Title: Security and Key Establishment in IEEE 802.15.4

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Problem description:

Internet of Things (IoT) is a network where devices, sensors, vehicles, buildings, and humans communicate and collaborate, along with collecting and exchanging information. IEEE 802.15.4 specifies the lower layers for low-rate wireless networks, which are widely seen as the foundation for current IoT communications. One of the potential weaknesses of the IEEE 802.15.4 standard is the lack of specification for key establishment and management.

This thesis will focus on key management for device-to-device security in IoT. It will review and compare the proposed protocols, and include both formal and informal security analysis, as well as analysis of both key management requirements and key agreement protocol design for IoT security. Another goal of the thesis will be to suggest improvements and alternatives to the proposed protocols.

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Contents

List of Figures

List of Tables

Listings

List of Acronyms

6LoWPAN IPv6 over Low power Wireless Personal Area Networks.

AES Advanced Encryption Standard.

AKES Adaptable Key Establishment Scheme.

APKES Adaptable Pairwise Key Establishment Scheme.

BAN Burrows-Abadi-Needham.

CCM Counter with CBC-MAC.

CTR Counter.

DoS Denial of Service.

ECC Elliptic Curve Cryptography.

ECDSA Elliptic Curve Digital Signature Algorithm.

GPS Global Positioning System.

GUI Graphical User Interface.

IEEE Institute of Electrical and Electronics Engineers.

IETF Internet Engineering Task Force.

IoT Internet of Things.

IP Internet Protocol.

KCI Key Compromise Impersonation.

LEAP Localized Encryption and Authentication Protocol.

LKR Long-term Key Reveal.

MAC Message Authentication Code.

MIC Message Integrity Code.

MSC Message Sequence Chart.

OSI Open Systems Interconnection.

PFS Perfect Forward Secrecy.

RAM Random Access Memory.

RFID Radio Frequency Identification.

RSA Rivest-Shamir-Adleman.

SKR Session-Key Reveal.

SNMP Simple Network Management Protocol.

TCP Transmission Control Protocol.

UDP User Datagram Protocol.

WPAN Wireless Personal Area Network.

wPFS Weak Perfect Forward Secrecy.

WSN Wireless Sensor Network.

Chapter 1
Introduction

This should be the introduction to the thesis.

Chapter 2
Background and Related Work

2.1 Internet of Things

Over the last decade, a concept called the *Internet of Things* has gained increased attention, both from the research community and commercial actors, as well as from consumers. The term IoT was, accordingly to most sources, coined in 1999 by the British visionary Kevin Ashton in a presentation about Radio Frequency Identification (RFID) [4] [49]. Ashton's definition of the concept was a world where computers do not depend on human beings to provide them with information. Out of all the petabytes of information available on the Internet, the majority has been created and captured by humans performing some sort of action. In his opinion, IoT is about providing computers with the ability to gather information on their own.

A computational device containing some sort of sensor is attached to your everyday physical device, creating a bridge between our physical world and the cyber world [33]. The connection to the Internet allows us to monitor and control these devices and sensors from a remote distance. Another vital part of IoT is device-to-device communications, essentially enabling devices to communicate with each other without human aid, and exchange and retrieve information. Such devices could be sensors monitoring some operation, a physical area, or even attached to a physical body. The possibilities are more or less unlimited. Imagine a home automation and surveillance system for your cabin, where lights, heaters, smoke detectors, underfloor heating, motion detectors, security cameras, garage and so on, are all interconnected with each other through small wireless devices. As it is called the *internet* of things for a reason, your system and devices would be accessible over the Internet, allowing you to monitor the current status of your cabin remotely from your couch at home, as well as looking at historical data of the different sensors and devices. When the weekend arrives and you head for the mountains, the IoT provides you with an opportunity to preheat different (or all) sections of the cabin, deactivate the alarm, and perhaps instruct the sauna to start getting cosy.

Another approach is to avoid using a monitor to remotely control the system, and instead allowing the system to observe and act on your behaviour. We want the devices to know us and figure out the correct thing to do without us telling them. For example, when pulling your car into the driveway, you want the garage door that is connected with your car to open up. The garage notifies your front door that you are home, which conveniently unlocks and notifies your house to turn on the lights in your hallway and perhaps the heater in your living room.

The possibilities that are revealed as the IoT grows larger and the services expand are infinite. The concept is highly applicable for different scenarios involving home automation, standalone consumer products, industrial and environmental facilities, as well as medical surveillance. While larger automation systems for homes and facilities have been the target for the research community and early adopters, the consumer market has been focused on so-called *wearables*. Wearables are fundamentally devices that you wear, such as smart watches, fitness trackers, virtual reality glasses, headphones, and smart clothing. Such human-centric devices are less about automation, and more focused on personal improvement. Nevertheless, the increase in IoT devices possibly provides us with a more cost efficient future, both in our use of time, as well as energy and consumption of other resources.

As the IoT is built upon the Internet, it faces the same types of security issues as the Internet itself. The amount of "things" connected to the Internet is calculated to be 6.4 billions by the end of 2016, which is almost a 30% increase from 2015. By 2020, the expected number of these "things" is more than 20 billion [27], providing attackers with equally many possible devices to attack. Given the knowledge that some of these devices may be medical (or have other sensitive applications), we quickly recognize potential catastrophic scenarios.

The IoT architecture can resemble the neural system of the human body. The perception layer controls our sensors which we use to obtain information about our environment by observing, feeling, smelling, tasting or hearing. As previously described, IoT devices are often deployed with one or more sensors to perform these "human operations" for information collection. The perception layer is mainly focusing on sensing and allowing IoT devices to observe their environment and collect information. Examples of such technologies are RFID, Wireless Sensor Network (WSN), and the Global Positioning System (GPS) [31]. Information from our human sensors are carried to the brain through a neural network. Much alike in IoT, the collected information is transmitted using the transportation layer. The transportation layer is running over some wireless or wired medium such as 802.15.4, 6LoWPAN, 3G, Bluetooth or Infrared. Finally the information is processed by an intelligent entity. In our human body example, this would be the brain. In the IoT, the brain would be an intelligent processing unit in the application layer which is

able to compute and evaluate actions based on the received information [32] [52]. The application layer is also responsible for controlling the sensors, and performing global system management, and present data for the end user of the system.

As these layers covers different characteristics of IoT, they consists of different types of hardware and provide different types of services, hence they are subject to different types of security threats and solutions. The most adjacent problems to the scope of this thesis are the problems related to key establishment and key management, which define how two devices safely can establish secure communication between each other. Or in other words, how collected information is safely transmitted between the sensors and the "brain".

In an IoT world, the protection of data and privacy is an essential part. As previously mentioned, IoT technology may be a solution for problems involving sensitive information. In a medical facility, a possible scenario could be a WSN, which is a dynamic and bi-directional network of nodes where each node has one or more sensors connected to it. A patient may have sensors implanted in their body, as well as different instruments attached for measuring different properties. All these devices communicate with each other wirelessly, and the network is therefore a possible target for an attacker. To prevent the attacker from eavesdropping, and possible forging content in the network, encryption and authentication at the different nodes is crucial.

2.2 The IEEE 802.15.4 Standard

Following the evolution of IoT, the need for cheap devices to communicate efficiently between each other has arisen. Existing architectures such as 802.11 (WiFi) and Bluetooth are too expensive in terms of processing and energy consumption, as the idea of IoT is to connect even the smallest devices to a network or Internet. As these devices are small, they have a limited battery life, and hence need to use energy in a highly efficient matter.

Protocols using the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard are envisioned for applications supporting smart homes, medical surveillance, monitoring systems for environmental and industrial systems, as well as sensor systems for heating and ventilation. As we know from the IoT, it is really the imagination that puts an end to the possibilities for interconnected devices. The OSI stack defines the internal structure of communications systems, and is shown in Figure 2.1. As the 802.15.4 standard only defines the physical and data link layer of the OSI stack, which can be seen in Figure 2.1, specifications need to be developed to utilize the possibilities provided by 802.15.4 in the upper layers. ZigBee [2], maintained by the ZigBee Alliance, is the most notable example of specifications

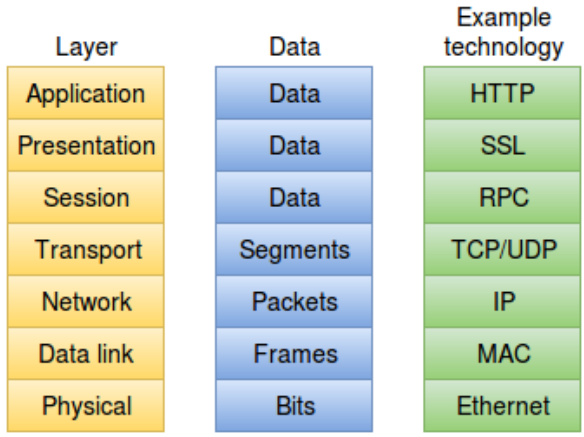

Figure 2.1: The OSI stack with layers, the data they carry, and an example of technology running on the different layers.

that uses 802.15.4 as its base. Others include WirelessHART [26], MiWi [50], and ISA100.11a [43].

The fundamental intention of the 802.15.4 standard is to provide low-rate, low-power communication between devices within a sensor network or Wireless Personal Area Network (WPAN). Its main use case is to let multiple devices within a short range communicate with each other over a low-rate radio, while maintaining a modest energy consumption. Figure 2.2 paints a picture of what 802.15.4 is, compared to more well-established concepts such as WiFi (802.11) and Bluetooth, focusing on energy consumption, complexity and date rate. While being smaller and more cost efficient than those found in more complex networks, devices running on 802.15.4 networks have a much more limited range (about 10 meters), and in most cases a throughput below 250 Kbps [29]. Not only is the 802.15.4 standard significantly lighter in terms of data rate and power consumption, it is also aimed at a different market than regular WPANs. WPANs are oriented around a person, creating a personal network for the user, which has higher demands to data rate, and can allow a higher energy consumption. 802.15.4, however, focuses on interconnecting devices that do not necessary have this constraint, such as industrial and medical applications.

Four basic security services are provided in the 802.15.4 link-layer security package, namely access control, message integrity, message confidentiality, and replay protection (sequential freshness) [48]. The IEEE 802.15.4 standard is delivered with a total of eight different security suites, providing none, some, or all of the described security services, and it is up to the application designer to specify and enable the

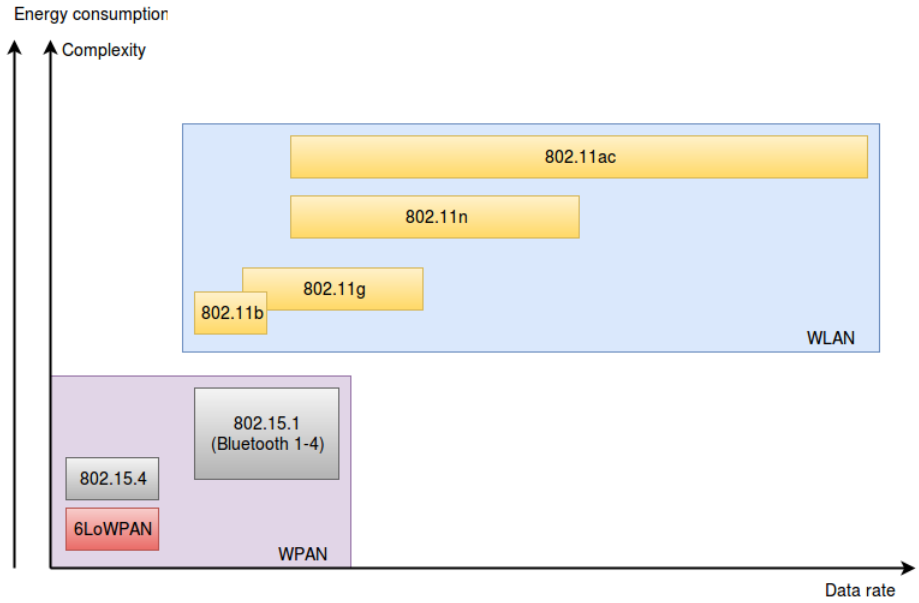

Figure 2.2: Figure of IEEE 802.15.4's operational space compared to other wireless standards [29].

desired security properties. In the most secure end of the scale we find Advanced Encryption Standard (AES)-Counter with CBC-MAC (CCM), which is encryption using the block cipher AES with either 32, 64 or 128-bit Message Authentication Code (MAC). Such a suite provides both strong encryption and possibly unforgeable messages (a 64-bit MAC gives an adversary a 2^{-64} chance of successfully forging a message, and is used to enable legitimate nodes in the network to detect if a received message have been tampered with). On the other end of the scale we find a suite providing only confidentiality using AES in Counter (CTR) mode. This suite does not, however, provide any form of authentication – giving adversaries the possibility to forge messages, which can not be said to be especially secure. One of the things the 802.15.4 standard does not specify is how to deal with key establishment and key management, which therefore has to be dealt with in the higher layers.

2.3 6LoWPAN: Putting IP on Top of 802.15.4

Initially, the Internet Protocol (IP) was considered to be too "heavy" for low-power wireless networks such as the ones described by the 802.15.4 standard. The idea of implementing IP on top of 802.15.4 networks was born as early as 2001 under the question "Why invent a new protocol when we already have IP?"[41]. With IP, the community already had a bundle of existing protocols for management, transport,

configuring and debugging, such as Simple Network Management Protocol (SNMP), Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), as well as standardized services for higher layers such as caching, firewalls, load balancing, and mobility. Nevertheless, the initial idea of using IP in combination with sensor networks or WPANs was not accepted by various groups such as ZigBee [41]. The rejection did not, however, stop the initiative, and a group of engineers within Internet Engineering Task Force (IETF) started designing and developing what would later be known as 6LoWPAN.

A significant advantage with combining IP and 802.15.4 is the simplification of the connectivity model between various devices in the networks. As most 802.15.4-based specifications usually need custom hardware that tends to be complex, the possibilities to interconnect different networks with each other is somewhat limited. By turning to IP, the need for complex connectivity models is obsolete as it is possible to use well-understood technologies such as bridges and routers. Another advantage with using IP is that the routers between the 6LoWPAN devices and the outside networks (so-called edge routers) do not need to maintain any state as they are only forwarding datagrams.

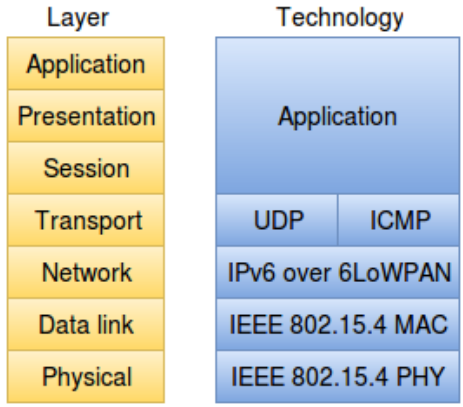

Figure 2.3: Figure of the 6LoWPAN stack, which uses the 802.15.4 physical and link layer, but adds an adoption layer in the network layer.

6LoWPAN enables wireless 802.15.4 sensor devices to connect directly to the Internet via IPv6 by providing an adoption layer in the network layer between it and the data link layer as shown in Figure 2.3. The adoption layer provides a unique functionality which both fragments and compresses incoming packets to enable the embedded devices in 802.15.4 networks to receive the packets while using the least amount of memory and energy [35]. Its fundamental idea is that you only "pay" for what you use. The dispatch header field identifies the type of header to follow, and consists of 1 byte [41]. Such a header starts with either 00 or 01, respectively

indicating whether the frame is a non-6LoWPAN frame or a regular 6LoWPAN-frame. Currently, only five different dispatch headers have been defined [30]. Therefore, there is a fair space for new headers as the standard and technology evolves. However, the special case of a header consisting solely of ones, adds an additional byte to the header, enabling a total of 320 different header types [41]. This greatly differs from IPv4 and Zigbee which define only one monotonic header, and can be used to greatly minimize the header size of a packet as some types of frames may consist of smaller payloads than others.

Compared to other alternatives such as ZigBee or Z-wave, 6LoWPAN's implementation did not prove to be any more expensive in terms of code size and Random Access Memory (RAM) requirements. 6LoWPAN seems to be a natural choice for the future IoT as a networking protocol. It is scalable thanks to IPv6, and its headers can be compressed to only a few bytes using its fragmentation and compression mechanism. Following the expected bloom in IoT devices over the next few years (20 billion by 2020), and the fact that the IPv6 address space is not going to be exhausted any time soon (roughly 2^{95} addresses for each and every one of us), 6LoWPAN may be a reasonable approach.

2.4 Key Establishment and Key Management

As described, IoT devices communicate with each other over the network by utilizing some network protocol. There is, however, not always a guarantee for that the network used for communication is secure. An attacker may be eavesdropping on the network, and may even be capable of intercepting and spoofing traffic sent between different nodes. From a security perspective, the described attacker is violating both the confidentiality and integrity of the exchanged information. To cope with this, devices should be encrypting and authenticating the data that they are exchanging.

Key establishment is a fundamental idea in cryptography where two (or more) communicating parties exchange information in order to generate cryptographic keys which enable them to perform some sort of cryptography on the messages that are sent between them. The problem is, however, how to safely agree upon the keys to use in the encryption-decryption process when the network itself can not be trusted. For IoT devices and sensor networks, confidentiality and data integrity are important aspect. As previously described, IoT devices have limited resources in terms of battery life and processing abilities, making key establishment schemes that works great in other networks with access to more resources, such as WiFi, infeasible in an IoT scenario.

2.4.1 Symmetric Encryption

In modern cryptography, encryption and decryption are in most cased done either by using symmetric key encryption or asymmetric key encryption. Symmetric key encryption is the case where communicating parties possesses the same key which is used for encryption as well as decryption messages that are sent between them. While being a straightforward and fast way of encrypting information, it has a major drawback in the case of one of the parties is compromised, then the channel that initially was secure would now be insecure as the adversary could easily encrypt any message that it intercepts.

2.4.2 Asymmetric Encryption

In the 1970s, Whitfield Diffie and Martin Hellman introduced the Diffie-Hellman key exchange, which was one of the first practical examples of public key exchange within cryptography [22]. Asymmetric encryption (or public-key encryption) is the case where each communicating nodes possess a public key and a corresponding private key. The public key is published and used by anyone who wants to send an encrypted message to the node. When the node receives a message that is encrypted with its public key, it uses the private key which is generated from the public key to decrypt the message. In the (un)likely case of being compromised, the node could simply generate a new key pair consisting of a public and a private key, and publish the new public key for others to send encrypted messages under.

Of the different algorithms in use today, the Rivest-Shamir-Adleman (RSA) cryptosystem is the most commonly used, which provides both key exchange and authentication [51]. Asymmetric encryption is significantly more computationally costly compared to symmetric encryption. This has lead to a hybrid solution where a symmetric session key is established and encrypted under the public key of each recipient, which reduces the computation time of encryption and decryption, giving a more efficient encryption scheme.

2.4.3 Security Attributes in Key Establishment Schemes

Authentication

Authentication is an important aspect of key establishment. More specific, confirming the identity of the entity you are establishing keys with, as well as the keys. If authentication is skipped, then the protocol will be weak for so-called man-in-the-middle attacks where an adversary intercepts and relays messages between two communicating parties to learn or modify its content. One of the traditional key exchange infrastructures for enforcing authentication in the Internet is to use a trusted third party [39]. Usually this third party is a secure key server that is responsible for

serving cryptographic keys to users and programs. The keys that are provided by the key server is usually included in a certificate containing additional information about the identity of the owner of that particular key. Example of such systems is the well-known public key system OpenPGP [1], which is used for encrypting electronic mail. For systems using symmetric encryption, authentication can be achieved through construction of MACs, which are cryptographic values generated from a symmetric key and the plaintext message. This enables the receiver of a message to compute the same MAC from the decrypted ciphertext and the shared symmetric key, and provides both authenticity of the sender and the integrity of the received message.

Known-Key Security

Session keys are single-use symmetric keys that are used for a given period of the communication before being exchanged and deleted from the system, and never to be used again. Known-key security is a property where the leak of information is minimized in the case of one (or multiple) session keys are compromised. For example in the case where session keys are derived from the private key, then the compromise should not lead to the compromise of the private key, nor any of the past or future session keys.

Perfect Forward Secrecy

Following in the lines of known-key security, Perfect Forward Secrecy (PFS) is a security attribute where in the case of the long-term private key of one (or both) of the communicating parties being compromised, it should not lead to the reveal of any of the past session keys that are used in the communication between the parties. The Heartbleed incident in 2014 was a painful example of the need for PFS, where a bug in the OpenSSL cryptographic software library leaked secret keys for certificates, as well as user names and passwords [24]. Attackers were able to retrieve 64 kilobytes of the memory of web servers for each attack (or "heartbeat"), which could be used to retrieve the private long-term key of the web server. The private key could then be used to retroactively decrypt all traffic that had previously been recorded.

PFS is a desirable security property for key establishment protocols, but it is often difficult to achieve. Weak Perfect Forward Secrecy (wPFS) is a weaker type of PFS, where the adversary is assumed to be *passive* [34]. In the case of a long-term key compromise, previous sessions are guaranteed to be secure, but only if the adversary was not actively interfering with the protocol during the session.

Key-Compromise Impersonation

In this case, an adversary has obtained the long-term private key of an honest entity A. Key Compromise Impersonation (KCI) prevents the adversary both from impersonating A to other entities (establishing session keys with them), as well as preventing the adversary from impersonate other entities in communication with A (masquerading as a different entity in order to establish a session key with A). In practice, a party possessing the private key of A is able to decrypt both past and future traffic going to and from A.

Key Control

Key control is to prevent a party from computing a part of the session key without input from the other party. Essentially, one of the communicating parties should not be able to force the secret session key into something of its own choice. Key control is usually accomplished through both parties creating a random value, which is shared with the other party, and computed together into the shared key, for example in the Diffie-Hellman key exchange.

Unknown Key-Share

Unknown key-share resilience is an attribute in key agreement protocols where a key shared between two entities A and B can not be shared with any others without they both consenting to it. When A and B are establishing a shared key, attacks targeting this process may want to convince A that it is sharing the key with B, while B in fact is under the impression that it is sharing the key with a third entity C. After the key establishment process is finished, A believes it has established a key with B (which is correct), but B is under the belief that it has established a key with C. This results in that when B thinks it is sending a message to C, A is the actual receiver of the message.

2.4.4 Key Establishment Schemes

The simplest possible scheme for key establishment is the network-shared key scheme, where every node in the network possesses the same key which is used for encryption and decryption between all nodes in the network [44]. While being easy to set up, it leaves the network vulnerable to node compromises as wireless sensor nodes often are deployed in hostile and unattended areas, where the compromising of one node is equal to the compromising of the entire network [35]. Also, in 802.15.4, the network-shared key scheme is incompatible with replay protection, moving the responsibility of implementing such measures to the higher layers [48].

Pairwise keys is a better symmetric key scheme, where each node pair possesses their own symmetric key for communication between them. This, however, leads to

higher memory requirements as the node in worst case has to store the symmetric key for $N-1$ nodes, where the number of nodes in the network can be high [44]. Group keying is another approach where groups of nodes share the same symmetric key. This greatly reduces the memory consumption for the devices, and can provide a mild version of compromise resilience. Unfortunately, group keying is not supported in IEEE 802.15.4 [48].

Pairwise random keys is another scheme that can support the hunt for pairwise keys while still maintaining a modest memory consumption. When using such a scheme, a node only possesses a part of the pairwise keys which when added up constitutes the entire pairwise key pool. The idea of such an approach is to create a multi-hop path between nodes, essentially connecting the entire network together while eliminating the need for storing $N-1$ keys.

2.4.5 Key Establishment Schemes in Wireless Sensor Networks and the Internet of Things

When it comes to WSN applications, symmetric encryption algorithms have historically been the most mature ones [31]. However, there exists several drawbacks with technology utilizing symmetric encryption. For starters, their key exchange protocols are often complex which is a constraint for the scalability of the network. Also, as the IoT devices are placed in possible hostile environment, they may be physically tampered with by adversaries [35]. If they should successfully compromise one of the nodes, then the security of the entire network may be at stake. Finally, authentication is a rather complex and inconvenient procedure with symmetric encryption involving MAC which leads to higher requirements for storage space, overhead in messages, and increased energy consumption.

It has been an underlying assumption in the research community that public-key cryptography has been an unsuitable solution for key establishment and key management in WSNs and other IoT related networks [51] [28]. While improving the security over symmetric key encryption, and also providing easier authentication and higher scalability, it still has issues related to energy consumption due to higher computational complexity as well as being time consuming [25]. However, public-key cryptography algorithms such as Rabin's Scheme, NtruEncrypt and Elliptic Curve Cryptography (ECC) have proven promising results when implemented efficiently for wireless platforms [31] [28]. Especially ECC and its implementation of Elliptic Curve Digital Signature Algorithm (ECDSA) have proven to be over four times more energy efficient than RSA-1024 [51]. One of the main advantages with ECC over more commonly used public-key algorithms such as RSA is the reduced key size, which in leads to greater memory and energy savings, while providing approximate the same level of security (ECC-160 is equivalent to RSA-1024 in terms of cryptographic

strength) [5].

Bottom line, there is no scheme that provides a clear advantage over others, symmetric or asymmetric, as they all have different advantages and disadvantages. It is up to the application designer to find and implement the best suited scheme based on the infrastructure, available resources, and security demands of the particular network.

2.5 Formal Security Analysis

As security protocols grows larger and more complex, they become more and more difficult for humans to analyse. One of the examples of the need for formal security analysis is the Needham-Schroeder protocol [42] from 1978. The Needham-Schroeder Public-Key Protocol is based on public-key cryptography and was intended to allow two communicating parties to mutually authenticate each other. Throughout this section, the protocol will be used as an illustrative example to underline the importance of formal security analysis.

One of the pioneering works on security analysis was conducted by Burrows, Abadi and Needham with their Burrows-Abadi-Needham (BAN) logic. BAN logic is a set of rules which can be used to determine whether received information is trustworthy or not, by formally describing the interaction between communicating parties [10]. It showed promising results in finding security flaws and drawbacks for several authentication protocols, but was later abandoned due to the fact that it verified insecure protocols as secure, and in some cases perfectly sound protocols to be insecure [38]. One of the protocols that was formally verified using BAN logic was the Needham-Schroeder protocol.

In fact, 17 years later after being deployed and widely used, Lowe discovered using the automatic tool Casper that the Needham-Schroeder protocol was insecure, and vulnerable to a man-in-the-middle attack [7] [36]. The discovery of that such a flaw had gone unnoticed for so many years puzzled the research community, leading to an increased interest in formal security analysis [18]. Researchers started developing tools for exhaustive search of the problem space of a protocol in order to detect possible abnormalities in protocol behaviour.

In order to conduct formal security analysis, we need a formal model to be able to study the protocol under precise assumptions. Formal security models are abstractions of descriptions of systems, aiming to improve the understanding of the security of the system by simplifying its interpretation. By defining a formal security model, we aim to discover and correct errors, incompleteness and inconsistencies in protocol specifications, before they are exploited by adversaries. A protocol specification is a

description of the behaviour of the different entities that are allowed to communicate with each other during an execution of the protocol [19]. More precise, a protocol description specifies the different roles in the protocol, each containing a sequential list of the messages that are sent and received from that particular role. It also contains the information of the initial knowledge of the protocol, which are the functions, constants and variables that the protocol needs to execute correctly. Such a specification is expressed using a formal language, which has well-defined syntax and semantics, for example process algebra, predicate logic, and lambda calculus.

The Dolev-Yao model is a formal intruder model used to prove the security properties of cryptographic protocols. While initially being a verification model built for public key protocols, the Dolev-Yao model is also the basis for most of the security analysis done by verification tools that focus on verifying secrecy and authentication properties [19]. The model is built upon three primary assumptions: Perfect cryptography, complete control of network, and abstract terms [23]. Firstly, the Dolev-Yao model assumes that the cryptography is perfect, essentially meaning that the cryptographic system can not be tampered with, and an encrypted message can only be decrypted by the party possessing the corresponding decryption key. The second assumption is that the adversary has complete control over the communication network, hence he is able to observe all messages that are sent between communicating parties, and can inject messages given that he is able to forge its content in a valid matter. Lastly, messages that are sent in the network are to be observed as abstract terms, where the attacker has two possible outcomes; either he learns the complete content of the message, or he learns nothing at all.

Falsification, presented by Popper in 1934, is the theory of presenting an observation that would disprove the correctness of an alleged theory, or more informally; It is not possible to prove a theory from a single correct observation, but a single observation that contradicts the theory is enough to disprove it [45]. The falsification process in model checking is to formally assess the security properties of the protocol in order to discover examples that disproves the claimed security by constructing counter-examples. Following in the same line of thoughts, we can perform verification by using formal models and languages to verify a statement (i.e. a security property). In formal security analysis, this is referred to as model checking, which uses the formal model to exhaustive verify whether it meets the alleged security properties [7]. Verification can also be done by constructing mathematical proofs for each of the security properties, proving that the alleged security is fulfilled.

2.6 Related Work

Chapter 3
Symbolic Security Analysis Using Scyther

There exists multiple state-of-the-art tools for performing formal analysis of security protocols, for example Avispa [46], ProVerif [8], Tamarin Prover [40], and Scyther [13]. This thesis uses Scyther as its tool for conducting formal security analysis, and the following chapter will give an introduction to Scyther, how it works, and examples of usages.

3.1 The Scyther Tool: Verification, Falsification, and Analysis of Security Protocols

Scyther is a tool for verification, falsification, and analysis of security protocols developed by Cas Cremers. The tool is based on a patter refinement algorithm that enables unbounded verification, falsification, will also enabling the tool to perform characterization [15] on the protocol. Scyther allows its users to verify security protocols in two different ways. The first option is to execute Scyther scripts through the command-line interface, which provides an output file containing the results of the protocol verification. Option two, is to use Scyther's own Graphical User Interface (GUI), which provides panels for both verification results, and in case of attacks being found; a visual graph of Scyther's proposed attack on the protocol. The most recent release of Scyther was published on April 4, 2014, and is currently available for Windows, OS X and Linux.

Security protocol specifications are built up of messages that are sent between different entities and computation that is done at either side. Much like a blueprint, these specifications define what a protocol is allowed to do, and how it is allowed to communicate [20]. The blueprint can then be modelled using Scyther, where the entities are converted into roles, the messages are converted into send and receive events, and the security requirements into claim events. Scyther performs complete characterization of a protocol, where roles are broken down to a finite set of representative behaviours by analysing all the possible execution traces where the

events hold. The intuitive idea behind this algorithm is that the set of execution traces together represents all possible ways in which the protocol could execute, and grouping them into patterns which are partially ordered, symbolic set of events [14]. From the patterns, Scyther is able to construct a complete set of attack traces for each security claim. When analysing protocols, the realizable traces are compared to the attack traces. If none of these realizable traces of the protocol exhibits an attack trace, then there exists no attack, and the security property is verified.

Most protocols can be characterized into a finite set of traces, which enables Scyther to perform *unbounded* verification of the protocol. This greatly differs from the majority of other verification tools which perform *bounded* verification [15] [18]. When performing bounded verification, there exists a finite set of traces that the tool is able to verify, meaning that the entire space of possible states is not covered in the verification process [16]. At best, such a verification can guarantee that the security requirements hold under a finite subset of the actual state-space. Unbounded verification, however, is to verify all possible states, or behaviours, of the protocol which is a great enhancement compared to bounded verification algorithms. In addition to handling an infinite state-space, Scyther's algorithm is also guaranteed to terminate, which gives it the ability to provide useful results even when it is not able to establish unbounded correctness, or in the scenario of where no attack is found.

As mentioned, a protocol specification contains a set of roles which serves as blueprints that describes what the protocol is able to do. When executing the protocol, each of the different roles can be executed multiple times, and in parallel with each other by one or more agents [14]. An execution of a role is referred to as a *run*, and defines an unique instance of the protocol with respect to local constraints and the binding between the role and the actual agent acting out the roles behaviour. Scyther allows its users to state security claims which are evaluated as they appear in the protocol trace, either ending in a successful verification of the security property, or in a failure. In the presence of a failure for some security property, Scyther will provide a concrete attack on the protocol by utilizing one of the attack traces from the pattern, and it will also present an attack graph to easier illustrate the threat. If the protocol developer is unsure of what types of claims that should be stated for each role, Scyther has support for so-called verification of automatic claims, where Scyther will provide the appropriate claims for each variable or key based on its type.

Another of the major novelties in Scyther is the possibility for performing so-called multi-protocol analysis, which in short terms is to analyse multiple protocols that are co-existing in the environment. Such an analysis has previously been infeasible because of an incredible wide state-space, but thanks to Scyther's unique algorithm that operates on an unbounded state-space, it allows for conducting multi-protocol analysis.

Scyther is available in two versions. The first version is a plain implementation of Scyther, while the second version also contains options for creating a stronger adversary compromise model than the Dolev-Yao model. The compromise edition contains different LKR rules, which is used for modelling different adversary capabilities such as KCI, wPFS, and PFS, along with support for known-key security.

3.2 Scyther Syntax

The syntax used in `.spdl`-files, which are protocol files that can be run and verified by Scyther, can resemble popular object-oriented languages such as C, C++ or Java. Listing 3.1 contains the structure of a minimum working example of the protocol known as APKES, consisting of an outer class defining the protocol and multiple agents (or roles) inside the protocol. In this example, we define that our protocol consists of two communicating parties; U and V, without giving them any specific behaviour.

```
protocol APKES(U, V){
  role U { };
  role V { };
};
```

Listing 3.1: Example of the structure of a protocol modelled in Scyther, consisting of roles with different behaviours.

For each of the different roles in the protocol, behaviour can be added as a sequence of send and receive events, as well as variable declarations, constants and claims. For the U role, we can define a simple behaviour as shown in Listing 3.2, where U generates a random nonce `Ru` and sends it to V, before receiving a message from V containing the random nonces `Ru` and `Rv`. All events are labelled with either `send` or `recv` followed by a subscript and a number. The number indicates the message's position in a Message Sequence Chart (MSC), and must be incremented for each message sent.

```
role U{
  fresh Ru: Nonce; # Freshly generated nonce
  var Rv: Nonce; # Variable for receiving a nonce

  send_1(U, V, Ru); # Send message to V containing Ru
  recv_2(V, U, Ru, Rv); # Receive message from V containing
   Ru and Rv. Store Rv in variable
};
```

Listing 3.2: Terms can be generated, and sent and received when communicating with other agents.

Typically, a `send`-event has a corresponding `recv`-event at the receiving role with the same number.

```
role V{
  [...]

  recv_1(U, V, Ru); # Receive message sent from U containing
    Ru. Store Ru in variable
  send_2(V, U, Ru, Rv); # Send message to U containing Ru
   and Rv
};
```

Listing 3.3: Corresponding events in role V to events in role U.

Along with support for creating fresh nonces, variables, and terms, Scyther also provides a wide set of cryptographic elements such as hash functions, symmetric-key cryptography, public-key cryptography, as well as declaring user specific types and macros, which are abbreviations of complex expressions into simpler once. In Listing 3.4, a hash function is used to define a function that generates a Message Integrity Code (MIC) (which is essentially the same as a MAC). On the next line, we have created a macro representing the generation of a pairwise key between U and V. The key is represented as an encryption of the two values `Ru` and `Rv` using a symmetric key that is shared between U and V. Constants and functions defined outside of a role are considered to be global, and available to all of the defined roles in the protocol. When the protocol run reaches the `send_3` event, it looks up the macro for pairwise key and computes it by encrypting the `Ru` and `Rv` values using the symmetric key shared between U and V. `send_3` also contains an example of a MIC of the constant `msg` sent from U to V, which is created by hashing the message and the pairwise key

together using the predefined hashfunction `MIC`.

```
hashfunction MIC; # An hashfunction to represent a Message
    Integrity Code (MIC) generation.

macro PairwiseKey = {Ru, Rv}k(U, V);

role U {
  [...]
  const msg;
  send_3(U, V, {msg}PairwiseKey, MIC(msg, PairwiseKey)
}
```

Listing 3.4: Example on how to use hashfunctions, macros and encryption.

3.2.1 Security Claims

A sequence of events within a role is usually followed by a set of claim events. Claim events are used for describing security properties of a role, for example that some value should be considered secret, or that certain properties hold for authentication. Such claims can be formally verified using Scyther. If the protocol is not instructed with any security claims, Scyther is able to generate the appropriate claims for the protocol with respect to secrecy and authentication by using the "Verify automatic claims" alternative provided by the GUI.

Secret

The first, most trivial security claim is secrecy. Secrecy expresses that the stated property is to be kept hidden from an adversary, even in the case of where the adversary controls the network used for communication. However, if one of the agents gets compromised by the adversary and the protocol is executed between an honest agent and the adversary, it would in the end learn what was meant to be kept hidden from it [19]. The secrecy claim does not hold for such cases (nor is it intended to), but for each case where the protocol is executed between two honest agent where the secret property is successfully kept hidden from the adversary. For our example protocol, we can claim that the two values `Ru` and `Rv` are supposed to be secret and thereby hidden from the adversary as shown in Listing 3.5. These claims will obviously fail as we have not specified that any encryption should be used on the messages that are passed between the two roles.

```
role U{
  [...]

  # Claims:
  claim_F1(U, Secret, Ru);
  claim_F2(U, Secret, Rv);
};
```

Listing 3.5: Example of how to claim secrecy for terms in Scyther.

Session-Key Reveal (SKR)

Session keys are created at the end of a key establishment process, and are usually used for a session of the communication, before being replaced. When they expire, they are deleted from the system and never used again, limiting the amount of ciphertexts available for the adversary to perform cryptanalysis. In Scyther, the claim SKR is used to identify the session keys in the protocol, and claim that they are secret. SKR can be used by Scyther to model unknown key share attacks (as described in Section 2.4.3), where Scyther will reveal any session key to the adversary, given that its session identifier (i.e. run identifier) differs from the current session's [12]. For the SKR claim to function correctly, Scyther's session-key reveal checkbox needs to be checked in the settings. If the SKR claim is used without enabling this setting, the claim is verified as a regular secrecy claim as defined above.

Aliveness

Aliveness is considered to be the weakest form of authentication, guaranteeing to the initiator of a protocol (U) that if it completes a run successfully, then the intended responder (V) of the run has previously executed the protocol [37]. This does not necessarily mean that V knew that he was interacting with U, nor does it mean that it has executed the protocol any time recently.

Weak Agreement

Weak agreement strengthens the authentication form introduced as aliveness. Such an authentication states that the responder in fact was executing the protocol with the initiator (U), and not just having run the protocol at some point in time [37]. By claiming that the protocol holds under the weak agreement, we state that if U successfully completes a run with the intended responder (V), then V confirms that it has previously run the protocol with U. Such a claim would prevent an adversary from acting as a responder by running another run of the protocol in parallel with a run with U, and conducting a man-in-the-middle-attack. The Needham-Schroeder

case presented in Chapter 2 failed on this claim, allowing Lowe to construct his attack.

Non-injective Agreement

Where the authentication provided by weak agreement does not specify which of the two communicating parties acted as initiator and responder, non-injective agreement does. It guarantees that if the initiator (U) successfully completes a run of the protocol, apparently with the responder (V), then V has completed a run with U, where he acted as a responder [37]. This does, however, not indicate that they both have executed exactly one run. There is still a possibility that U has executed multiple runs with a responder which he believed to be V, but may in fact have been communicating with the adversary. Another guarantee provided by non-injective agreement is that if U also sends a set of variables to V in the completed run, then they both agree that the data values correspond to all in the sent set of variables. In Listing 3.6, the example protocol claims that V is "alive", has run the protocol at some time with U, and that during this particular run, it was U and V that was communicating.

```
role U{
  [...]

  # Claims:
  claim_U1(U, Alive);
  claim_U2(U, Weakagree);
  claim_U3(U, Niagree);
};
```

Listing 3.6: Example of how to claim authentication by use of alive, weak-agreement, and non-injective agreement.

Non-injective Synchronization

Synchronization requires that all protocol messages occur in the expected order with their expected values, and that the behaviour is equivalent to as if the protocol was executed without the presence of any adversary [21]. An injective synchronization property states that the protocol executes as expected over *multiple* runs, claiming that it is not possible for an attacker to use information from previous runs to disrupting the current protocol execution [19]. Such an attack is known as a replay attack, and is used by an adversary to inject traffic into the protocol execution to induce undesirable or unexpected behaviour. Scyther, however, does not support this enhanced form of synchronization, hence it strongest type of synchronization is

non-injective synchronization. Because of this, Scyther is not able to verify whether or not a protocol is secure against replay attacks. Listing 3.7 contains an example on how to claim non-injective synchronization for the example protocol.

```
role U {
  [...]

  # Claims:
  [...]

  claim_U4(U, Nisynch);
}
```

Listing 3.7: Claim for declaring non-injective synchronization in Scyther.

Running, Commit

Running and commit signals can be used as a form of authentication for some variables from a set of terms sent in a message. By using these signals (in Scyther modelled as claims), we can verify that a variable sent from U to V, and then returned to U, has not been changed from its initial value during transmission. From a formal view, this can be seen as non-injective agreement over a set of terms [17].

The expression $claim(V, Running, U, Ru)$ denotes that V is currently executing the protocol with U, and with the nonce Ru. In U's case, $claim(U, Commit, V, Ru)$ indicates that the protocol as reached a point where authentication is claimed (U has completed the protocol run with V), where Ru is the variable that it claimed to be exchanged during this part of the run [47]. Usually, the *commit* claim is stated at the end of the protocol run. For the correctness of the *commit* claim to hold, it requires that the *running* signal is added in the communicating role, and preceding the *commit* claim in the trace.

This pattern is a scheme for authentication properties, but it also allows for expressing authentication for additional information specific to the particular, for example some variable inside the message. Occurrence of a *commit* signal in U's protocol run guarantees that a corresponding *running* signal has previously occurred in V's protocol run, which guarantees that the received message containing Ru must have been transmitted by V [47]. Listing 3.8 contains an example of how we can claim non-injective agreement over a variable, in this case the nonce Ru.

```
role U{
  [...]

  send_1(U, V, Ru);
  recv_2(V, U, Ru, Rv);
  claim_U5(U, Commit, V, Ru); # Authentication over the term
    Ru is claimed
};

role V{
  [...]

  recv_1(U, V, Ru);
  claim_V6(V, Running, U, Ru); # Claim that V is currently
   running the protocol with U with the value Ru
  send_2(V, U, Ru, Rv);
}
```

Listing 3.8: Example of a running, commit claim in Scyther to provide authentication for a set of terms.

3.3 Defining an Adversary Compromise Model

Formal adversary models are described in Section 2.5. Compromising of long-term keys can, for example, allow an adversary to recover previous session keys (and future) and decrypt the traffic if the protocol does not provide forward secrecy. Another option is for the adversary to perform KCI where it impersonates the victim towards other agents, or impersonate other entities in communication with the victim. Scyther allows for customizing different adversary models through its settings for a adversary compromise model, which enables a strong Dolev-Yao style adversary with support for verifying security properties such as PFS, wPFS, KCI and known-key security. These security properties are decomposed in Table 3.1 into their basic property, type of security property, and what adversary model (which will be elaborated in the next section) provides them.

Security property	Basic property	Adversary model
KCI	Authentication	{LKR, Actor}
PFS	Secrecy	{LKR, After}
wPFS	Secrecy	{LKR, Aftercorrect}
Known-Key Security	Session key secrecy	{SKR}

Table 3.1: Relationship between security properties and the adversary models in Scyther [6].

The initial adversary in the Dolev-Yao intruder model has access to the long-term keys of the communicating parties that do not participate in the current run of the protocol. In other words, if A and B are communicating with each other, then the adversary has access to C's private long-term key during the execution of the protocol. Scyther's initial intruder model, however, does not have access to these keys without directly specifying it in its LKR settings. When enabling {LKR, Others}, the adversary is identical to the Dolev-Yao intruder model, and has access to the long-term private keys for other agents than the those currently involved in the protocol execution [6].

Section 2.4.3 mentioned KCI, where an adversary in possession of A's long-term private key is able to impersonate A when communicating other agents, or impersonate other entities when communicating with A. Such an attack can be performed by the adversary after enabling {LKR, Actor} in Scyther's adversary compromise model. Forward secrecy is the security property where previous communication is protected in the case of compromising of the long-term key, and is enabled in the adversary model by specifying {LKR, Aftercorrect} and {LKR, After}. These properties restricts the compromise of long-term keys to only occur after the protocol execution [6]. {LKR, Aftercorrect} is used to model wPFS, and is the weaker case of forward secrecy, where the adversary is considered to be *passive*. For the adversary model, this would restrict it from both injecting messages and obtaining the private keys of the communicating parties after the protocol run. {LKR, After} models an *active* adversary capable of actively interfering with the protocol during it run while obtaining the long-term private keys, hence protocols able to provide secrecy in the present this adversary is said to provide PFS.

Figure 3.1 illustrates the different LKR rules in two dimensions; *when* a compromise occurs, and *whose* long-term keys are compromised. The rows indicate when the compromise occurs, and can either be before the run, during, or after. Columns describe whose keys are compromised, where actors are agents that execute the protocol, peers are communicating partners during the execution, and others are agents not participating in the protocol run. The different capabilities are captured

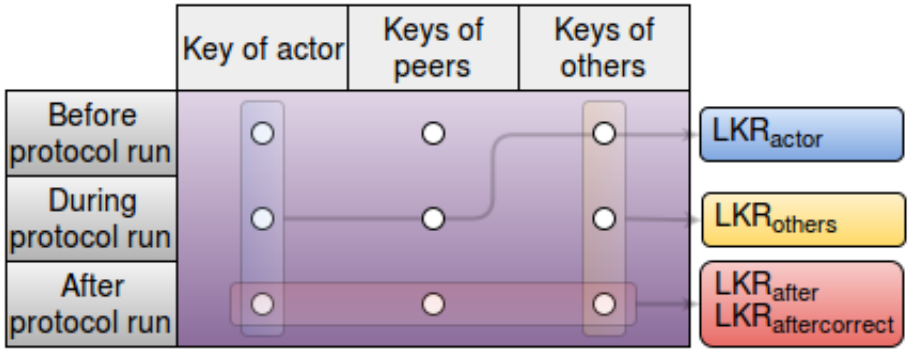

Figure 3.1: Mapping of LKR rules. Rows display when the compromise occurs, columns display whose data gets compromised, and the boxes captures the capabilities of the different adversaries, which are labelled to the right [6].

and labelled as different LKR rules, as shown on the right hand side of the figure.

In addition to compromising long-term keys, Scyther is also able to model the security property for known-key security. By enabling the SKR rule, the adversary is allowed to obtain all session keys whose session identifier (the identifier of that particular run of the protocol) differs from the current run's identifier.

3.4 Scyther's Graphical User Interface

As mentioned, Scyther provides a GUI for easily understand and assess the security of a protocol. If we continue on our example from the section on Scyther's syntax, we now want to verify all the stated security claims. By using the GUI, we can configure the verification process by providing a maximum number of runs, the adversary compromise model, as well as more advanced options for how to prune the search space. Scyther provides three options in its GUI; verification of claims, verification of automatic claims, and characterization of the protocol [15]. Figure 3.2 contains the results of running a verification of the claims previously described for a secure protocol.

When no attacks are found, Scyther provides either one two comments; *No attacks within bounds* or *No attacks*. In the first case, Scyther was not able to find any attacks within the bounded state-space, meaning that it may or may not be an attack in the unbounded state-space. The latter, however, states that there was not found any attacks within both the bounded and the unbounded state-space. In this case, Scyther can construct a formal proof of the absence of any attacks, hence the security property is successfully verified. Scyther returns an `Ok` status code and a *Verified* message for each claim that is successfully verified. As we see in Figure 3.2, Scyther

Claim				Status		Comments
APKES	U	APKES,U1	Alive	Ok	Verified	No attacks.
		APKES,U2	Weakagree	Ok	Verified	No attacks.
		APKES,U3	Niagree	Ok	Verified	No attacks.
		APKES,U4	Nisynch	Ok	Verified	No attacks.
		APKES,U5	Commit V,Ru	Ok	Verified	No attacks.
	V	APKES,V1	Alive	Ok	Verified	No attacks.
		APKES,V2	Weakagree	Ok	Verified	No attacks.
		APKES,V3	Niagree	Ok	Verified	No attacks.
		APKES,V4	Nisynch	Ok	Verified	No attacks.

Figure 3.2: Results of a verification process using Scyther where all claims are successfully verified.

is not able to find any attacks on the protocol. To illustrate the case of Scyther actually finding an attack, we try to verify the claims introduced in the paragraph on secrecy in Section 3.2.1, claiming that `Ru` and `Rv` are secret. In our example protocol, both nonces are sent in plaintext between U and V, hence this claim will naturally fail, as seen in Figure 3.3.

Claim				Status		Comments	Patterns
APKES	U	APKES,F1	Secret Ru	Fail	Falsified	At least 1 attack.	1 attack
		APKES,F2	Secret Rv	Fail	Falsified	At least 1 attack.	1 attack

Figure 3.3: Results of a verification process using Scyther when a claim fails.

The status *Falsified* states that the claim is provable false. When a claim is proved to be false, Scyther will also provide a comment; either *At least X attack(x)* or *Exactly X attack(s)*. In the first case, X attacks where found by Scyther, but the search is not able to detect whether or not there may be other attacks as well. In the other case, Scyther can prove that within the given state-space, there are exactly X attacks. Whenever Scyther finds an attack on a protocol, it will also provide a concrete description of the attack as graph. An example of such a graph is shown in Figure 3.4. It contains a description of the different runs that the adversary executes, and shows how it can pass or intercept messages across different runs to learn some secret information or construct an attack.

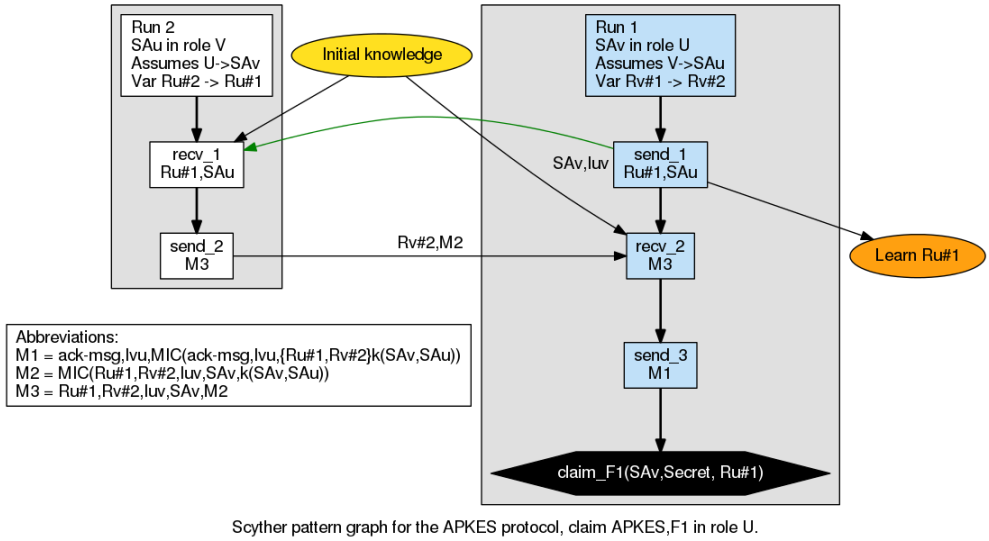

Figure 3.4: When Scyther finds an attack on a protocol, if will also provide a graph of the attack.

Chapter 4
Adaptable Pairwise Key Establishment Scheme (APKES)

APKES is a proposed protocol for handling key establishment and key management in 6LoWPAN. It is currently implemented in the operating system Contiki, which is an operating system targeted at the sensor network community, but has not undergone any formal security analysis. This chapter will cover its ideas, and conduct a formal security analysis using Scyther.

4.1 Introduction to APKES

As previously described, 6LoWPAN is a protocol stack for integrating WSNs running on 802.15.4 with IPv6 networks, and enables the nodes in the network to communicate with each other or remote hosts over IP. APKES provides a framework for establishing pairwise keys for nodes in 6LoWPAN networks. The advantage with pairwise keys over other key schemes such as a network-shared key is related to node compromises. In 6LoWPAN networks, devices are often placed in potential hostile and unattended areas, greatly increasing the possibility of being tampered with by attackers. In the case of a network shared key, the whole network would be compromised in the event of a node compromise. Also, the attacker would be able to add new nodes to the network, as the upper-layer protocols rely on the 802.15.4 security sub-layer which is able to filter out replayed packets and prevent injection, but not discover node compromises [35]. A solution to the tampering problem could be to construct tampering-proof nodes, but this is expensive and difficult, hence not a preferable solution [3]. Pairwise keys, however, would only compromise the communication going to or from that particular node. Figure 4.1 illustrates how APKES is implemented at the link layer along with the 820.15.4 security sublayer.

APKES provides a "pluggable" key establishment scheme for 6LoWPAN networks using pairwise keys, where the developer of a 6LoWPAN network picks an appropriate key establishment scheme and delegates APKES into handling the key establishment with other nodes [35]. As there is really no superior scheme for 6LoWPAN networks,

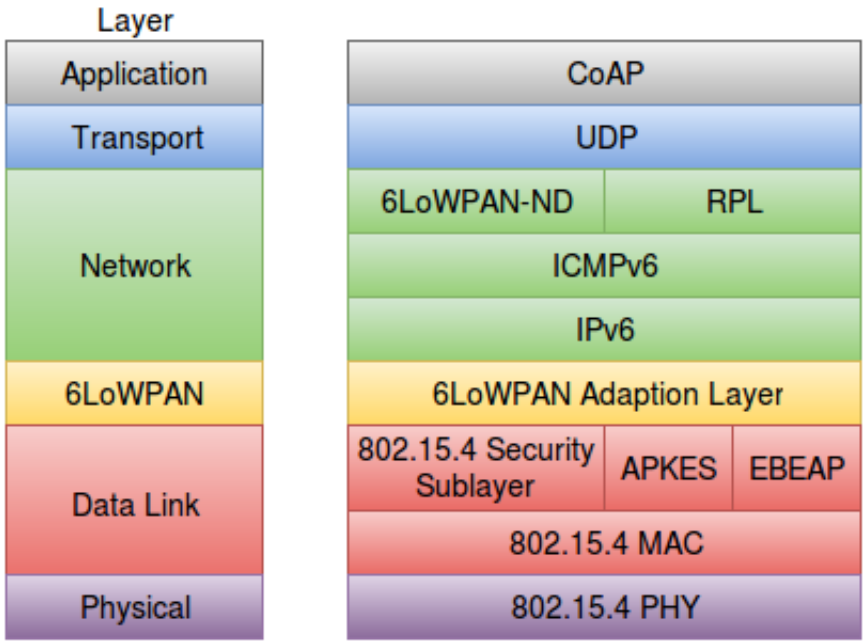

Figure 4.1: APKES is positioned in the data link layer in the 6LoWPAN stack expanding the 802.15.4 security sublayer [35].

the use of pluggable schemes enhances the overall usability of the protocol, as the developer can use the most appropriate scheme based on the challenges he faces. The only function of the plugged-in scheme is to feed APKES with the shared secret for communicating nodes, and APKES will handle both key establishment and key management. Examples of pluggable schemes that has been suggested for APKES are Localized Encryption and Authentication Protocol (LEAP) [53], Blom's Scheme [9], and random pairwise keys [11]. In the case of random pairwise keys, path key establishment has to be implemented in addition to APKES.

During the key establishment, a responding node goes from not a neighbour, to a tentative neighbour, before ending up as a permanent neighbour, giving that the key establishment was successful. The change of neighbour status is implemented to prevent Denial of Service (DoS) attacks on nodes by flooding them with `HELLO` messages, which would force them to reply with `HELLOACK`s, potentially drain their battery. Also, injecting and replaying `HELLOACK`s and `ACK`s would also aid an attacker in draining the network's nodes for battery. Upon receiving a `HELLO` message, V checks if U is already a neighbour, and that it has available space in its list of tentative neighbours, which is limited to M_t neighbours.

By limiting the number of tentative neighbours, V is protected against consecutive `HELLO` messages, which are discarded without being processed when the number of tentative neighbours exceed M_t. The list of tentative neighbours is processed for each `HELLO`, where neighbours whose expiration time has exceeded are deleted. Permanent neighbours are potentially created upon receiving valid non-replayed `HELLOACK`s and valid `ACK`s from non-permanent neighbours.

4.1.1 Protocol specification

Key establishment in APKES consists of a three-way handshake, as described in Figure 5.1. When a node U in a 6LoWPAN network running glsapkes wants to establish contact with other nodes, it broadcasts an unauthenticated `HELLO` message containing a random nonce Ru. Upon receiving a `HELLO`, V computes a random nonce, Ru, as well, and stores the concatenation of the two. V then waits for a random time T_w. The waiting period is introduced to avoid flooding U with responses, as there may be an unknown number of nodes that received the broadcast message. After T_w, V loads its key $K_{v,u}$ from the pluggable key scheme, and uses this key to authenticate a `HELLOACK` message containing the computed R_v nonce and the received R_u. MICs are generated by the 802.15.4 security sublayer, through the use of CCM*, which is a modified version of the regular CCM allowing for the payload of the frame to be encrypted using AES with a 128-bit key [35]. APKES uses $K_{v,u}$ to authenticate the `HELLOACK`, and sends it to U. Afterwards, V obtains the pairwise key $K'_{v,u}$ for future communication with U, by plugging $K_{v,u}$ it into the AES algorithm along with the two nonces.

When U receives a `HELLOACK` message, it verifies the attached MIC by extracting its key $K_{u,v}$ from the pluggable scheme and computing the MIC for the concatenation of R_u and R_v. U then computes the pairwise key for communicating with V by plugging it into AES algorithm. U also checks that the R_u value has not been tampered with, and is equal to the value it initially sent in its `HELLO` broadcast. The three-way handshake is ends with U sending an `ACK` to V that is authenticated using $K'_{u,v}$. When V receives the `ACK`, it verifies the MIC by using its pairwise key $K'_{v,u}$. After this process, U and V have agreed upon a shared pairwise key where $K'_{u,v} = K'_{v,u}$.

Three-way handshake in APKES

$$
\begin{aligned}
U &: \textit{Generate } R_u \textit{ randomly} \\
U \rightarrow * &: \texttt{HELLO}\langle R_u \rangle \\
V &: \textit{Generate } R_v \textit{ randomly. Wait for } T_w \leq M_w \\
V &: K_{v,u} \textit{ from pluggable scheme} \\
V \rightarrow U &: \texttt{HELLOACK}\langle R_u, R_v \rangle K_{v,u} \\
V &: K'_{v,u} \;=\; AES(K_{v,u}, R_u || R_v) \\
U &: K_{u,v} \textit{ from pluggable scheme} \\
U &: K'_{u,v} \;=\; AES(K_{u,v}, R_u || R_v) \\
U \rightarrow V &: \texttt{ACK}\langle\rangle K'_{u,v}
\end{aligned}
$$

Figure 4.2: Figure of the messages sent between communicating parties during APKES' three-way handshake. $\langle msg \rangle K$ indicates that the frame is authenticated using the key K.

4.2 Formal Security Analysis of APKES using Scyther

4.2.1 Key establishment

4.2.2 Key agreement

4.2.3 Security properties

Authentication

Key authentication = Secrecy of keys

Entity authentication = aliveness

implicit authentication -> Do not know whether or not the other party possesses the session key (yet). Explicit –> got a MAC signed using the session key

HELLOACK: Implicit key authentication ACK: Explicit key authentication ????

Key Compromise Impersonation

Impossible to achieve in protocols relying on symmetric keys? Need asymmetric? Boyd book.

Unknown Key Share

key confirmation

non-injective synch / non-injective agreement

Forward Secrecy

Not able to achieve in symmetric key?

4.2.4 Adversary Model

Specifying security properties

4.2.5 Results

4.2.6 Recommendations

Chapter 5

Handling Reboots and Mobility in 802.15.4 Security

AKES. Allow nodes to leave and join network. Discover new neighbours. Reboot.

Three-way handshake in APKES

$$
\begin{aligned}
U &: \textit{Generate } R_u \textit{ randomly} \\
U \rightarrow * &: \texttt{HELLO}\langle PAN_u, ID_u, R_u, C_u \rangle \\
V &: K_{v,u} \textit{ from pluggable scheme} \\
V &: \textit{Generate } R_v \textit{ randomly. Wait for } T_w \leq M_w \\
V &: K'_{v,u} \;=\; AES(K_{v,u}, R_u || R_v) \\
V \rightarrow U &: \texttt{HELLOACK}\langle PAN_u, ID_u, PAN_v, ID_v, R_v, I_{u,v}, C_v, P_u \rangle K_{v,u} \\
U &: K_{u,v} \textit{ from pluggable scheme} \\
U &: K'_{u,v} \;=\; AES(K_{u,v}, R_u || R_v) \\
U \rightarrow V &: \texttt{ACK}\langle PAN_v, ID_v, PAN_u, ID_u, I_{v,u}, C_u \rangle K'_{u,v}
\end{aligned}
$$

Figure 5.1: Figure of the messages sent between communicating parties during AKES' three-way handshake. $\langle msg \rangle K$ indicates that the frame is authenticated using the key K.

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Appendix

Appendix A

A.1 Scyther - APKES

```
/*
  Adaptive Pairwise Key Establishment Scheme (APKES)
*/

usertype KeyingMaterial;
usertype Index;

hashfunction MIC;

macro PairwiseKey = {Ru, Rv}k(U, V);
macro helloack-mic = MIC(Ru, Rv, Iuv, SAv, k(U,V));
macro ack-mic = MIC(ack-msg, Ivu, PairwiseKey);

const SAu; # U's Short Address
const SAv; # V's Short Address

const Iuv: Index; # U's index in V's list of neighbours
const Ivu: Index; # V's index in U's list of neighbours

const ack-msg;

protocol APKES(U, V)
{
  role U
  {
    fresh Ru: Nonce;
    var Rv: Nonce;
```

```
  # HELLO
  send_1(U, V, Ru, SAu);

  # HELLOACK
  recv_2(V, U, (Ru, Rv, Iuv, SAv, helloack-mic));

  #ACK
  send_3(U, V, (ack-msg, Ivu, ack-mic));
  #send_3(U, V, I );


  # Claims:
  claim_U1(U, Alive); # V was "alive" as U was able to
 execute the protocol correctly
  claim_U2(U, Weakagree);
  claim_U3(U, Niagree); # Non-injective agreement
  claim_U4(U, Nisynch); # Non-injective synchronization
  claim_U5(U, Commit, V, Ru); # claim that the recv2 value
   of Ru has not been changed from the send_1 Ru-value

  claim_U7(U, Secret, PairwiseKey); # The pairwise key is
 kept secret from adversary


}

role V
{
  fresh Rv: Nonce;
  var Ru: Nonce;

  # HELLO
  recv_1(U, V, Ru, SAu);
  claim_V6(V, Running, U, Ru); # To make sure that the Ru
 is not tampered with.

  # HELLOACK
  send_2(V, U, (Ru, Rv, Iuv, SAv, helloack-mic));

  # ACK
```

```
    recv_3(U,V, (ack-msg, Ivu, ack-mic));
    #recv_3(U, V, MIC(Ru));

    # Claims
    claim_V1(V, Alive);
    claim_V2(V, Weakagree);
    claim_V3(V, Niagree);
    claim_V4(V, Nisynch);
    claim_V5(V, Secret, PairwiseKey);


  }
}

protocol EBEAP (U,V)

{



}
```

scripts/apkes.spdl

A.2 Scyther - AKES

```
/*
  Adaptive Key Establishment Scheme (AKES)
*/

hashfunction MIC;

macro PairwiseSessionKey = {Ru, Rv}k(U,V); # Where k(U,V) is
    the key from the plugged-in scheme
macro HelloAckMIC = MIC(PANu, IDu, PANv, IDv, Rv, Iuv, Cv,
   Pu, PairwiseSessionKey);
macro AckMIC = MIC(PANv, IDv, PANu, IDu, Ivu, Cu,
   PairwiseSessionKey);

const PANu; # U's Personal Area Network (PAN) Id
const PANv; # V's Personal Area Network (PAN) Id
```

```
const IDu: Agent; # U's extended, short or simple address
const IDv: Agent; # V's extended, short or simple address

const Cu; # V's frame counter of the last accepted frame
    from U
const Cv; # U's frame counter of the last accepted frame
    from V

const Pu; # Flag indicating whether or not U is currently
    one of V's permanent neighbours

const SAu; # U's Short Address
const SAv; # V's Short Address

const Iuv; # U's index in V's list of neighbours (EBEAP)
const Ivu; # V's index in U's list of neighbours (EBEAP)

const ack-msg;


protocol AKES(U, V)
{
  role U
  {
    fresh Ru: Nonce;
    var Rv: Nonce;

    # HELLO
    send_1(U, V, PANu, IDu, Ru);

    # HELLOACK
    recv_2(V, U, {PANu, IDu, PANv, IDv, Iuv, Rv, Cv, Pu,
    HelloAckMIC}k(U,V));

    # ACK
    send_3(U, V, (ack-msg, PANv, IDv, PANu, IDu, Ivu, Cu,
    AckMIC));

    # Claims
  claim_U1(U, SKR, PairwiseSessionKey); # The pairwise
    session key is kept secret from adversary
```

```
  claim_U2(U, Alive); # V was "alive" as U was able to
    execute the protocol correctly
  claim_U3(U, Weakagree);
  claim_U4(U, Niagree); # Non-injective agreement
  claim_U5(U, Nisynch); # Non-injective synchronization

  }

  role V
  {
    var Ru: Nonce;
    fresh Rv: Nonce;

    # HELLO
    recv_1(U, V, PANu, IDu, Ru);

    # HELLOACK
    send_2(V, U, {PANu, IDu, PANv, IDv, Iuv, Rv, Cv, Pu,
    HelloAckMIC}k(U,V));

    # ACK
    recv_3(U, V, (ack-msg, PANv, IDv, PANu, IDu, Ivu, Cu,
    AckMIC));

    # Claims
  claim_V1(V, SKR, PairwiseSessionKey);
  claim_V2(V, Alive); # V was "alive" as U was able to
    execute the protocol correctly
  claim_V3(V, Weakagree);
  claim_V4(V, Niagree); # Non-injective agreement
  claim_V5(V, Nisynch); # Non-injective synchronization

  }

}
```

scripts/akes.spdl