and more energy efficient when compared to the public key algorithm. They also mentioned that, although symmetric key cryptography is preferable to public key cryptography, it also has some limitations. There is no methodical key changing option in practice which invites more research on flexible rekeying methods. Herrera *et al.* [26] pointed out a vital limitation of symmetric key based cryptography; they said a single node tampering in symmetric key design becomes a threat to the whole network. As a result, all master keys need to be pre installed in the sensor nodes again.

Nilsson *et al.* [37] presented asymmetric key management for the wireless process con-

trol environment. In their design, they proposed a key changing methodology of sensor nodes after a certain period of time. Their main intention was to design and verify the framework. They did not address the resource constraints of the sensor node and their design was not practically implemented. Their encryption and decryption technique operated via five symmetric and one public key. This results in adding many computational overheads like memory and communication. Establishing rekeying in this protocol requires three messages.

Hu *et al.* [27] designed and implemented a sensor node which incorporates a RSA public key and an XTEA symmetric key. They analyzed the performance in terms of computation time, memory size, energy and cost. Nevertheless, the procedure of forming the rekeying key was not highlighted. In addition, the total computational time and energy requirement is significantly high.

Herrera *et al.* [26] published a paper which focused on key distribution in WSN. They designed and implemented symmetric key distribution among sensor nodes using public key cryptography. Additionally, they did not store the master key in the sensor nodes before network establishment. They claimed their design as energy efficient as well as scalable. They showed the result of their architecture in terms of execution time and energy. Generation of a new key involves six steps which are quite expensive for resource constrained WSN. Their design also sends the new key over the network which is prone to attack by the eavesdroppers. They did not mention any protection against attacks on WSN.

In this section, the research based on ZigBee protocol using Arduino and XBee incorporating symmetric key cryptography is reviewed. Pu and Chung [41] proposed a group of key update methods for RC4 use in WSN, and implemented in Telos platform. Aziz *et al.* [15] presented a wireless system using XBee to monitor and process the temperature and humidity data a in tissue culture laboratory, but did not mention the security services in their proposal. Kukkurainen *et al.* [32] depicted message encryption and message authentication code based on the RC5 block cipher in a KILAVI sensor network platform.

KILAVI is an open platform for deploying low data rate and low power consuming applications [32]. Dickerson *et al.* [21] proposed an RC4 based encrypted sensor network and tested it in Mica2 network sensors with an Atmega128 microcontroller. They also compared the performance between RC4 and RC5. Hyncica *et al.* [28] tested the XBee performance in a small office environment and presented some important features related to XBee communication.

All of the above mentioned research is centred on choosing the appropriate sensor device and imposing security in the network. After analyzing the background research it can be concluded that symmetric key cryptography is more suitable for WSN than public key cryptography because the provision for changing the keys makes it more robust. In previous research [26], [37], [27], the authors described rekeying procedure in WSN. In my design, the shortcomings of the previously stated rekeying methods are mitigated. According to Nilsson *et al.* [37], five cryptographic keys were required to accomplish their design, whereas in my design only two cryptographic keys are used to confer the network security. Hu *et al.* [27] practically implemented their framework but did not discuss the formation of a new key. In my proposed architecture a 40 bytes long new key is generated using hash functions. Herrera *et al.* [26] used six steps to create a new key which is sent over the network by the sensor nodes and receiver. On the other hand, the proposed design needs only two steps for building a new key and there is no need to send the keys over the network. All three of the above mentioned studies only portrayed key distribution mechanisms without shedding any light on data sending procedure. My proposed framework shows key distribution, as well as data sending, which ensures data authentication and integrity with its real life implementation.

Chapter 4

Proposed Framework Design

This chapter highlights the details of my proposed framework design. It also includes how my design achieved security features and prevented attacks.

In this thesis, I have proposed a new rekeying based security protocol for WSN. This scheme provides confidentiality and authentication of sensor data. The notations used in this protocol are described in Table 4.1.

Table 4.1: Notation used in rekeying framework

Symbol	Description
N_1,N_2.....N_n	Sensor Nodes
R	Receiver/Base Station
T_{op}	One time password based on system time
M_k	Initial Symmetric key between receiver and sensor nodes
N_{Mk}	Unique new symmetric key for every sensor shared with receiver
E_k( )	Encryption operation executed by the sensor nodes
D_k( )	Decryption operation executed by the receiver
Hash( )	Operation to create new key
H ( )	Generate HMAC for data verification

The framework for rekeying is shown in Figure 4.1.

At the time of initiation, the sensor nodes are loaded with the initial master key and the receiver also possesses the same key. Rekeying can be instituted in the nodes periodically.

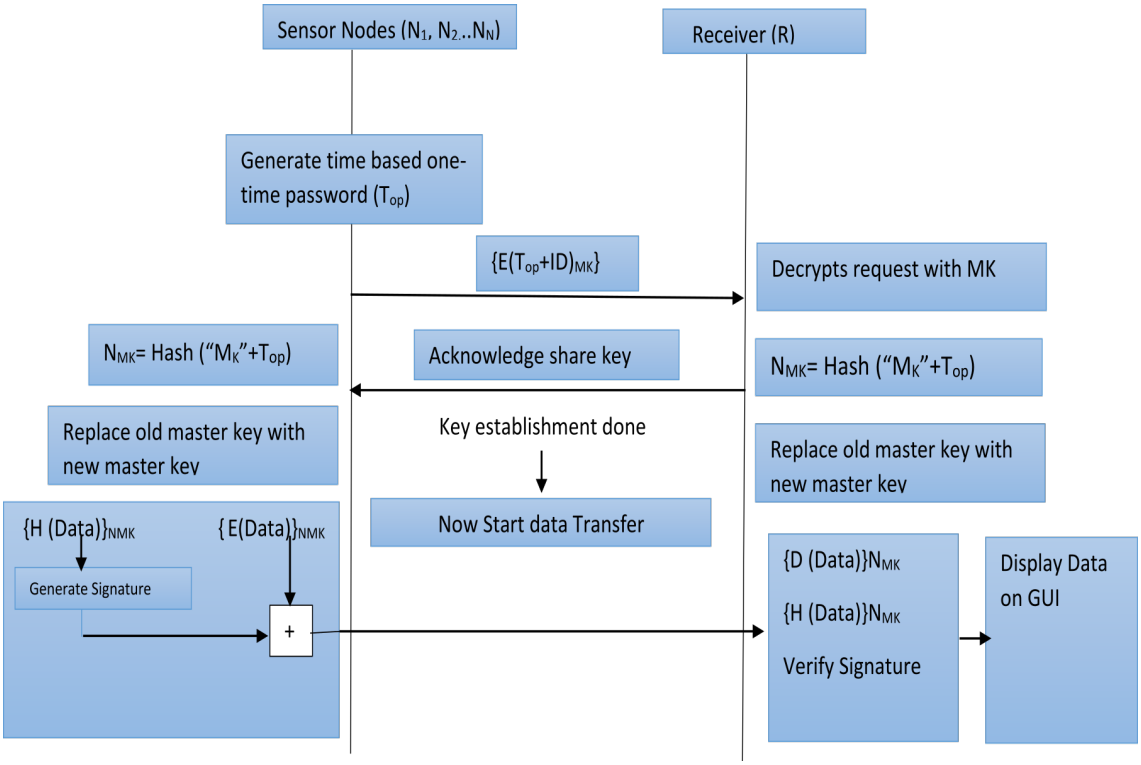


Figure 4.1: Rekeying and data transfer between sensor node and receiver

Each node containes a software based real time clock (RTC) to generate a one time password. To protect against reply attacks, each and every rekeying initiation is accompanied with this one-time password. This password is a randomly generated number depending upon the real time clock of that particular system. Here F () is a function which takes the system time as input and produces a one time password as output.

One time password (Top) = F (system-time)

The system time is based on the current date and time, so the password changes after using it once. As previously mentioned, this one time password protects against reply attacks as well as forfends an attacker to reply to old messages which is a fundamental requirement for the rekeying operation in proposed framework.

This unique password is encrypted with an initial master key and is sent to the receiver along with a signature. This signature is a hash message authentication code (HMAC). The receiver decrypts the password, retrieves that exclusive password and verifies the signature.

To perform the encryption operation, stream cipher based encryption RC4 is used. The new master key is formed in both the sensor nodes and in the receiver using a one way hash function from the initial master key and the one-time password. Following this, the receiver acknowledges to the sensor nodes that a new master key has been created. To address the requirement of not reusing a key more than once, each produced key is distinct. The new master key is the product of a hash function h ( ) based on SHA-1. The new master key is 40 bytes long. It is produced using the following formula:

$$New\ master\ key\ NMK = h\ (Top \parallel MK)$$

When the new master key is generated, the sensor nodes encrypt sensor data using this key and also calculate a signature using a cryptographic hash. The encrypted data and signature are then transmitted to the receiver side.

As soon as the receiver receives the encrypted data and signature, it uses the new master key to decrypt the sensor data and this is followed by the formation of a signature. The new signature is compared with the received signature and verified. Finally, if everything is authenticated, the data is displayed on the monitor. The signature is generated using the following function on both sides. Here HMAC is the message digest of hash function based on the secret key and input.

$$Signature = HMAC_{NMK}(\text{"Sensor Data"})$$

4.1 Security Issues Attained by the Design

My proposed framework achieved the following security issues:

4.1.1 Confidentiality:

In my design, symmetric key cryptography RC4 is used to encrypt a new key generation session as well as during data transmission. As data is encrypted, it is protected from the intruders and confidentiality is ensured.

4.1.2 Data integrity and authenticity:

The data should not be altered or modified during transmission known as data integrity, and to confirm that the data is from a genuine sender is termed data authenticity. The incorporation of HMAC safeguards both data authenticity and integrity. Cryptographic hash SHA-1 is used to produce HMAC to attain both data integrity and authenticity.

4.1.3 Forward and backward secrecy:

When the attackers compromise a current key, they should not gain access to either the preceding messages encrypted with the former keys or the upcoming messages encrypted with the onward keys. These are referred to respectively as backward and forward secrecy. To attain forward and backward secrecy, the use of the same key for a long period of time is avoided. Instead, there is an option for changing that key according to the requirements of the application.

4.2 Attack Prevention

My recommended system prevented the following attacks:

4.2.1 Man in the middle attack:

In the proposed framework, a master key is used at first and later on there is a provision for changing the master key so that the communicated data is encrypted at all times. This approach guarantees that no attackers can interfere in the middle pretending to be an authentic node.

4.2.2 Reply attack:

The system can avoid reply attacks on messages by means of a method generating a unique number capable of detecting identical successive messages. Each and every communication in my designed framework is accompanied by a one-time password. This enables the sender and the receiver to detect and reject replayed messages.

4.2.3 Tampering:

The sensor nodes in the WSN are not fully protected against external attacks. The attacker may compromise a sensor node and steal cryptographic information. This thesis highlights this fact and how to resist spreading attacks over all the sensor nodes. Therefore, the design goal is to protect other nodes if one of the nodes is compromised by the attackers. As rekeying is done periodically and different keys are used for different sensor nodes' communication, compromising a sensor node will not compromise the whole network. As a result, the attackers cannot decrypt information which is intended for the other nodes.

4.2.4 Sybil attack and hello flood attack:

In a Sybil attack, an outsider can act as an internal node. On the other hand, attackers try to authenticate themshelves by broadcasting hello messages. However, the system can prevent both of these attacks because every communication is established using a cryptographic operation and HMAC. This makes it difficult for an outsider to act as an insider. As there is an unique ID in the node, and communication is established using encryption and HMAC, the authentic node does not respond to other hello flood messages.

Chapter 5

Hardware Component

This chapter discusses the hardware which was used in my experiment. This chapter also includes some of the related sensor motes which are available in the market.

5.1 Arduino

A group of single board microcontrollers simplifying the establishment of interactive objects or environment are called Arduino. This hardware is comprised of an open source hardware board containing an 8-bit Atmel AVR microcontroller or a 32-bit Atmel ARM microcontroller. The most up to date models are also equipped with a USB interface including six analogue and fourteen digital pins. The users are allowed to connect the CPU with various interchangeable add on shields by using the property of Arduino being a standard connector. Most of the Arduinos deploy megaAVR series of chips with a 5 volt regulator and a 16 MHz oscillator. Unlike other devices which need an external programmer, the Arduino microcontroller along with the boot loader makes the uploading of programs on chip flash memory easier and convenient [2].

5.2 Arduino Uno

The Arduino Uno refers to a microcontroller board consisting of 14 digital input/output pins, 6 analogue inputs, a 16 MHz ceramic resonator, USB connection, power jack, an ICSP header and a reset button. This board, based upon ATmega328, can work independently when connected to a computer via USB or powered with an AC-to-DC adaptor or a battery.

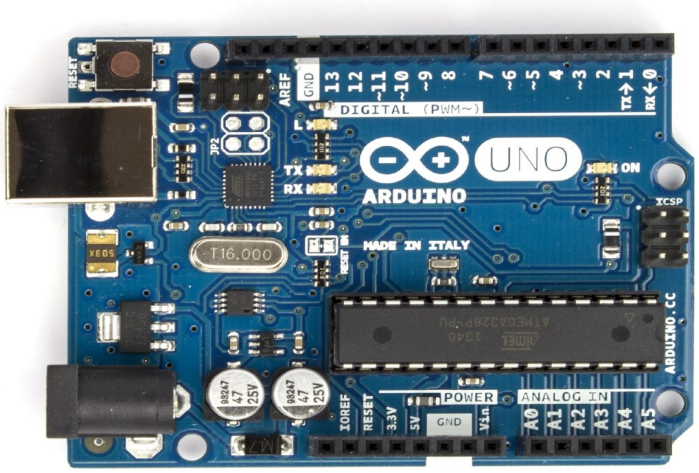


Figure 5.1: Arduino UNO [3]

The board has a power jack which is connected to the adaptor by plugging a 2.1 mm center positive plug or the leads from the battery are attached with the Gnd and Vin pin headers. The major power pins of the board are VIN, 5V, 3V3, GND, IOREF and the optimum power range for proper working is 7 to 12 volts. The ATmega328 has a memory capacity of 32 KB with 2 KB SRAM and 1 KB EEPROM.

Each of the 14 digital pins in the Uno functions at 5 volts, can provide or receive a maximum of 50 mA, has an internal resistance of 20-50 kOhms and is capable of working as both input or output by utilizing pinMode, digitalWrite, and digitalRead functions. However, some pins can uniquely act as Serial, External Interrupts, PWM, SPI, LED, TWI, AREF or reset. The Arduino Uno has an excellent communication facility for connecting with computers, other Arduinos or microcontrollers. The ATmega328 has a provision for serial communication which materialize as a virtual com port to software on the computer. Arduino Uno uses Arduino sketch for programming. The ATmega328 is pre equipped with a boot loader for uploading the code without any external hardware or the device can also be programmed through ICSP escaping the boot loader [3].

5.3 Arduino XBee Shield

The XBee shield, based on the XBee module from Maxstream and constructed in association with Libelium, is a device through which the Arduino board can communicate wirelessly using ZigBee. This has the capability to communicate up to 100 feet indoor or 300 feet outdoor. The XBee shield can be configured for a wide range of broadcast and mesh networking options and also can work in command mode. This device has the provision for breaking each of XBees pins to a through hole solder pad. It contains analogue inputs covered with the shield and female pin headers for the use of digital pin 2 to 7. It has two small, removable plastic sleeves for fitting onto two of the three pins labeled XBee/ USB, which are known as jumpers. The serial communication between the XBees microcontroller and FTDI USB-to-serial chip on Arduino board is ascertained by these jumpers [4].

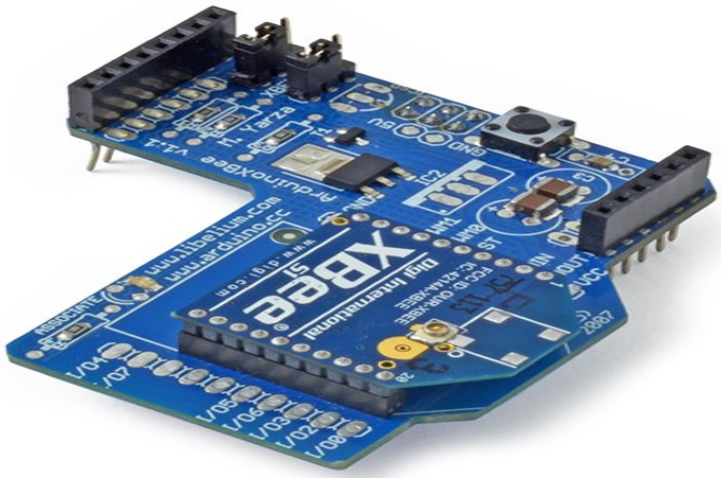


Figure 5.2: Arduino XBee Shield [4]

5.4 XBee

XBee is a group of radio modules from Digi International. It was introduced in 2005 and is based on point-to-point and star communications. The working requirements of the XBee radios are power, data in and data out, sleep and reset mode. Programmable XBee,

Figure 5.3: XBee [11]

which is a special version, also has a built in onboard processor for the users. XBee radios are capable of supporting a huge range of radio frequencies like 2.4 GHz or 902 - 928 MHz or 865 - 868 MHz. The XBee radios are available in two hardware footprints: through hole with 20 pin sockets and 37 pads surface mount.

The latter is compatible with both high and low volume deployments and is also cost-effective. The XBee is effective at working in both transparent data mode and application programming interface mode. Data received in the DIN pin is broadcasted to the receiver radio unmodified in transparent data mode, whereas in API mode the data is wrapped into packets for addressing, parameter setting and delivery feedback. XBee modules are appropriate for a variety of network architectures including ZigBee, 802.15.4, and Wi-Fi. Digimesh, a protocol from Digi has decreased the complexity of ZigBee protocol remarkably [11].

5.5 XBee Explorer USB

This is a serial based unit for the XBee line which is convenient to use with all XBee modules and supports Wi-Fi bee and Bluetooth bee. When the unit is plugged into the XBee explorer and attached to a mini USB cable, it is possible to gain access to serial

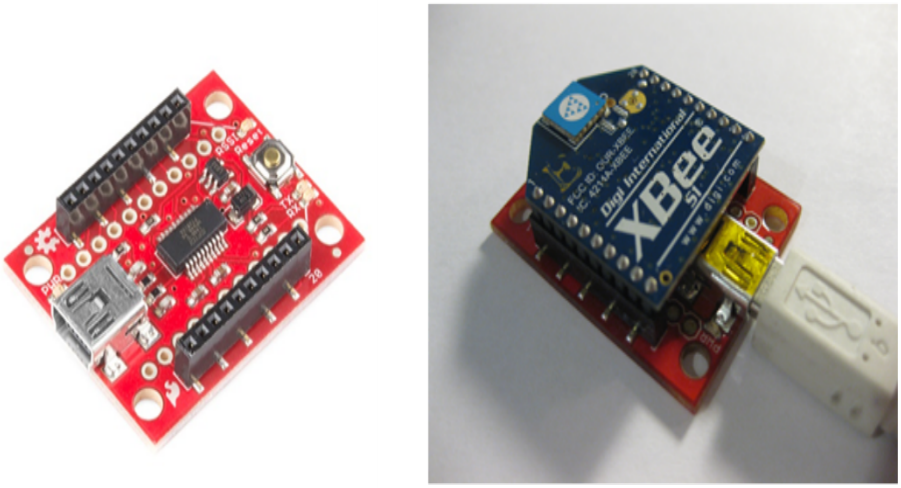


Figure 5.4: XBee with explorer [12]

and programming pins of XBee unit. This board is configured with an FT231X USB to serial converter for translating data between the computer and the XBee, a reset button and a voltage regulator to supply ample power. The device is also equipped with four LED indicators for pointing out the power status, data transmission or receiving, signal strength of data reception and association. These LED indicators are named as received signal strength indicator (RSSI), Power (PWR), Transmitting (TXD), Receiving (RXD). The use of a USB adaptor board for the XBee wireless module allows effective communication between PC to PC or PC to robot and can modify the configuration of an XBee device using PC through XCTU software. Moreover, the device can act as Communication Device Class of USB family and gives the opportunity to use the USB port as a normal serial port. The board can divide each of the XBees I/O pins to a pair of breadboard compatible headers allowing efficient use of the wide functionality of XBee [12].

5.6 Temperature Sensor TMP36

The TMP36 is a precision centigrade temperature sensor which is low voltage and the voltage output is linearly proportional to the celcius temperature. It is user friendly and does not require any external calibration for its accuracy. The voltage input for this sensor

is typically 2.7 to 5.5 VDC and the output voltage can be converted to temperature by using the scale factor of 10 mV/°C. The functioning range for this sensor is -40°C to + 125°C with an accuracy of 2°C over temperature and 0.5°C linearity [7].

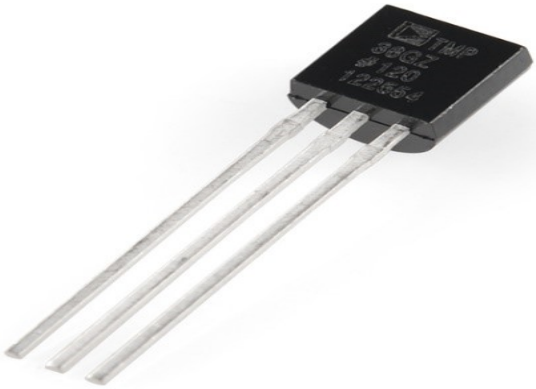


Figure 5.5: Temperature sensor [7]

5.7 Related Sensor Motes

5.7.1 TelosB:

The University of California at Berkley first introduces TelosB for performing research work in sensor network. This equipment consists of 16 bit, 8MHz TI MSP430 microcontroller with 10kB RAM, 48 KB flash memory and 16 KB EEPROM. It has built in sensors like light, temperature or humidity sensors. The indoor range for TelosB is 20 to 30 m whereas the outdoor range is 75 to 100 m with the data rate of 250 kbps [46].

Figure 5.6: TelosB mote [46]

5.7.2 MicaZ:

MicaZ is based on 802.15.4 protocol consisting of microcontroller ATMEL ATMega 128L. The data rate for this device is 250 kbps [5].

Figure 5.7: MicaZ mote [5]

5.7.3 Waspmote:

Waspmote is a product of Libillium having microcontroller ATmega1281 and EEPROM 4 KB. The power requirement is around 0.7uA during the phase of hibernation [8].

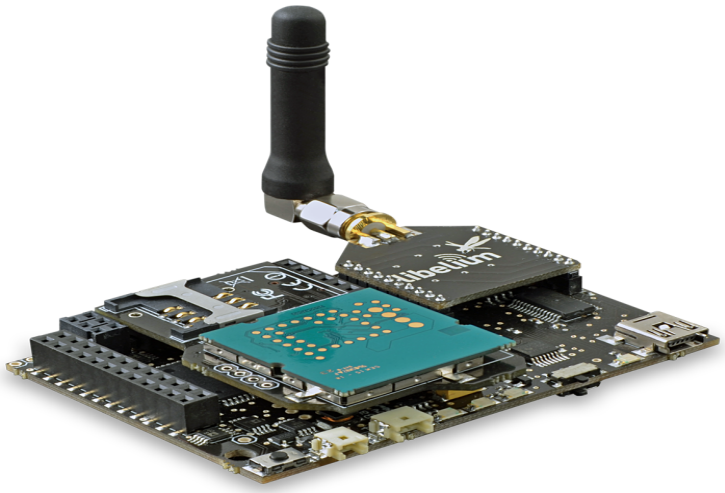


Figure 5.8: Waspmote senor node [8]

5.7.4 Shimmer:

Shimmer is a sensor node which is principally built for the wireless body sensor network, whose main utilization is in the health sector. An important property of shimmer is that it can use Wi-Fi and Bluetooth simultaneously [6].

Chapter 6

Implementation of the Proposed Framework

This chapter will discuss the implementation of my proposed framework. My description covers all the small details of system architecture processing and implementation. This chapter focuses on circuit set up, hardware configuration, program implementation and communication in a stepwise approach.

6.1 Architecture of the System

6.1.1 Circuit and Wiring:

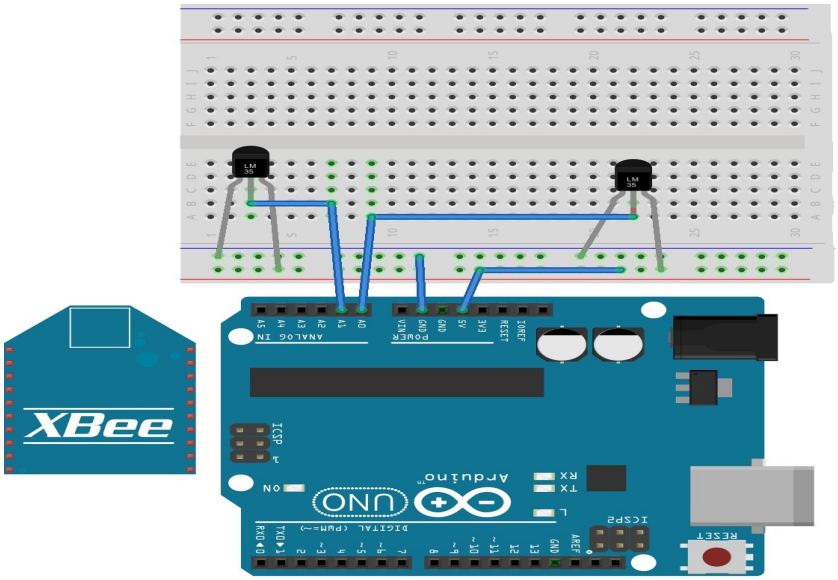


Figure 6.1: Circuit wiring of Arduino, Breadboard and Sensor

In my design, four sensor nodes equipped with temperature sensor were used to act as the sender while a laptop was used as receiver to accomplish the task. On the receiver end, an XBee was attached to the XBee shield connected with the COM port of a laptop. The sensor node was composed of Arduino, Arduino XBee shield, XBee, breadboard and temperature sensors. Wiring was used to connect the Arduino node with the sensors. The wiring and circuit design is depicted in Figure 6.1.

6.2 System Programming Phase

6.2.1 Communication establishment:

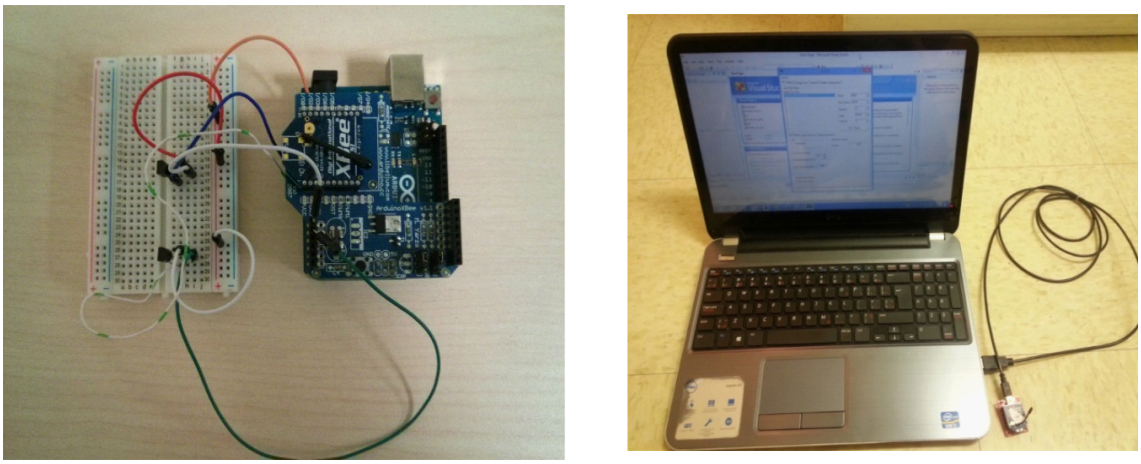


Figure 6.2: Working sensor node and receiver end

The communication started with using the XBee in the proposed design architecture. In the beginning of the experiment communication was made between two sensor nodes. One of the key requirements for this step was to configure the XBee to communicate in the ZigBee network. I used X-CTU software to configure the XBee. During the experiment, all XBee were configured with the addresses along with PAN ID and baud rate. The PAN ID and baud rate should be the same to make a communication in an XBee based ZigBee network. Subsequently, the XBee was attached in the XBee Arduino shield. After that, a program was written in a Arduino Sketch to transmit sample data between nodes. As the two sensor nodes had the addresses and were in the same PAN, successful communication

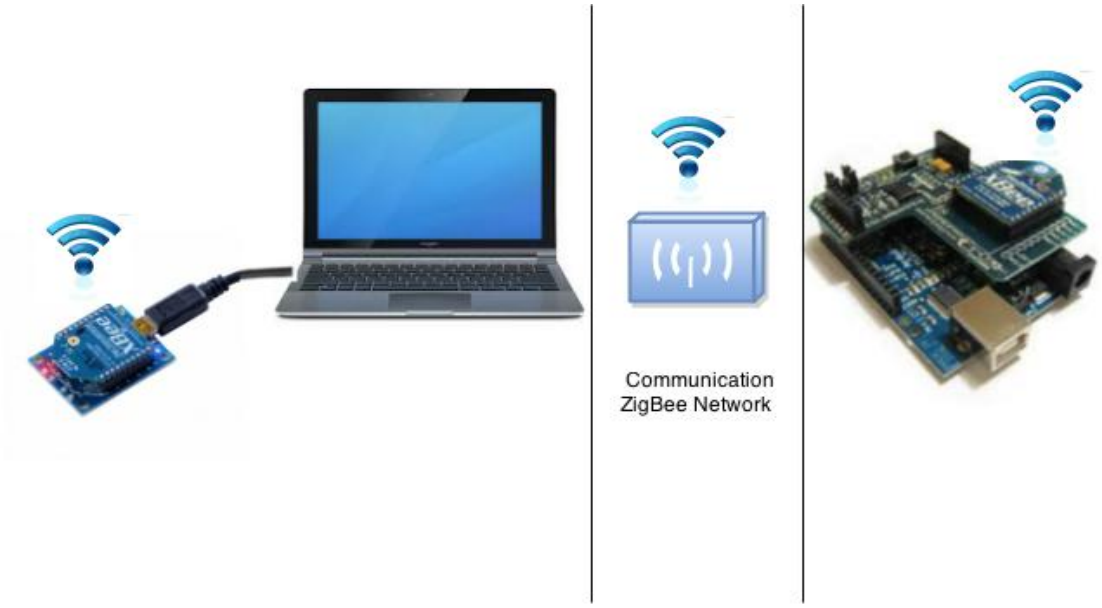


Figure 6.3: Simple communication between the sender and the receiver

establishment was achieved between the nodes.

The next step was to make a communication between the sensor nodes and the receiver which was a laptop. Here, both XBee were configured according to the needs of the system. As XBee was connected in the COM port of the laptop, a program was written to read the COM port data and processed it accordingly with addresses to identify the sensor nodes and data. During the time of the experiment, the program was set to read incoming bytes and was designed to read appropriate bytes received on the XBee receiver node. The whole program was written in Java to read and process COM port data. Consequently, the design was verified with different sample data and parameters to check the stability of the network. The significant finding of this phase lay within data reading from the COM port. Several problems were encountered in reading the data at the receiver end and few data were lost during reading. However, this problem was solved by introducing the byte counts in the program.

6.2.2 Replacing the old key and rekeying:

At the time of deployment, the sensor nodes and the receiver were loaded with a fixed key. At the initial phase the sensor nodes changed the predefined key. To change the key, a program was written and uploaded. The program was based on RTC (real time clock), which generated a one-time password. This password is a truly random construct from real time. Even after every second, the program generates a different password. Consequently, this password was encrypted with an RC4 symmetric key encryption which was written in Arduino Sketch, and it produced a ciphertext in Hexadecimal format. The initial key was used to complete the operation and SHA-1 was used to generate a signature. The ciphertext and signature were transmitted over the network. The receiver received the ciphertext and signature, extracted the address of the sender and started processing on the receiver side.

A Java based program was written on the receiver side which decrypted the ciphertext and verified the signature. The receiver also used the initial predefined key to decrypt the ciphertext. Therefore, the receiver along with the sensor nodes were using cryptographic hash SHA-1 to produce new keys based on the same one-time password. This new key was 40 bytes long. Both the sender and the receiver replaced their initial key with the new 40 bytes key. Finally, the receiver acknowledged to the sensor nodes that a rekey had been formed. This key was used for further communication until the formation of a new key. The fundamental goal of this phase was to create a new key. I surveyed to choose the method for forming a new key. Finally, cryptographic hash function was picked to create the new key. The main reason behind choosing hash function is the one-way property of the hash function. On the receiver side and the sender side the same program was written which produced a new key. The synchronization between the nodes was also accomplished. When the sensor nodes began to operate, every node changed its key using the proposed framework. Thus, the receiver has different symmetric keys for communication with different nodes which made it very hard for the eavesdroppers to break the security of the network. For larger networks, the use of database to store different keys for different nodes

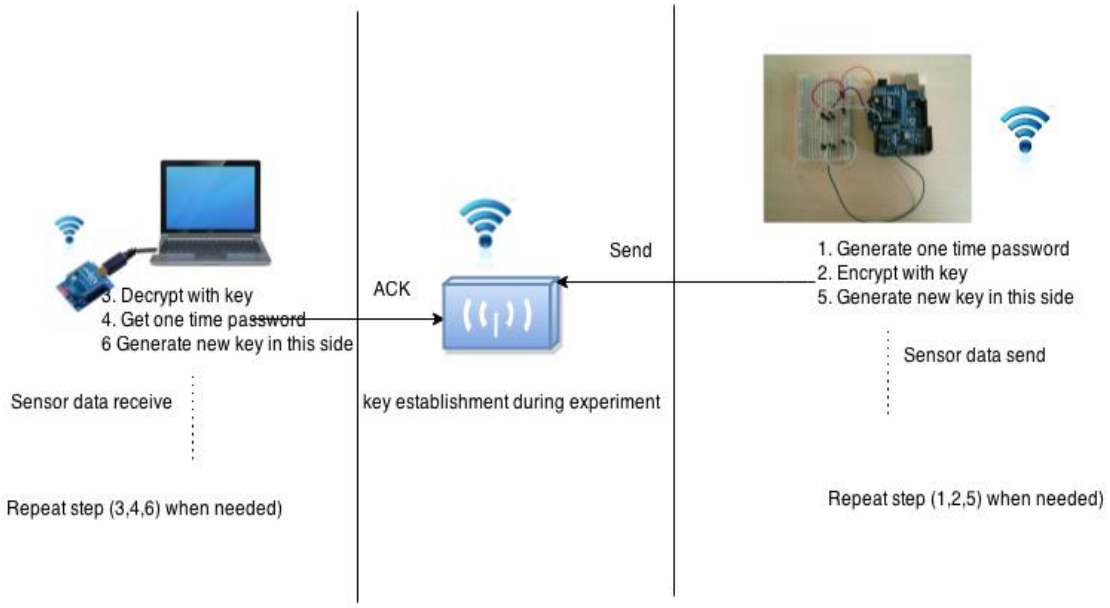


Figure 6.4: Key establishment during experiment

is appropriate. The simplified version of this phase is portrayed in the Figure 6.4.

6.2.3 Data transfer between the sensor nodes and the receiver:

After changing the pre-installed key, the sensor nodes began to transmit data with the new key. A program was written in the sensor nodes to read sensor data continuously. Encryption algorithm RC4 and hash algorithm SHA-1 were executed in Arduino for encryption as well as signature generation. Next, the data was encrypted with the new key using RC4 encryption which produced a ciphertext. At the same time, hash function SHA-1 was used to produce a signature of 20 bytes. The SHA-1 produces a 20 bytes signature irrespective of the data size. Afterwards, the ciphertext, (for example, *B3, CE*) was transmitted along with a hash value, like *4d134bc072212ace2df385dae143139da74ec0ef*, over the ZigBee network. Each ciphertext separated itself using a comma, and each hash value separated itself using new line.

The receiver station received the ciphertext and signature and it split the ciphertext and hash value in the early stage. Then, it processed both ciphertext and hash value on the receiver side using the program. On the receiver side the RC4 program decrypted the

received ciphertext, for example *B3, CE*, using the same new key shared between the sender and the receiver. For instance, the receiver got *24* as an output after decryption. Then, the receiver forwarded *24* to the SHA-1 function. The SHA-1 function generated the new hash value based on the decrypted value, in this case *24*. The new hash value was then compared with the received hash value to check the authenticity and integrity of the received messages. After verifying, the value was displayed or stored for further processing.

During the data transmission phase, the sensor nodes might change their keys. So, the request was initiated from the sensor nodes and the same steps for key generation were repeated until the keys were replaced with the latest key.

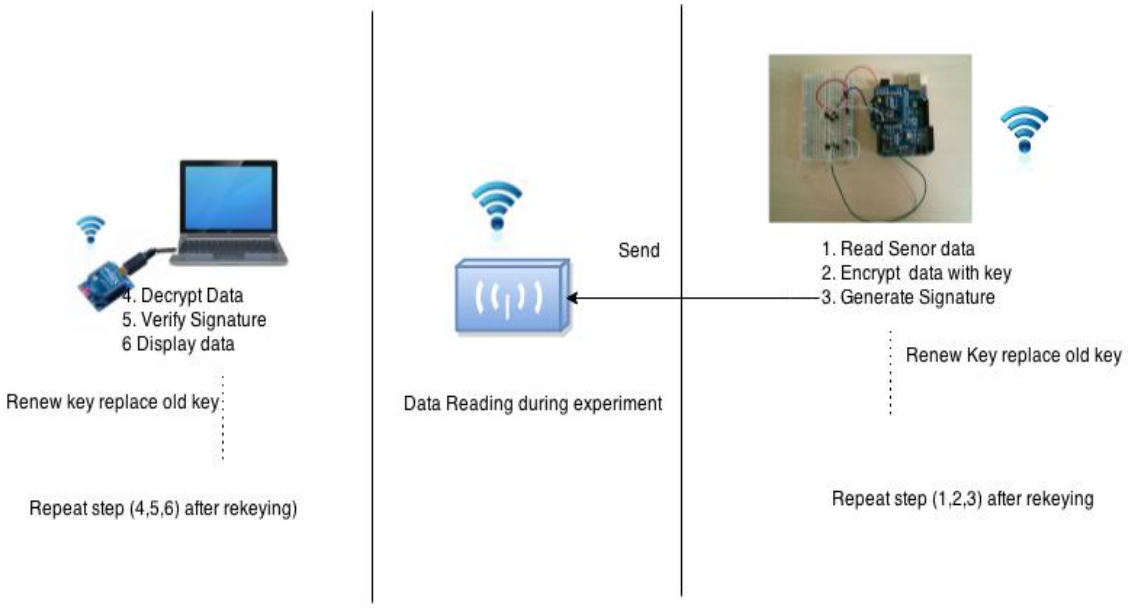


Figure 6.5: Data transfer between the sender and the receiver

At this stage, it was difficult to separate each and every ciphertext, as well as the hash values. When the ciphertext was sent, it was received in the COM port as an individual value instead of the original ciphertext. For example, if the original ciphertext was *CE*, the COM port would receive it as the individual value *C*, and individual value *E*. Then individual values were combined to extract the original ciphertext. Furthermore, identifying each and every ciphertext was challenging as the data was arriving very fast (Example: 100 data in per second). To manage the fast arriving data a code was written. The data transfer stage is

illustrated in Figure 6.5.

6.2.4 Implementing the whole concept in Mesh network:

As XBee Series 1 was used in my experiment, it comes with the facility of an in built firmware DigiMesh. This facility of XBee Series 1 was utilized to build mesh networking in my experiment. The mesh networking protocol is very powerful in terms of flexibility and scalability. It supports multiple points of failure recovery, as well as it is very easy to add more nodes to the network. As there are multiple paths in the network, the chances of losing data were very low.

The work began with configuring XBee Series1 in XCTU. The Digimesh networking comes with the unique network identifier. So, each XBee was configured with a unique network identifier and address. As in the proposed framework, communication was built between the sender and the receiver. Thus, each sender was configured with the destination address of the receiver. If the sender were out of the range of the receiver, the intermediate node would act as a router to forward data to the appropriate destination.

After successful configuration of XBee Series 1, the proposed framework was tested both in closed and open environments. In the closed environment it was hard to understand the working capability of mesh networking. Therefore, I chose an open environment to test the framework. For testing purposes, a sensor node was placed far from the receiver and was checked in the graphical monitor that whether it received any data from a remote node. The remote node was situated out of the range of the receiver node. To test the DigiMesh functionality, another sensor node was placed in between the remote node and the receiver. At this time, the middle node was acting as a router between the remote node and the receiver. In the meantime, the middle node also sent data to the receiver. After that, two more nodes were added which were distant from each other. Then, the functionality of the network was checked again. The Mesh networking protocol is portrayed in Figure 6.6.

At the time of deploying the sensor nodes, problems arose regarding sending data by

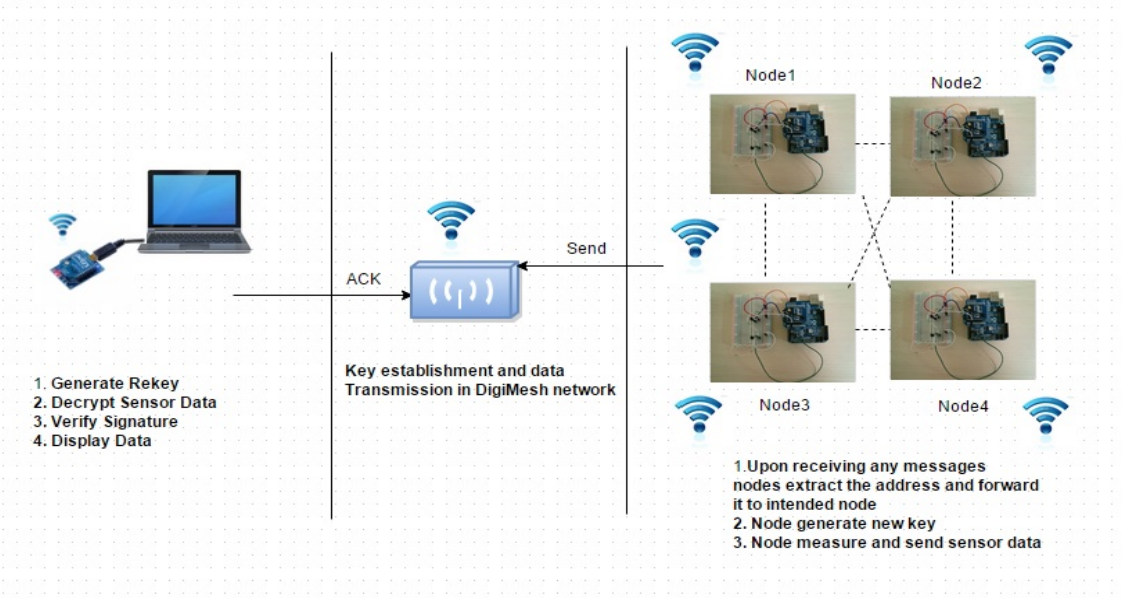


Figure 6.6: The whole concept in Digimesh

the sensor nodes. In the early stage of deployment, few data were coming to the receiver from the selected node and few data were missing. There were two reasons behind this. One was the obstacles in the route between the sender and the receiver. The other one was the synchronization. It was observed that, if all the nodes start sending data at the same time resulting in collision, it may lead to loss of data. In the Arduino Sketch, there is a functionality of *delay ( )* which was properly maintained in all of the sensor nodes. This ensured collision free travel towards the network and, thus, confirmed stability and synchronization of the network.

6.2.5 Graphical user interface on the receiver side:

Figure 6.7 is the working graphical user interface to monitor nodes. For better depiction and understanding of GUI, a sample model with two nodes are represented and described. In this figure, GUI is divided into four parts.

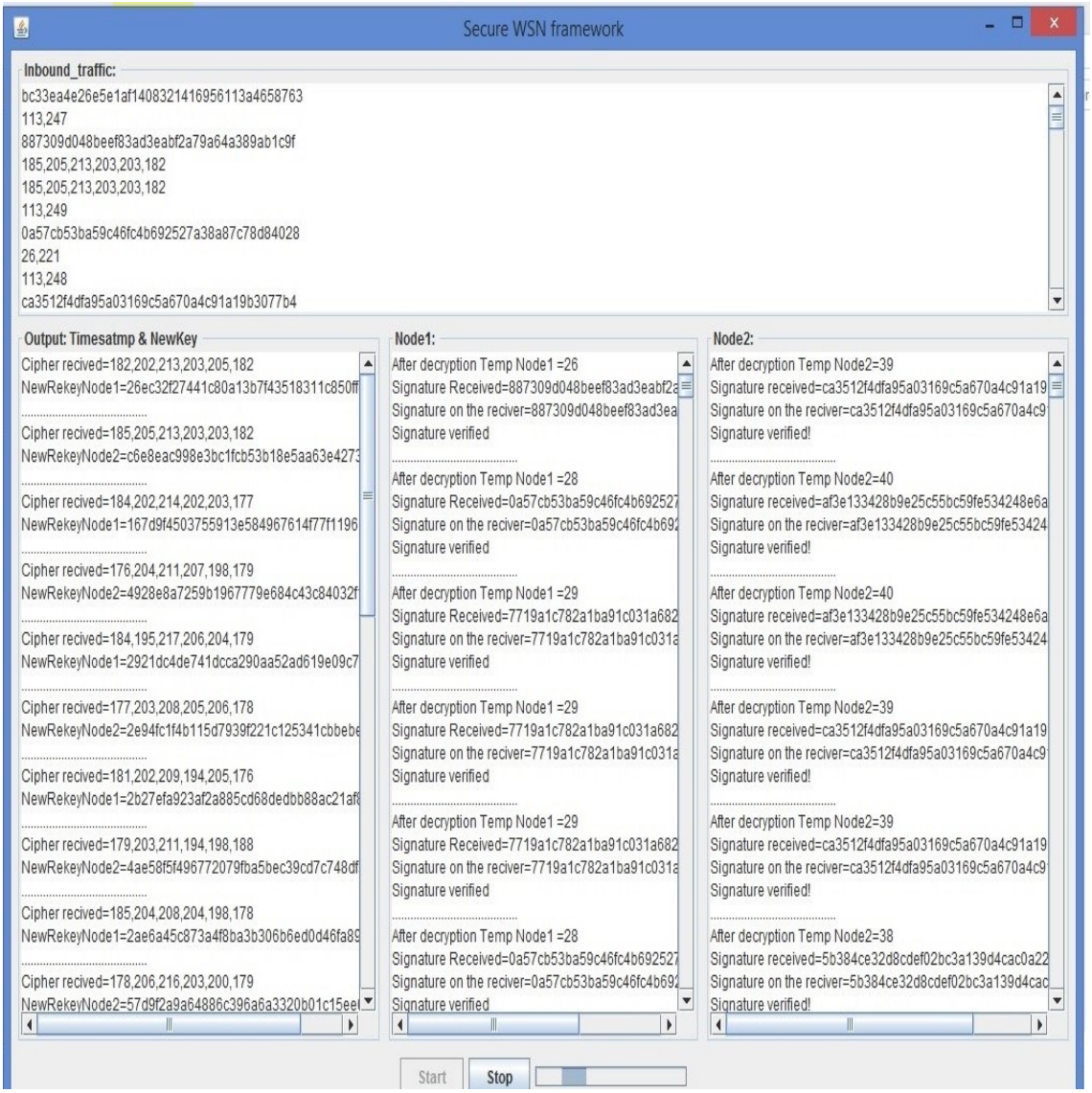


Figure 6.7: The working graphical user interface

The upper part shows inbound traffic; all the traffic which was received in the receiver end is shown in this portion. The lower left hand portion displays ciphers related to key changes. That portion illustrates different ciphers received for different nodes. One important thing to note is that a unique cipher was always received. The sender sent a one-time random password which is reflected in the GUI. This side also shows that, after decryption and processing, a new key was generated that is also unique for each node communication. The 40 bytes long key was displayed and used for further processing. The middle portion

and the right portion are almost identical. However, they are showing different data. At the beginning, it decrypted temperature which is shown to be 26. The signature was generated and verified based on temperature in these cases, and is shown in the GUI.

Chapter 7

Testing and Evaluation

In this chapter, the performance of my proposed framework is demonstrated in terms of execution time, power, energy, latency and throughput. Every detail of the testing phase and experiment was considered. I tested the performance of encryption and cryptographic hash algorithm on my proposed architecture. This chapter also compares my testing outcomes with previously conducted research.

7.1 Execution Time

In the testing phase the execution time was divided into two parts. One portion dealt with the time taken by the sensor nodes and the second portion was the time consumed by the receiver. Code was written, both on the sender and the receiver side, to measure the execution time. In the sensor node, the Arduino UNO was loaded with a program which measured the time consumption for each operation. The clock was started before the operation, which recorded the starting time, while the clock was stopped after operation, which recorded the ending time. After that, the measurement was taken by subtracting the starting time from the ending time. The same procedure was followed on the receiver side. For better performance, the time was calculated in nanoseconds and it was later converted to milliseconds.

The sensor node spent 26 ms to initialize the key, 8.5 ms for encryption, 4.5 ms for signature and 0.5 ms in sensor reading. Therefore, 39.5 ms time in total was needed from sensor reading to cryptographic operation. In contrast, the receiver side needed 2.65 ms

time in total from generation of key to cryptographic operation, which included 0.35 ms for key generation, 1.4 ms for decryption and 0.9 ms for signature. When considering temperature reading, the offered architecture took about 42.15 ms for the sender and receiver portions together. The transmission time for ZigBee DigiMesh varied based on the distance of the node. In the testing phase, the nearest node took around 85-100 millisecond for 8 byes of data, whereas the farthest node took around 120-130ms, which made the total time consumed approximately 120 millisecond for the closest node and 165 millisecond for the farthest node. The computation time in the sensor node is depicted in Table 7.1, followed by a pictorial demonstration in Figure 7.1

Table 7.1: Execution time for a sensor node

Operation	Time (ms)
Key initialization	26
New rekey generation	4
Encryption	8.5
Decryption	8.7
Signature	4.5
Sensor data read	0.5

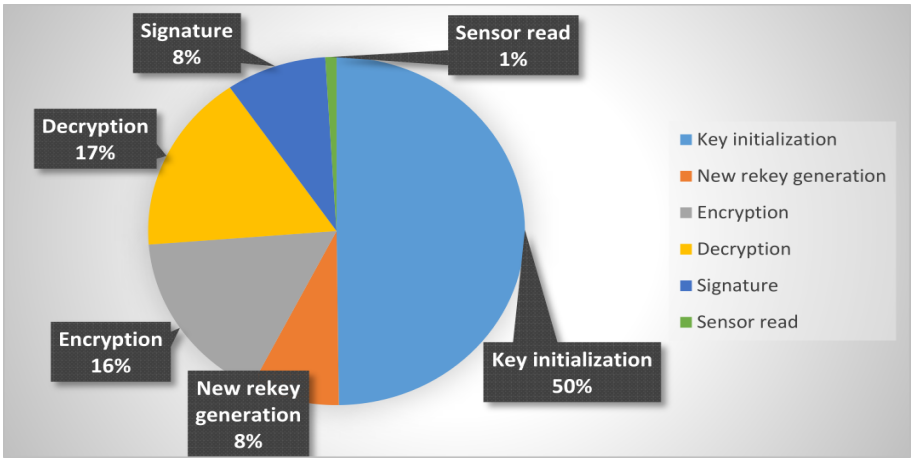


Figure 7.1: Execution time taken by a sensor node

The above figure displays the data of Table 7.1 where the different segments of the pie chart show the execution time for different operations. The major portion of time was for

the key initialization, which was around 50% of the total time followed by decryption and encryption, which consumed around 17% and 16% of the total time respectively. The least time consuming procedure was the sensor reading, which took only 1% of the total time.

7.2 Execution time for variable size of sensor data

7.2.1 Encryption:

The execution time of the encryption algorithm for diverse data size in sensor nodes is plotted in the graph below. This graphical representation, in Figure 7.2, shows that, with the increasing data size, the execution time also increased with the use of encryption algorithm. The data range considered here was 8 to 128 bytes. For 8 and 16 bytes of data, the time requirement increased very little: these required 10.2 ms and 11.64 ms respectively. When the data size was increased from 16 to 32 bytes, the consumed time also increased steeply from 11.64 to 62.48 ms. After that, this increasing pattern remained identical for both 64 and 128 bytes data. The 64 bytes data consumed 179.85 ms, and the 128 bytes data deployed 427.08 ms in the sensor nodes with the encryption algorithm.

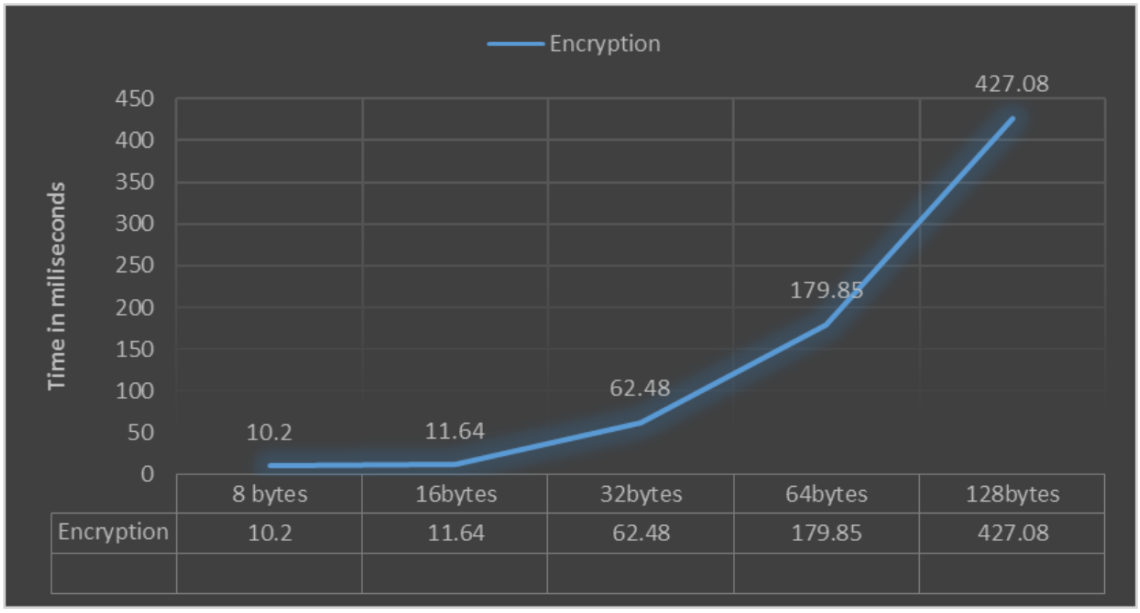


Figure 7.2: Execution time for different sizes of sensor data with encryption

7.2.2 Signature generation:

The linear diagram in Figure 7.3 depicts the execution time for signature generation of a sensor node when dealing with different sizes of data ranging from 8 to 128 bytes. This diagram reflects the hash algorithm effects for signature generation over variable data size. It can be clarified from the figure that, when the data size varied between 8 and 32 bytes, there was almost no change in execution time for signature. From data size of 32 to 128 bytes, there was a steep linear increase of execution time. For 32 bytes of data, the sensor node deployed in 4.15 ms, whereas for 64 bytes, the time reached to 8.18 ms. After 64 bytes to 128 bytes, the pattern of increasing time remained unchanged, and 128 bytes of data needed around 12.316 ms execution time in the sensor node for signature generation.

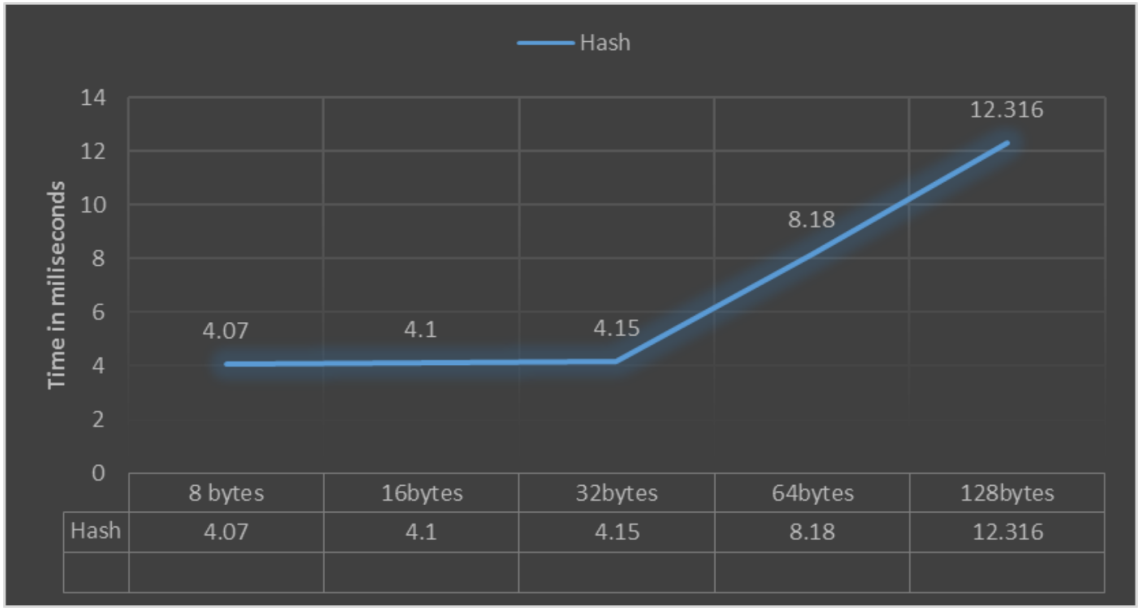


Figure 7.3: Execution time required by different sizes of sensor data for signature generation

7.3 Current consumption

In the proposed design, the current consumption was measured by the multimeter. For example, a code for signature generation was uploaded in Arduino Uno and then the current consumption of this mote was measured using the multimeter. This procedure was

repeated for different operations. A library of the Arduino was used which helped Arduino to consume less current. For sensor node operations the current consumption for diverse functions ranged from 50-57 mA. Different processes needed a variable amount of current which is clearly depicted in the Table 7.2.

Table 7.2: Current consumption by a sensor node

Operation	Current consumption (mA)
Key initialization	57
New rekey generation	56
Encryption	53
Decryption	54
Signature	55
Sensor data read	50

In the experiment, the XBee Series 1 radio was used to transmit data over the DigiMesh network. This radio consumed 50-60 mA of current resulting in a double of the current consumption of the sensor nodes. The total current consumption of a sensor node after introducing the radio is outlined in the Table 7.3.

Table 7.3: Current consumption by a sensor node including radio

Operation	Current consumption (mA)
Key initialization	117
New rekey generation	116
Encryption	113
Decryption	114
Signature	115
Sensor read	110

The information from the table is represented with the help of a pie chart. The segments of the pie chart demonstrate the percentage of the total current consumed by different operations in the sensor nodes after introducing the radio. Figure 7.4 demonstrates that the highest current utilization was for key initialization followed by rekey generation and signature, whereas the sensor reading needed the lowest current. Though there was some

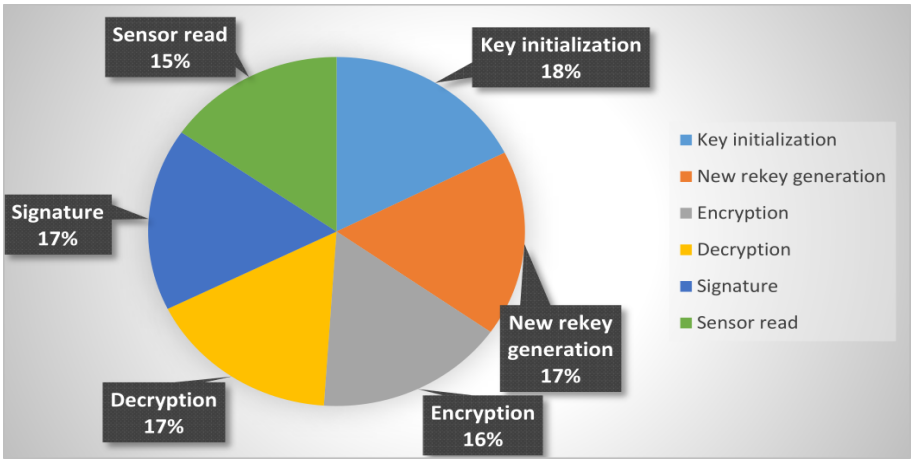


Figure 7.4: Current consumption by a sensor node

difference in current consumption among the different procedures, unlike execution time, the current consumption was almost identical for diverse operations.

7.4 Energy consumption

The energy E in joules (J) is calculated using the following formula [9]

$$E_{(J)} = P_{(W)} \times t_{(s)} \tag{7.1}$$

So the formula can be written as

$$joules = watts \times seconds \tag{7.2}$$

Which is represented as

$$J = W \times s \tag{7.3}$$

$$mJ = J/1000 \tag{7.4}$$

On the other hand, to calculate watts, the following formula is used [1]

$$E_{(Wh)} = Q_{(mAh)} \times V_{(V)}/1000 \tag{7.5}$$

So, the formula can be demonstrated as

$$watt - hours = milliampere - hours \times volts/1000 \tag{7.6}$$

Which is represented as

$$Wh = mAh \times V/1000 \tag{7.7}$$

The energy consumption for different sensor node operations are varied. This information is mentioned in Table 7.4 below, followed by a visual demonstration in the pie chart in Figure 7.5.

Table 7.4: Energy consumption by a sensor node

Operation	Energy (mJ)
Key initialization	15.21
New rekey generation	2.32
Encryption	4.80
Decryption	4.96
Signature	2.59
Sensor data read	0.275

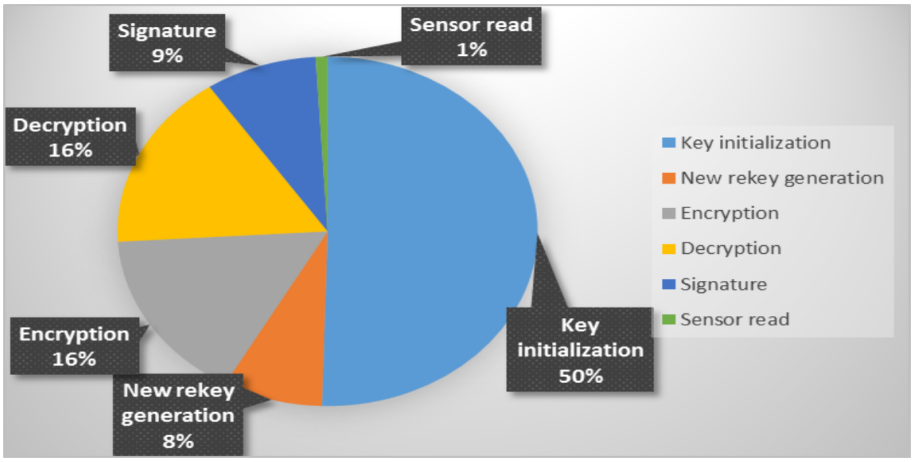


Figure 7.5: Energy consumption by a sensor node

7.5 Introducing power saving on the sensor node

As previously discussed in chapter 2, the nodes in a DigiMesh network can act as sleeping nodes at any time. To save power in the network, the radio was activated when needed to send data over the network. It reduced around 60 mA of current consumption. In a DigiMesh network, the sleeping and awakening cycle of XBee requires special attention. The mechanism consists of both hardware and software part. Pin 9 of the XBee functions as a control pin for the sleep request. To make the radio sleep, the pin is set to a high voltage, and to wake, the pin is set to a low voltage. On the other hand, when considering the programming part, the sleep request is controlled by the Arduino. The nodes used in this experiment consumed around 35 mA of current when both the micro-controller and radio were in sleeping mode. When performing an operation on the micro-controller, the current consumption increased to around 50-60 mA. The procedure used to put the XBee to sleep is outlined in Figure 7.6. In the figure, a wire which passed the command for voltage variation from the Arduino was connected from pin 9 of the XBee to digital pin 6 of Arduino.

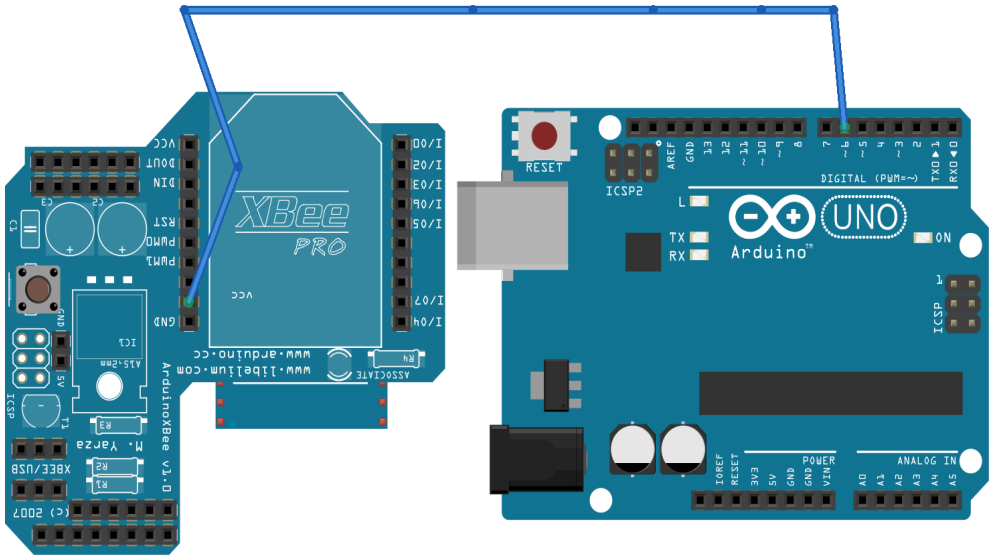


Figure 7.6: Circuit design to sleep XBee radio

The following figure shows a comparison of current consumption of a sensor node between active mode and sleep mode.

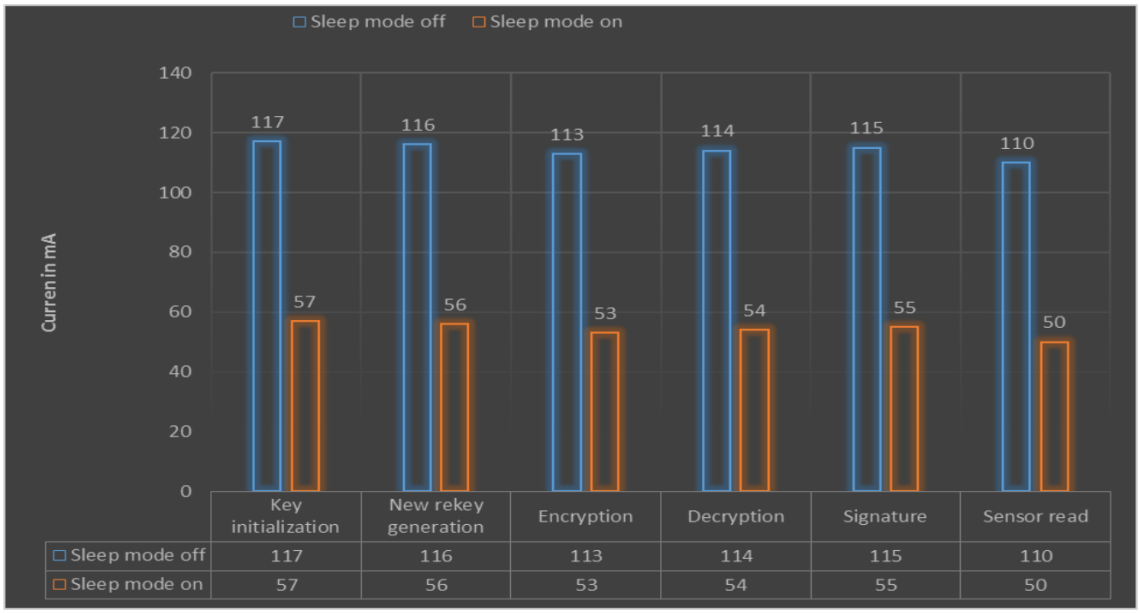


Figure 7.7: Comparison of current consumption with sleep mode on and sleep mode off

The following figure shows the comparison of the energy consumption of a sensor node between active mode and sleep mode.

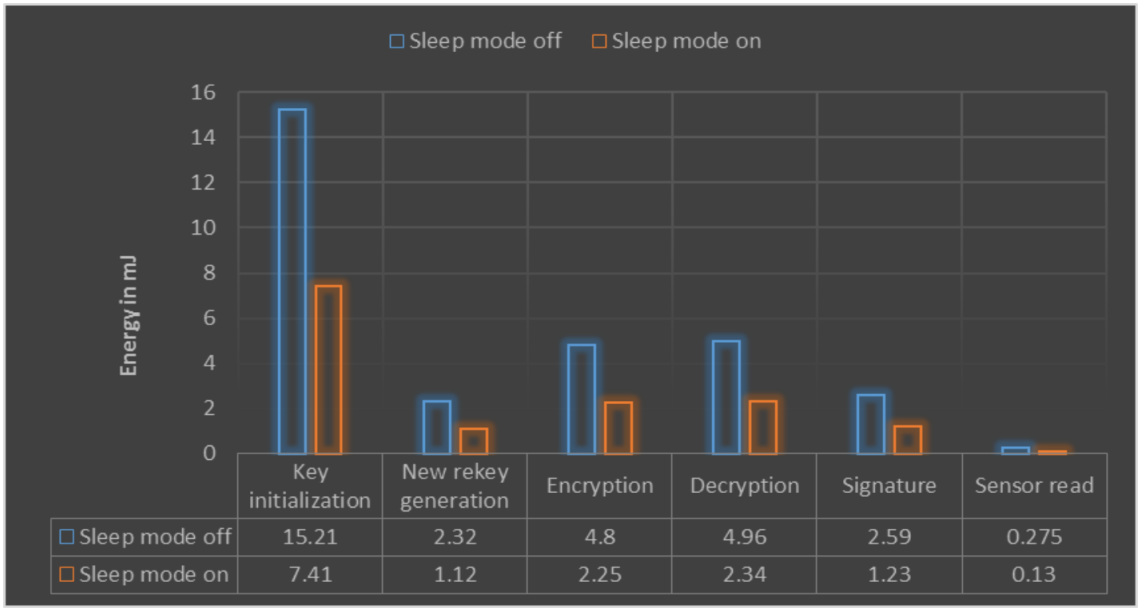


Figure 7.8: Comparison of energy consumption in sleep mode on and sleep mode off

7.6 Comparison with previous works

This work is compared with previously conducted works in respect to execution time, power and energy.

Herrera *et al.* [26] tested their proposed design on a CSIRO opal mote [29]. This opal mote model consisted of an integrated TPM. The TPM has built in RSA. The authors used RSA to encrypt data. They did not mention the key generation. They described the key generation time. For signature generation and verification, they used cryptographic hash SHA-1.

Hu *et al.* [27] evaluated their performance on TrustedFleck which is based on Atmel AT97SC3203S TPM chip. They tested their performance based on RSA, TinyECC and Xtea. However, they focused their results on RSA, as it has built in TPM. Like Herrera *et al.* [26], SHA-1 was also used for signature generation and verification.

During their work, the researchers measured the performance of a single sensor node in terms of key criteria. They uploaded the program and monitored a single sensor node performance based on execution time, power and energy. In my experiment, the same steps were conducted for testing and then the results of my work were compared with their work. During comparison, the memory constraint was also considered for executing the encryption algorithm.

7.6.1 Execution time:

The following bar diagram represents the comparison between my proposed design and two other previous studies, in regards to execution time for generating a new key. For key generation, the difference between my study and others was nominal, whereas in other operations my framework performed better. For encryption and decryption, the testing architecture took 8.5 and 8.7 ms. On the other hand, the design by Herrera *et al.* [26] needed 257 ms for encryption and 972 ms for decryption. When considering the design by Hu *et al.* [27], it took 55ms and 750 ms for encryption and decryption respectively. The condition

remained the same for signature and initialization. The testing protocol performed better, and took 4.5 ms for signature and 26 ms for initialization. In contrast, Herrera *et al's.* [26], study utilized 305 ms for signature and 836 ms for initialization. Hu *et al.* [27], in their study, did not mention initialization and their protocol employed 787 ms for signature, which was more than the time consumed by my offered architecture.

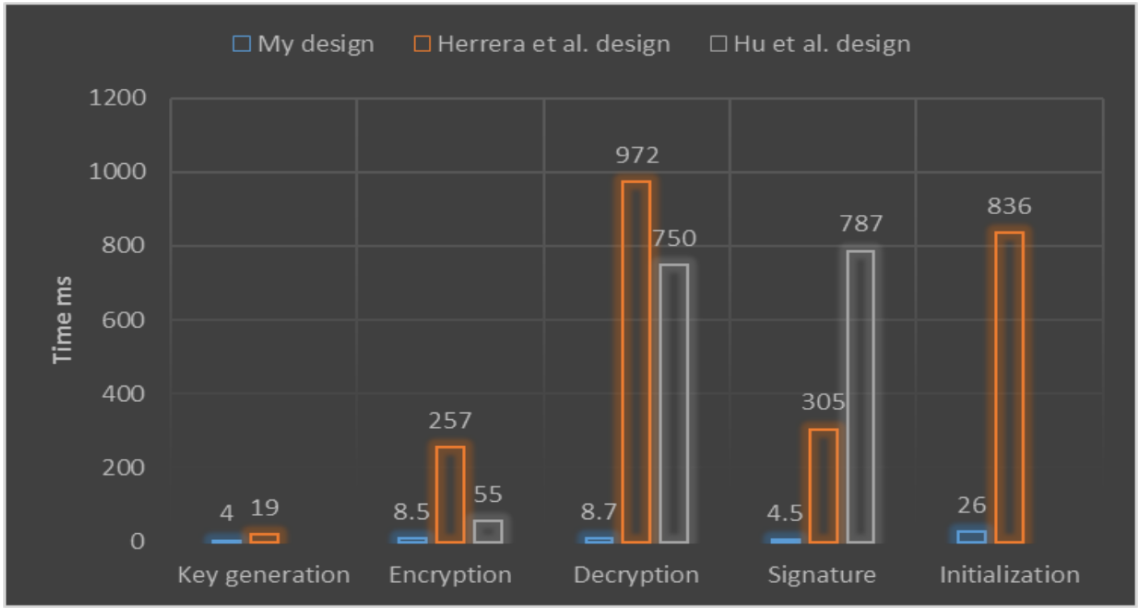


Figure 7.9: Comparison of execution time with Herrera *et al.* [26] and Hu *et al.* [27]

7.6.2 Current consumption:

The current consumption between my study and the studies done by Herrera *et al.* [26] and Hu *et al.* [27] is compared and graphed in a bar diagram. It shows that my design consumed more current than the other two designs in almost all operations. The framework by Herrera *et al.* [26] needed 70 mA for key generation, 80 mA for encryption, 80 mA for decryption, 80 mA for signature and 60 mA for initialization. When considering my protocol, the figures were 116 mA for key generation, 113 mA for encryption, 114 mA for decryption, 115 mA for signature and 117 mA for key initialization reflecting more current consumption for the use of Arduino Uno and XBee radio. Hu *et al.* [27] did not discuss key generation or initialization. However, their design needed 50.4 mA for encryption, 60.8

mA for decryption, and 60.8 mA for signature generation. This is less than the current consumed by the Herrera *et al.* [26] framework.

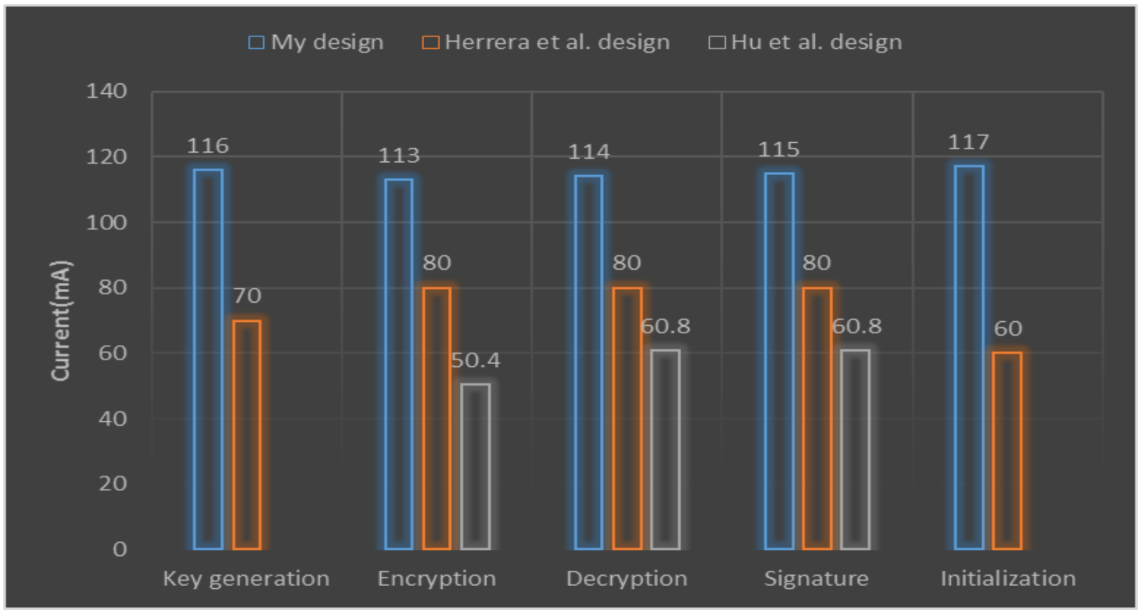


Figure 7.10: Comparison of current consumption with Herrera *et al.* [26] and Hu *et al.* [27]

7.6.3 Energy consumption:

The comparison of energy consumption between my designed protocols, and the architecture designed by Herrera *et al.* [26] and Hu *et al.* [27], is plotted in the Diagram 7.11. It reveals a constant lower energy consumption in various operations of my design when matched to the other two protocols. Among all the functions, the most energy was needed for initialization, in my design, which was 15.21 mJ. Other energy consuming functions included 2.32 mJ for key generation, 4.80 mJ for encryption, 4.96 mJ for decryption and 2.59 mJ for signature. As per the protocol of Herrera *et al.* [26], which was the most energy consuming, 5.7 mJ was needed for key generation, 84.3 mJ for encryption, 326.59 mJ for decryption, 323.57 mJ for signature, and 273.87 mJ for initialization, exceeding the amount of energy used by my protocol. Again Hu *et al.* [27] limited their description to encryption, decryption and signature but consumed less energy than the Herrera *et al.* [26] framework. In that framework, 8.31 mJ was consumed for encryption, 136 mJ for decryption and 143

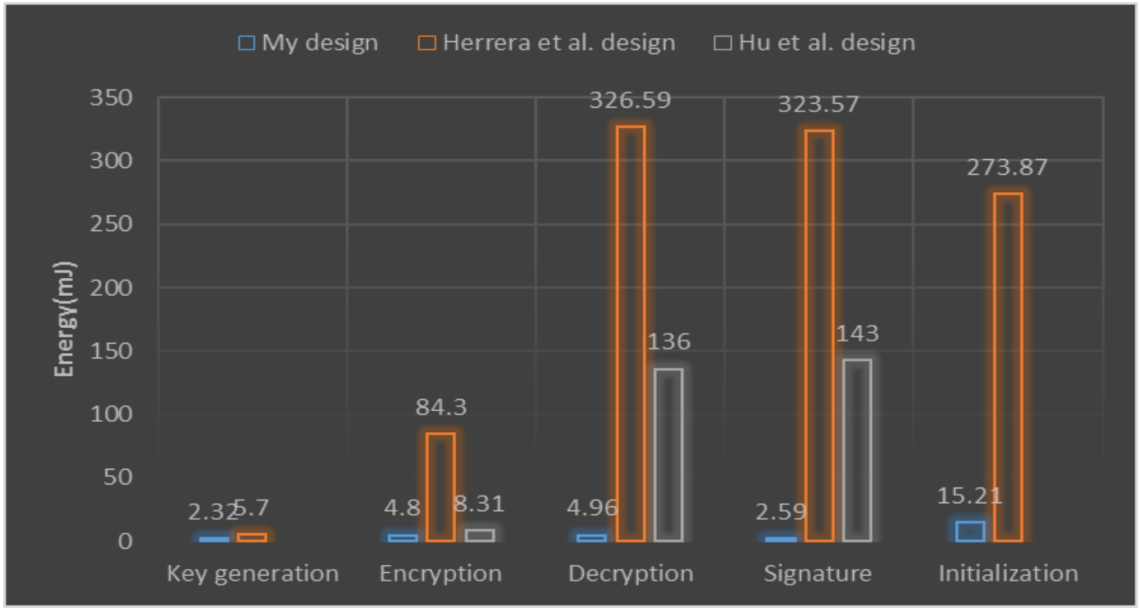


Figure 7.11: Comparison of energy consumption with Herrera *et al.* [26] and Hu *et al.* [27]

mJ for signature.

7.6.4 Explanation for low energy consumption:

In my experiment all the operations took significantly higher current which was in the range of 110-117 mA. However, my design consumed considerably less energy which is in the range of 0.275 mJ to 15.21 mJ for different operations. When comparing my work with the work of Herrera *et al.* [26] and Hu *et al.* [27], the current consumption of their work is less than my design which was in the range of 60-80 mA. Nevertheless, their operations consumed significantly high amount of energy ranging from 5.7 to 326.59 mJ. All the operations in my proposed design consumed less execution time and it is reflected in the low energy consumption by my proposed design. One of the factor that could affect the result, is the resistant of the device used. I did not consider the resistant in my experiment. The previous works with which I compared my result, also did not address the resistant of their device in their experiment.

7.7 Latency

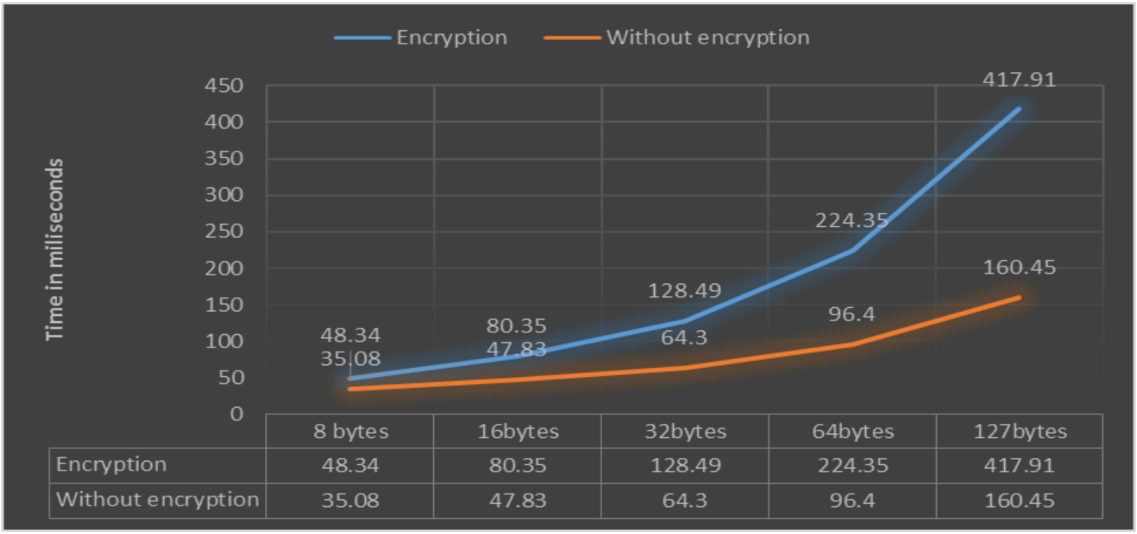
Latency is the indicator of the time required for data transmission between the sender and the receiver. Latency can be determined as a single trip latency or round trip latency. In a single trip, one way transmission time is measured, whereas a round trip calculates two way transmission time. At the time of the experiment, various data sizes were considered for latency calculation. I tested the impact of different data sizes in several operations on the sensor nodes. For calculating the latency time, the nearest and the farthest sensor nodes from the receiver were considered.

The latency was measured with or without incorporating the DigiMesh network. While encrypting varieties of data size value and generating their signature using hash function, the latency was measured for different sensor nodes. During the time of experiment, the receiver was equipped with an XBee connected to a laptop; on the other side, there were four sensor nodes, two within range of the receiver and two out of range. As DigiMesh was applied to the network, the nearest node could act as an intermediate router for data transmission from the far nodes.

As my proposed framework was implemented, first the nearest node was considered for data encryption and signature generation. In the process of encryption, around 100 sample data were used and the average was taken. The same procedure was repeated for signature generation. While performing encryption and signature generation for all other nodes, a similar procedure was repeated. To accomplish these measurement, a program was written on the receiver side which counted the bytes and extracted the time difference among the consecutive data. In my experiment, the data usage was limited to 127 bytes as the XBee based on the ZigBee network has the capability to transmit a maximum of 127 bytes of data.

At the beginning of the experiment, the data was sent with encryption and also without encryption from one of the sensor nodes. The time taken by the data to travel with or without encryption is compared and diagrammed in the Figure 7.12.

Figure 7.12 shows that the time taken for data transmission was calculated with 8, 16, 32, 64 and 127 bytes of data. When the data was not encrypted, the time consumption was less, whereas encrypted data took more time. It is noteworthy that the relationship between increasing time and increasing data size was linear.



	8 bytes	16bytes	32bytes	64bytes	127bytes
Encryption	48.34	80.35	128.49	224.35	417.91
Without encryption	35.08	47.83	64.3	96.4	160.45

Figure 7.12: Latency calculation for encrypted and non encrypted data

In the second step of the latency experiment, signature generation time for a variety of data size was calculated. It was observed that signature generation travel time was similar irrespective of the data size and remained in the range of 64-65 milliseconds which is portrayed in Figure 7.13

Contrary to the previous experiment, the signature generation travel time showed a different trend. In the first experiment, latency was in increasing order, whereas for hash operation the time difference was negligible. Any size of data took almost the same amount of time. This phenomenon could be explained by the fact that hash operation creates the same size of output for any given size of input data. That is the reason behind the negligible travel time difference for signature generation using hash.

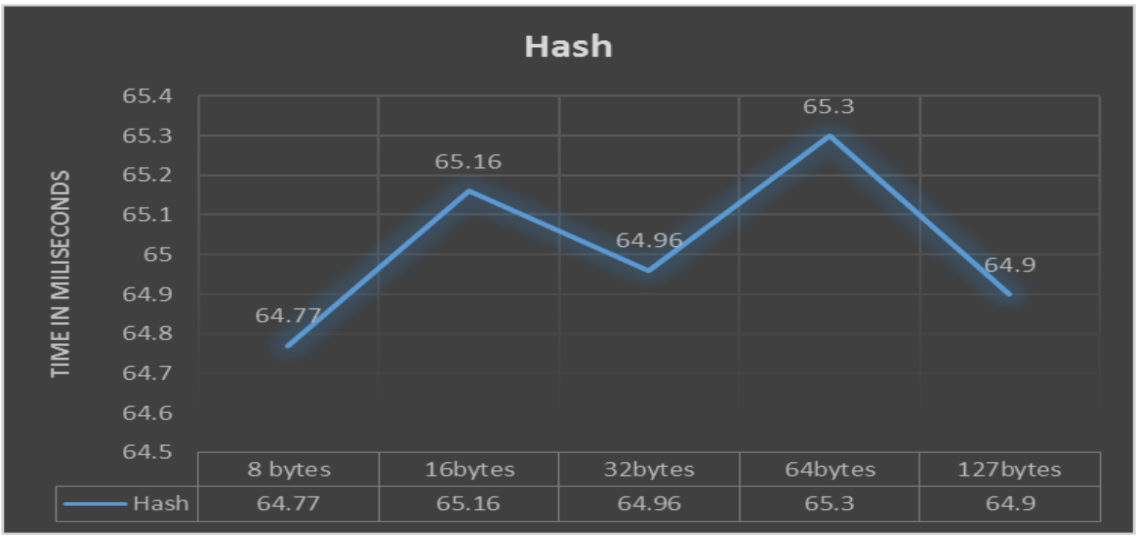


Figure 7.13: Latency calculation for cryptographic hash

7.8 Latency calculation in Digimesh

The following Figure 7.14 is a diagramatic representation of the experiment setup for testing in DigiMesh.

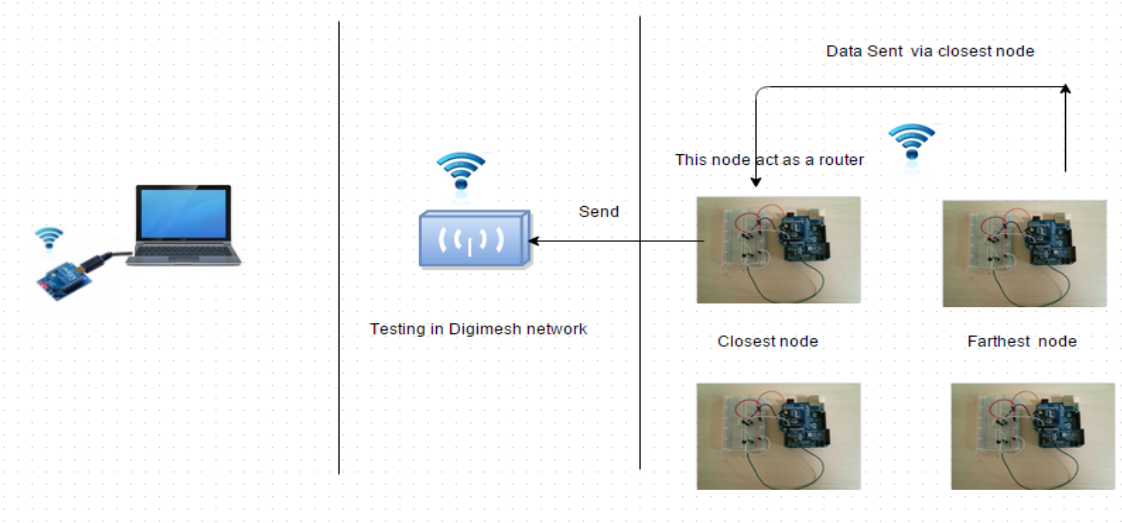


Figure 7.14: Experimental setup for testing in DigiMesh

In this stage of the experiment, latency was calculated using DigiMesh. The nearest node was considered for this purpose, as before, and the results are plotted in the Diagram 7.15. It was seen that for RC4 encryption the latency time was showing an increasing

pattern with increasing data size, whereas the hash value remained constant irrespective of the data size; this supported previous experiments.

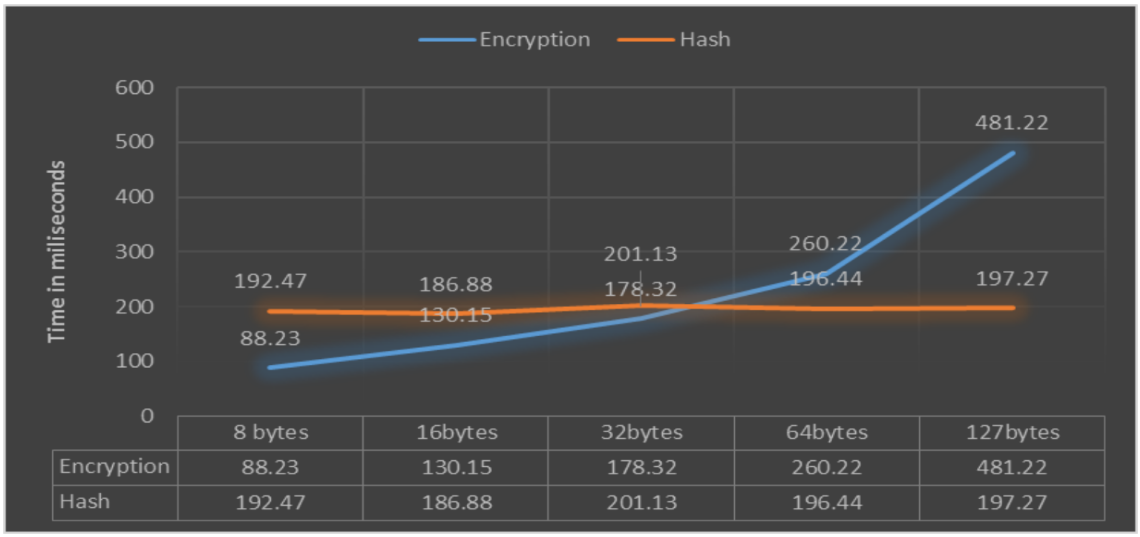


Figure 7.15: Latency experiment for the closest node

When comparing Figure 7.12 and 7.13 with Figure 7.15, it is noted that both for RC4 encryption and signature generation, the DigiMesh network consumed more time. For example, for 8 bytes data without the DigiMesh network, the time consumed for the RC4 encryption was 48.34 millisecond, and for signature generation the time spent was 64.77 milliseconds. When DigiMesh was applied to the nearest node, the consumed times were 88.23 milliseconds for RC4 encryption and 192.47 milliseconds for hash generation.

Figure 7.16 shows the RC4 encryption time and signature generation time for the remote node. The remote node consumed more time than the nearest node both for RC4 encryption and hash generation. This was true for any size of data ranging from 8-127 bytes. However, the trend of increasing latency time for RC4 encryption and similar signature generation time with increased data size remained the same as for the nearest node.

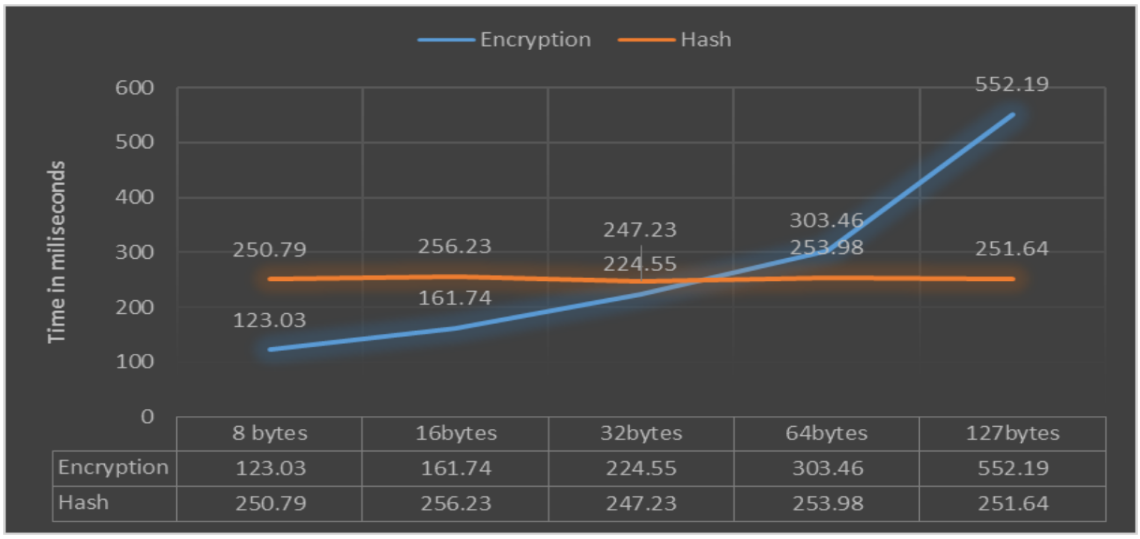


Figure 7.16: Latency experiment for the remote node

7.9 Throughput

Throughput is the amount of bits transferred over the network for a particular period of time. Throughput depends on latency which is discussed in the previous section. The equation to calculate throughput is [39].

$$TP = \frac{8 \times number \quad of \quad bytes}{total \quad transmission \quad time \quad in \quad milliseconds}$$

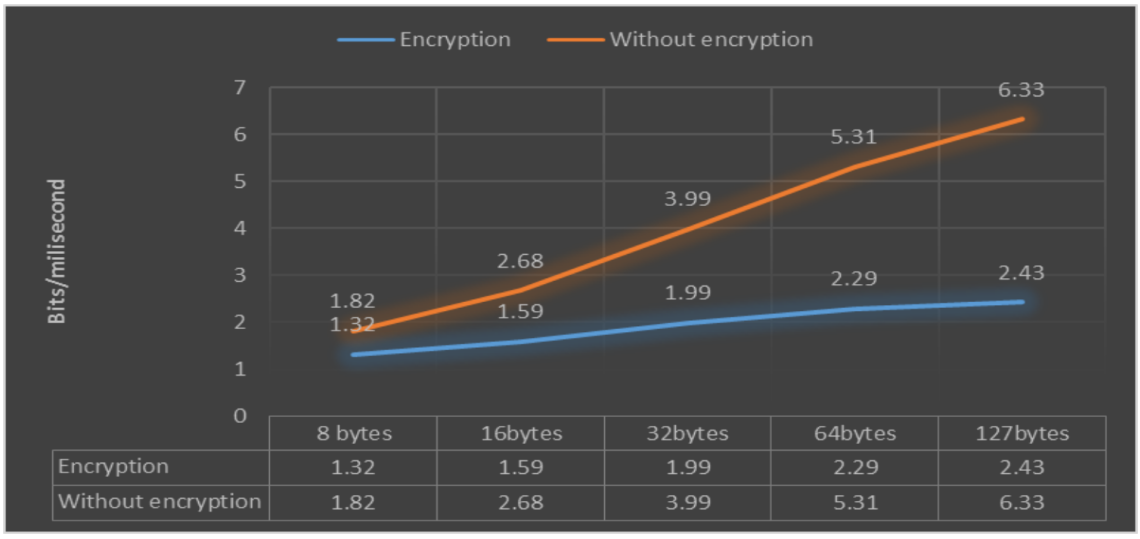


Figure 7.17: Throughput for sensor data with and without encryption

The above figure shows throughput of sensor node data with encryption and without encryption. The throughput increased linearly with the increase of data size. Moreover, without encryption the throughput rate was better than with encryption.

In the meantime, hash function was applied in the sensor nodes. After introducing hash function, the performance of the sensor nodes in terms of throughput was increased. These result are depicted in Figure 7.18. From the figure, it is clear that the hash function throughput also increased linearly with increased data size. As in the previous section, with the increased data size, the hash operations performed better than the encryption operation because of the output data size.

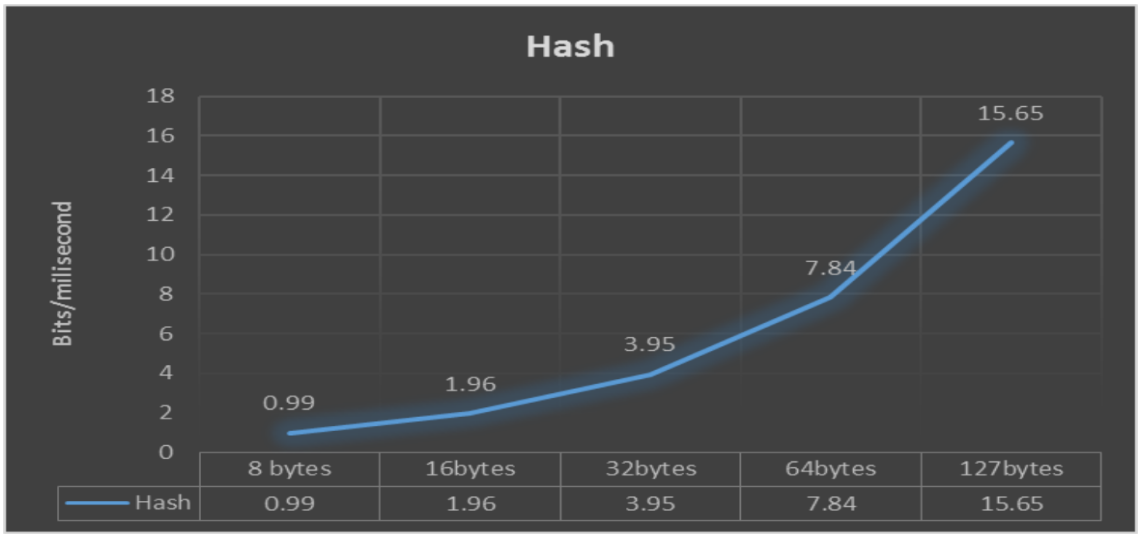
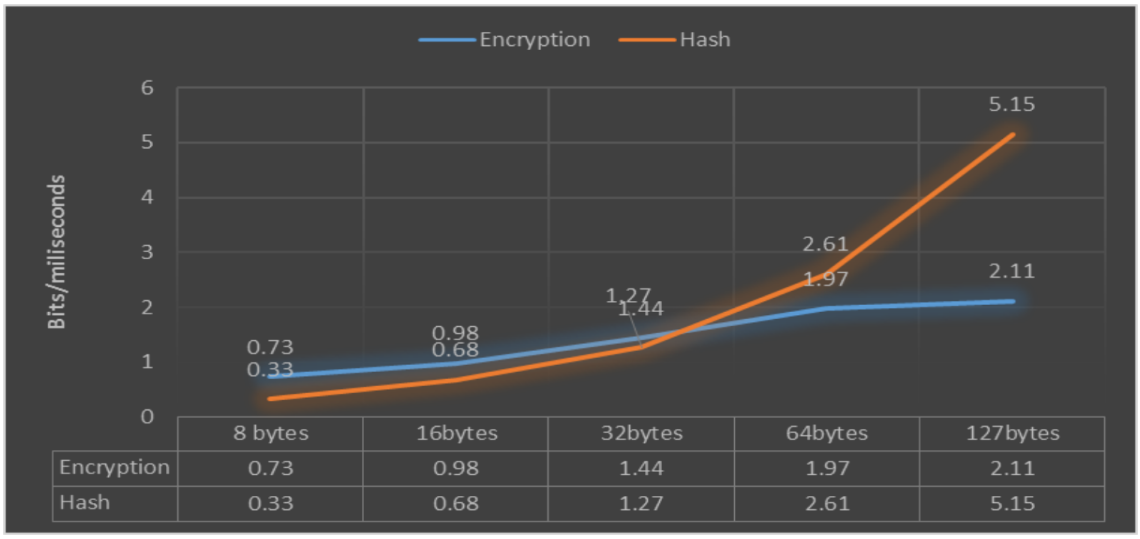


Figure 7.18: Throughput for sensor data with hash generating signature

7.10 Throughput in Digimesh

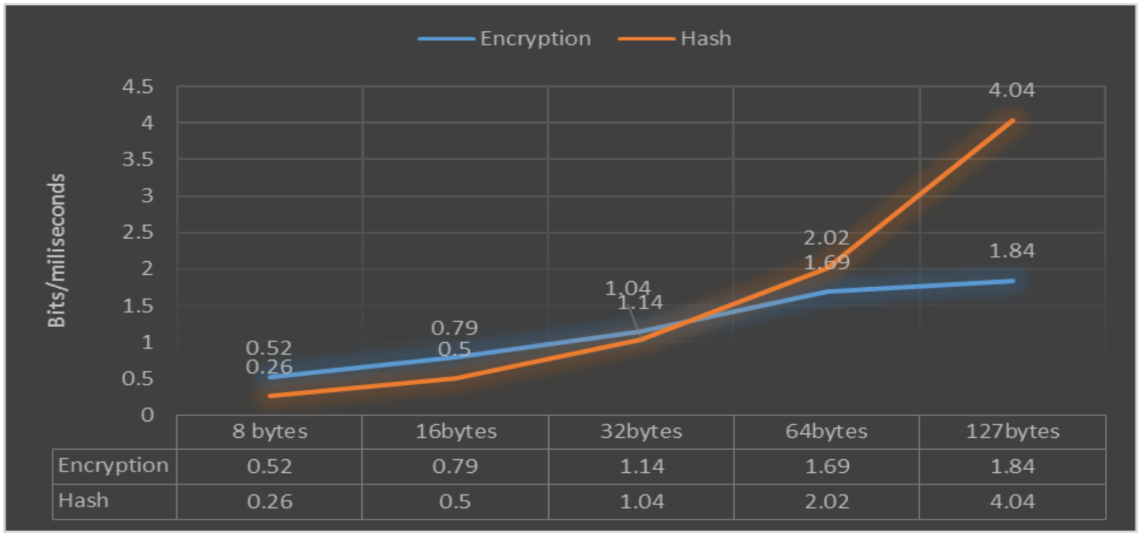
In Digimesh, the throughput was calculated for the nearest node and for the farthest node. Figure 7.19 shows the throughput rate for encryption and hash generation in the nearest node which was faster than the farthest node. For example, if the data size was 127 bytes, the throughput for encryption was 2.11 bits/milliseconds and for hash generation was 5.15 bits/milliseconds



	8 bytes	16bytes	32bytes	64bytes	127bytes
Encryption	0.73	0.98	1.44	1.97	2.11
Hash	0.33	0.68	1.27	2.61	5.15

Figure 7.19: Throughput for the nearest node in the DigiMesh network

Figure 7.20 reflects the throughput for the farthest node. Here it is observed that, for the same data size encryption, throughput was 1.84 bits/milliseconds and signature generation throughput was 4.04 bits/milliseconds. Both the figures clearly depict that the farthest node was slower than the nearest node for any data size.



	8 bytes	16bytes	32bytes	64bytes	127bytes
Encryption	0.52	0.79	1.14	1.69	1.84
Hash	0.26	0.5	1.04	2.02	4.04

Figure 7.20: Throughput for the farthest node in the DigiMesh network

Chapter 8

Conclusion and Future works

8.1 Conclusion

WSN is gaining popularity in recent time which raises concerns about the security issues of the network. In the background section, the different security attacks and their influences over the network are mentioned. The details of the security attacks reflect that, node capture attack is of prime consideration. The use of the same key and its use for a long time, both leave a network vulnerable to a node capturing attack. Therefore, forming new keys after a certain period and ensuring proper security in the keys improves the security of the network. To fulfill this requirement, a new key formation and distribution protocol has been presented that assures an efficient and secured end to end confidentiality of sensor data. This scheme was based on the symmetric encryption technique. Following the implementation, the security issues attained by my offered design are mentioned in the design and analysis section. At the time of my key formation, a time based password was used with hash function which also provided uniqueness to the key.

In my research after designing, the protocol was implemented in real life with the help of an Arduino Uno microcontroller and XBee, along with sensors and a laptop as the receiver. After successful implementation of the framework, the empirical performance of the design was studied. The performance of this protocol was measured in respect to execution time, energy consumption and power. The results were compared with previous works which showed a better outcome. In conclusion, the secured key distribution and data reading has provided a better security in the network with the reconfiguribility option, and has been

efficient regarding energy consumption and execution time.

At the end of the thesis, the following goals have been achieved:

1. Rekeying based key distribution protocol using symmetric encryption was proposed and implemented.

2. The new 40 bytes of key was generated periodically.

3. The framework achieved data integrity, confidentiality, authenticity, and forward and backward secrecy.

4. This design prevented some of the common attacks like man in the middle attack, reply attack, tampering, sybil and hello flood attack.

5. The entire concept was implemented in reconfigurable Arduino UNO nodes with XBee Series 1 radio. A DigiMesh network was formed to test the outcome of the sensor network.

6. The performance of the proposed architecture was measured in terms of execution time, energy utilization, current consumption, latency and throughput.

7. The outcome of the testing protocol was compared with previously implemented research works and it has shown better result when considering execution time and energy efficiency.

8.2 Future works

This protocol has been tested on a small network with four nodes. In the future, the robustness of this protocol could be verified by introducing more nodes in the network.

The further extension of this protocol could be achieved by introducing Bluetooth in the sensor side along with XBee and Arduino. As every smart phone is equipped with a Bluetooth facility, the inclusion of Bluetooth would ensure expansion of the framework to larger group of users.

After processing data in GUI, the data could be further sent over the Internet. This would help to expand the applications of the proposed framework in the current trend of

WSN.

The response of the protocol could be tested with different real time attacks on the sensor nodes. The system could be upgraded with a key which is more than 40 bytes long.

There is also a provision to upgrade the graphical user interface with more user flexibility and interactivity.

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