KEY DISTRIBUTION AND DISTRIBUTED INTRUSION DETECTION SYSTEM IN WIRELESS SENSOR NETWORK

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for the degree of doctor of philosophy

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DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledged.

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(Piya Techateerawat)

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PUBLICATIONS

1.) P. Techateerawat and A. Jennings, “Energy efficiency of Intrusion detection systems in wireless sensor network”, in *2006 First International Workshop Intelligent Agents in Wireless Sensor Networks (IA-WSN)*, Hong Kong, Dec 18-22, 2006, pp. 227-230. (http://cs.acadiau.ca/~eshakshu/IA-WSN-2006.htm) Related to chapter 4 and 5.

2.) P. Techateerawat and A. Jennings, “Hint Key Distribution for Sensor Networks”, in *International Joint Conferences on Computer, Information, and Systems Sciences, and Engineering (CISSE 2006),* Online conference, 2006. (http://www.cisse2006.org/) Related to chapter 4.

3.) P. Techateerawat and A. Jennings, “Analyzing the Key Distribution from Security Attacks in Wireless Sensor”, in *International Joint Conferences on Computer, Information, and Systems Sciences, and Engineering (CISSE 2006)*, Online conference, 2006. (http://www.cisse2006.org/) Related to chapter 5.

4.) P. Techateerawat and A. Jennings, “Adaptive Intrusion Detection in Wireless Sensor Networks”, accepted at *The 2007 International Conference on Intelligent Pervasive Computing (IPC-07),* Jeju Island, Korea, Oct 11-13, 2007. (http://www.sersc.org/IPC2007/) Related to chapter 4 and 5.

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ABSTRACT

This thesis proposes a security solution in key management and Intrusion Detection System (IDS) for wireless sensor networks. It addresses challenges of designing in energy and security requirement. Since wireless communication consumes the most energy in sensor network, transmissions must be used efficiently. We propose Hint Key Distribution (HKD) for key management and Adaptive IDS for distributing activated IDS nodes and cooperative operation of these two protocols.

HKD protocol focuses on the challenges of energy, computation and security. It uses a hint message and key chain to consume less energy while self-generating key can secure the secret key. It is a proposed solution to key distribution in sensor networks.

Adaptive IDS uses threshold and voting algorithm to distribute IDS through the network. An elected node is activated IDS to monitor its network and neighbors. A threshold is used as a solution to reduce number of repeated activations of the same node. We attempt to distribute the energy use equally across the network.

In a cooperative protocol, HKD and Adaptive IDS exchange information in order to adjust to the current situation. The level of alert controls the nature of the interaction between the two protocols.

Chapter 1. Introduction

1.1 *Wireless Sensor Network*

Sensor networks have been developing rapidly in recent years and their deployment is an advantage for new applications. Sensor networks are an innovation combining wireless communication, sensing features and embedded technology. Sensor devices also support self-organization and long periods of operation e.g. 1-5 years.

Limitations of the sensor network are a constraint in battery capacity, processing power and memory because effortless deployment requires a small size device. In addition, the sensor network is designed to operate as a group (or cluster) with a large number of nodes, thus the cost of each node should be kept to a minimum. Therefore, CPU, memory and battery capacity are limited.

1.2 Security

Security in the sensor network is a significant challenge as the resources in sensor devices are not sufficient for operating traditional security protocols. This weakness could expose vulnerability to adversary attack. However, protection of sensitive data in many applications, such as those for military and business operations, is required.

To secure a network, a common solution is to use encryption. However, a large number of nodes with self-organization need a key management system that organizes a secret key. Since the most energy intensive operation of the sensor network is communication, traditional key distribution cannot be directly applied to the sensor network. In addition, the process of capability in the sensor network is significantly less than general personal computers. Therefore, an adversary could have an advantage in the large difference of processing capability. This is also a drawback in implementing security in the sensor network.

Intrusion Detection System (IDS) is a system that always monitors events in the network. When the network is under attack, the system raises an alarm and the network is able to prepare for the adversary. Additionally, IDS could enhance the security level in the network because key management can secure the network with encryption while IDS monitors the misbehavior. However, the implementation of IDS in sensor network also has challenges in limited resources. As sensor networks operate in a large field, IDS has challenges in monitoring network traffic on this large scale.

1.3 Proposed Solution

Due to the constraint of resources in sensor nodes, security protocols are required to develop a new methodology. Traditional protocols need a high processing capability and a large amount of energy. Sensor networks need to be deployed with self-organization.

This thesis proposes Hint Key Distribution (HKD) for key management and Adaptive IDS in distributing activated IDS node. These protocols can also be operated in cooperation for dynamic adjustment to suit the situation. The main objective to develop these protocols is to minimize energy consumption while protecting the network from common attacks in general use. In Adaptive IDS, energy consumption is expected to be distributed across the entire network, and the total energy consumption in the network is also expected to be used in the most efficient way.

1.4 Contribution

The first contribution of this thesis is the design and implementation of HKD, Adaptive IDS and cooperative operation between HKD and Adaptive IDS. The design of these protocols indicates the limitation of energy, computation and security. The second contribution is a design of an evaluation method to verify security and resource usage in sensor network. The third contribution is an analysis of our proposed protocols. Our studies show that HKD can enhance the system lifetime while security strength is equivalent to existing protocols. Adaptive IDS expands coverage area while energy consumption is distributed through the network. In cooperative protocols, the operation could adjust the security level according to the situation, but it consumes more energy than non-cooperative protocol.

1.5 Thesis Structure

The remainder of this thesis is organized as follows.

Chapter 2 explains features of sensor network, the definition of security, how intrusion detection system operates in the case of attacks in network.

Chapter 3 discusses existing cryptography, key management protocol and intrusion detection system protocol from researchers' points of view.

Chapter 4 introduces our proposed solutions for security in sensor network. Our HKD uses hint message to reduce the amount of energy consumption and avoid exposing an actual key. A key and key chain is generated in each node from pre-installed master key. Our Adaptive IDS uses voting algorithm and threshold to elect activated IDS node. The threshold can reduce the number of repetitions of activation of the same node, so energy consumption is distributed across the network. In cooperative protocol, information is exchanged for dynamic adjustment to suit different situations.

Chapter 5 evaluates and analyzes our HKD, Adaptive IDS and cooperative protocol. HKD reduces the amount of energy consumption more effectively than other protocols while it can protect the network from common attacks. Adaptive IDS can distribute selected node with repeated activation of the same node being reduced. In cooperative protocol, security can be its strength, and a safe scenario consumes less energy than non-cooperative protocols. However, in general this will consume more energy.

Chapter 6 concludes our work and suggests future work in sensor network security.

Chapter 2. Background

2.1 Wireless Sensor Network

Investigation of wireless sensor network has been increasing in recent years [1-6]. A vision for sensor network is a large number of nodes deployed in a large field. Every node establishes the routine of network and communication without support of existing infrastructure. Sensor network is expected to operate for many years without human maintenance. It is also presumed to be self managing in nodes joining, leaving and node failure. As a result, wireless sensor network faces new challenges [7].

2.1.1 Ease of Installation

Ease of installation is a crucial requirement in sensor networks since a location cannot be assumed to have an existing infrastructure. For instance, sites installed with sensor network can range from buildings to rivers in the forest. Therefore, each node must be operated as a complete unit that is equipped with necessary components including power source, computing unit, communication unit, data storage and sensor. In addition, size of each node should be small because large node size is difficult to deploy. Furthermore, the large node size raises issues of security, inconvenience in transportation and impact on the environment. For example, figure 2.1 shows Mica2 node [8, 9] which size is only 58 mm x 32 mm x 7 mm but contains processor, memory, wireless radio and battery, so each node can operate as a complete unit. Consequently, Mica2 can easily be deployed in the field and does not require external infrastructure to operate as a sensor node.

2.1.2 Large Coverage Area

Large coverage area is a major feature of sensor networks which assists in collecting data from the field. It requires a large number of nodes in a system, usually

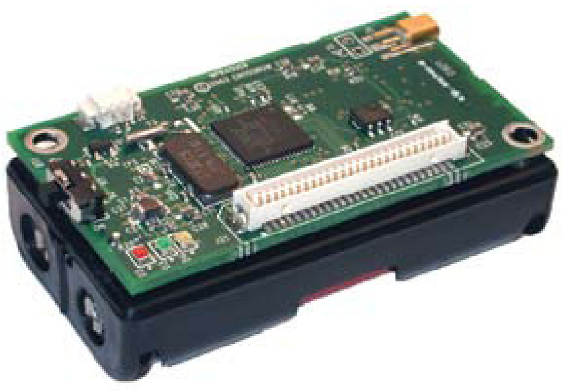


Figure 2.1 Wireless Sensor Mica2 node.

hundreds or thousands. For example, forest monitoring may need thousands of nodes to observe and collect data. These sensor nodes also need to be deployed over the forest. In [10], it is supported that such large number of nodes in the field improves sensor network operation in a wide area, which also enhances battery lifetime.

Furthermore, coverage is also a quality benchmark of sensor networks. Since data collection depends on the range, location and density of sensor nodes, coverage is an important aspect to observe data. This coverage benchmark could be graded from the best to the worst in support path which represents how well communication path is working. The support path calculates the number of possible paths in the cluster and determines the number of support nodes along the path. The best coverage contains the largest number of support nodes in the path while the worst coverage contains the least number of support nodes. The larger number of support nodes also assists in energy savings in multi-hop routing and redundancy in the event of node failure.

2.1.3 Unattended System

Unattended system is one of the goals in sensor network design. In large scale, test and maintenance of each specific node is not an efficient method. For example, if a cluster that contains ten thousands nodes conducts maintenance of ten percent of nodes every month, administration would need to deal with a thousand nodes monthly. To avoid excessive maintenance, sensor networks should be operated as an unattended system [11].

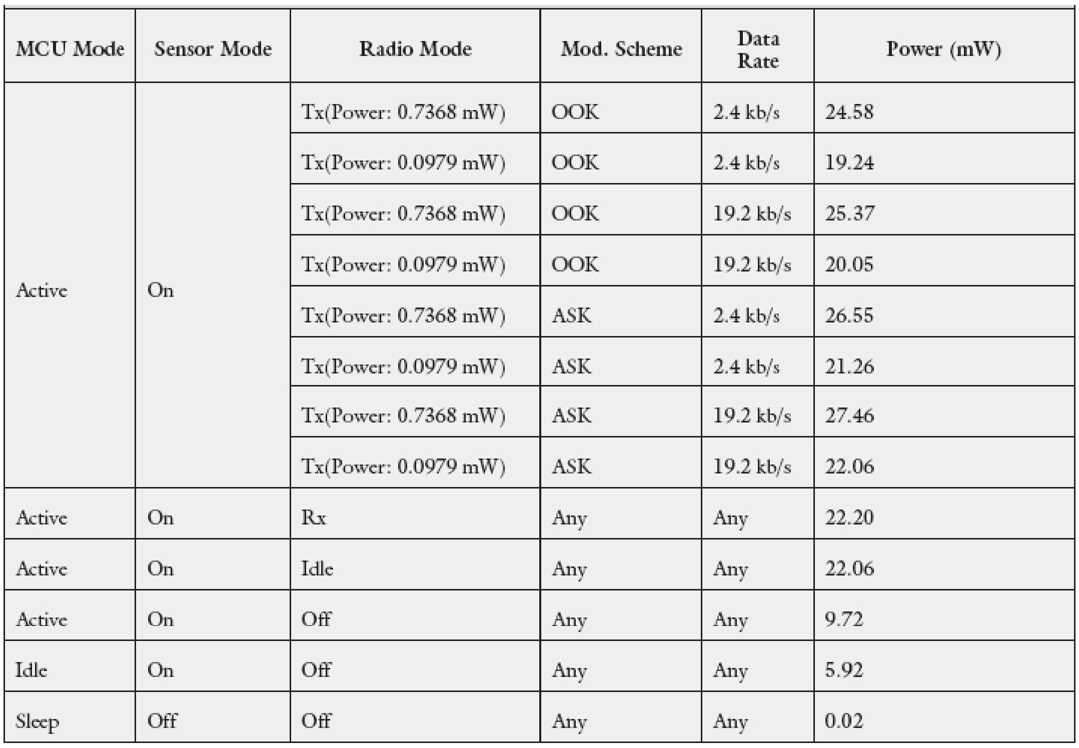
2.1.4 Long Battery Life

Long battery life is a crucial factor in sensor networks because it is impractical to replace battery in each node after the deployment. Furthermore, sensor network is operating as an unattended system so an equipped energy source is expected to operate for years. Consequently, energy consumption in sensor nodes needs to be minimized to enhance the battery lifetime. In general, wireless communication consumes most energy in sensor nodes [1, 10-12]. To extend the battery lifetime, it is necessary to minimize the amount of output transmit power and the frequency of messages. Since sensor networks consist of a large number of nodes deployed in the area, energy in communication can be optimized by using multi hop routing [13-17]. Instead of transmitting a message over a long range, message can be passed through others nodes located between sender and receiver. In addition, sleep mode can improve the operation lifetime because the amount of energy could be reduced by switching the system to sleep mode when the system is idle [18].

Sleep mode is an energy saving state which turns off wireless radio and non-essential components. In sensor network, there is a period in which system does not perform computation, transmission and reception of data. Therefore, as shown in table 2.1, battery lifetime can significantly be increased by the use of sleep mode which turns off components in the system. Yet, during the sleep mode, sensor nodes cannot send and receive any data. This could result in a failure of the reception of transmission of data. Therefore, during the use of sleep mode, it is essential to keep a balance between energy to be saved and the system operation. Otherwise, overall performance could fail due to the difficulty in communication. Currently, there are a number of protocols to manage sleep mode [18-22]. For example, SPAN protocol [14] manages sleep mode for a specific area. As in a dense area only a few nodes need to wake up and prepare for receiving data, which enables others to use the sleep mode. This protocol shows the effectiveness of a balance between energy and performance.

To design sensor networks, it is essential to consider battery characteristics. Considering the capacity of battery, the battery cannot be fully used due to the energy extracted via chemistry [21, 23-25]. For example, a 1500 mAh battery is estimated to provide 15 mA for 100 hours, but in practice the amount will be less than the estimated amount. In addition, Alkaline AA-battery would not be constantly discharged at 1.5 V, but it drops to nearly 1.2 V in its half-life. Likewise, the voltage of Lithium battery drops sharply when the battery is nearly empty although the battery provides more constant voltage than others.

Alternatively, solar cell panels can be used to supply energy. This strategy lets the sensor node absorb solar energy in daylight as well as use excess energy to recharge the battery. In solar energy supply [2, 26-28], solar cells show different characteristics from battery and behaves as a voltage limited current source. When incident solar radiation decreases, the current decreases. As a result, energy output is unstable and requires a battery to stabilize the voltage.



MCU Mode	Sensor Mode	Radio Mode	Mod. Scheme	Data Rate	Power (mW)
Active	On	Tx(Power: 0.7368 mW)	OOK	2.4 kb/s	24.58
		Tx(Power: 0.0979 mW)	OOK	2.4 kb/s	19.24
		Tx(Power: 0.7368 mW)	OOK	19.2 kb/s	25.37
		Tx(Power: 0.0979 mW)	OOK	19.2 kb/s	20.05
		Tx(Power: 0.7368 mW)	ASK	2.4 kb/s	26.55
		Tx(Power: 0.0979 mW)	ASK	2.4 kb/s	21.26
		Tx(Power: 0.7368 mW)	ASK	19.2 kb/s	27.46
		Tx(Power: 0.0979 mW)	ASK	19.2 kb/s	22.06
Active	On	Rx	Any	Any	22.20
Active	On	Idle	Any	Any	22.06
Active	On	Off	Any	Any	9.72
Idle	On	Off	Any	Any	5.92
Sleep	Off	Off	Any	Any	0.02

Table 2.1 Power consumption in Medusa II nodes [21].

2.1.5 Wireless Communication

Wireless communication is used to exchange information between nodes and base station. While sensor networks have a main objective, to collect sensor data from the field, data transmission via a wire is impractical because of coverage area and installation. It can be said that wireless communication is the solution for data exchange. Sensor networks involve many data transmissions as base stations use the communication for requesting data, organizing the network and maintaining security. Sensor nodes also use communication for routing paths, exchanging information among nodes and responding to the base station. For example, Mica2 [8, 9, 29, 30] is equipped with 868/916 MHz Multi-Channel Radio Transceiver.

To handle a transmission packet, the system needs to interact with network Media Access Control (MAC). It manages a radio signal, amplitude shifting, background noise and delay. When receiving a packet, radio signal is transmitted from RF transceiver to radio control system which processes and encapsulates a packet following the protocol standard. Then, information is passed to the application for further use as shown in Figure 2.2. In contrast, the process of sending a packet is conducted in reverse order to packet receiving. As there are many processing steps, jitter may affect the application. However, normally transmission delay is greater than processing delay. These procedures in low level protocols are abstracted from the application layer so application developers are not required to organize this process [31].

MAC Protocol of sensor networks is differentiated from other wireless networks in that it must create a network infrastructure among a large number of nodes and share resources efficiently among these nodes. This is an important issue in order to extend the operating lifetime of sensor networks. There are two major techniques which are implemented in MAC protocols. The first technique is Frequency Division Multiple Access (FDMA) that transmits data over many channels although most FDMA protocols consume more energy to organize channels and transmit over multiple channels. The second technique is Time Division Multiple Access (TDMA) that transmits data on a single channel and organizes each transmission by allocating a time frame. Although both FDMA and TDMA have been adjusting to meet the requirement in sensor networks, many researchers favor TDMA. This is because the nature of TDMA, which has low power consumption, can be an advantage for sensor networks. A communication slot also can be arranged for each node so it minimizes collisions in transmitting. In addition, TDMA supports low-duty cycle operation because sensor nodes only need to turn on the radio to assigned channel [18]. For example, Eyes MAC protocol for Sensor network (EMACs) [14] is a self organizing network based on TDMA protocol. It can transmit data to the base station without data routing. EMACs also manage TDMA slots by the division of time frame into three periods; a communication request period to initiate the communication, a traffic control period to organize transmission channel, and a data period to transmit data. Moreover, there is research attempting to develop hybrid TDMA/FDMA [32]. Since hybrid TDMA/FDMA can switch between TDMA and FDMA, TDMA is used when the sender consumes more power, so this means that idle channels can be turned off to reduce energy consumption. FDMA can be used when the

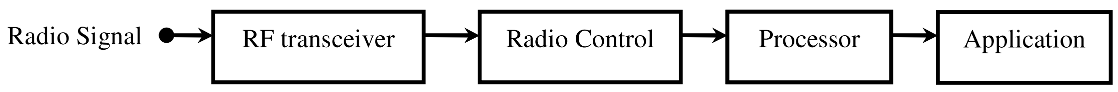


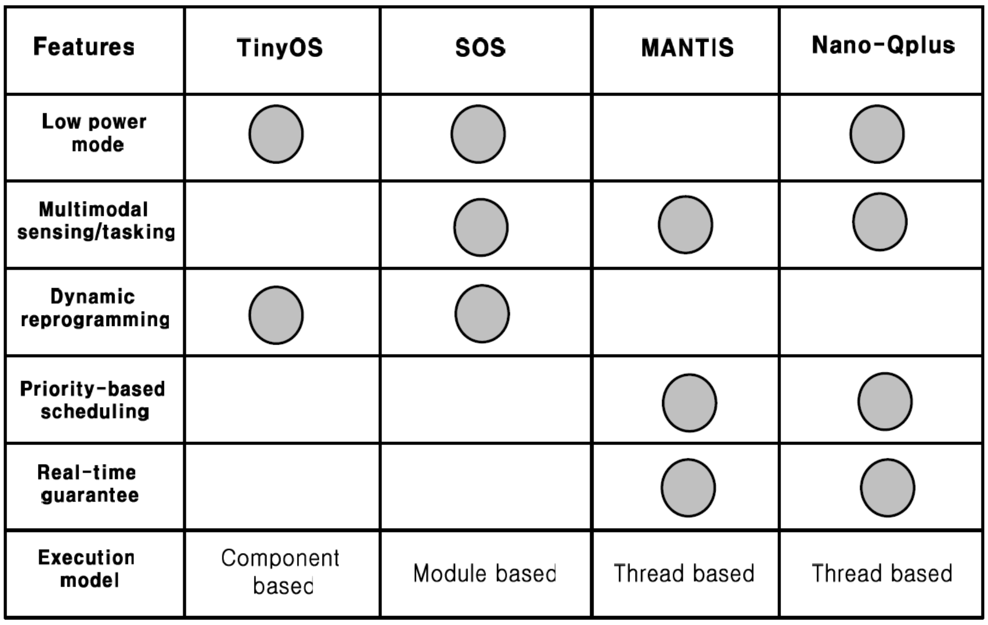
Figure 2.2 Radio processing procedure in receiving a packet for wireless sensor devices.

receiver consumes more power than the sender which decreases power on synchronizing during the transmissions [32].

A control mechanism when a packet is sent and received is organized by carrier sense. There are two major techniques: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CD mechanism attempts to transmit data immediately. If a collision is detected, it backs off for a random period before re-transmitting. CSMA/CA applies handshake mechanism to avoid a collision. In the handshake, the sender transmits Request-to-Send (RTS) and waits for Clear-to-Send (CTS) from the receiver before starting transmission. Since this handshake is very short, the performance is significantly improved [18].

2.1.6 Sensor

Sensor is a component interpreting analogue signal to digital signal. This capability can be used to measure environment data and transmit to the system. Previously, there were issues regarding sensors in interfaces between the sensor and the system, and restrictions of power supply and data transfer. Since digital sensors have been introduced, the stack of the sensor is abstracted for the developer and is well integrated with the system. Currently, sensors have dramatically improved in terms of accuracy, power consumption and size. There are many types of sensors such as light, temperature, pressure, magnetic, vibration and humidity sensors. Therefore, a number of applications can select the proper sensor to meet their requirements. For instance, Analog Devices



Features	TinyOS	SOS	MANTIS	Nano-Qplus
Low power mode	●	●		●
Multimodal sensing/tasking		●	●	●
Dynamic reprogramming	●	●		
Priority-based scheduling			●	●
Real-time guarantee			●	●
Execution model	Component based	Module based	Thread based	Thread based

Figure 2.3 Comparison of sensor network operating system [34].

AD7418 [33] is temperature sensor containing analogue-to-digital converter chip as well as an interface protocol.

2.1.7 Operating System

An operating system in sensor network is required for the effective management of the hardware capabilities while it is also necessary to support concurrency-intensive operation in a manner that achieves efficient modularity and robustness [33]. Efficient management handles processor, memory, wireless communication and battery. The software also needs to organize the resource for multithread access which is simultaneously used in some circumstances. With these restrictions, many systems design proprietary operating systems and architecture for particular applications. For instance, TinyOS [35, 36] is widely used by developers and researchers. TinyOS is a lightweight operating system which supports a limited resource device. In addition, it is coordinated with wireless network infrastructure. Although TinyOS needs to be modified for specific systems, it is one of the most efficient operating systems in embedded systems. Moreover, there are other operating systems which are designed for sensor network such as Contiki [37], Nano-RK [38], SOS [39], MANTIS [40] and Nano-Qplus [34] which are shown in figure 2.3. To compare with each of the others, TinyOS is based on event-driven execution and focuses on power management. It also provides flexibility on scheduling to support unpredictable events in sensor network. SOS has an objective in achieving dynamic reprogramming as well as updating a joining node. MANTIS and Nano-Qplus add real-time scheduling to support time-sensitive task. However, Nano-Qplus has an advantage in consuming less power and task latency.

2.1.8 Differentiated from Ad Hoc Networks

As embedded technology has been improved, many wireless network protocols have become more popular although the number of protocols confuses the community. As an example, mobile ad hoc network has a similar function to the wireless sensor networks in terms of embedded system, mobile devices and wireless communication. However, it focuses on mobility, in which nodes are able to move randomly as well as their routers. This applies in communication among vehicles and stations [41]. To compare with sensor networks, the ad hoc protocol has more capabilities in higher data rate, lower packet drop rate and less overhead in mobility communication. In general, sensor networks transmit data rates in the order of kilobytes per second compared with megabytes per second in ad hoc network [42]. Additionally, ad hoc protocol requires more performance, bandwidth and energy supply than sensor networks. The ad hoc architecture is also different in operation lifetime, sleep mode, resource and cost because sensor network uses a large number of nodes so each node must be relatively cheap which is in opposition to ad hoc node. The battery lifetime in ad hoc protocol is not regarded as an issue since it always has a supply of power from infrastructure. Although it looks similar in terms of wireless communication to sensor network, the ad hoc usage of resources is different.

2.2 Security

Fundamentally, security concerns three aspects: confidentiality, integrity and availability. It also covers four threats: interruption, interception, modification and fabrication [43]. In addition, cryptography is a mathematical method that provides a mechanism to secure data. Network and software security determine different vulnerabilities in particular systems. Hence, security software must organize proper security control for specific systems [44].

2.2.1 Security Definition

Security can be defined as the management of risk which entails confidentiality, integrity and availability. Firstly, confidentiality is concerned with only allowing authorized users to access systems and information, and secondly integrity is concerned with only letting authorized users modify the information and systems. Lastly, availability is concerned with allowing authorized users to access the information and systems when needed. This availability can be indicated by capacity of service, waiting time, fault tolerance and level of concurrency. A common crisis of availability is the denial of service attack. Therefore, consideration of these three security aspects is essential, and they are related to each other [44, 45].

To develop security applications, this thesis must address a variety of threats. A threat is a circumstance in which data or systems have potential to be under attack. It also can be the result of human error and failure of software design. Threats from adversary can be in different forms, and these can be categorized into four forms: interception, interruption, modification and fabrication [46] as shown in figure 2.4. Interception is a situation that an unauthorized user gains access to system. In passive mode, the interceptor may not leave any sign or evidence so the system could find it difficult to detect the threat. Interruption is a circumstance that systems or data are unusable. For example, an attacker erases data and destroys system files so system and data cannot be operated properly. Modification threat is a situation where an unauthorized user changes data, alters programs and modifies hardware components. Most of these threats could be easily detected by integrity techniques, yet many challenges remain difficult to detect.

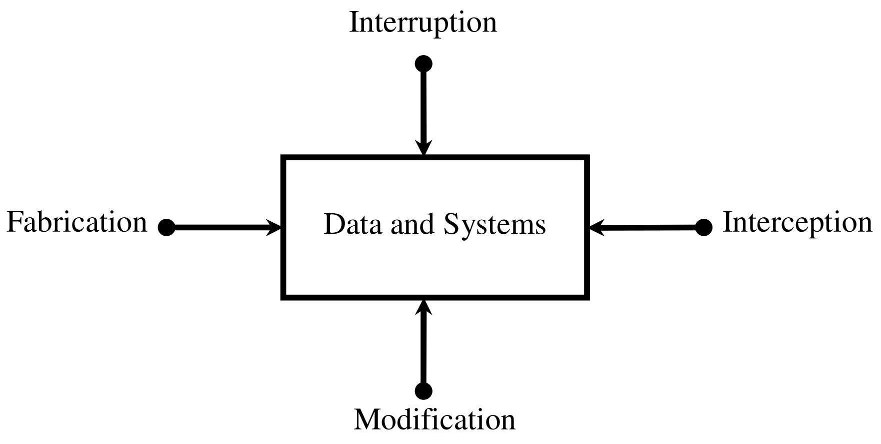


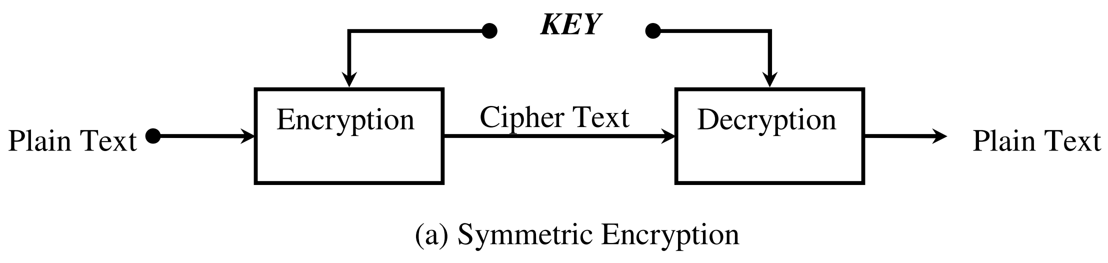
Figure 2.4 Security threats of data and systems.

Fabrication is a circumstance where an unauthorized user inserts imitation transactions to a network which may add or change an existing database. These are four fundamental threats which must be included in security objectives [44].

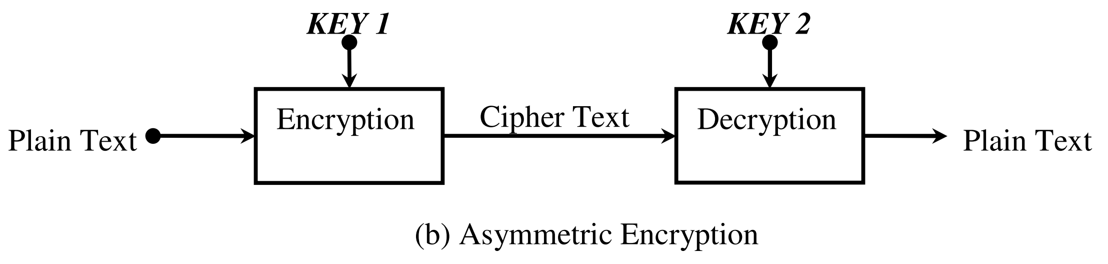
2.2.2 Cryptography

Cryptography is a process of applying mathematic calculation to maintain secrecy of data. It uses encryption and decryption to hide data from unauthorized users. Original data or plaintext is converted to encrypted data or cipher text in the process. The cipher text can only be decrypted by predefined password or key. To consider the four security threats, encryption delivers a solution for interception, interruption, modification and fabrication. For interception, encryption prevents unauthorized users from reading or listening to data. For interruption threat, encryption prevents the other parties so that only authorized users are allowed to access the data. For modification threat, encryption could secure data by detecting violation of data integrity. For fabrication threat, authentication could manage and validate the authorized users. Therefore, encryption is one of the solutions to secure data in an insecure environment [47, 48].

Both encryption and decryption require a password or key to secure data which allows only authorized users to access [49]. In symmetric encryption, encryption and decryption use the same key. However, asymmetric encryption uses a pair of keys by



(a) Symmetric Encryption



(b) Asymmetric Encryption

Figure 2.5 Encryption process

using one key for encryption while another key is used for decryption as shown in figure 2.5.

The difference between symmetric and asymmetric encryption shows the trade off between performance and security strength. Since symmetric encryption uses the same process to encrypt and decrypt, it is faster than asymmetric encryption to compute. However, asymmetric encryption is computed with modulo and prime number, thus the probability in breaking encryption on data is less. In the mechanism, the symmetric encryption needs one key while asymmetric encryption uses two keys. The key must be kept securely in symmetric. In asymmetric cryptography, one key must be kept secret and another one can be broadcasted publicly [50]. In a common application, secrecy and integrity of data and transmitting files are used for the symmetric cryptography while key exchanges and authentications are used for the asymmetric cryptography.

Symmetric encryption is able to establish a secure channel between sender and receiver by sharing a key. As sender and receiver can communicate to each other, this authentication verifies that established channel is set up by legitimated users. However, a network has many users requiring secure channels, thus using a separated key in each channel would not be convenient. Therefore, asymmetric encryption could provide a solution by preparing the pair of keys for every user. The fist key is a private key kept secretly by the user, and another key is a public key which other users could obtain. Therefore, each user requires only a pair of keys to communicate with the others.

Nowadays, encryption systems combine both symmetric and asymmetric as one system to enhance the security. For example, Pretty Good Privacy (PGP) [51] is a security scheme using both symmetric encryption and asymmetric encryption. The process of PGP mechanism begins with the generation of a symmetric key for sender, and after that receiver's public key is used to encrypt this symmetric key. Next, sender sends this encrypted message to receiver, and due to this process the receiver can decrypt the message with receiver's private key. After that, the receiver can obtain the symmetric key from the message and is then ready to establish a secure channel. In a large network, every user has different keys, so it is necessary to organize the keys as a part of key management. In key management, key distribution is required to exchange the keys among the network.

Key distribution is a method used to share secret keys among the parties before establishing a secure transmission. In symmetric key cryptography, both parties have a secret key which must be exchanged prior to the establishment of a secure channel. In asymmetric key cryptography, the public key is used to exchange and set up a secure channel without exposing the private key. In addition, setting up a secure channel could use shared secrets such as a random number and second key for authentication. In sensor network, key distribution generally places secret keys in the nodes before deployment. So, every node has an initiated key to establish a secure channel [50]. This method can be called **key pre-distribution**. However, systems still require a method of exchanging and updating keys among the nodes. Thus, keys need a secure tunnel for delivery in the networks. Generally, the public key can be used to establish a tunnel in order to exchange keys later on. However, many systems do not have the capability to operate public key so they need to use shared keys instead.

There are many protocols for establishing a secure channel with both asymmetric and symmetric cryptography. Each protocol has different advantages and disadvantages

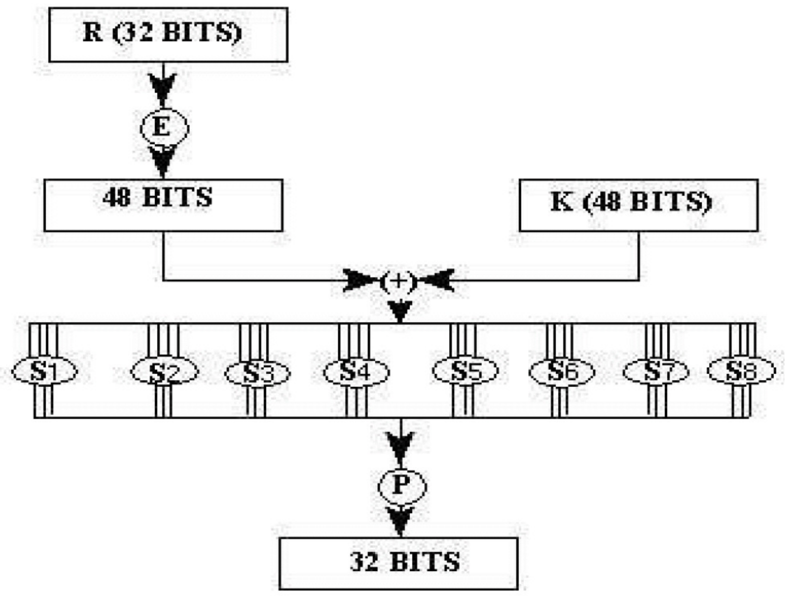


Figure 2.6 The function of DES [52].

and is suited for different circumstances. Therefore, the implementation of cryptographic infrastructure needs the understanding of the characteristics of the protocols.

Data Encryption Standard (DES) [52-54] is an encryption method which uses a block of key to encode data. It begins by dividing data into blocks then computing each block with a block of key. The output is swapped and this operation performed again with another block of key. This cycle is repeated for 16 rounds with 64-bit block size. Of the key block, only 56 bits are used while the remaining 8 bits are dropped. The latest development of DES is Triple DES which repeats the computation of DES three times. Nevertheless, DES is considered to be insecure because key size is relative small for the computing capabilities of today and DES keys are also able to be broken in less than 24 hours.

Advanced Encryption Standard (AES) [55, 56] is proposed as an encryption standard by the U.S. government. It improves on DES in faster computing, eased implementation and less memory requirements. Key size in AES can be varied between 128, 192 and 256 bits but block cipher is fixed at 128 bits. An algorithm operates in four steps: substitute bytes, shift rows, mix columns and add round key. Byte substitution transforms data by using a defined substitution table. Then, the rows of data are shifted

```
  ROUNDS = 10
  state: matrix[4][4]
  key:   matrix[4][4]

encrypt()
{

  for (i=0;i<ROUNDS-1;i++)
  {
     state = AddMatrix(state,key)
     state = SubstMatrix(sbox,state)
     state = ShiftRows(0,1,2,3,state)
     state = MultMatrix(encrypt_matrix,state)
     key   = NextKey(i,key)
  }

  // final round
  state = AddMatrix(state,key)
  state = SubstMatrix(sbox,state)
  state = ShiftRows(0,1,2,3,state)

  key   = NextKey(ROUNDS-1,key)
  state = AddMatrix(state,key)
}
```

```
  ROUNDS = 10
  state: matrix[4][4]
  key:   matrix[4][4]

decrypt ()
{
  // initial round
  state = AddMatrix (state,key)
  state = ShiftRows (0, -1%4, -2%4, -3%4,
                    state)
  state = SubstMatrix (invsbox,state)

  for (i=ROUNDS-2,i>0;i--)
  {
    key = prevKey (i,key)
    state = AddMatrix (state,key)
    state = MultMatrix(decrypt_matrix,state)
    state = ShiftRows (0, -1%4, -2%4, -3%4,
                      state)
    state = SubstMatrix(invsbox,state)
  }
  key = prevKey (0,key)
  state = AddMatrix (state,key)
}
```

Figure 2.7 AES Encryption (Left) and AES Decryption (Right) [57].

and put into order in blocks. Next, column data is mixed by multiplying a polynomial to each element in that column. In the final step, a key is added to each element. Currently, AES is being extensively analyzed by researchers but no evidence has been found which shows any critical security weaknesses.

Public key cryptography [58-65] is a popular protocol using asymmetric cryptography. It manages a pair of keys (public key and private key) for exchanging information. The private key needs to be kept secret by the owner while the public key is able to be broadcast publicly. The relationship between these two keys is that a message encrypted with one key must be decrypted with the other key. For example, a message which is encrypted with Bob’s public key must be decrypted with Bob’s private key. However, the private key cannot be derived from the public key. Therefore, the authentication of sender and receiver can be verified by implementing public key cryptography. An example of secured communication is the combining of both private and public key to use as a shared key. Suppose Bob attempts to talk with Alice securely. Since Alice’s public key can be broadcast publicly, Bob retrieves Alice’s public key. Then, Bob combines his own private key with Alice’s public key. As a result, Bob has a shared key. On Alice’s side, this shared key can be computed by combining her private

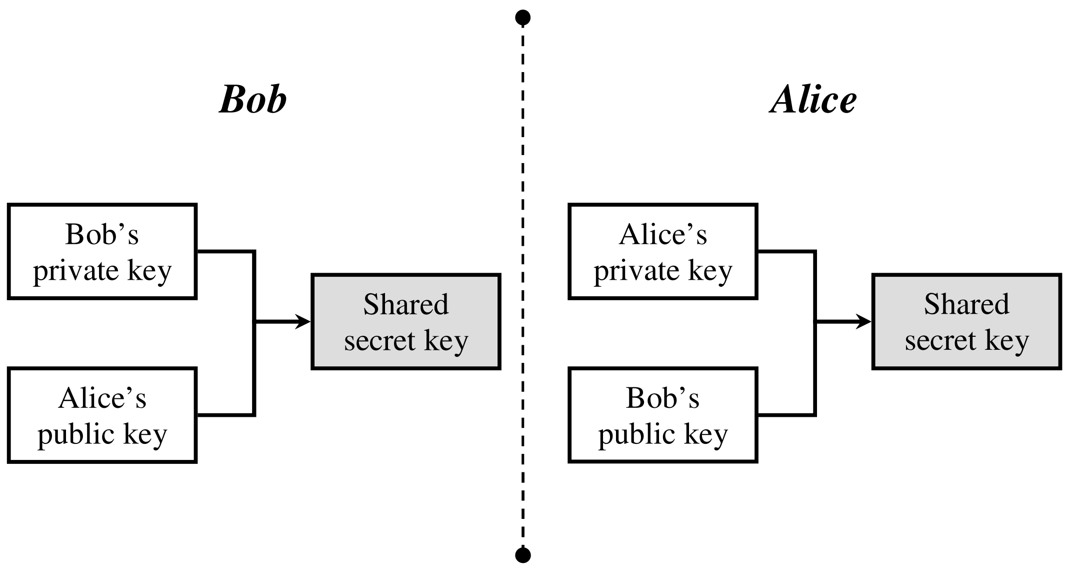


Figure 2.8 Shared secret key derived from private and public key.

key with Bob's public key as shown in figure 2.8. This method is derived from its own private key and the other side's public key so the same shared key is given for both sides. Consequently, both Bob and Alice can talk securely by setting up a secure channel using this shared key [50, 66].

2.2.3 Attacks in Wireless Networks

Today, wireless networks are widely used and the number of users has increased significantly. Initially, attacks on wireless communication have been very few because of insufficient time for the attacker to learn the technology. Currently, there are a number of risks involved in wireless networks. Attackers may be able to exchange information on the Internet about wireless protocols, encryption, bugs and tools. Consequently, several attacks should be dealt with by security systems.

Man-In-The-Middle Attack [67] is an attack in which a secure session is hijacked by an intruder placing itself between sender and receiver. Generally, the attacker participates at the beginning of the session. For example, when a user is connecting to the server, attacker acts as a server. As a result, the user mistakenly sends an initiation packet

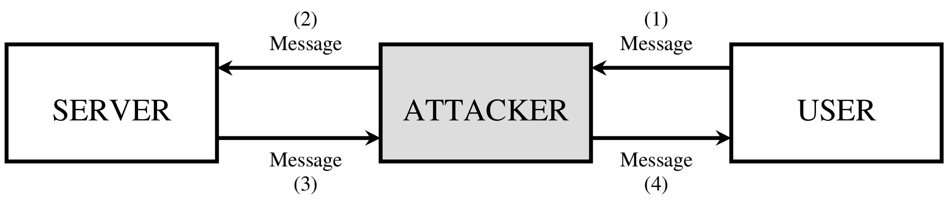


Figure 2.9 Data interception in Man-in-the-Middle Attack.

to the attacker. The attacker does not need to process the message from the user, but only passes this message to the actual server. Then, the server replies to the message from attacker and the attacker passes this data to the user as shown in figure 2.9. As a result, the attacker can retrieve user data and passwords. Also, the attacker can modify data from the actual server before returning messages to the user. In the wireless network, this is a critical issue. As every packet is transmitted over shared medium, it is easy to receive the imitated packet.

Denial of Service Attack (DoS) [68-70] is a threat to availability of systems or networks such as jamming networks, protocol attacking, traffic redirection and SYN flood in TCP. In general, a large number of packets are transmitted to the target system resulting in overloading and causing failure of the systems hardware. For instance, the SYN flood is a popular DoS attack in TCP because many protocols require setting up of sessions for connections. This set up requires three stage TCP handshakes which transmit at least three packets before completing a session set up as shown in figure 2.10. For attackers, they simply send a large number of SYN packets to the target. Then, the target maintains SYN connections and waits for ACK packets until the system is overloaded or malfunctions. As a result, attackers could break the target system or even enter into a protected area.

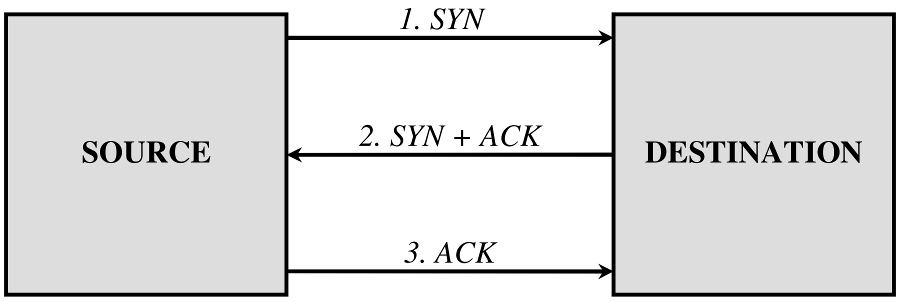


Figure 2.10 Three way handshake in TCP.

Wormhole Attack [71] is a threat where packets from attackers can tunnel into the network without authorization. The attacker then establishes a tunnel between wireless and wired networks to pass the packets through a restricted zone. Network security could be harmed and routing tables could malfunction due to attack. In wireless networks, attackers could set up a long range connection and conceal their identity. Therefore, the system is confronted with this challenge. Similar to **Blackhole Attack** [72], attackers broadcast imitated messages during setup of path. So, they could manipulate transmitting packets.

Routing Table Attack [73] aims to interrupt the operation of routing in the network. There are many strategies that attackers can use to attack the routing tables. For example, the attacker could attempt to insert new entries in a routing table until it overflows. Therefore, the routing system is then halted. In addition, the attacker could modify a routing table by sending update routing packets. As a result, routing tables may operate incorrectly and cause the network to become congested.

Jamming Attack [74, 75] is a threat in which the attacker transmits the same radio frequency as a current transmission. Therefore, the current transmission cannot keep operating which results in the communication failing. In this attack, the attacker is required to examine the current frequency from sender then jam the signal. Although this technique penetrates this weakness of wireless, new transmission protocols prevent this attack by often changing the frequency by using a frequency hopping spread spectrum.

2.2.4 Attacks on Encryption

Both symmetric and asymmetric cryptography hide a plaintext in cipher text. If attackers can retrieve the key, they can reveal the plain text. In most cases, attackers must attempt by trial and error from a large range of possibilities before finding the correct key. Therefore, they use several techniques for breaking the keys and revealing the plain text. These techniques could search for the key which may range from a simple dictionary word to a complex random code. As a result, they could harm trust in security and network operation.

Brute Force Attack [76-78] is a method to break a cipher text by attempting a large number of key sets. The procedure begins by decrypting the cipher text one key at a time until completing the entire key set. Therefore, a lot of computation is used to perform a brute force attack. If key size is n, the number of key sets is 2^n. On average, a correct key could be found when half of the key sets have been tried. For instance, brute force expects to find the key from 2^{128} possible keys at 2^{127} trials. When used against complex encryption, the brute force attack is deemed to be an infeasible operation because computation time increases exponentially in correspondence to the key size. For example, if key size increases from 64 bits to 128 bits, the set of key possibilities increases from 2^{64} to 2^{128}. Therefore, expected computation time also increases from 2^{63} to 2^{127} times. In practice, computing 2^{128} key possibilities is infeasible because with today's computing power, brute force attack will complete the process in millions of years. However, the brute force attack can still be used as a security benchmark to compare the strength of different security schemes.

Known Plaintext Attack [78] is an attack model where the adversary has samples of information and uses them to reveal a key. Since knowing part of the information could reduce the number of key possibilities, the number of trials is reduced significantly. For example, when key size is 128 bits, there are 2^{128} key combinations to compute. However, if obtained information could reduce key possibilities by 25%, the adversary only needs to compute for the remaining 96 bits. Consequently, the number of possible computations is reduced from 2^{128} to 2^{96} which is equivalent to a decrease of more than 99.99%. Therefore, cryptography is weaker when part of the secret is revealed even though a system is implemented with a strong security defense.

Other Attacks. In general, cryptography stores secret data using block ciphers which arrange data as a fixed size group. A normal plain text is broken into a small group of text with a pre-defined size. Therefore, data is easy to encrypt and decrypt with cryptography. However, there is a lot of cryptanalysis that can be done to observe this characteristic and invent mathematical models to attack block ciphers. **Square Attack** [79] uses substitution and permutation to break the block ciphers. **Differential Cryptanalysis Attack** [80] blocks ciphers by working out how the input is related to output and analyzing differences. **Mod n Cryptanalysis Attack** [81] focuses on the block cipher properties of binary addition and bit rotation modulo.

2.2.5 Intrusion Detection System

An Intrusion Detection System (IDS) is a security system that monitors network for malicious activities. An alarm is raised when suspicious events occur so system can implement a security policy to defend against the attack [82]. Since common security systems are designed to block violations from external hosts by defining a policy, authentication system and firewall, any inside attacks are difficult to detect. IDS can address this issue by monitoring user activity, system activity, network activity and system configurations. These input data feed to IDS for analysis of abnormal activities [83]. IDS can be implemented as host based or network based. The host based type installs IDS in every required monitoring station to observe activity in only that host. Network based IDS can monitor an entire network from this station. Since sensor network has an energy constraint, the host based topology is not a favored solution because every node needs to be awake and must continually analyze its own activities. This behavior could reduce sensor network lifetime significantly.

The IDS mechanism can be categorized into signature based and anomaly based. Signature based mechanism analyzes an event by comparing current events with a signature database. The database contains a characteristic record of events and a corresponding task. For example, the signature based database could contain a number of authentication failures, corresponding signal and updating key. It is a simple static task as opposed to the anomaly based method. Anomaly based contains a model of the system which is trusted. In this model, the character of activities, nodes behavior and exceptions

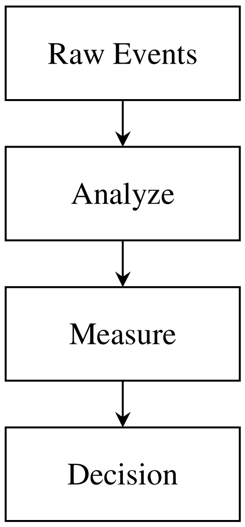


Figure 2.11 Procedures of Intrusion Detection System

are built from history data. This model is able to change in the future when network behavior changes. An advantage of anomaly detection is more flexibility. However analyzing real time behavior uses more memory and processing than signature based. In a sensor network, system state can become critical when it relies on anomaly detection.

After IDS detects an abnormal event, the system should raise an alarm. A response action also needs to be placed in the system. In a sensor network, calling staff should not be an option unless an extreme event is detected. Therefore, system should prepare activities for handling suspicious events. The activities should deploy a policy or update key to prevent any adversaries from breaking into the system. An alarm in IDS could report incorrectly which can be categorized into two types. Type I error or false positive is a fault alarm when node is under attack. Type II or false negative is an event that system does not raise an alarm under attacks. A large number of false positive affects confidences in the system while a large number of false negative could expose an opportunity for adversary to attack the system. Consequently, performance of IDS system could be observed from false positives and false negatives. In sensor network, security is critical because of the possibility of node compromise. As IDS could monitor for weaknesses and patterns from attacks, it could minimize impact on sensor network. However, it has a challenge in implementing an IDS operation in sensor network because real time monitoring reduces a battery lifetime significantly. Therefore, a solution is required to keep a balance between performance and battery lifetime [84].

Chapter 3. Literature Survey

This chapter presents a review of security issues in sensor networks. It begins with presenting a general cryptographic challenge in sensor network, followed by reviewing a proposed key distribution mechanism and a proposed intrusion detection scheme. This chapter is concluded with challenges in key management and intrusion detection system as well as requirements for security protocols in sensor network.

3.1 Cryptographic Issues in Sensor Network

Sensor networks present challenges in security design [85-90] because of resource constraints in processor, memory and battery. Since asymmetric cryptography needs powerful computation and memory, it is too expensive for tiny sensor devices. On the other hand, symmetric cryptography requires less memory and computation than asymmetric cryptography but it is not as flexible as asymmetric cryptography.

Security in sensor network involves authentication, data secrecy, preservation of availability and service integrity. The authentication needs to ensure an origin of packet and sender because wireless communication requires a shared medium where an adversary could inject and modify the transmitting data. A typical challenge of authentication in sensor network is that adversary obtains a secret key from compromised node and authenticates itself to the network. Data secrecy protects against the adversary from listening to communication data. This problem could be avoided by simple encryption. However, an adversary could capture a large set of transmitting data and perform encryption analysis which could reveal the sensitive information. There is a significant difference in capacity between adversary and sensor network. For example, sensor devices could contain a single ATMEL-ATMEGA 128L 8 MHz processor [91-93], 512 Kbytes memory and a battery pack for power supply. An adversary could in contrast use farm server with multiple 3 GHz processors, terabytes of memory and an unlimited supply of power. Therefore, securing data in low capability devices from attack using high capability system can be a significant challenge. Jamming signals, Denial-of-Service (DoS) attacks and node failure are also challenges. Service integrity requires ensuring the accuracy of data which could be corrupted from noise and environment. A protocol must guarantee the aggregated data to be trustable so it will not degrade the system usability [86].

A common solution is to establish a secure channel in transmission. However, the system has difficulties in sharing and organizing keys [94]. Since a sensor network has limited resources, the mechanism of protocol needs to be efficiently used on bandwidth and communication.

To avoid modification threat, watermarking is a process that can be used for marking origin of data [95-99]. In an untrusted environment, mobile nodes face a challenge in protecting themselves against tampering. There are several proposed solutions for modification threat in the mobile agent. Time Limited Blackbox Security [100] suggests a token structure containing data, issuer, expiration and signature. An advantage is to allow the party to verify itself with a token from current time and expiration time. However, it has a drawback on modifying property of token because there is no rule for an access authorization. Although it protects against a modification threat, the sender could modify the token without restrictions. Therefore, it cannot prove a sender's identity. In addition, adversaries can perform a replay attack in this system since a token can be reused. Consequently, the token system cannot support the security requirement in sensor network. In addition, secure communication could adapt from watermarking and tamper-proofing [95, 101]. The protocol protects data from being malicious by placing a watermark in each protected packet. Although the key is revealed, the adversary cannot obtain messages because data will be destroyed when the protocol detects malicious activity. However, it needs a public key in the exchange message when using wireless communication, otherwise this protocol will not be scalable in large networks. Thus, this protocol cannot be used in sensor network because of excessive energy consumption in using public key. In [102], asymmetric protocol consumes 226.65-293.20 mJ in key generation compares to 7.83-9.92 μJ in symmetric key set up. The difference could be up to 30,000 times of energy consumption which can be a significant effect to sensor node lifetime. Therefore, symmetric protocol is more favored for security in sensor network.

3.2 Key Management

To use symmetric cryptography in sensor network, every party must exchange a key prior to using encryption. Key distribution is required for delivering the key to legitimate nodes. Key management requires ensuring that every legitimate node has an accurate key at the exact time which involves many challenges such as organizing joining nodes, key updating and overcoming node failures [103-105]. Since sensor network is a large group of networks, scalability and efficiency in key management are necessary. In addition, the key management server needs to organize packet loss, key loss and key retransmitting.

Since sensor nodes are easy to deploy and self organize, a connection and security are self-constructed in the sensor network. In the initial stage, the base station has no information of nodes in the cluster so it has to broadcast in order to set up the networks and security. From a security perspective, the verification of a legitimate node is a challenge because every node in the cluster appears to be anonymous. A common solution is placing a key in sensor node before deployment which is called “key pre-distribution”. This can reduce setting up procedures as well as verifying the nodes identity. In [106], security has been evaluated from key pre-distribution. It shows that a larger cluster with many key sets can reduce the chance of keys being broken by adversaries. Authentication is set up by broadcasting by each node to neighbors. The neighboring nodes receive the nodes identification and key spaces index. In the case that neighboring nodes have the same key space, they can compute a secret key to share with each other. Therefore, neighbors set up the keys with entire network and can then communicate securely. This algorithm uses less memory and overhead while enhancing security with multi-hop. However, security only relies on sealing one key space for the entire network. Although adversary has a challenge in breaking this key space, it can obtain all the sensor nodes’ keys when the key space is broken. Secondly, this protocol has limited flexibility in updating of keys. As this protocol suggests 64 bit keys can be used to secure the network, but this key length can be broken quickly [54, 66, 107, 108]. In addition, sensor network is not static and sensor nodes may often join and leave. Key updating and maintenance are necessary. However, the idea of large key space and key pre-distribution are an advantage in sensor network security. Therefore, this is a motivation to develop our solution.

As a completed solution, there are many protocols that propose key management in large scale network. For example, Localized Encryption and Authentication Protocol (LEAP) [109, 110] is a key management protocol designed for sensor networks based on symmetric key. In LEAP, the base station distributes the group key to the entire network for generating the keys. Protocol mechanism relies on simple key broadcasting and broadcasted keys are encrypted by a common key that comes pre-installed in every node.

With the assumption of developer, adversaries do not have this common key so the group key is never exposed. However, adversaries can use cryptographic analysis to reveal the broadcasting key because the computing capacity of adversaries could be significantly greater than that of sensor nodes. In addition, LEAP is not aware of unreliable communication in sensor networks including packet loss and node failures. Therefore, this chapter reviews more sophisticated protocols: Efficient Large-Group Key Distribution (ELK) and Security Protocols for Sensor Networks (SPINS) in the following sections.

3.2.1 Efficient Large-Group Key Distribution (ELK)

Efficient Large-Group Key Distribution (ELK) [94] proposes a key distribution mechanism for key updating and key recovery from hint message. The hint message contains key verification of contribution nodes so received node can generate key from this information in key updating. Key updating begins with generating a hint message from parent nodes' information. Since a parent node recognizes all secret keys in child nodes, it provides the hint message for child nodes to generate a new key from previous key. Once a child node receives a hint message, it can generate the new key from hint information. To avoid malicious messages, the new key can be verified with the hint message so received node can be assured that the hint message is sent from the parent node. ELK updates joining nodes and leaving nodes by organizing a tree hierarchy. However, this can be a drawback when implemented. Since it cannot be assumed that network routing in the sensor network is organized in a tree hierarchy, ELK is difficult to implement. Although routing uses a tree hierarchy, sensor networks can regularly change structure. Therefore, updating hierarchy in one part of a tree requires updating the key in every related node. This causes inefficiency in energy consumption which is not suitable for sensor network. Nevertheless, the hint message mechanism provides secure processing because adversaries need to perform O(2^n) using brute force to reveal a key. This is a motivation for our proposed solution which described in chapter 4.

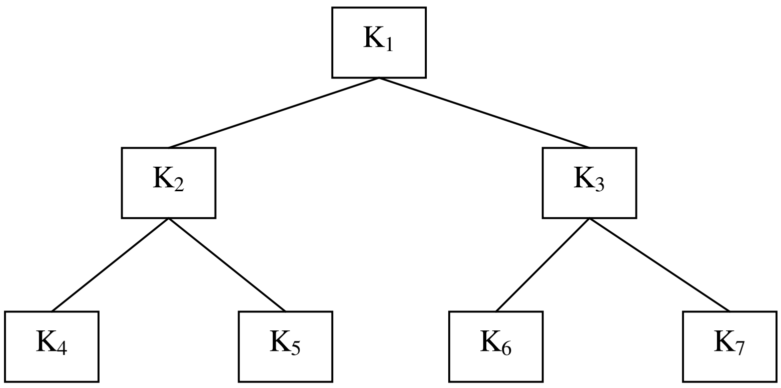


Figure 3.1 Hierarchical key tree in ELK [94].

ELK uses pseudo-random function (PRF) to generate and manage the key tree. The PRF uses a key as input to generate four different outputs. These outputs are key length, hint message, encrypted update key message and update key. On constructing the key tree, parent nodes are required to gather all child node keys and use PRF to compute the individual keys. For example in figure 3.1, key K_1 is computed by operating PRF function on child keys K_2, K_3, K_4, K_5, K_6 and K_7. To manage joining and leaving nodes, parent nodes must update the key corresponding to new child nodes' keys as well as acknowledge every connected node [103]. Therefore, key tree requires a number of message exchanges, which can drain sensor network resources.

3.2.2 Security Protocols for Sensor Networks (SPINS)

Security Protocols for Sensor Networks (SPINS) [111], is a security protocol designed for energy constrained devices which maintain confidentiality, authentication and integrity. SPINS achieves secure communication and trust of data. It also supports key set up in sensor network. In addition, SPINS is able to update keys regularly. Therefore, it should be used as a benchmark to compare to our proposals.

$$A \rightarrow B:\ C_A$$

$$B \rightarrow A:\ C_B, MAC(\ K_{AB}, C_A \,||\, C_B)$$

$$A \rightarrow B:\ MAC(\ K_{AB}, C_A \,||\, C_B)$$

**MAC () : Message Authentication Code*

Figure 3.2 Counter exchange mechanism in SNEP.

SPINS contains two security algorithms: SNEP and µTESLA. SNEP is a security mechanism for verifying integrity and data freshness whereas µTESLA is an authentication method for data broadcasting.

SNEP is an authentication protocol to protect against replay attack. A counter adds an overhead to each packet. The counter is synchronized in both sender and receiver before communicating and incremented with every block of data sent. Therefore, counter number is never repeated. In addition, initial counter value is transmitted securely with the master key. In each packet, overhead size is only 8 bytes. The counter exchange mechanism is shown in figure 3.2. C_A and C_B are counters in nodes A and B. K_{AB} is the shared master key among node A and B. MAC(K, M) is the message authentication code of M. In this mechanism, the first two steps synchronize the counter on both parties. The last step is an acknowledgement message to ensure the counter has been received [111].

µTESLA is a modified protocol of TESLA to broadcast and secure communication for a large number of nodes. The mechanism uses key verification and a key chain. In key verification, µTESLA uses symmetric cryptography instead of digital signature in TESLA. The number of senders is limited in µTESLA to reduce memory usage because each sender is required to construct a new key chain. Overhead is only per session instead of per packet. These modifications are due to resource constraints in sensor network. To set up the key chain, base station broadcasts K_0 to every node in the cluster. Then, each node can generate K_1, K_2 … K_N from K_0 by using a one-way function as shown in figure 3.3. To start secure communication, nodes use the key backward from the last key K_N to K_0 so the adversary cannot generate this chain key. For example, when an adversary can crack the message and obtain K_2, it can generate K_3, K_4 … K_N. However, the next round of broadcasting messages will use K_1 which cannot be generated by the adversary because key chain uses one-way function, thus it only can compute forward. However, it cannot compute backward. Therefore, stealing current key does not affect the rest of the key chain.

µTESLA has a nonce and verification in the overhead. Nonce is a value to ensure a freshness of data which is similar to SNEP technique. In the verification, receiving node can verify the correct sender from the correct key. In addition, broadcasting data uses key delay disclosure. This mechanism can avoid a problem in transmission delay and enhance security. Since data is encrypted two keys ahead, current key can be used to verify the packet but it cannot decrypt the data. For example, if current key uses K_3, K_3 is used to encrypt a packet while K_1 is used to encrypt data in the packet. When packet is received, node decrypts the packet with K_3 and waits until K_1 to decrypt data. The benefit of this mechanism is being able to decrypt with a correct key when there is packet loss or delay. Secondly, encrypted data still cannot be revealed even though an adversary can obtain the current key because the one-way chain cannot be computed backward. Therefore, µTESLA supports a sensor network environment with unreliable communication and a large number of receivers. It reduces energy consumption by using self-authenticating keys and low overhead size in communication. However, SPINS has drawbacks in verifying compromised nodes because there is no mechanism to determine the compromised node. Therefore, at an initial stage if adversary could proceed as one node in the network then the base station would provide the adversary with the key. In addition, SPINS is based on source routing so it could expose a risk through traffic analysis and denial-of-service attack. Furthermore, key chain is updated based on time basis so it cannot be adaptive to the situation e.g. high risk situation and normal situation.

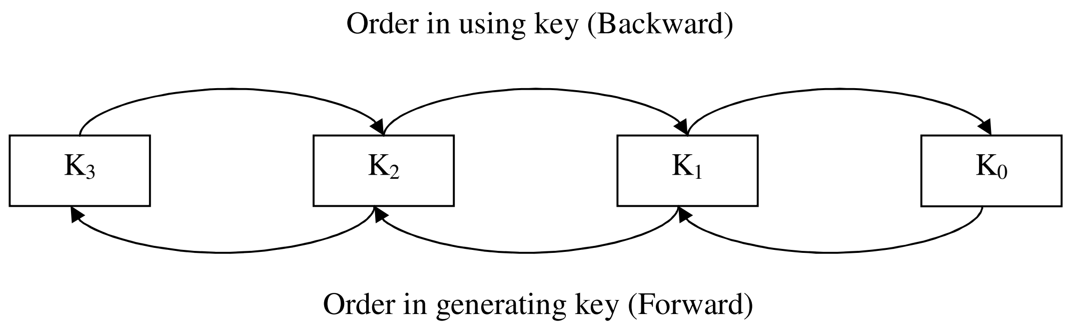

Order in using key (Backward)
K_3
K_2
K_1
K_0
Order in generating key (Forward)

Figure 3.3 Key chain in μTESLA

3.3 Intrusion Detection System

Intrusion Detection System (IDS) has been developed and improved in traditional networks [112-117]. A decentralized IDS [118, 119] is proposed in ad hoc networks to select IDS activated nodes. These nodes have the responsibility of monitoring a network covering neighboring nodes and its node. An advantage of decentralized IDS is an increase in coverage and security. Since ad hoc network spreads the nodes in large scale, it is impractical to monitor only the base station. When an adversary reaches the base station, it may be too late to protect ad hoc nodes. Secondly, distributing IDS through a network minimizes the risk of attack because there are many nodes monitoring network behavior. The adversary could easily capture a few nodes but capturing all nodes is not simple. However, these solutions require a complicated node election process which involves intensive communication and computation. Therefore, these solutions cannot apply to a direct application in sensor network because of resource constraints.

The IDS in sensor network adapts traditional and ad hoc solutions to meet the requirements. In [120], a mechanism of IDS in sensor network is proposed. The detection model is based on rules or signature database. When behavior fails the test, an alarm is raised. The simulation shows that straight forward attacks including message delay, jamming, data alteration and message loss can be detected effectively. A large history database also improves detection performance by nearly 100%. However, this simulation does not consider an untrusted environment and unreliable communication. Nevertheless, performance should be less effective than the ideal scenarios. In [121], IDS model is improved by dynamic monitoring of sensor networks. The result shows that detection mechanism can be configured to meet a resource in sensor network. However, a deployment of IDS activated node is based on reliable and recognized infrastructure. The implementation can be a challenge in practical. In [122], it supports a detection mechanism which can be operated in sensor nodes. However, the deployment of IDS is assumed that adversary does not know the sensor nodes location but base station and sensor nodes recognize their locations. Nevertheless, identified location increases a cost of extra equipments and energy, thus it may not effectively use in general application. In addition, IDS should not rely on nodes location because adversary could identify nodes location from physical nodes and radio detection.

From the previous section, IDS mechanism can be effectively implemented in wireless sensor devices. However, the challenge is how to distribute the IDS in sensor network environment to spread the energy use. As a completed solution, there are a number of distributed IDS protocols. In [123], protocol uses a cooperative decision from detection nodes. However, anomaly detection model and voting algorithm prove a poor performance and high false alarm rate. To avoid these problems, distributed IDS with localize decision are proposed [124-127]. These mechanisms improve the performance and scalability. With a voting algorithm, high intrusion detection rate is proved in the result [124]. However, these mechanisms are designed for wired network so it could be difficult to directly implement in sensor network. Therefore, Agent-based IDS is reviewed in the following section because of efficient distributed IDS and voting algorithm in wireless network.

3.3.1 Agent-based IDS

Agent-based IDS [128, 129] which activated IDS is selected from voting as shown in figure 3.4. Each node has one vote for their gateway. In dense clusters, the percentage of agent nodes is reduced because each agent node can cover more neighboring nodes. In addition, agent nodes are selected based on the number of votes, thus the algorithm ensures that selected node is placed in high traffic. This also increases the coverage of IDS monitoring in large cluster. However, voting requires a network hierarchy e.g. tree structure. Hierarchy maintenance is costly in sensor networks because network structure is changed regularly due to joining nodes, leaving nodes and node, link failures. Hence, this voting algorithm selects agent nodes efficiently but cannot be implemented in sensor networks directly.

3.4 Conclusion

In summary, ELK proposes efficient key management with self-generated key and minimizes communication with hint messages. However, it requires tree structure maintenance and regular updates between parent nodes and child nodes. Further, it is too expensive for sensor network. SPINS introduces a key chain and reduces energy consumption by symmetric cryptography. However, it broadcasts an actual key in setting up and only protects this secret key by using a counter and symmetric cryptography. Since an adversary could have high capacity computers, transmitting actual key with

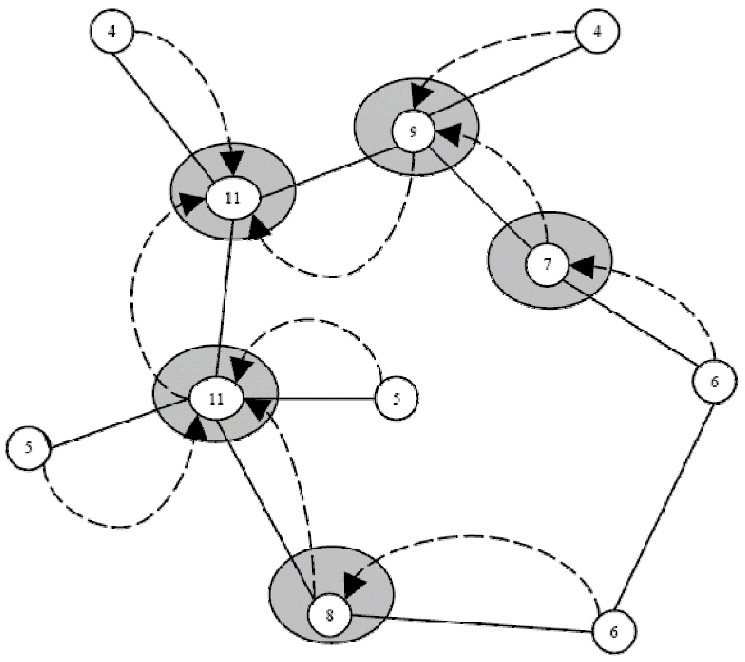


Figure 3.4 Agent-based IDS where grey node activates IDS, solid line is the available network connection and dotted line is the voted message [128].

symmetric cryptography is a weakness. In addition, at least three exchanged packets are required to set up secure channel. It can be inefficient because sensor network is not a reliable network so packet loss and error can occur. Since communication is the largest energy consumer, this procedure may consume a large amount of energy. Furthermore, key chain in SPINS is only updated on time basis. Therefore, base station cannot request nodes to change keys corresponding to the situation unless the base station re-deploys key chain which requires a lot of communication and energy. Therefore, the following items are the requirements of key management in sensor network.

1. The number of messages used to establish key should be minimized because the communication among nodes is the largest component of energy consumption.
2. A key should be generated in its node and should not be transmitted in communication because it can expose a security risk.
3. Base station should be able to update the key without re-deploying entire key chain.
4. Protocol should able to manage leaving nodes, joining nodes and node failures.

Distributed Intrusion Detection System is required for increasing coverage and security protection. Intrusion Detection System (IDS) is also important because there is no other protection when an adversary breaks into network. Distributed IDS selects agent nodes for activating IDS. Since a sensor network has no infrastructure and limited resources, this is a critical challenge. Therefore, the following issues are the requirements of distributing IDS in sensor network

1. Selecting agent nodes should select high traffic nodes in order to have higher chance to detect more attacks.
2. Protocol use should consume a small amount of energy because sensor network has limited resources.
3. Selected nodes should be changed each round in order to distribute energy consumption equally in the cluster.

Chapter 4. Hint Key Distribution & Adaptive IDS

This chapter introduces an approach of Hint Key Distribution (HKD) and Adaptive Intrusion Detection System (Adaptive IDS). Since chapter 3 describes the challenges, this chapter explains protocols and mechanisms for organizing key management and intrusion detection in sensor networks. Firstly, overview architecture and mechanisms of HKD are described. The theoretical performance is also presented while further evaluation is in chapter 5. This chapter continues explaining the challenges of intrusion detection. The Adaptive IDS is proposed for organizing distributed intrusion detection in the cluster. This chapter is concluded by discussing cooperation between HKD and Adaptive IDS.

4.1 Hint Key Distribution (HKD)

4.1.1 Overview

Our Hint Key Distribution (HKD) is proposed for key management in sensor networks so sensitive data can be protected. As discussed in chapter 3, sensor networks have limited resources so key management has to be re-developed. HKD provides a number of unique advantages. It also focuses on minimizing energy consumption and reducing risks by transmission of the key hint. HKD is developed based on hint message from ELK [94] and key chain in SPINS [111]. The mechanism of the protocol is described in the next section.

4.1.2 Mechanism

To develop HKD, our objective is to secure communication and the network. We assume that the base station has the highest computing capacity and is equipped with an extensive power supply. Second, physical attack must be defended from attacks including key and program stealing. In this thesis, nodes are assumed to be safe from physical tampering. Nodes can be protected from tampering by implementing Watermarking, Tamper-Proofing and Obfuscation [101, 130-132]. We assume that network routing is established before performing the key distribution. The environment is assumed to be high risk with adversaries surrounding the network. Intruders have the ability to intercept every message of transmission as well as high performance computers and power supply

In each node, master key (K_M) and common key (K_C) are pre-installed. The master key K_M is an initial key for generating the key chain. It is used as an input for a one-way function to compute a consequence key. Common key K_C is used in the initial stage in which the key has not been set up so the setting up message is encrypted and confidential. Additionally, encryption and decryption with correct key ensures authorized senders and receivers. In our HKD, base station generates a hint message. In addition, the base station is the most trusted device so it takes the responsibility of broadcasting and making decisions on key setting up and key updating.

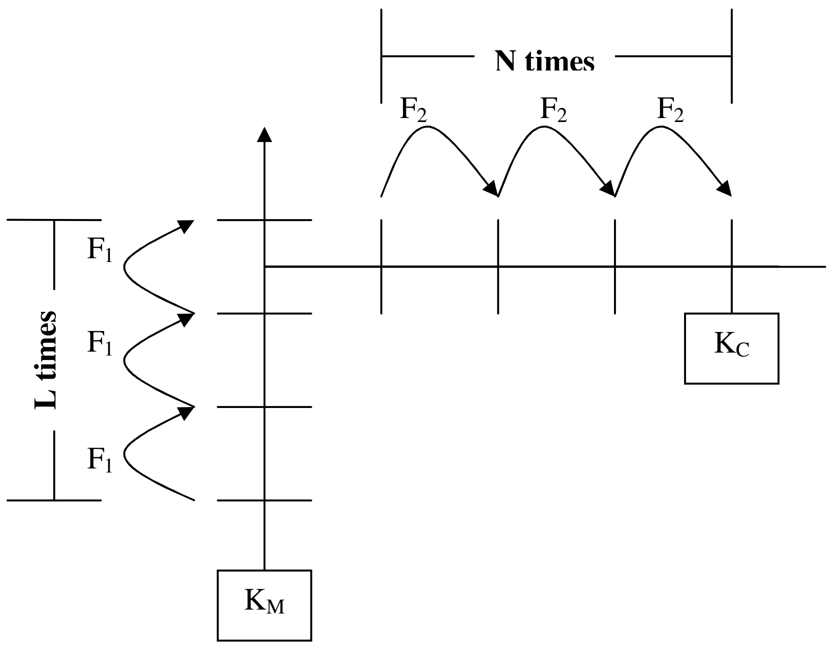


Figure 4.1 Procedure to find current key K_C from master key K_M by using one-way function F_1 and F_2 where L and N are random numbers.

To construct a key, there are two kinds of operations. Both sender and receiver contain two one-way functions F_1 and F_2. These one-way functions can compute forward but they cannot compute backward. Therefore, exposing current key does not affect the key chain and master key K_M. Secondly, using two one-way functions instead of one in SPINS [111] can increase the key space, makes it more difficult for an adversary to break.

4.1.3 Implementation

Sender generates hint message which contains a hashed value of current key. Current key K_C is generated from master key K_M and one-way function F_1 and F_2. Master key K_M is used as an input. This key generating computes both F_1 and F_2 iteratively as shown in figure 4.1. As discussed in chapter 3, generating a key chain in a node can secure the key and simplify operations. One-way function F_1 is the first function to iteratively compute for L rounds where L is a random number. Then, one-way function F_2 begins to iterative compute for N rounds where N is another random number. Both one-way function F_1 and F_2 are different functions in increasing a key space which increases the degree the difficulty of breaking the key. To compare with one one-way function, key space increases from L to L x N. This is equivalent to increasing from O(n) to O(n^2), where L is equal to N. In addition, using two one-way functions can eliminate the need to re-deploy master key K_M because changing the key chain can be done by simply selecting new random numbers L and N. Then, current key K_C is changed to a new key chain because changing number L shifts the key chain to a new row. In the implementation, the random number L in the next round must be greater than the current number so key will not be repeatedly used. In addition, more rounds of updating keys can increase key space. For example, if random number L is in the range [1, 2, 3 … 20], after 20 rounds, the possibility of L is in the range [20, 21, 22 … 400]. Therefore, this key chain supports a long operation lifetime in sensor networks.

```
select random number $L$
load key $K = K_M$
for $j$ = $L$ downto 0 do
    compute key $K = F_1[K]$
end for
store key $K_M = K$
compute hashed value $S_1 = H[K]$
select random number $N$
for $j$ = $N$ downto 0 do
    compute key $K = F_2[K]$
end for
compute hashed value $S_2 = H[K]$
encrypt message $(S_1|S_2)$ with key $K_C$
broadcast message $K_C(S_1|S_2)$
```

Figure 4.2 Generating hint procedure in HKD where $K_C(S_1|S_2)$ encrypts S_1 and S_2 with common key K_C.

To implement, sender is required to update master key K_M from previous computing one-way function F_1 because random number L is always added on top of previous value. Therefore, it can reduce processing time by processing from previous data. In addition, sender needs to prepare hashed value from hash function H. The procedure as shown in figure 4.2 begins by selecting random number L. Then, sender performs one-way function F_1 on K_M iteratively L times. After that, it stores new key as a master key K_M and finds hashed value $H[K_M]$ as S_1. Next, sender selects the second random number N for number of computing one-way function F_2. After completing, it computes hashed value and stores in S_2. At the same time, sender encrypts both S_1 and S_2 with common key K_C and broadcasts to the network

```
decrypt message with key $K_C$
extract $S_1$ and $S_2$ from broadcasted message
load key $K = K_M$
while $H[K]$ not equal to $S_1$
    compute key $K = F_1[K]$
end while
store key $K_M = K$
while $H[K]$ not equal to $S_2$
    compute key $K = F_2[K]$
end while
until store $K$ as secret key
```

Figure 4.3 Receiver procedure in HKD

Receiver is pre-installed with master key K_M, one way functions F_1 and F_2, and hash function H. Updating key procedure in receiver is shown in figure 4.3. When updating message is received, receiver decrypts message with common key K_C and then it obtains S_1 and S_2. Next, receiver computes one-way function F_1 with master key K_M as an input. This process continues until hashed value of the computed key is equal to S_1. Then, the computed key is stored as master key K_M and begins computing second one-way function F_2. The key is repeatedly computed until its hashed value is equal to S_2. After that, receiver uses this computed key as a current key for securing communication.

Hint message is a message that provides information for generating current keys and key chains as shown in figure 4.4. The hint message contains two hashed values which are generated from sender as shown in figure 4.2. The first hashed value allows a node to construct a key chain while the second hashed value constructs the current key. In the node, master key K_M is an input of the process. The master key is computed by using the first one-way function to generate the next key. The hashed value of output key is compared to the first hashed value in hint message. When the result does not match, the process re-computes the output with the first one-way function and re-compares the hashed value until the result matches. After that, the second hashed value is compared to the hashed value from the second one-way function. The output from the first one-way function is an input for this process. Then, this second one-way function is iteratively computed until the hashed value matches the hashed value in hint message. The advantage of using a hint message is that transmitting message in shared medium does

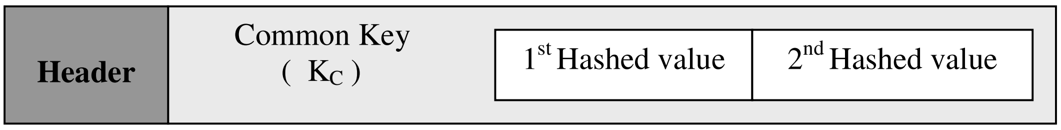


Figure 4.4 Hint message structure where message encrypts 1st Hashed value and 2nd Hashed value with common key K_C.

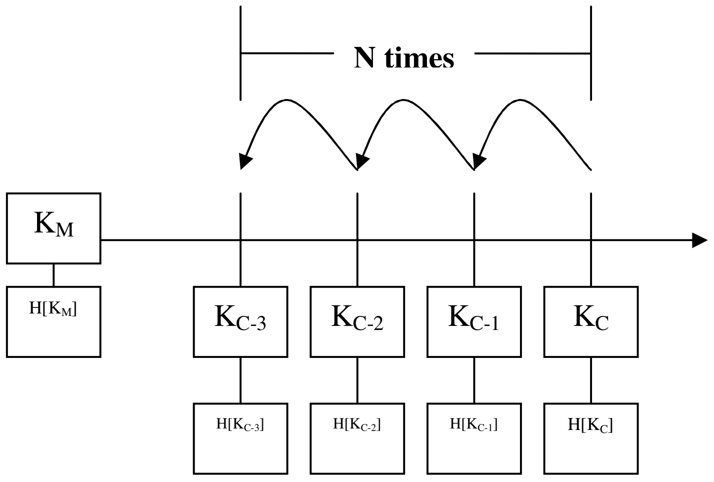


Figure 4.5 Keys stored in memory.

not expose an actual key which means it is more difficult to break the key. In addition, hashed value is smaller fixed size compared to an actual key. Therefore, energy consumption in communication can be reduced. Finally, the process is stateless for generating current key and key chain so they can be constructed from any hint broadcasting. This also assists nodes with packet loss and joining nodes to generate keys.

Updating key procedure. There are two ways to perform the key update procedure. First, updating an entire key chain is computed as shown in sender and receiver parts. Second, updating a current key within the same key chain is quicker and uses less energy for short term purposes. Sender uses the same master key K_M and reduces random number N to compute hashed value. Receiver is not required to compute first one-way function F_1 because it uses the same key chain. To find a current key, it computes a shorter key chain from master key K_M to second one-way function F_2. In the implementation, both sender and receiver do not to need to compute these one-way functions F_1 and F_2 because this key chain has been computed previously. Therefore, sender only looks for hashed value in previous computed key while receiver only matches the received hashed value and the previous computed key. The structure of memory in both sender and receiver is shown in figure 4.5. An example is assumed in which both sender and receiver currently use master key K_M and current key K_C. To update key, sender could randomly select K_{C-1}. Since this key is already computed, sender simply picks $H[K_M]$ and $H[K_{C-1}]$ and then encrypts with common key K_C. Next, it broadcasts to the network. When receiving this message, receiver can obtain $H[K_M]$ and $H[K_{C-1}]$ by decrypting with common key K_C. After that, it searches for hashing value in memory as in figure 4.5 and obtains K_{C-1}. An advantage of this updating key is reducing computation which minimizes both energy consumption and delay. In addition, using a key backward can protect against adversary computing new key from previous key because this key chain is computed from one-way function.

Joining node and **packet loss** are supported by our HKD. Since next round of key updating contains hashed value, joining nodes can generate a current key from initial master key K_M. In packet loss, next hashed value provides sufficient information for receivers to generate a current key. In addition, the hashed value is unique so it ensures the same current key in both senders and receivers. The only drawback is when a joining node in a network has been in operation for some time. The joining node requires more computation time which can cause a delay in communication.

4.1.4 Features

As HKD is implemented with hint message, key chain and key self-generating, it provides a number of features which are described as follows.

The number of messages required in key establishment is reduced. HKD uses key pre-distribution and hint key technique to construct a key so only one message is required. This message contains only a hint for current key which is sufficient for authorized nodes to construct the key. When comparing with SNEP in SPINS [111], at least three messages are required to set up a secure channel. This can enhance system lifetime as well as reduce setting up period.

Keys are generated in each node. In HKD, the base station gives each node a hint so a key can be constructed from this hint. The hint message is the hashed value of the current key. Since authorized nodes have pre-installed key, they can compute current key from the hint. However, hint message does not provide enough information for adversaries to generate keys because a hashed value cannot be computed backward to find the actual key.

Updating key is flexible for base stations. In HKD, the base station can update the key immediately to correspond to the situation by broadcasting hint message. Then, every node will update their key from this broadcast. Therefore, their key can be updated dynamically based on the situation. In addition, the base station can use secret key longer in low risk environment thus energy consumption in updating key can be reduced.

In addition, hint message is very small in size so it can be attached as a part of transmission data. If the system decides to maximize battery lifetime, base station can attach the hint to the first block of data in each session. So receivers can update keys immediately when the message is received. The data is also protected with the updated key in this transmission.

Protocol supports leaving nodes, joining nodes and node failures. Since HKD can update the key by hint message, organization of tree is not necessary. In leaving nodes and nodes failures adjusting or communicating as in ELK [94] is not required. Joining nodes do not require special maintenance because the hashed value in hint message has sufficient information for new authorized nodes to generate the key.

Protocol should minimize resource consumption in key management. HKD uses symmetric cryptography because asymmetric cryptography consumes more energy. This also increases lifetime of the system besides compact communication. Furthermore, HKD is stateless so it does not require a large space in memory. The memory only stores pre-installed key, hints and current keys.

4.2 Adaptive Intrusion Detection System (Adaptive IDS)

4.2.1 Overview

As discussed in chapter 3, key management can protect networks against from external attacks. There is no security protection when communicating among compromised nodes. Therefore, intrusion detection system (IDS) is required to monitor behavior in these compromised nodes. Since traditional IDS is too expensive to directly implement in sensor networks, a new protocol is required for limited resource devices. Chapter 3 also demonstrates that IDS mechanism can be reconfigured and implemented in wireless sensor devices. In addition, distributed IDS also increases coverage and enhances security in sensor networks. However, electing an activated node is a challenge because sensor network structure could be altered frequently and the activated node should be on a high traffic spot. These challenges are considered in the developing of our Adaptive IDS mechanism which is described in the next section.

4.2.2 Mechanism

To develop Adaptive IDS, our objectives are electing a high traffic node and distributing energy consumption equally in the cluster. To reduce energy consumption, each node has an internal clock which triggers for each round of electing nodes (voting round). Our protocol assumes that time is synchronized in every node before deployment. Every node has pre-installed IDS software which can be activated and de-activated. In addition, each node has a threshold number which increases quickly when IDS is activated whereas this number slowly decreases when it does not activate IDS. A diagram of Adaptive IDS protocol is shown in figure 4.6. When a new voting round is triggered, every node broadcasts their voting message to neighboring nodes. Voting messages contain node ID and current time while receivers keep all these messages from neighboring nodes. When the voting timeout occurs, each node counts the received votes. Then, received votes are subtracted by threshold number and kept as voting number. The current time of received messages is sorted to find the median. If the current time of that node differs by a large amount, time is adjusted corresponding to the median time. Then, each node backs off for a period of time with nodes receiving higher number of votes having a shorter backoff time. After that, a node sends a bidding message to inform neighboring nodes that this node has a high voting number. If the receiver has a higher voting number, it will broadcast a bidding message otherwise it will wait for the time out. When bidding period is completed, the node with the highest voting number activates IDS and increases its threshold. On the other nodes, IDS is de-activated and has its threshold reduced, after which the voting procedure is finished. Since Adaptive IDS does not use maximum power for broadcasting voting message, the cluster is separated into many small groups each with an IDS activated node. Furthermore, threshold number can avoid repeatedly activating IDS in the same node so energy consumption is distributed uniformly in the cluster.

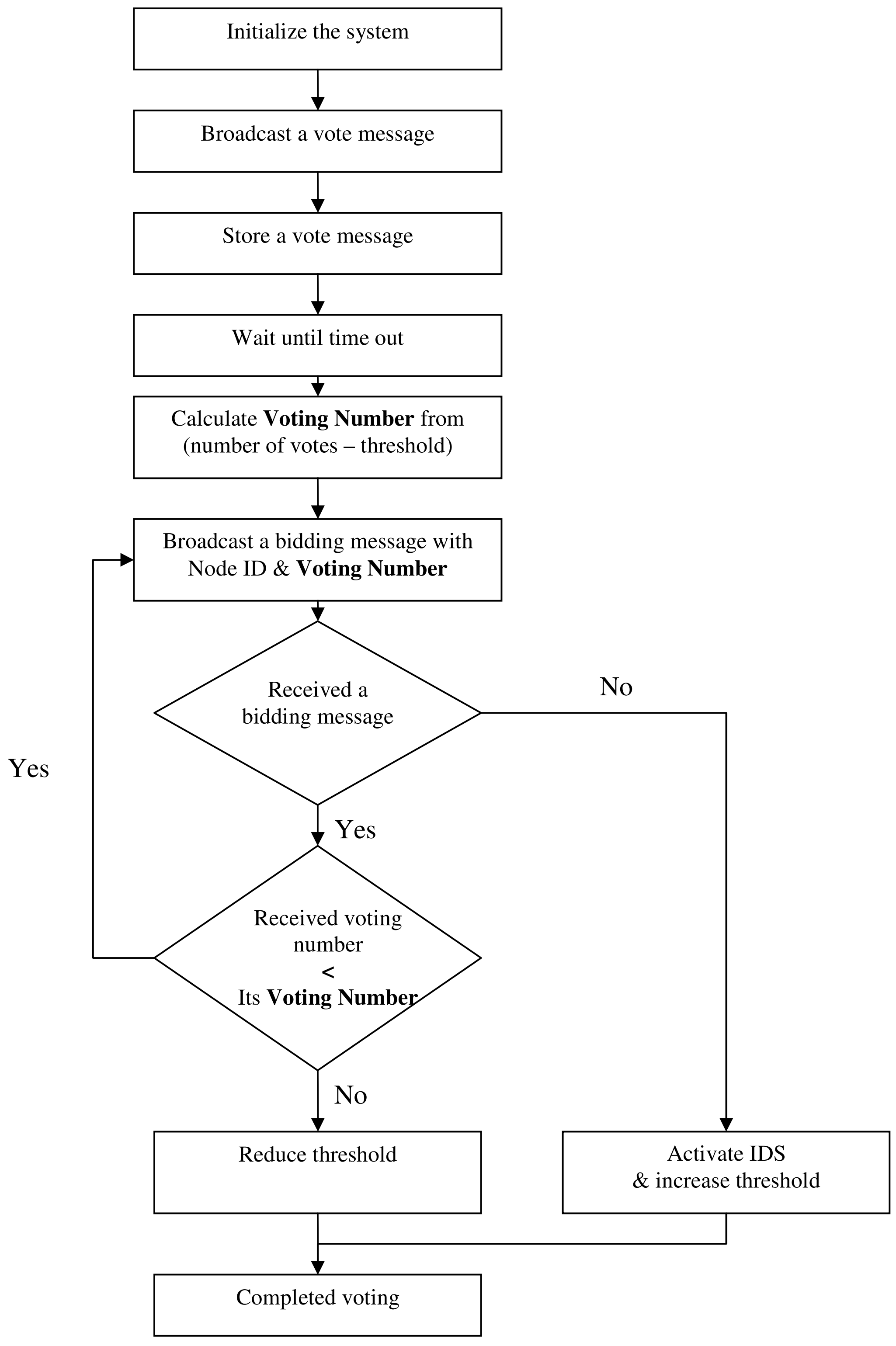

Initialize the system
Broadcast a vote message
Store a vote message
Wait until time out
Calculate **Voting Number** from (number of votes – threshold)
Broadcast a bidding message with Node ID & **Voting Number**
Received a bidding message
No
Yes
Yes
Received voting number < Its **Voting Number**
No
Reduce threshold
Activate IDS & increase threshold
Completed voting

Figure 4.6 Voting procedure in Adaptive IDS for each sensor node.

4.2.3 Implementation

Clock adjustment. In Adaptive IDS, it is assumed that time is synchronized in every node before deployment and inaccuracy in the clock is less than one minute each year. The maximum operation lifetime of sensor network is five years. Therefore, the worst case of time difference is five minutes so Adaptive IDS sets time out for ten minutes for the waiting period. However, time in each node is adjusted based on received message. Therefore, a node should not differ more than one minute. In addition, the adjusted time, which is compared to median of received messages, uses a boundary of one minute. Although there is a transmission delay, the delay in one hop broadcast is an insignificant effect compared to one minute boundary. This procedure is shown in figure 4.7.

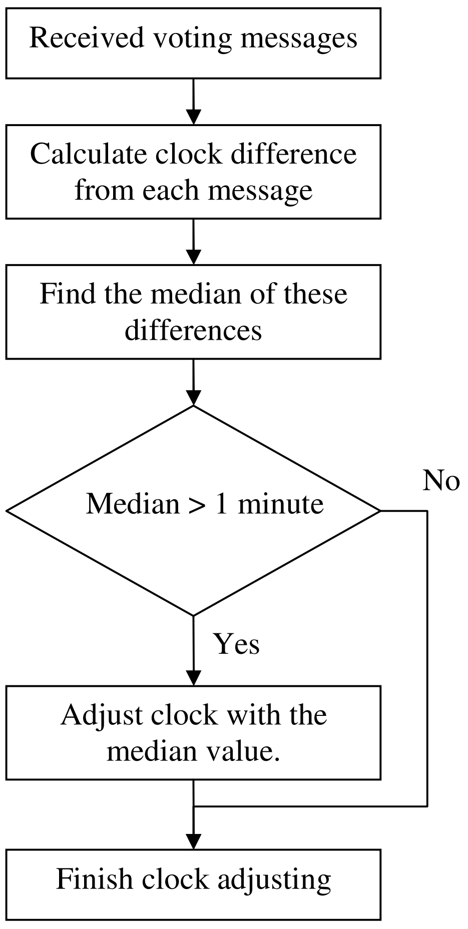

Received voting messages
Calculate clock difference from each message
Find the median of these differences
Median > 1 minute
No
Yes
Adjust clock with the median value.
Finish clock adjusting

Figure 4.7 Clock adjusting procedure in Adaptive IDS for each sensor node.

Threshold. Adaptive IDS uses the threshold number for allocating IDS activated nodes uniformly in the cluster. The threshold number is used to subtract a received voting number so each node is not likely to activate IDS at all times. The threshold number has both an increasing and decreasing delta. The increasing delta is always larger than the decreasing delta. When node activates IDS, the increasing delta is added to the current threshold. The decreasing delta is subtracted from the current threshold when node does not activate IDS in that round. The initial threshold is configured as zero before the deployment where increasing delta and decreasing delta are pre-configured. If the intent is to deploy a dense network, increasing delta can be configured with a large number e.g. more than five while decreasing delta is normally set at one. For example, if the increasing delta is five and decreasing delta is one, it could avoid repeatedly activating the same node for approximately five rounds. However, Adaptive IDS suggests that in general the increasing delta should be set to between two to four while the decreasing delta should use a value of one. This can change IDS activated node and select a high traffic spot.

4.2.4 Features

Adaptive IDS is implemented with voting algorithm and threshold number. Therefore, it provides a number of features which are described as follows.

Activated node should be placed in high traffic area. Since an activated node must respond for both neighboring nodes and itself, it should be the node surrounded by neighbors. Network traffic could be used for measuring density of neighboring nodes. Adaptive IDS mechanism selects a node with the highest traffic in a region so one activated node can cover many neighboring nodes. Voting is used to determine a number of traffic and neighbors because a high number of votes is equivalent to a large number of neighboring nodes. This also demonstrates a chance of intense traffic. Conversely, a low voting number means there is less network traffic passing through that node. As a result, the voting protocol could reduce the number of activated nodes and energy consumption in the cluster. In addition, the high traffic nodes can monitor more events which increase the chance of detecting an attack.

Protocol should consume a small amount of energy. Most energy consumption in sensor networks is in wireless communication. To save in energy consumption, the number of exchange messages in protocol should be minimized. Adaptive IDS protocol requires transmitting one voting message for every node and one bidding message for activated node. Therefore, Adaptive IDS protocol requires an average of two messages for activated node and an average of one message for non-activated node. In addition, it does not require any complicated process to elect activated node. Therefore, only a small amount of energy consumption is required for Adaptive IDS.

Energy consumption in activating IDS should be distributed equally in the cluster. Adaptive IDS protocol is such that activated node always monitors network and battery could run out quicker than non-activated node. In general, Agent-based IDS always selects the highest traffic nodes to activate IDS [128, 129]. However, a sensor network should not repeatedly activate the same node until the battery runs out because network will lose high traffic nodes which are the nodes with most connectivity. Furthermore, sensor network has a large number of nodes and large coverage areas so an objective must be to maintain the largest number of nodes in order to increase the system lifetime. Therefore, Adaptive IDS introduces a threshold number to activate different nodes in different rounds. The threshold number increases quickly when IDS is repeatedly activated while it decreases slowly when IDS is not activated. As a result, energy consumption of IDS is shared by the entire cluster.

4.3 Cooperation between HKD and Adaptive IDS

4.3.1 Overview

An intention in developing HKD is for securing network communication with secret key while consuming only a small amount of energy in sensor networks. To develop Adaptive IDS, our intention is to provide distributed IDS in sensor networks where energy consumption is also uniformly distributed. Cooperation between HKD and Adaptive IDS can reduce the individual weakness and strengthen the security because HKD protects the network by data encryption. Adaptive IDS monitors internal network behavior for malicious events and attacks. In addition, the mechanisms in both protocols can support each other. The voting message in Adaptive IDS can be encrypted by using current key from HKD in order to avoid message tampering and replay attack. In addition, Adaptive IDS can inform the system if the current network is under attack so HKD can update a new key chain immediately. Adaptive IDS can also detect misbehavior if intruders attempt to corrupt an updating key in HKD. Therefore, cooperation between HKD and Adaptive IDS can enhance the network security for both external protection and internal detection.

4.3.2 Mechanism

Both Adaptive IDS and HKD operate in the application layer. However, they require information to be exchanged to improve efficiency.

Adaptive IDS information. Adaptive IDS provides protection for a situation of network and provides alerts when network is under attack. The situation may be categorized into normal situation, suspicious situation, alert situation and extreme risk situation. A normal situation is a situation in which IDS does not detect any violation from the network so HKD could use current key chain longer to reduce energy consumption. A suspicious situation is a situation in which IDS detects some rules

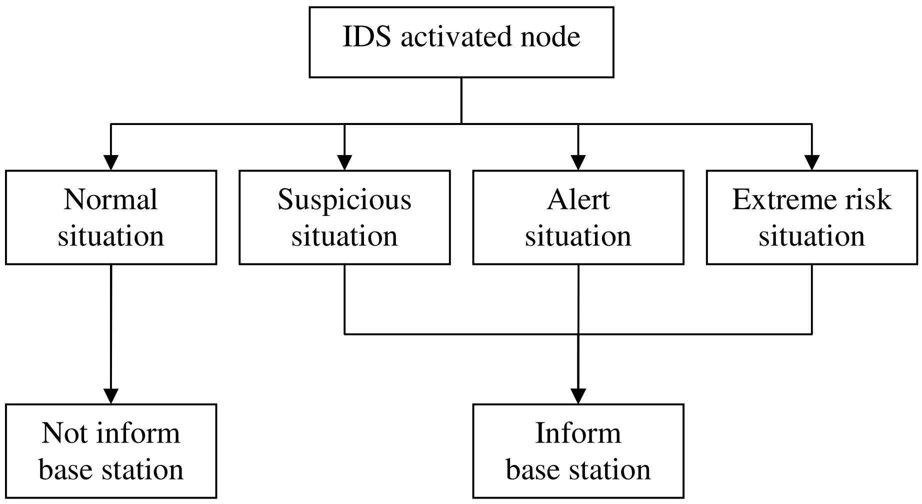


Figure 4.8 Exchange information procedure for Adaptive IDS.

violation but still does not trigger the alert signal. HKD could shorten the period of using the current key and change key chain regularly. Alert situation is a situation in which IDS has found a critical rules violation so HKD immediately changes the current key and key chain to secure the network. Finally, an extreme risk situation is a situation in which IDS has identified a critical attack and HKD cannot update key chain e.g. due to jammed signal. Network should apply the strongest policy e.g. apply RSA or re-start the entire network.

HKD information. HKD provides a status of key management in the network. The status can be classified as management status or activity status. Management status is categorized as normal management, trust management and secure management. Normal management uses the same key chain for a period of time while trust management uses the same key chain for longer period because there is no suspicious event reported from Adaptive IDS. Therefore, a system can save more energy. In secure management, key chain is updated more often when Adaptive IDS raises an alert signal. Activity status is categorized into idle, key updating, key chain updating and error. When there is no activity in key management, it is called as idle. Key updating and key chain updating are

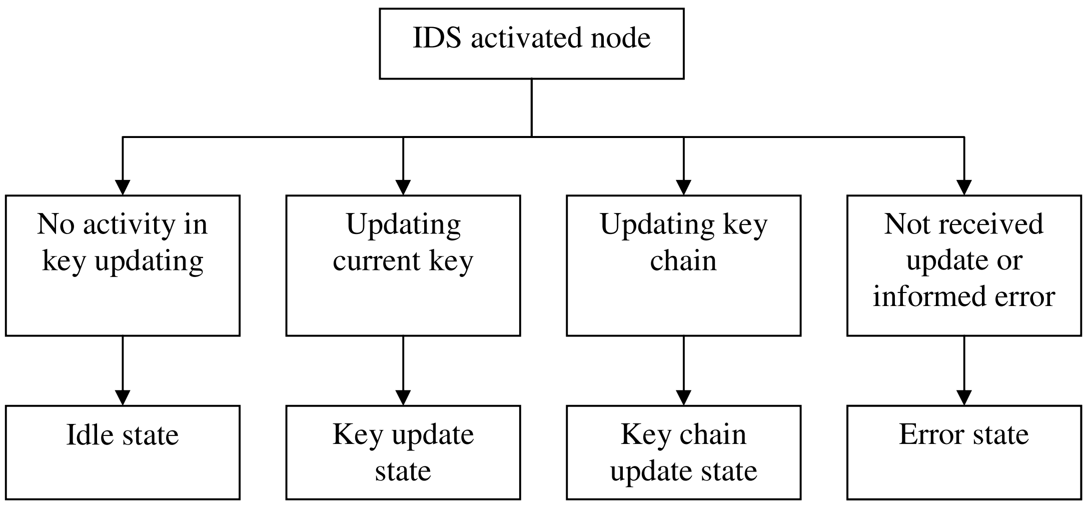


Figure 4.9 To distinguish activities of HKD in IDS activated node.

informed to Adaptive IDS when base station broadcasts the updating message. Error state demonstrates a confliction of key management in base station or difficulty in transmission of the updating message. This information is sent to Adaptive IDS for improving monitoring in each situation.

4.3.3 Implementation

To exchange information, base station and IDS activated nodes are required to cooperate. Since intrusion detection system operates in activated node which is placed around the field, these activated nodes are required to inform HKD of the current situation. As HKD is operated by base station, IDS activated nodes and base station need to exchange updated information. However, increasing transmitted packets is equivalent to increasing energy consumption in sensor nodes. Adaptive IDS does not require transmission of updated information in a normal situation. Therefore, it only informs base station in dangerous situations including a suspicious situation, alert situation and extreme risk situation. A diagram which illustrates this is shown in figure 4.8.

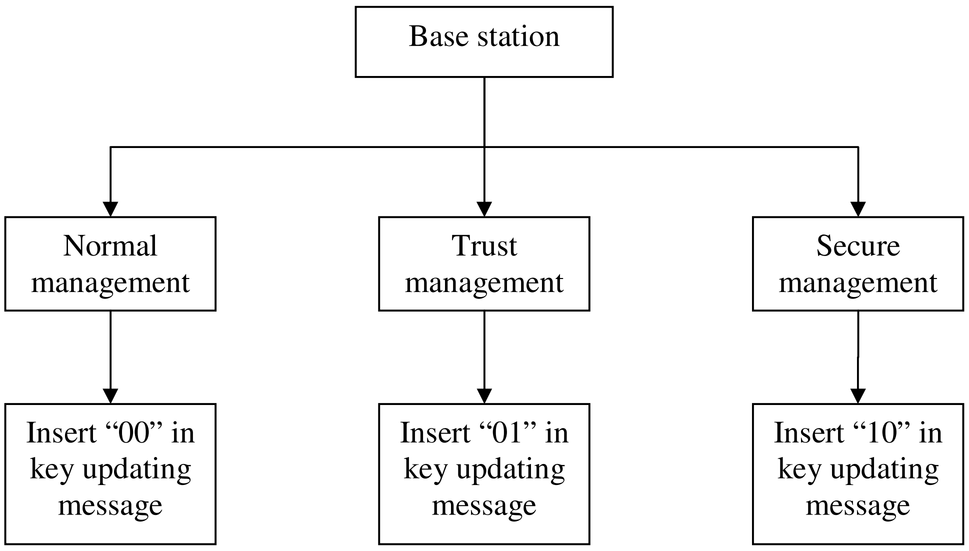

Base station
Normal management
Trust management
Secure management
Insert "00" in key updating message
Insert "01" in key updating message
Insert "10" in key updating message

Figure 4.10 Informing current key management from HKD to IDS activated nodes

To implement, base station is not required to inform Adaptive IDS of the current key management activity because these nodes can classify these activities from broadcasting message. For example, Adaptive IDS recognizes idle state when base station does not broadcast an updating message. Key updating and key chain updating state are recognized when base station broadcasts updating messages. In addition, error state is recognized when Adaptive IDS does not receive the updating message for a long period or receives the error state message from base station. A diagram of these states is shown in figure 4.9.

For management status in HKD, base station informs the IDS activated nodes by inserting current status in key updating message. When the IDS activated nodes receive the key updating message, they also recognize the current management status. For example, key updating message has 2 bits for current management status where normal management is represented with "00", trust management is represented with "01" and secure management is represented with "10". A diagram which illustrates these tasks is shown in figure 4.10.

4.4 Conclusion

In summary, this chapter demonstrates our proposed solution for security in sensor networks. There are two main components in the system: Hint Key Distribution (HKD) and Adaptive Intrusion Detection System (Adaptive IDS).

Hint Key Distribution (HKD) manages key distribution in the network by using the base station. The base station generates and broadcasts hint messages to the network. The hint message contains hashed value of current key chain and current key so authorized nodes can construct keys corresponding to this information. Keys are constructed from iterative computation of two one-way functions. In addition, hint message supports joining nodes and packet loss because key construction is stateless. An important benefit in HKD is the minimizing of energy consumption in communication while the base station can dynamically update key based on the situation.

Adaptive Intrusion Detection System (Adaptive IDS) is a process for selecting an IDS activated node in the network. As distributed IDS enhances coverage and security, some sensor nodes should activate IDS. Adaptive IDS uses voting algorithm with a threshold to select a high traffic node to activate while avoiding repeatedly activating the same node. Since monitoring the network is an energy intensive activity, repeatedly activating the same node could exhaust the battery quicker than the other nodes. Ideally, all nodes should have an equal lifetime. Therefore, our threshold method in Adaptive IDS ensures that uniform energy consumption in IDS is maintained in the sensor network. In addition, Adaptive IDS protocol consumes a small amount of energy in voting procedure where messages transmitted is on average two messages in activated nodes and one message in non-activated nodes.

As a cooperative system, both HKD and Adaptive IDS can improve efficiency by sharing information. HKD provides a management status and set of possible current activities. Management status is categorized into normal management, trust management and secure management. Current activity is categorized into idle, key updating, key chain updating and error state. In Adaptive IDS, there are four situations including normal situation, suspicious situation, alert situation and extreme risk situation. The IDS activated node is required to inform base station in suspicious, alert and extreme risk situations. In normal situation, IDS does not detect any rules violation so HKD can use a current key for a longer period to save energy. In suspicious situation, IDS detects a minor rules violation so HKD updates current keys regularly. In an alert situation, IDS detects critical violation and triggers the alarm so HKD updates key chain immediately. In extreme risk situation, IDS raises an alarm and HKD cannot update the key immediately so base station applies the strongest policy e.g. restart the entire network.

To implement both protocols, network is protected from external attack by key management HKD while internal attack is monitored by Adaptive IDS. Also, energy consumption in the protocols is kept to a minimum to ensure that both protocols are usable in sensor networks. Furthermore, the cooperation between the two protocols improves dynamic operation so energy consumption is reduced in a safe environment while security is strengthened in a dangerous situation.

Chapter 5. Evaluation

This chapter gives an evaluation of HKD, compared with ELK and SPINS in key management. In the second section, Adaptive IDS is compared with Agent-based IDS [128, 129], core and boundary defense. The chapter begins by description of metrics, parameters and scenarios in the evaluation. Models are then constructed. Finally, cooperation between HKD and Adaptive IDS is analyzed and compared with the non-cooperative protocol.

5.1 Hint Key Distribution (HKD) Evaluation

This section describes metrics for evaluating key management including HKD, ELK and SPINS. Then, we define the operational scenarios in the evaluation. Finally, the performance of HKD, ELK and SPINS are analyzed and discussed.

5.1.1 Metrics of Performance

5.1.1.1 Security Strength

This metric is required to determine the strength of security from attacks including brute force attack, known plaintext attack, replay attack, man-in-the middle attack and denial of service attack. Since a main objective of key management is to prevent intruders, the attacks on protocols must be evaluated.

5.1.1.2 Resource Usage

The metric considers the amount of energy consumption in communication and computation. As communication is the most energy intensive activities in sensor networks, it must be minimized. This metric also determines the system lifetime for the protocol operations.

Sensor network devices have a limited resource so protocol must use this resource efficiently. Processing time and memory are also considered because these are limited in sensor networks.

5.1.2 Parameters of Evaluation

Parameters of the key management evaluation are explained. These parameters are considered in security and resource usage.

5.1.2.1 Security Strength

Simulated attacks are used for evaluating key management because they demonstrate the resistance of protocols against a cryptographic analysis which adversary uses for breaking the key. Key space is a parameter that is used in comparison of the security strength because a larger key space means a longer time to break the key. In addition, each attack exploits different vulnerabilities. Brute force attacks can be used as a benchmark to estimate an average time to find the current key. Known plaintext attack is evaluated with the situation that part of the information is exposed so the time to find the current key is expected to be reduced. Replay attack is evaluated whether or not the protocol is vulnerable to message replay. Similarly, vulnerabilities of the man-in-the-middle attack are evaluated.

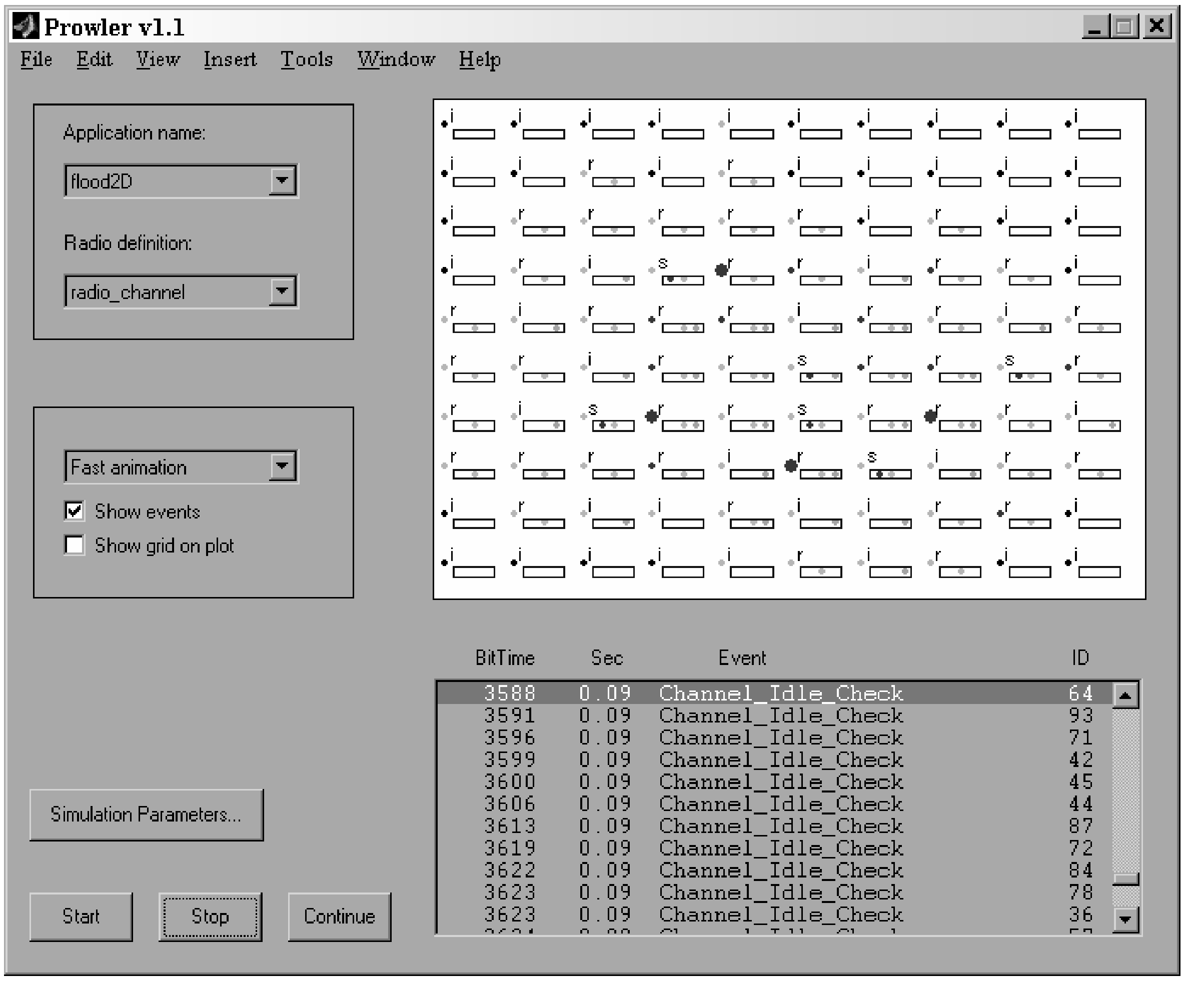
5.1.2.2 **Resource Usage**

The number of messages, message size and frequency are used as parameters because communication is the most energy consumption in sensor networks. The evaluation uses this information to calculate an estimation of system lifetime.

Processing time is used to determine the computing capability of Central Processing Unit (CPU). Memory size is also needed to determine the requirements in implementing protocols because sensor network devices have limited memory size.

5.1.3 Evaluation Scenario

To standardize the evaluation, SmartDust [102, 133-137], Strong Arm chips [102, 138] and Xscale [102, 139-142] are used as analysis platforms. Power is supplied from 3 volts battery with capacity of 2,200 mAh. Our model sets up 10 nodes in each cluster and sampling rate is 1 Hz with 50 Kbps bandwidth. Wireless communication consumes 4.8 mA in receiving and 12 mA in transmitting. In idle mode, energy consumption rate is 5 μA. In addition, there is end-to-end data communication between node A which is a base station of the cluster and node B which is placed in the cluster. A path between A and B is connected along the nodes in the same cluster as: $A \rightarrow n_1 \rightarrow n_2 \rightarrow \ldots n_m \rightarrow B$. This network also has a routing path set up. Each node in network has a strong physical protection. Adversaries cannot break the device to retrieve the key or data inside directly. Also, the length of secret key is evaluated with 40 and 128 bits. To compute the key chain, MD5 and SHA-1 are used as hint functions (H) to evaluate the protocols.



Application name: flood2D

Radio definition: radio_channel

[✓ Show events]

Show grid on plot

```
BitTime   Sec    Event                ID
 3588     0.09   Channel_Idle_Check   64
 3591     0.09   Channel_Idle_Check   93
 3596     0.09   Channel_Idle_Check   71
 3599     0.09   Channel_Idle_Check   42
 3600     0.09   Channel_Idle_Check   45
 3606     0.09   Channel_Idle_Check   44
 3613     0.09   Channel_Idle_Check   87
 3619     0.09   Channel_Idle_Check   72
 3622     0.09   Channel_Idle_Check   84
 3623     0.09   Channel_Idle_Check   78
 3623     0.09   Channel_Idle_Check   36
```

Figure 5.1 GUI of Prowler software [143].

Adversaries have Sun UltraSparc II 440 MHz server. The UltraSparc is 64 bits RISC based on architecture with 16 KB data cache and 2 MB external cache. Its wireless antenna can reach the entire network. When an adversary launches attacks, it can be initiated from anywhere along a path.

The Prowler software [143] is a simulator used for the security strength and energy consumption. Prowler is a wireless network simulator which is based on MATLAB. The simulator is based on an event-driven model and supports graphic interface as shown in figure 5.1. The operation of nodes is developed on an event basis as shown in figure 5.2. For periodic tasks, clock parameter or Clock_Tick could be used for

```
switch event
case 'Init_Application'
    signal_strength=100;
    %%%%%%%% Memory  initialized here %%%%%%%%%%%
    memory=struct('send',1, 'signal_strength',
signal_strength);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if ID==1 % first node starts flood
        Set_Clock(1000)
    end
case 'Packet_Sent'
    % do nothing
case 'Packet_Received'
    if memory.send
        p=sim_params('get_app', 'P');
        if rand<p
            Send_Packet(radiostream(data,
memory.signal_strength));
        end
        memory.send=0;
    end
case 'Collided_Packet_Received'
    % this is for debug purposes only
case 'Clock_Tick'
    Send_Packet(RadioStream(data,
memory.signal_strength));
end
```

Figure 5.2 Example of source code in Prowler [143].

assigning the task. A wireless communication is built in the program which can adjust the parameters e.g. signal strength and error rate. Our adversary in simulator is also developed in this Prowler with high processing capability (UltraSparc II) and high transmitting power. Sensor network nodes are equipped with limited capacity battery and less transmitting power than adversary. The energy consumption varies with signal power, message size and activities. Simulation results are exported to MATLAB for further analysis.

5.1.4 Performance Model

This section presents the theoretical model of ELK, SPINS and HKD security strength and resource usage metrics.

5.1.4.1 Performance of ELK

Security Strength. For the number of key bits n, key space is 2^n. The adversary is required to compute at least 2^{n-1} keys in brute force attack [94]. To update key, hint message is used to hide an actual key from the adversary. In addition, the adversary has some difficulties in obtaining the group key because a cluster contains a large number of nodes. This is a significant advantage in sensor networks because network size tends to be hundreds or thousands nodes.

Resource Usage. Energy is used to compute and broadcast messages in the established tree when nodes join or leave the network. When nodes are joining, each node can compute individually without broadcasting messages. To update the key, a hint message is broadcast in order to allow new key to be constructed. The best scenario for effective energy consumption is that each node updates its key without broadcasting messages. This only requires small computation and memory. In the average case, hint messages are broadcasted so each node needs to consume power in communication and computing new key. The hint message size corresponds to the number of left and right contribution nodes in the tree because hint messages are generated from all keys in child nodes. In the process of key construction, firstly a message is decrypted, and secondly to match with the hint, the key is computed. The worst case scenarios are both setting up tree and leaving nodes. The server begins computing a new key, which corresponds to the current existing nodes, and broadcasts the updating message. Each node, then, computes its key. Therefore, it requires the number of messages to verify the status of tree and broadcast updating messages as well as computing key in each node.

As tree structure needs to be maintained, a regular communication is required for ELK. In addition, this protocol does not support packet loss because the consecutive packet loss can be interpreted as leaving node, and consequently tree needs to be re-constructed. Furthermore, changing key in the child nodes requires the entire parent nodes to be updated, which is quite expensive. For concrete evaluation, the result is shown in next section.

5.1.4.2 **Performance of SPINS**

Security Strength. Key space is 2^n where n is key bits, so brute force can find the current key on average by computing 2^{n-1} times. Yet, decrypting message requires two keys so brute force needs to compute at least 2^n keys. To find a key chain, key space is $N \cdot 2^n$ where N is the maximum number of possible keys in the key chain. However, adversaries have a difficulty in obtaining number N because it has never been stated in any message. Therefore, adversaries require computing all possibilities by beginning from small number of N. For example, $N \cdot 2^n$ where N begins from 1, 2 … ∞. Hence, the maximum computing time of a master key is $N! \cdot 2^n$. When a base station updates a new key chain, an adversary is required to re-compute this key chain again. Therefore, a key chain is protected by security that is higher than that for a simple key. In addition, a key chain is regularly updated, thus the key chain is secured in a period of time.

Resource Usage. With SmartDust node, 98% of energy consumption is from communication which can be categorized into data transmission with 71%, header transmission with 20% and Nonce transmission with 7%. Computation uses only 2% of energy cost as shown in table 5.1. Although most energy consumption is from communication, it is a common behavior in sensor networks. In computing, processing time in key set up is 3.92 ms [111]. Memory uses 120 bytes for the protocol. Therefore, SPINS demonstrates a capability of implanting security in sensor nodes.

71%	Data transmission
20%	Header transmission
7%	Nonce transmission (Freshness verification)
2%	Encryption computation

Table 5.1 Energy cost in SPINS [111].

5.1.4.3 **Performance of HKD**

Security Strength. Key space is 2^n for current key where n is key bits so an average 2^{n-1} computation is required for brute force attack. To compute the current key chain, the key space is $N \cdot 2^n$ where N is the maximum number of possible keys in each key chain. To find a master key in HKD, key space is $L \cdot N \cdot 2^n$ where L is a number of possible key chains. However, adversaries have difficulties in obtaining numbers L and N except the node that has already obtained all master keys, key chains and current keys because there is no information stated on the numbers. Since the number of L and N could be varied from zero to infinity, it is infeasible to calculate the maximum number of L and N in one time. The adversary requires computing from smaller numbers of L and N. Ideally, the adversary begins computing each set as follows.

(L=1, N=1), (L=1, N=2) … (L=1, N=N);

(L=2, N=1), (L=2, N=2) … (L=2, N=N);

…

(L=N, N=1), (L=2, N=2) … (L=L, N=N).

Although the adversary could keep the previous computing numbers L and N, it is infeasible to store the previous 2^n x L x N in UltraSparc II. Therefore, the adversary needs to re-compute numbers L and N. As a result, the maximum computing time of key chain is $N! \cdot 2^n$ while the maximum computing time of master key is $L! \cdot N! \cdot 2^n$. Therefore, master key is the largest key space in HKD which is equivalent to the most secure key.

Resource Usage. As HKD uses the similar one-way function as SPINS, memory usage is equal to 120 bytes. However, key set up requires the comparison of hint so it requires more 80 bytes. In addition, key chain needs to be stored in memory all the times. If key size is 64 bits, 80 bytes of memory is required for key chain size of 10. Therefore, the total memory is approximately 280 bytes. In simulation, 400 bytes memory is reserved, but on average it uses 200-350 bytes. In communication, energy use is less than SPINS because the number of communication is reduced and message size is smaller. The details are demonstrated in next section.

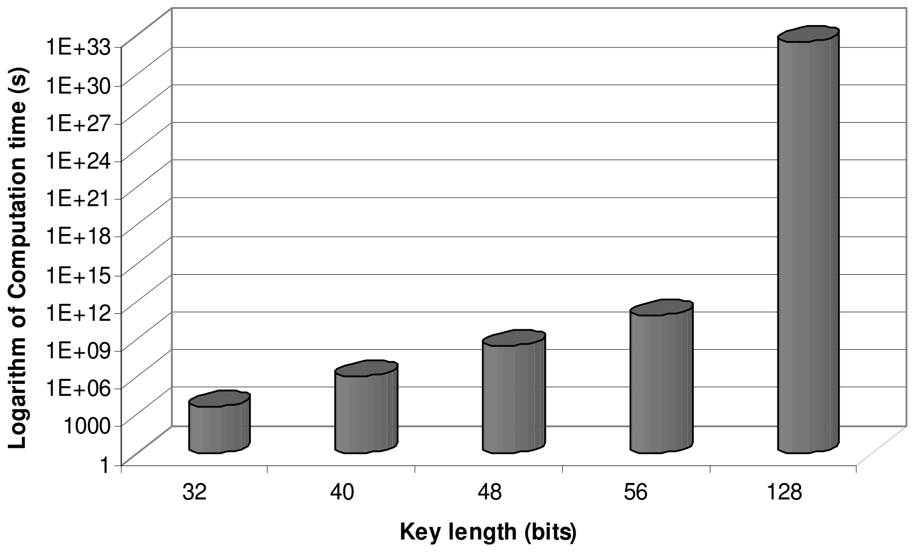


Figure 5.3 Logarithm of computation times for current key in brute force attack.

5.1.5 Evaluation

5.1.5.1 Security Strength

ELK, SPINS and HKD are evaluated from brute force attack plain attack, replay attack, man-in-the middle attack and denial of service attack.

Brute Force Attack is computed by adversaries and described in section 5.1.3. In general, a larger key space increases the time of finding the correct key. As shown in figure 5.3, increasing key bits increases a computation time. In these three protocols, the strength of the current key is based on the number of key bits. The larger key bits show a stronger security is similar as an ideal model. For example, to compare between 128 bits key and 64 bits key, it is necessary to make brute force compute the average 2^{127} and 2^{63} times respectively. Therefore, usage time in computation increases by 1.84×10^{19} times. In SPINS, a decrypting message must use two keys: current key and second next key. Therefore, brute force must use two times more than the others or 2^n. As UltraSparc II computes each key in 2 μs [144], it requires 1.10×10^6 seconds (~12.7 days) for 40 bits key. To compare with 128 bits key, it requires 3.4×10^{32} seconds (~ 1.08×10^{25} years).

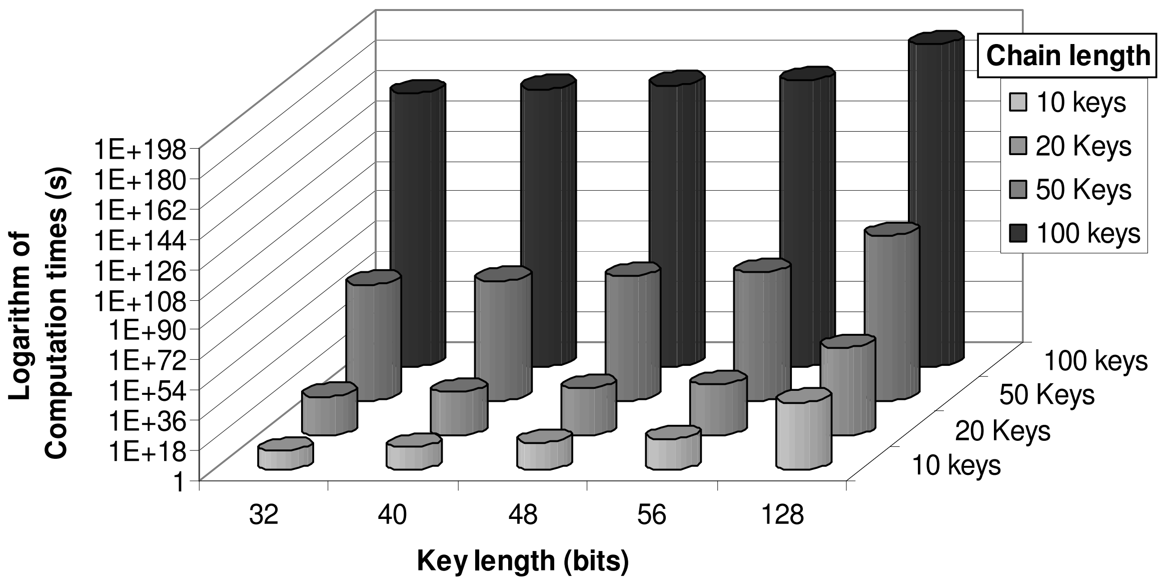


Figure 5.4 Logarithm of computation times for the key chain in brute force attack.

Therefore, the protection of a current key from these three protocols is sufficient for a general use because a key is often changed. However, sensitive data should use a larger key such as 128 bits.

SPINS and HKD use a key chain to generate a current key whereas ELK does not have a key chain. A key chain is expected to be more secure than a current key because it can generate all the keys for a period. As shown in figure 5.4, a larger key chain increases computing time in an adversary. In practice, the number of keys in each key chain is unknown so adversary needs to compute all key chain sizes. For example, if the maximum key chain size is 10 in UltraSparc II, brute force will find 40 bit key chain in 3.99×10^{12} s (1.27×10^{5} years) and 128 bits key chain in 1.23×10^{39} s (3.91×10^{31} years).

A master key in HKD is protected with more key space which the size is $L! \cdot N! \cdot 2^n$ as explained in section 5.1.4.3. Since number L is added in the previous round, the total value of number L increases each round. Therefore, key space increases every key updating. For example, if L is in the range [1, 2, 3 ..., 10], then the maximum number of L is 10. Key space for master key is $10! \cdot N! \cdot 2^n$ in the first round. However, after 10 rounds key space increases to $100!\cdot N!\cdot 2^n$ which is 2.57×10^{151} times larger. Therefore, a master key is protected more secure than a key chain and a current key in HKD.

In brute force attacks, although the current key in ELK, SPINS and HKD has the same key space size, SPINS has the advantage in using two keys for the decryption of messages. ELK lacks regular updating in individual current key because a group key is based on other node keys. To update a key in one child node, all parent nodes also need to update their keys. However, ELK has an advantage in the group key because a larger number of nodes increase difficulty for the adversary to break the group key. For the key chain in both SPINS and HKD, key space has the same size so it has the same security strength. In addition, HKD master key is the most secure key, especially when key chain is updating many times.

In a long term, the current key is periodically updated in these three protocols so the adversary must obtain the current key in a short period of time. Since the key chain in SPINS and HKD is used backward, it ensures that the adversary could not generate the next key. In ELK, next key depends on the other nodes. If the adversary does not obtain the other node's key, it cannot generate the next key. A master key in HKD is not renewed regularly so it has more risk than SPINS. Although HKD does not expose information of master key, if the adversary can obtain related information, it is a risk for HKD.

Known Plaintext Attack is an attack where an adversary obtains a part of information to assist in revealing the key. Since this information is a clue for the key, the key space is reduced corresponding to the information. Group key in ELK and the current key in both SPINS and HKD are vulnerable to this attack to the same extent. In our simulation, when the adversary has retrieved sufficient information to cut the key space down to 50%, it reduces computation times by more than 99%, compared to a brute force attack. According to our case study, in brute force attack, 40 bits key is originally revealed in 1.10×10^6 s (12.7 days), reduced to 104.5 s (1.7 minutes). Therefore, the current key with small bit number is crucial with this attack. Although key chains in ELK and HKD are still difficult to break, they can be critical when combined with other attacks. In the case of master key in HKD, a hint message does not expose any information or is related knowledge so it is not vulnerable to this attack.

	SPINS	HKD	ELK
Regular renew key	√	√	
Regular renew key based on event			√
Regular renew key chain	√	√	
Regular exchange information among nodes	√		√
Regular verify time counter (Nonce)	√		

Table 5.2 Security features in each protocol.

Replay Attack is an attack in which transmission messages are repeated or delayed. In SPINS and HKD, a current key is updated regularly compared to updating on event basis in ELK. Therefore, these two protocols ensure the freshness of the key to avoid the adversary using replay message. In addition, SPINS has a benefit in using a nonce which is a counter for protecting network from replay attack. As a result, SPINS is the only protocol in these three protocols that has a nonce in the communication, therefore it is the most secured against replay attack.

Man-in-the-middle Attack is an attack that focuses on the weakness of sender and receiver validation. In ELK, SPINS and HKD, security only relies on a current key. It is sufficient to protect real time and general data, but not sensitive data. When a current key is revealed, the attack could do major harm to the network including substitution and phishing attack. So, the sensitive data requires encrypting with another password.

Denial of Service Attack (DoS) is one of the most severe attacks in sensor networks since it could jam network and burn out the batteries. It can also operate in the physical layer which these protocols cannot control. Our simulation shows that DoS can empty the battery in sensor nodes by continuously transmitting messages for 1.24 days. In the case that the adversary can encourage sensor nodes to reply the messages, it could empty the battery in 9.69 hours in the worst case scenario. The consequence from high power signal is that network could be jammed and blocked from surrounding nodes.

In summary, security of the current key in ELK, SPINS and HKD is roughly equivalent in general use. However, SPINS has better security protection by using two

Protocol	Message size (bytes)	Estimated operation time (days)
ELK (best case)	23-38	967
ELK (average)	23-38	108
ELK (worst case)	23-38	53
SPINS	598	277
HKD	64	715

Table 5.3 Energy consumption in communication for each protocol.

keys in decrypting message although key space does not significantly increase. Key chain in both SPINS and HKD is secured with a larger key space ensured a longer computing time for attackers. In addition, a master key in HKD has the largest key space among all the keys which are equivalent to the most secure key. However, HKD does not renew the master key regularly so it could be revealed in a long term. Furthermore, all three protocols only rely on the key, so the adversary could do harm to the network if a key is revealed. Finally, all three protocols are not able to resist a denial of service attack.

5.1.5.2 **Resource Usage**

This section evaluates ELK, SPINS and HKD in resource usage and energy consumption. As wireless communication is the most energy consumption in sensor networks, our simulation focuses on the message transmission

Table 5.3 is the simulation result which shows the energy consumption in HKD, SPINS and ELK. This simulation focuses on the message size and system lifetime. The estimated system lifetime is calculated from protocol operations which neglect sensors and non-related operations. ELK (best case) updates the key by self-generating with the low number of messages. In ELK (average), hint messages and tree maintenance messages are used. ELK (worst case) needs to re-organize tree structures frequently due to packet loss and leaving nodes. Therefore, exchanging messages and many key updates are required. In SPINS and HKD, the protocols do not reflect the structure of network so simulation uses the average scenarios.

The result shows that the expected lifetime in HKD is almost three times greater than SPINS because SPINS requires an authentication among the nodes before transmitting the data. In addition, ELK (average) and ELK (worst case) consumes more energy than HKD because ELK uses a tree to distribute keys, which are opposed to traditional broadcasting in HKD. Additionally, a leaving node in lower branch of the tree in ELK requires many messages to adjust the tree as well as update the key. Although ELK (best case) shows the best performance, it rarely occurs in practice because sensor networks are unreliable and many unexpected events often occur. SPINS demonstrates the average performance among three protocols because it reduces the number of communication and uses a self-generating key. HKD shows the best energy consumption because it uses only one broadcasting message to set up the key while joining nodes do not need the extra communication. In addition, packet loss does not affect the key generating in HKD.

In computing resource, our simulation uses MD5 as a hash function. MD5 consumes 0.59 µJ/byte, which can be compared to 3DES computation 6.04 µJ/Byte [144]. So sensor nodes have the capability to compute this function and are also able to perform HKD. High power processor Strong Arm chip computes each MD5 140 µs in small wireless network device [144]. In simulation, random numbers L and N are in the range of 1, 2, 3 … 20. On average, MD5 is required to be computed 20 times (average 10 times each for L and N). This equals to 2.80 ms (140 µs x 20 times). To compute MD5 in low power CPU (Xscale in energy safe mode), it requires 180 µs [144] for each computation or 3.60 ms (180 µs x 20 times) per key distribution. HKD uses the similar one-way function as in SPINS. Therefore, the total operation time is the sum of hash function and one way function. As each one way function uses 3.92 ms, two one way functions use average 7.84 ms. The total time in generating key in HKD is between 10.64 ms and 11.40 ms. Therefore, our simulation ensures that computation time in HKD does not exceed the capabilities of a sensor node. However, this processing time is more than 3.92 ms in SPINS. In ELK, it is the worst performance in simulation because operations in the protocol are involved with asymmetric cryptography. It uses up to 2 minutes for

	HKD	SPINS	ELK
Not require re-organizing structure	√	√	
Self-generating key	√	√	
Support packet loss	√	√	
Construct key from hint message	√		√
Not require exchanging information	√		

Table 5.4 Energy saving feature in each protocol.

generating key in the deep tree hierarchy. In summary, the highest computation time is for ELK which is a large difference from HKD and SPINS because ELK does not focus on energy consumption and using asymmetric cryptography. SPINS uses the average energy consumption while HKD saves most energy because of the least communication messages.

ELK uses the largest size memory because of asymmetric cryptography. In the 10 levels tree, 6.86 MB is used to compute a key which is infeasible for sensor nodes. SPINS uses only 120 bytes memory for the protocol. In addition, HKD uses 280 bytes in the memory. Therefore, both SPINS and HKD could be implemented in sensor nodes while SPINS is the most efficient in memory usage.

In conclusion, approximately 98% of energy usage in the protocols is from communication task as shown in table 5.1. The larger bits keys provide a significant improvement in security networks as shown in figure 5.1 and 5.2. The characteristic of the protocols are shown in table 5.2 and 5.4. Finally, the comparisons of energy consumption in these protocols are shown in table 5.3. ELK uses an excessive resource especially memory and CPU which are infeasible to implement in sensor networks. The reason is that ELK uses asymmetric cryptography and it does not focus on minimizing the resource usage. In SPINS, memory and CPU usages are the lowest among three protocols followed by HKD and ELK respectively. In addition, HKD uses the lowest energy in operation. Therefore, HKD can enhance the most system lifetime. However, it still uses memory and CPU processing more than SPINS.

5.2 Adaptive Intrusion Detection System Evaluation

This section describes metrics that are used to compare Adaptive IDS to Agent-based IDS [128, 129], core defense and boundary defense. We also define the operational scenarios to be used for evaluation. Finally, a comparison of Adaptive IDS and the others is analyzed and discussed.

Adaptive IDS is described in section 4.2. The protocol selects high traffic nodes to activate IDS. These nodes monitor the network for suspicious events and raise alarm when needed. The voting algorithm ensures that selected nodes are in the traffic areas so the number of activated nodes can be reduced. In addition, threshold number in the algorithm expects to reduce the repeated activating in the same nodes.

5.2.1 Metrics of Performance

5.2.1.1 **Efficiency in Distribution**

The metric analyzes coverage area to determine the effectiveness of IDS distribution. The main objective in distributing IDS activated node is to increase coverage, so the coverage area needs to be evaluated. In addition, the distribution should be evaluated on the basis of the efficiency of spreading IDS activated node. In ideal model, distribution should select nodes uniformly.

5.2.1.2 **Energy Consumption**

Energy consumption in distributing IDS is the most important constraint for sensor networks. Since sensor networks require a long period operation, the energy consumption in distribution must be at a minimum level. The energy usage in distributed IDS involves communication and IDS activation. Therefore, the number of messages and activated nodes should be at a minimum.

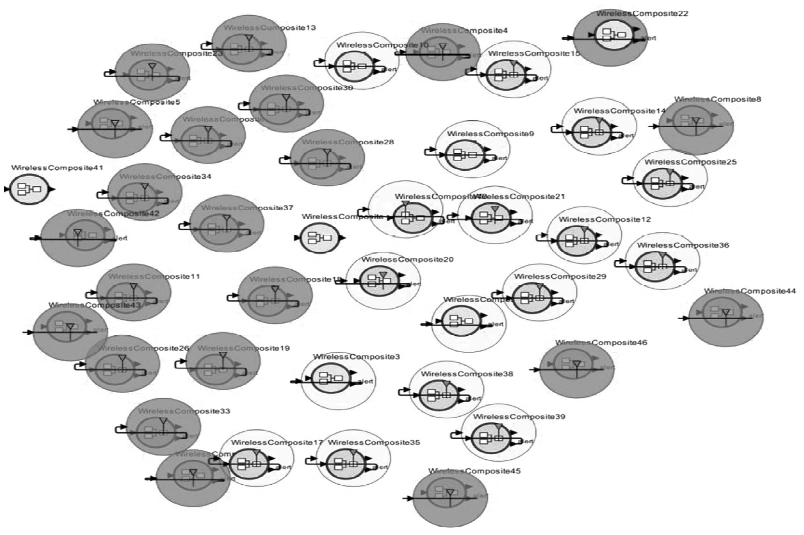
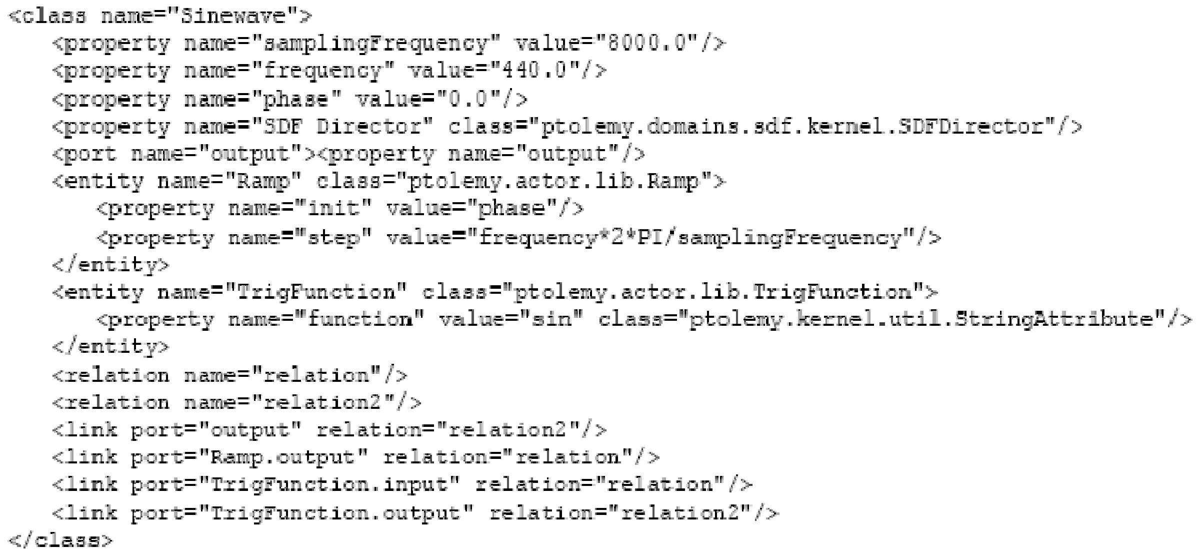


Figure 5.5 Nodes deployment in the simulation.

5.2.2 Parameters of Evaluation

5.2.2.1 **Efficiency in Distribution**

The percentage of coverage node is a parameter to determine the coverage area. As covered nodes are protected from IDS activated nodes, the number of coverage nodes determines the effectiveness of authentication. The higher number is preferable for secure systems as IDS can monitor more nodes. In addition, the number of IDS activated node is used as a parameter for evaluating distribution efficiency. The number of repeated activated IDS in each node also represents the efficiency of distribution. This is significant because consecutive activated the same nodes reduce an operation lifetime. An equal number of activating IDS in each node is the ideal result as a uniform distribution. However, a node location is not absolute as an ideal model. In practice, the number of repeatedly activated IDS can determine the efficiency of the distribution.



```
<class name="Sinewave">
   <property name="samplingFrequency" value="8000.0"/>
   <property name="frequency" value="440.0"/>
   <property name="phase" value="0.0"/>
   <property name="SDF Director" class="ptolemy.domains.sdf.kernel.SDFDirector"/>
   <port name="output"><property name="output"/>
   <entity name="Ramp" class="ptolemy.actor.lib.Ramp">
      <property name="init" value="phase"/>
      <property name="step" value="frequency*2*PI/samplingFrequency"/>
   </entity>
   <entity name="TrigFunction" class="ptolemy.actor.lib.TrigFunction">
      <property name="function" value="sin" class="ptolemy.kernel.util.StringAttribute"/>
   </entity>
   <relation name="relation"/>
   <relation name="relation2"/>
   <link port="output" relation="relation2"/>
   <link port="Ramp.output" relation="relation"/>
   <link port="TrigFunction.input" relation="relation"/>
   <link port="TrigFunction.output" relation="relation2"/>
</class>
```

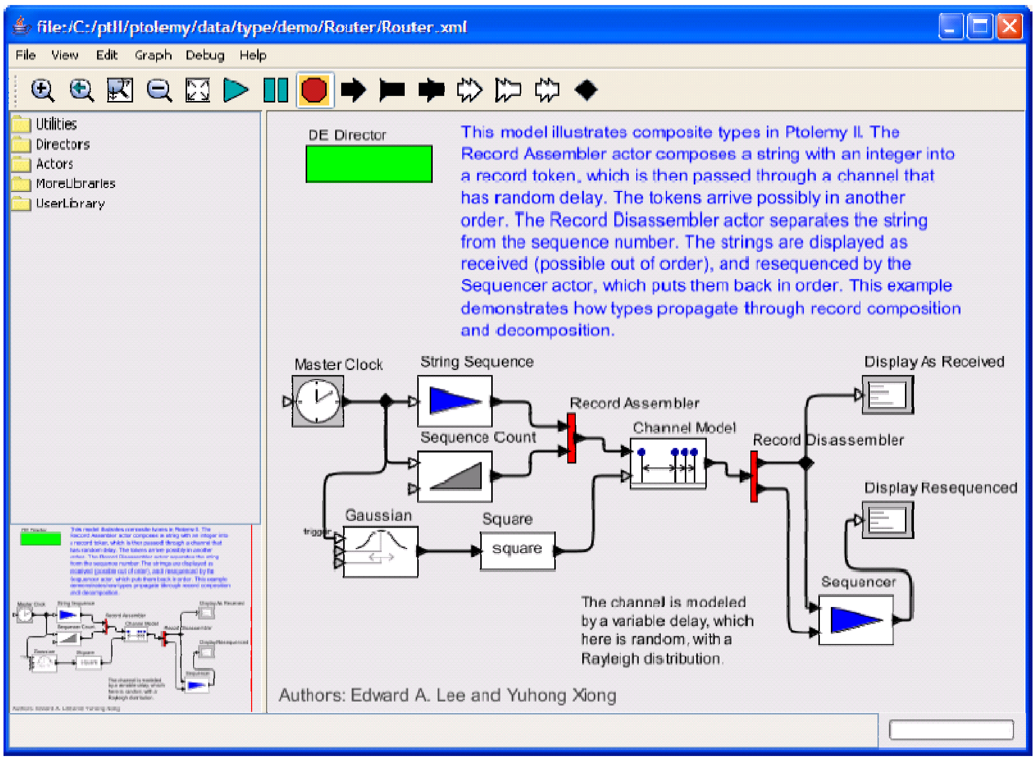
Figure 5.6 An example source code of sine wave [145].

5.2.2.2 **Energy Consumption**

Parameters in energy consumption are the number of IDS activated nodes and transmitting messages. Firstly, the number of IDS activated nodes can determine the energy usage in the entire cluster so less activated nodes are equivalent to less energy usages. Secondly, the number of activated nodes should be kept at a minimum to enhance the system lifetime. Since communication in sensor networks consumes most energy, transmitting messages determine the energy consumption in the distribution process. As voting procedure involves in exchanging messages, reducing transmitting message also reduces energy consumption.

5.2.3 Evaluation Scenario

In evaluation, network topology is developed with a base station located at the centre of a cluster. The cluster sizes are 10, 20, 40 and 80 nodes. The protocols are developed in Prowler software [146, 147] and Ptolemy II software [148-151] based on TinyOS structure. In this package, it contains sensor networks operations and communication components. Therefore, we create Adaptive IDS operated on application layers. The IDS mechanism detects an unusual behavior from rules violating. After the



This model illustrates composite types in Ptolemy II. The Record Assembler actor composes a string with an integer into a record token, which is then passed through a channel that has random delay. The tokens arrive possibly in another order. The Record Disassembler actor separates the string from the sequence number. The strings are displayed as received (possible out of order), and resequenced by the Sequencer actor, which puts them back in order. This example demonstrates how types propagate through record composition and decomposition.

The channel is modeled by a variable delay, which here is random, with a Rayleigh distribution.

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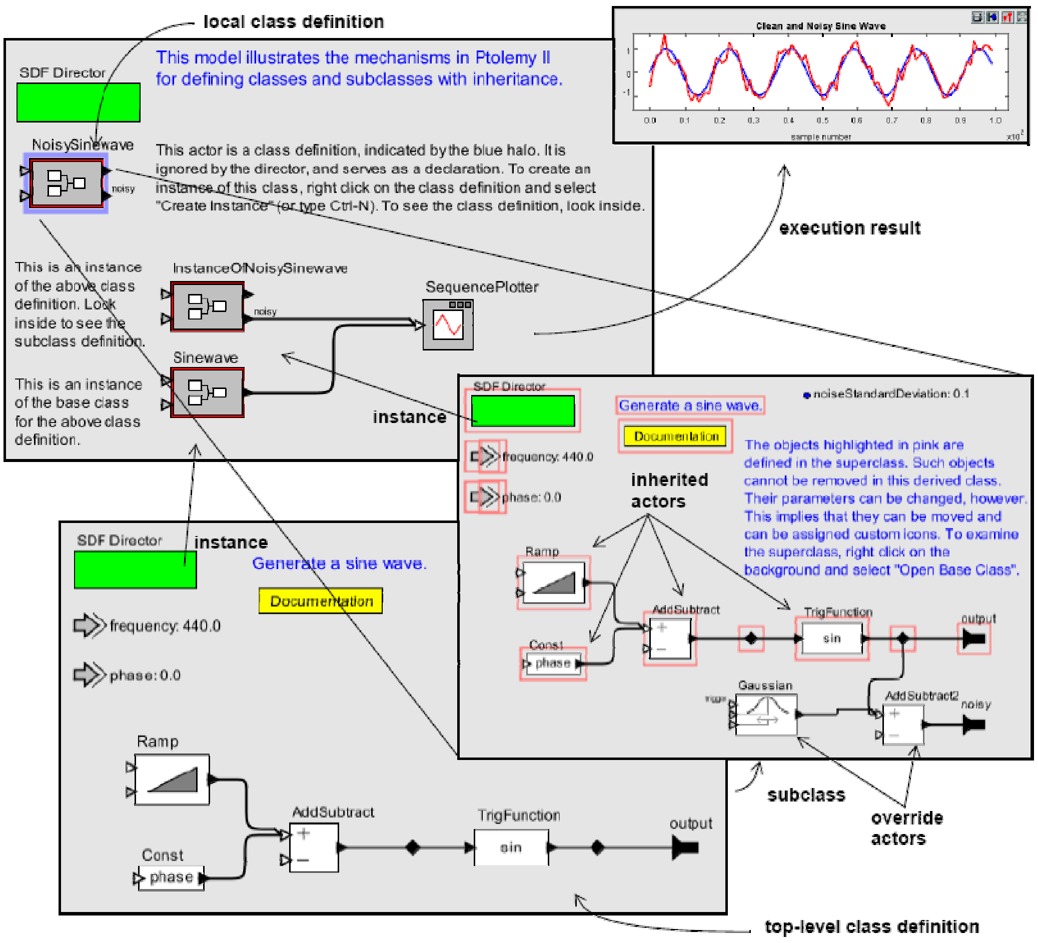
Figure 5.7 GUI of Ptolemy software [145].

IDS detects vulnerability, it raises an alarm signal to prepare for intruders. The scenarios with the same cluster size use the same deployment for result consistency. The deployment is shown in figure 5.5.

In simulation, only activated nodes operate traffic monitoring. Attack messages are imitated with communication messages with slightly modified contents and formats. Therefore, the adversary transmits alike actual communication message. The numbers of attacks are based on simulation models and cluster sizes.

The simulation in Ptolemy software is constructed as a module object. A source code is based on XML and JAVA as shown in figure 5.6. The software allows developers to create an operation flow in GUI as shown in figure 5.7. Wireless components are built in the software which can adjust the transmitting range. To develop sensor nodes, we add components in the node and connect the flows of these components. The components in this simulator include clock, operation, computation, calculation and wireless connection.



This model illustrates the mechanisms in Ptolemy II for defining classes and subclasses with inheritance.

This actor is a class definition, indicated by the blue halo. It is ignored by the director, and serves as a declaration. To create an instance of this class, right click on the class definition and select "Create Instance" (or type Ctrl-N). To see the class definition, look inside.

This is an instance of the above class definition. Look inside to see the subclass definition.

This is an instance of the base class for the above class definition.

The objects highlighted in pink are defined in the superclass. Such objects cannot be removed in this derived class. Their parameters can be changed, however. This implies that they can be moved and can be assigned custom icons. To examine the superclass, right click on the background and select "Open Base Class".

Figure 5.8 Hierarchical abstraction in Ptolemy [145].

The modules in Ptolemy are constructed hierarchically. The top level is an actor which a developer could insert operation, ports and link. After creating the actor, developers could create the data flow from input ports through operations module and output to external port. This includes a document link and defined parameters as shown in figure 5.8. In addition, we develop our Adaptive IDS module to cooperate with other components. Finally, simulation results are exported for further analysis.

5.2.4 Performance Model

5.2.4.1 Performance of Adaptive IDS

Adaptive IDS selects IDS activated nodes by an adaptive voting algorithm. This algorithm uses threshold number to reduce repeatedly activating the same node. As Adaptive IDS uses one hop count in voting, the coverage area is expected to be 100%. For example, if one hop neighboring node does not activate IDS, it must activate IDS itself. However, sensor nodes are rarely used as a stand alone device, so it normally selects some activated nodes. To distribute activated nodes, Adaptive IDS spreads the activated nodes in the entire network. However, the location of nodes affects the distribution because voting is based on one hop range.

In energy consumption, Adaptive IDS transmits the average two messages for activated nodes and average one message for non-activated nodes. In the ideal model, the number of activated nodes is based on the number of sub group. Since each sub group has one activated node, the number of sub group determines the number of activated nodes. Therefore, the number of activated is expected to be as O(log(n)) in theory.

5.2.4.2 Performance of Distribution Agent

Agent-based IDS [128, 129] selects IDS activated nodes by the voting algorithm. The voting selects the highest voted nodes (or gateway nodes) to activate their IDS. In one hop voting, the coverage area is expected to be 100% because voting message reaches nodes in one hop range. However, a greater hop count reduces the coverage area. A distribution for Agent-based IDS does not spread the activated node unless the network topology changes because the gateway is expected to be an activated node. Therefore, there is no dynamical distribution in Agent-based IDS.

In energy consumption, transmitting message is expected to be one message per node in each round because each node only sends one message to the gateway. However, energy is consumed more for the maintenance of the tree structure. In addition, the number of activated nodes is corresponded to the number of hop count. In one hop count, every parent node is expected to activate IDS therefore the number of activated node is expected be O(n).

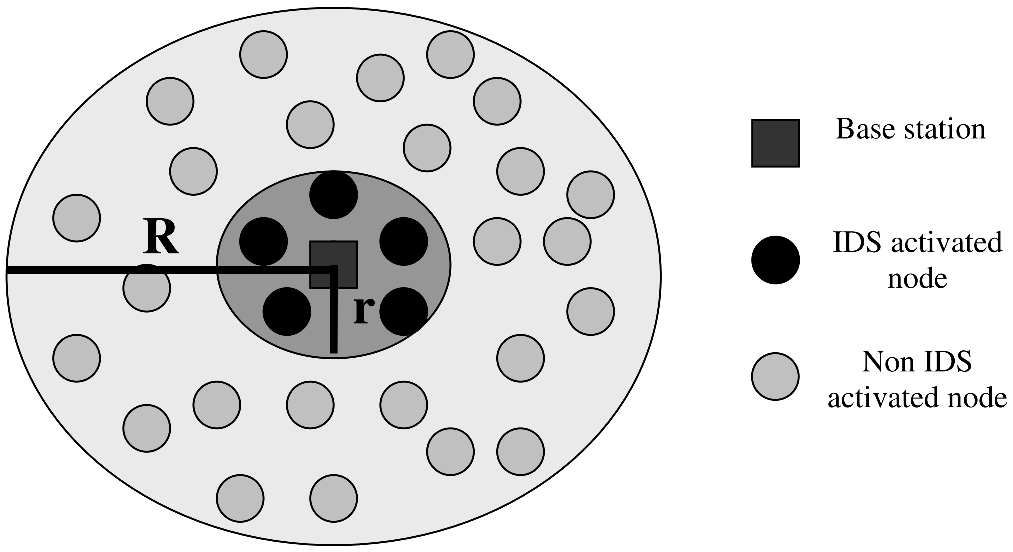


Figure 5.9 Core defense model.

5.2.4.3 **Performance of Core Defense**

Core defense is a traditional static defense strategy which selects activated nodes surrounding base station. It ensures that no intruder breaks into a base station in each cluster. This model defends from the most inner point and strikes back to the outer area. As core defense is the static strategy, the same nodes repeatedly activate IDS. The coverage area is very limited in core defense because its intention is to protect base station. The coverage area varies with cluster size and node density. In the ideal model, monitoring range surrounds the base station so the coverage area can be evaluated as a circle which is shown in figure 5.9.

Therefore, the ratio of coverage area is $\left(\frac{\P r^2}{\P R^2}\right)$

where **r** is radius of monitor range and **R** is radius of cluster.

This can be simplified as $\left(\frac{r}{R}\right)^2$

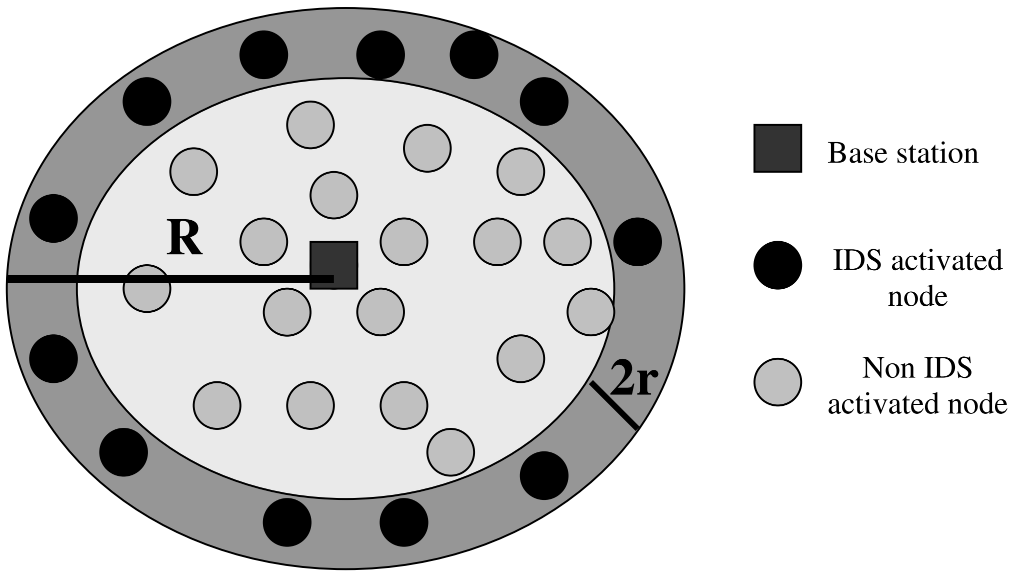


Figure 5.10 Boundary defense model.

In energy consumption, base station only broadcasts one hop message and then the receivers activate the IDS. Therefore, IDS activated nodes are surrounding the base station and do not require any maintenance. The number of IDS activated nodes is constant which covers the nodes in one hop range. In organizing, energy consumption is extremely low because the base station needs only one message in broadcasting for system lifetime.

5.2.4.4 **Performance of Boundary Defense**

Boundary defense is a static strategy which selects activated nodes at the perimeter of the cluster. It focuses on preventing an intruder from breaking into the cluster from the boundary line. As boundary defense is the static strategy, the same nodes repeatedly activate IDS. The coverage area is limited because the area is along the boundary line. The coverage area is dependent on node deployments as shown in figure 5.10. In the ideal model, the range of monitoring covers only the perimeter so the coverage area is the ring of the cluster.

Therefore, the ratio of coverage area is $\left(\frac{\P R^2 - \P(R-2r)^2}{\P R^2}\right)$

where **r** is radius of monitor range of each node and **R** is radius of cluster.

This can be simplified as $4r\left(\frac{R-r}{R}\right)$

In energy consumption, the base station is required to transmit prune messages so the last node in each prune is the boundary node. Then boundary nodes are activated IDS in their nodes. Theoretically, this procedure would be performed only one time in the system life time. Therefore, constructing a strategy uses only small amount of energy. In addition, the number of activated nodes is a constant and varied on the node deployment.

5.2.5 Evaluation

5.2.5.1 Efficiency in Distribution

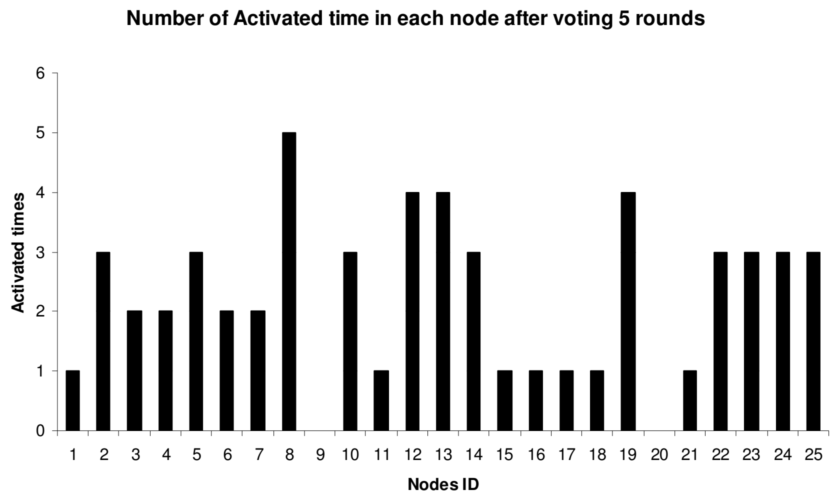
As discussed in section 5.2.4, the coverage area of Adaptive IDS is expected to be 100% similar as one hop voting in Agent-based IDS. However, the core defense and the boundary defense have smaller coverage area. To verify, we set up a simulation with cluster sizes 10, 20, 40 and 80 and attacks from adversaries. The attacks are launched from adversaries that are categorized into three types. A core attack launches attack messages in the area that is close to the base station while the boundary attack launches attack messages at the perimeter line. Inner attacks launch an attack message to the area between core and boundary. Since we focus on the efficiency of distribution, we neglect the number of false negatives. If IDS in activated node detects more than 50% of attacks, we define this to be detectable whereas define less than 50% of detect rate to be non-detectable. As shown in table 5.5, the result supports that Adaptive IDS and Agent-based IDS are detectable ranging from small to large size of clusters because voting algorithm in Adaptive IDS and Agent-based IDS ensures the coverage area. However, the core defense shows the weakness of cluster size 40 and 80. In cluster size 80, the core defense can detect attacks only in the core area. In the boundary defense, it shows the same weakness in the core defense but exposes the vulnerable in core and inner areas. Both the core defense and the boundary defense have less than 30% of the coverage area in cluster size 80. In summary, Adaptive IDS and Agent-based IDS have the same performance in the coverage where the core defense and the boundary defense show significant weaknesses in a large cluster.

Refer to figure 5.11, the number of repeatedly activated nodes is provided according to the simulation. As the core defense, the boundary defense and Agent-based IDS do not dynamically support distribution, the pattern shows that it repeatedly activates the same node. After the five rounds, Agent-based IDS votes the same nodes because the structure of network does not change. As the boundary defense and the core defense select boundary nodes and core nodes respectively, only nodes in selected area are activated. However, over a long period of operation, the pattern changes slightly because of packet loss and node failures. In adaptive IDS, the pattern shows the spread of activated nodes in the cluster. This pattern is not equally activated among nodes because some nodes are located in very high traffic locations so voting number is much higher than threshold number. As these particular nodes can represent others neighboring nodes, they still activate IDS for neighboring nodes. The number of activated nodes in simulation is higher than the ideal model as sensor networks always involve with packet loss and message collisions. To sum up, Adaptive IDS shows the distribution of activated node which improves more greatly than Agent-based IDS, core defense and boundary defense.

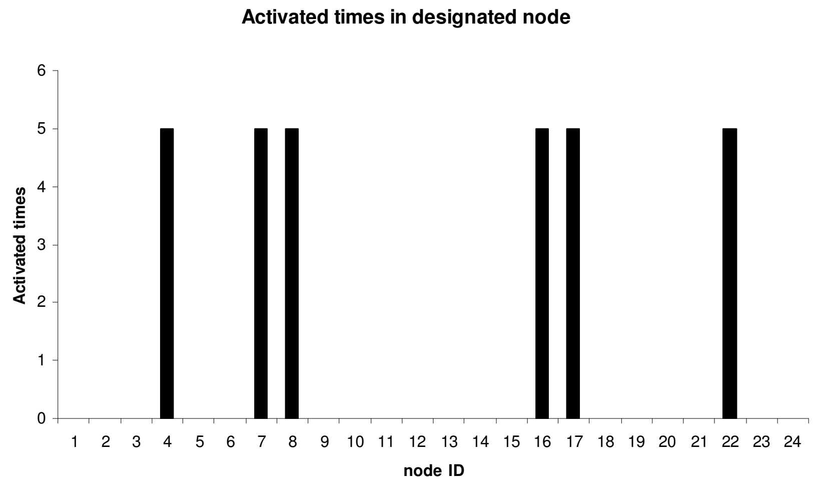
Adaptive IDS is evaluated which is shown in figure 5.12. As Adaptive IDS does not require hierarchy maintenance, the number of transmitting message is closed to linear which is equivalent to O(n). In addition, the performance in distributing activated nodes can be observed from a number of activated nodes. As it increases linearly, it ensures that a protocol can be scalable for a large network. Also, the larger size of a cluster increases the density of network. The percentage of required activated nodes decreases more than 20% in cluster size 10 and 80 while the collision of messages does not increase significantly. The collision of messages is crucial because the higher number can turn to more unnecessarily activated nodes. Yet, the biggest drawback of protocols is that the received number of messages increases exponentially. However, voting algorithm uses message broadcasting so it is hardly improved in this section.

Cluster size	Distribution Type	Core Attack	Inner Attack	Boundary Attack
10	Adaptive IDS	√	√	√
	Agent-based IDS	√	√	√
	Core Defense	√	√	√
	Boundary Defense	√	√	√
20	Adaptive IDS	√	√	√
	Agent-based IDS	√	√	√
	Core Defense	√	√	√
	Boundary Defense	√	√	√
40	Adaptive IDS	√	√	√
	Agent-based IDS	√	√	√
	Core Defense	√	√	X
	Boundary Defense	X	√	√
80	Adaptive IDS	√	√	√
	Agent-based IDS	√	√	√
	Core Defense	√	X	X
	Boundary Defense	X	X	√

Table 5.5 Efficiency in detecting attack for each distribution strategy.
√ is detectable while X is non-detectable

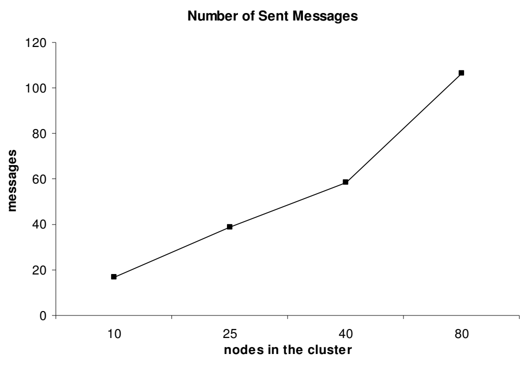


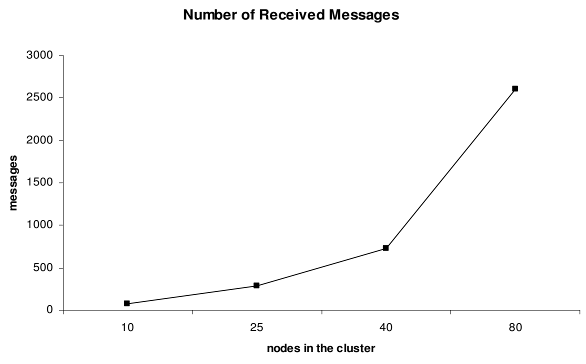
(a)



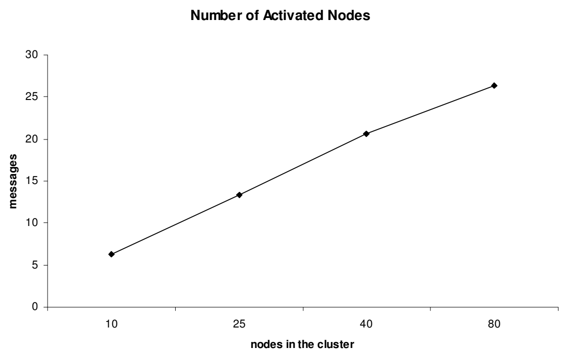
(b)

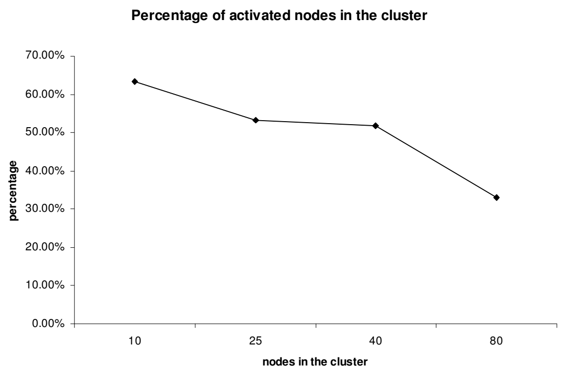
Figure 5.11 Pattern of how spreading activated node in the cluster (a) Pattern in Adaptive IDS (b) Pattern in Agent-based IDS, Core defense and Boundary defense



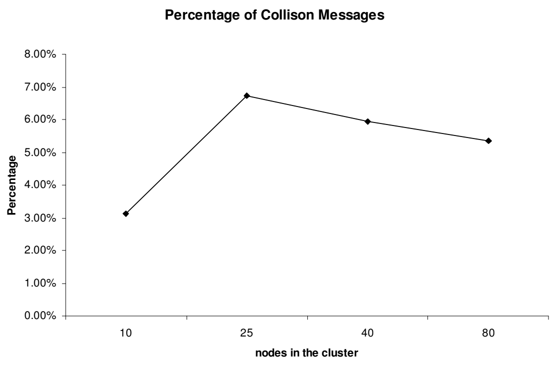


(a) (b)





(c) (d)



(e)

Figure 5.12 Performance of Adaptive IDS.

(a) Number of sent messages. (b) Number of received messages. (c) Number of activated nodes (d) Percentage of activated nodes in the cluster. (e) Percentage of collision messages.

5.2.5.2 **Energy Consumption**

The comparison of communication messages and activated nodes is shown in figure 5.13. Item (a) shows the comparison of communication messages in core defense, boundary defense and Agent-based IDS. Agent-based IDS uses the highest number, compared with both core defense and boundary defense. To compare with (b), the number of communication messages in Adaptive IDS has the same pattern as Agent-based IDS but it is slightly less in large clusters. This can be evaluated that the energy consumption in distributing activated node of Adaptive IDS is equivalent to Agent-based IDS but consumes significantly more energy, compared with the core defense and the boundary defense. In addition, the ratio of activated node in the cluster is shown in (c) and (d). The ratio reduces in all protocols when the cluster size is larger thus energy consumption ratio in entire system also reduces. However, (c) demonstrates core defense use the least activated node and boundary defense is the second least. In (d), Adaptive IDS has the best ratio as approximately 0.4 compared with about 0.6 in Agent-based IDS because Distribution Agent activates every node that receives vote. Therefore, Adaptive IDS improves the ratio number because the activated node is the representative node for neighbors. In summary, core defense is the most efficient in energy consumption while boundary defense is the second. Adaptive IDS and Agent-based IDS have the same pattern of energy consumption but Adaptive IDS improves energy in the number of activated nodes by approximately 20% in a cluster size of 80.

In conclusion, Adaptive IDS has an advantage in distributing activated nodes in the cluster. Although distribution is not equal to the ideal model, it improves energy consumption across the cluster. The coverage is better than static core defense and boundary defense while is equivalent to Agent-based IDS. In addition, the number of transmitting messages increases linearly at O(n) because hierarchy maintenance is not required. The number of activated nodes increases linearly which supports scalability for large networks. In addition, the ratio of activated node reduces so energy usage in the cluster also reduces. To compare with Agent-based IDS, both ratio and number messages improve because of the adaptive voting algorithm.

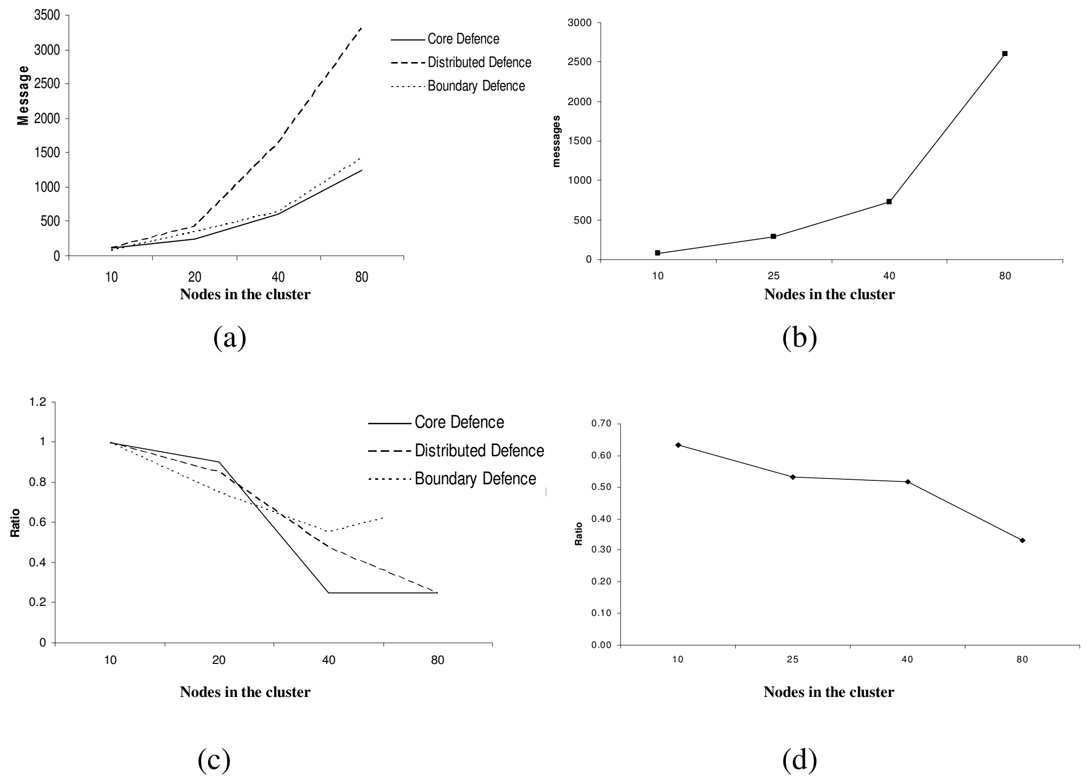


Figure 5.13 (a) shows number of message involved in distributing activated nodes of three protocols against Adaptive IDS in (b). (c) shows ratio of number of activated nodes in three protocols versus Adaptive IDS in (d).

However, the number of communication messages still increases exponentially which is the biggest drawback. This is because a large cluster can be excessive in energy consumption. Although the number of collisions does not increase significantly, it causes the activation of unnecessary nodes. Finally security is vulnerable because voting messages can be jammed and replayed. This security is improved when using cooperation between HKD and Adaptive IDS, which is explained in the next section.

5.3 Cooperation between HKD and Adaptive IDS

This section evaluates cooperation between HKD and Adaptive IDS compared with non-cooperative protocol. We also define operational scenarios which are used in the evaluation. Finally, a comparison of cooperative and static protocol is discussed and analyzed.

5.3.1 Metrics of Performance

5.3.1.1 **Energy Consumption**

Since cooperation between HKD and Adaptive IDS is expected to reduce energy usage in key management, energy consumption should be evaluated in order to compare a cooperative and non-cooperative protocol. Energy consumption of operation is measured from transmitting messages because it is the most energy intensive activity. In addition, the effectiveness of dynamically updating keys in cooperative protocol should be analyzed. In addition, Adaptive IDS should be evaluated with the energy consumption in both cooperative and non-cooperative protocol. Since it is expected that a cooperative protocol will enhance security, energy usage must be evaluated to compare the trade offs.

5.3.1.2 **Security Strength**

Cooperation between HKD and Adaptive IDS is expected to enhance the security of the voting algorithm of Adaptive IDS. Therefore, the differences between a cooperative and non-cooperative protocol should be evaluated. Since the voting algorithm in Adaptive IDS is the most important for distributing activated nodes, an adversary could attempt to attack this operation. Furthermore, if distribution is corrupted, IDS in sensor networks could malfunction. In addition, a cooperative protocol could affect security strength in both a safe and high-risk environment because the protocol uses dynamic key updating.

5.3.2 Parameters of Evaluation

5.3.2.1 Energy Consumption

System lifetime is a parameter in evaluating energy consumption for key management. As dynamic key updating is based on the environment, different situations could affect the system lifetime. Therefore, system lifetime of cooperative and non-cooperative protocol should be compared. In addition, the number of transmitted messages in cooperative protocol should be evaluated because an increase in security strength in voting algorithm could affect energy usage. Although the number of activated nodes causes significant energy consumption in Adaptive IDS, we neglect this fact in this evaluation because a cooperative protocol does not change activating method.

5.3.2.2 Security Strength

Security strength on attacks is a parameter in evaluating Adaptive IDS. Since the protocol is vulnerable against brute force, replay and jamming attacks, the protocol should be analyzed. In addition, this parameter is useful for implementing the protocol. In addition, we analyze brute force attack on cooperative protocol and compare to individual HKD in different situations.

5.3.3 Evaluation Scenario

The system lifetime is calculated based on SmartDust node with the same environment as in section 5.1.3. Power is supplied from a 3 volts battery with capacity 2,200 mAh. Our model sets up 10 nodes in each cluster and sample rate is 1 Hz with 50 Kbps bandwidth. Wireless communication consumes 4.8 mA in receiving and 12 mA in transmitting. In idle mode, energy consumption rate is 5 μA.

The security strength is set up as in section 5.1.3. An adversary has an UltraSparc II server with high performance antenna. This antenna can reach any part of the network as well as transmitting and receiving messages. The power supply in this server is unlimited.

5.3.4 Performance Model

5.3.4.1 **Energy Consumption**

Theoretically, energy consumption should be significantly reduced in a safe environment because each key can be used for a longer period. In a high-risk environment, a cooperative protocol should consume more energy than a non-cooperative protocol because it requires frequently exchanging and updating information.

In distributing activated node, energy consumption of the voting algorithm is expected to be similar to a non-cooperative protocol because enhancing security in Adaptive IDS uses encryption but transmitting messages does not change. Therefore, key management is responsible for the security while the voting algorithm remains the same. Consequently, the number of transmitted messages is still similar to the non-cooperative protocol.

5.3.4.2 **Security Strength**

Cooperative protocol is expected to improve security in voting algorithm. Since the original voting algorithm lacks verification and secrecy, the cooperative protocol should be improved in critical attacks including brute force attack and replay attack.

In addition, the security of cooperative protocol is expected to have mixed results because it acts differently in the different situations. In a safe environment, security strength should be less strong than non-cooperative protocol. However, in a high-risk environment the key is updated more frequently. Consequently, the system is more secure.

5.3.5 Evaluation

5.3.5.1 **Energy Consumption**

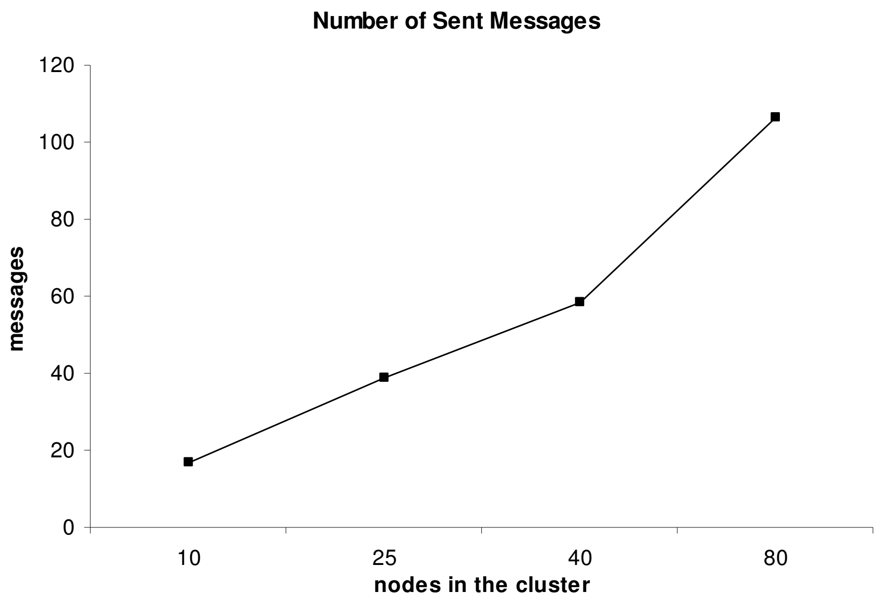
As shown in figure 5.14, the cooperative protocol is evaluated in three situations. A safe environment is a situation in which no alerts are triggered and no suspicious events are detected by IDS. Therefore, current key is used 50% longer. System lifetime of cooperative protocol can increase by 22.2% compared to non-cooperative protocol because of less frequent updating of keys and key chains. A high-risk environment is a critical situation in which IDS triggers an alert signal thus key is updated more frequently

Protocol	Message size (bytes)	Estimated operation time (days)
Cooperative protocol (Safe Environment)	64	874
Cooperative protocol (Risk Environment)	64	379
Cooperative protocol (Mixed Environment)	64	563
HKD	64	715

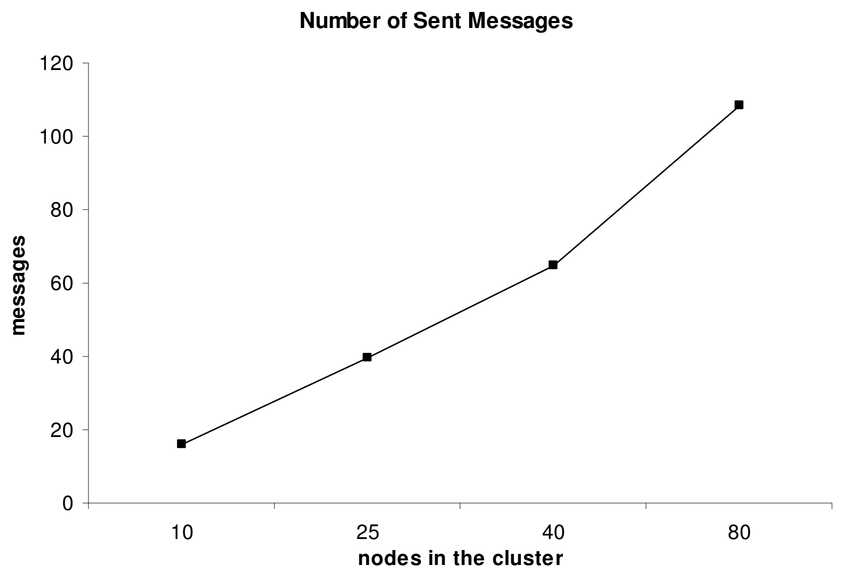
Figure 5.14 Comparing a system lifetime between cooperative protocol and individual HKD.

as well as key chain. The result shows that energy usage increases significantly from key and key chain updating. System lifetime is reduced by approximately 53% because key chain updating requires more computation and battery as well as transmission of messages in order to inform of an alert situation. A mixed situation is a combination of 50% risk situation and 50% safe situation. The result shows energy consumption increases by 21.3% from non-cooperative protocol because risk situation consumes more energy. Although safe situation can enhance system lifetime, sensor devices still need to update key regularly. Therefore, cooperative protocol consumes 21.3% more power in general situations.

Figure 5.15 supports a theoretical model in which the number of transmitting messages in voting algorithm does not significantly change in cooperative protocol. Since there is no change in algorithm, the cooperative protocol only encrypts voting message. Therefore, there is no significant energy use in voting algorithm of cooperative protocol.



(a)



(b)

Figure 5.15 Graphs shows transmitted messages in (a) individual Adaptive IDS

(b) Cooperative protocol.

5.3.5.2 **Security Strength**

In voting algorithm, Adaptive IDS does not have security protection from attacks. In a cooperative protocol, replay attacks can be prevented by encrypting the voting message with current key. In addition, the current key is changed more frequently than IDS distribution. Therefore, current key is changed in every round of voting. If an adversary attempts to perform a replay attack, the received node rejects the message because the message is encrypted with the previous key. Therefore, the current key can also be used for authentication. However, an adversary could attempt to do a replay attack with voting message in the same round. The receiving node ignores the repeated message because it is a duplicated vote. A vulnerability of the protocol is that an adversary can use the voting message from one sub group to use in another sub group. The worst result could be that more nodes are activated. Furthermore, the evaluation done by brute force attack takes a long period of time to break the current key while voting is completed in minutes so an adversary has no chance to create an imitated voting or bidding message.

Security strengths of key management in simulation shows mixed results because updating key is changed based on IDS information. Since the master key, key chain and key size remain the same, key space of cooperative protocol is the same as HKD. A difference is the frequency of key updating. In a high-risk environment, keys are updated more frequently so adversaries have less chance to break the current key. Therefore, the system is more secure. However, in safe situations keys are updated less frequently. This could be a vulnerability that an adversary could exploit. Nevertheless, safe situation is evaluated from non-suspicious event detected in which IDS ensures that no adversary in current network. As shown in the simulation, the worst case for security in a cooperative protocol is passive attack. Since an adversary does not perform any attacks, the network assumes that it is a safe situation. Therefore, an adversary can use this situation to break the key. Although brute force requires years to break the key, an adversary may use other techniques to break the key over a longer period.

5.4 Conclusion

This chapter evaluates HKD, Adaptive IDS and the cooperative protocol. The simulation compares these protocols with related protocols where a number of different parameters are used as benchmarks. The environment in simulation is set up based on real data but it neglects unrelated factors for clarifying the result.

In summary, security strength of the current key in ELK, SPINS and HKD is equivalent but SPINS enhances security in decrypting messages by using two keys. Key chain in both SPINS and HKD is secured with larger key space which ensures a longer computing time when brute force is used. In addition, the master key in HKD has the largest key space which is the most secure key in these protocols. However, HKD does not renew the master key regularly thus it could be vulnerable in the long term. Furthermore, all three protocols only rely on the key so an adversary could harm the network if the key is revealed. Finally, all three protocols are not able to resist denial of service attacks.

ELK uses excessive resources especially memory and CPU which is infeasible to implement in sensor devices because ELK uses asymmetric cryptography and does not focus on minimizing resource usage. In SPINS, usage of memory and CPU is the least among the three protocols followed by HKD and ELK respectively, while HKD uses the least energy in communication. Therefore, HKD can enhance system lifetime the most but still uses more memory and CPU processing than SPINS.

Adaptive IDS has an advantage in distributing activated nodes in the network. Although Adaptive IDS distribution is not followed to an ideal model, it improves energy consumption across the cluster. The coverage is better than static core and boundary defense while it is equivalent to Agent-based IDS. In addition, the number of transmitted messages increases linearly at O(n) because a tree hierarchy is not required. The number of activated nodes also increases linearly thus the Adaptive IDS is scalable for a large network. In addition, the ratio of activated nodes is reduced while node density increases so energy in the cluster is reduced. To compare with Agent-based IDS, both the ratio and the number of messages are improved because of its voting algorithm. However, the number of communication messages still increases exponentially which is the biggest drawback because a large cluster can consume excessive energy. Finally, security is also vulnerable because voting messages could be jammed and replayed.

A cooperative protocol consumes 21.3% more energy in general situations while it increases security strength in alert situations. However, it is still vulnerable if an adversary uses a passive attack because IDS cannot detect any suspicious activity. In addition, the voting algorithm is more secure with secret key and there is no significant energy usage in implementing security in this algorithm.

Chapter 6. Conclusion and Future Work

This thesis presents approaches to security in sensor networks which involves key management and distributing Intrusion Detection System (IDS). The summarized thesis work is described in a separated chapter. At the end of the chapter, we recommend future work to improve the protocols.

6.1 Chapter One (Introduction)

A brief introduction to the wireless sensor network is provided, and then a research method is presented to accomplish this thesis. An outline is also given with the summary of key points as well as contributions by this thesis.

6.2 Chapter Two (Background)

Chapter two presents the general background of sensor networks and the problems that are focused on in this thesis. A general definition of sensor network is described with characteristics and restrictions. Even though the sensor network provides advantages in self-organization, scalability, coverage, system lifetime and cost, it has trade offs in limited resource in individual nodes. Then, the chapter explains a security definition and cryptography as well as comparing both symmetric and asymmetric cryptography. Its advantages and disadvantages are also discussed before describing attacks. Since security is required to protect network from the attacks, understanding the attacks can aid in evaluating the security solutions. The attacks need to be covered both network attack and cryptography attack because network security should be protected from numerous attacks. Finally, chapter explains IDS. The advantage of monitoring from inside the network is that this can prevent attacks when adversaries break into the network and prepare the network when external attacks are launched. However, monitoring is an expensive task in sensor networks as well as the large coverage area is difficult to install and maintain. These are the challenges that this thesis is focusing on.

6.3 Chapter Three (Literature Survey)

This chapter reviews existing protocols and solutions for problems in key management and IDS for sensor network. Efficient Large-Group Key Distribution (ELK) is a protocol that allows each node to compute an individual key from a hint message. This hint message can reduce message size while not exposing any actual keys. However, keys are generated from child nodes' keys so a tree structure is required. Since sensor networks are not reliable, tree structure maintenance could use an excessive amount of energy. Security Protocols for Sensor Networks (SPINS) is a protocol designed for sensor networks. Since communication consumes the most energy in sensor networks, SPINS reduces the transmitted information. In addition, each node uses a key chain to enhance security because adversaries cannot compute the key backward. In IDS, there is a lot of research supporting the fact that IDS mechanism could operate in sensor networks. However, challenges are reducing energy consumption and monitoring networks of a large scale. Agent-based IDS proposes a solution by using voting algorithm. In each round, every node sends a vote message to their gateway. Then, receiving nodes activate IDS in their nodes. The result shows that selected node can cover the traffic of a network as well as distribute the agent or activated node.

6.4 Chapter Four (Hint Key Distribution & Adaptive IDS)

In this thesis, we propose Hint Key Distribution (HKD) for key management and Adaptive IDS for network monitoring.

HKD manages key distribution by using a base station to generate and broadcast hint message. The hint message contains the hashed value of current key and current key chain. Authorized nodes can construct a key from the hint message. Construction uses an iterative computation of two one-way functions. The benefit is protecting against an adversary computing the next key from the current key. In addition, HKD supports joining nodes and packet loss because generating key from the hint message is stateless. An important benefit in HKD is minimizing energy consumption in communication while enabling base station to dynamically update keys based on the situations.

Adaptive IDS is a distributing system for IDS activated nodes in the network. As distributed IDS enhances coverage and security, selected nodes should activate the IDS. Adaptive IDS uses a voting algorithm with a threshold to select a high traffic node to activate while avoiding repeatedly activating the same node. Since monitoring consumes a lot of energy, repeatedly activating the same node could empty the battery quicker than others. To make them usable in sensor networks, all nodes should have an equal lifetime. Therefore, the threshold in Adaptive IDS ensures that uniform energy consumption in IDS is maintained in the network. In addition, Adaptive IDS protocol consumes limited energy in the voting procedure where transmitted message is on average two messages in activated nodes and one message in non-activated nodes.

As a cooperative system, both HKD and Adaptive IDS can improve efficiency by sharing information. HKD provides a management status and current activities. In Adaptive IDS, there are four situations including normal situation, suspicious situation, alert situation and extreme risk situation. The IDS activated node is required to inform base station in suspicious, alert and extreme risk situations. To exchange information, in a normal situation IDS does not detect any rules violation thus HKD can use the current key for longer period to save energy. In a suspicious situation, IDS detects minor rules violations so HKD updates current key regularly. In alert situation, IDS detects critical violations and triggers the alarm so HKD updates key chains immediately. In an extreme risk situation, IDS raises an alarm and HKD cannot update the key immediately so the base station applies the strongest policy e.g. restarts the entire network.

6.5 Chapter Five (Evaluation)

This chapter evaluates HKD, Adaptive IDS and the cooperative protocol. In summary, security strength of the current key in ELK, SPINS and HKD are equivalent but SPINS enhances security in decrypting messages by using two keys. Key chain in both SPINS and HKD is secured with larger key space which ensures a longer computation time when brute force is used. In addition, master key in HKD has the largest key space so it is the most secure key in these protocols. However, HKD does not renew the master key regularly thus it could be vulnerable in the long term. Furthermore, all three protocols only rely on the key so an adversary could do harm to the network if the key is revealed. Finally, all three protocols are not able to resist denial of service attacks. In terms of energy consumption, ELK uses an excessive amount of resources, especially memory and CPU, which is infeasible to implement in sensor devices because it uses asymmetric cryptography and does not focus on minimizing resource usage. In SPINS, memory and CPU usages are the least among the three protocols. HKD is the second best between ELK and SPINS in memory and CPU usage while using the least energy in communication. Therefore, HKD can enhance system lifetime the most but still uses more memory and CPU processing power than SPINS.

Adaptive IDS has an advantage in distributing activated nodes in the cluster. Although distribution is not followed an ideal model, it improves energy consumption across the cluster. The coverage of Adaptive IDS is equivalent to Agent-based IDS and better than static core defense and boundary defense. The number of activated nodes increases linearly thus scalability is supported in a large network. In addition, the ratio of activated nodes is reduced while cluster size increases so energy in the cluster is also reduced. To compare with Agent-based IDS, both ratio and number messages are improved because of its voting algorithm. However, the number of communication messages still increases exponentially which is the biggest drawback. This is because a large cluster can consume excessive amounts of energy. Finally, security is also vulnerable because voting messages can be jammed and replayed.

Cooperative protocol consumes more energy by 21.3% in a general situation but it increases security strength in an alert situation. However, it is still vulnerable if an adversary uses passive attack because IDS cannot detect any suspicious activity. In addition, voting algorithm is more secured with a secret key and there is no significant energy usage in implementing security in this algorithm.

6.6 Future Work

This section suggests the future work based on our proposed solution. In key management, a cooperative protocol consumes significantly more energy in a risk environment because key is updated quicker. Future work may consider threshold or adaptive algorithm to adjust this situation. Although network is under attack, repeated attacks in the long term may not require frequent updating of keys. However, there is a challenge in this task because improving energy consumption normally decreases the effectiveness of security. In addition, it can be difficult to predict different situations.

In distributing IDS, the proposed solution uses threshold number to distribute energy consumption across the network. Future work may consider the amount of remaining battery as a deciding factor. Since the main objective is using energy equally in every node, battery is the best factor to measure. However, there are several challenges in using these parameters. Standardization of hardware and battery could not be done effectively across the entire network. A history of energy consumption does not enable accurately predicting energy use in the future. Finally, battery does not release a consistent amount of power. For example, 50% of remaining battery is not double the capacity of 25% remaining battery in practice because chemistry and holding capacity of battery is not ideal.

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