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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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Abstract

IPv6 over Low power Wireless Personal Area Network (6LoWPAN) is a concept that enables an Internet Protocol (IP) connection over networks that use the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard and has a focus on low-power devices with limited computational power. This has made 6LoWPAN an exciting technology for future device-to-device communications and the Internet of Things.

This thesis presents, to the author's knowledge, the first formal security analysis of APKES, AKES, and SAKES, which are proposed protocols for establishing keys in IEEE 802.15.4 networks that utilize the 6LoWPAN. APKES and AKES were proven to have none or few issues that were discovered by the formal security analysis, and may, therefore, be possible schemes for future key establishment in 6LoWPAN. Multiple weaknesses were discovered in SAKES, where this thesis has aimed to improve the protocol by implementing necessary measures and validate these improvements using Scyther.

Sammendrag

6LoWPAN, av det engelske begrepet “IPv6 over Low-power Wireless Personal Area Network”, betegner et personlig trådløst nettverk som bygger på IEEE 802.15.4 standarden. Nyvinningen ved dette nettverket er at det tillater enheter å kommunisere med hverandre og omverdenen gjennom bruk av protokollen Internet Protocol, bedre kjent som bare IP. 6LoWPAN har et spesielt fokus på å minimalisere energibruken i nettverket. Dette gjør at mindre, billigere og enklere enheter kan kobles med hverandre og omverdenen, noe som har gjort 6LoWPAN til en spennende teknologi for fremtidens enhet-til-enhet-kommunikasjon og “tingenes internett”.

Denne masteroppgaven presenterer, til forfatterens kjennskap, de første formelle sikkerhetsanalysene av tre protokoller for etablering av krypteringsnøkler i 6LoWPAN: APKES, AKES og SAKES. APKES og AKES blir bevist til å inneholde ingen eller få alvorlige feil, noe som gjør dem til aktuelle protokoller for etablering av krypteringsnøkler i 6LoWPAN. Det ble oppdaget flere svakheter ved SAKES. Derfor blir flere mulige forbedringer til protokollen presentert, implementert og verifisert ved hjelp av Scyther.

Preface

This thesis has been submitted in the fulfilment of Masters of Science in Communication Technology, with a specialization in information security at the Norwegian University of Science and Technology (NTNU) in Trondheim. The thesis is original, unpublished, and independent work by the author E. Klevstad.

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Finally, I would like to thank you as a reader. By completing these last sentences, you have at least read one page of my thesis.

Cheers.

Eirik Klevstad

Trondheim, 10th June 2016

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List of Acronyms

6LoWPAN IPv6 over Low power Wireless Personal Area Network.

AES Advanced Encryption Standard.

AKE Authenticated Key Exchange.

AKES Adaptable Key Establishment Scheme.

APKES Adaptable Pairwise Key Establishment Scheme.

AS Authentication Server.

BAN Burrows-Abadi-Needham.

CA Certificate Authority.

CCM Counter with CBC-MAC.

CTR Counter.

DoS Denial of Service.

EAP Extensible Authentication Protocol.

EBEAP Easy Broadcast Encryption and Authentication Protocol.

ECC Elliptic Curve Cryptography.

ECDH Elliptic Curve Diffie-Hellman.

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.

IKE Internet Key Exchange.

IoT Internet of Things.

IP Internet Protocol.

KCI Key Compromise Impersonation.

KDC Key Distribution Center.

LEAP Localized Encryption and Authentication Protocol.

LKR Long-term Key Reveal.

MAC Message Authentication Code.

MIC Message Integrity Code.

MSC Message Sequence Chart.

NTNU Norwegian University of Science and Technology.

OSI Open Systems Interconnection.

PAN Personal Area Network.

PFS Perfect Forward Secrecy.

RAM Random Access Memory.

RFID Radio Frequency Identification.

RSA Rivest-Shamir-Adleman.

SAKES Secure Authentication and Key Establishment Scheme.

SKR Session-Key Reveal.

SNMP Simple Network Management Protocol.

SPDL Security Protocol Description Language.

SS Service Server.

TCP Transmission Control Protocol.

TGS Ticket Granting Service.

TGT Ticket Granting Ticket.

TLS Transport Layer Security.

UDP User Datagram Protocol.

WLAN Wireless Local Area Network.

WPA Wi-Fi Protected Access.

WPA2 Wi-Fi Protected Access II.

WPAN Wireless Personal Area Network.

wPFS Weak Perfect Forward Secrecy.

WSN Wireless Sensor Network.

Chapter 1

Introduction

1.1 Motivation

Information is the new natural resource. It is around us at all times, the possibilities of reshaping it into value are endless, and it is renewable. All we need to do is capture it. Computer devices equipped with sensors can capture a particular property of the physical world, and convert it into information. The information can then be exchanged with other devices, processed, computed on, or transformed into something new. To collect as much information as possible, we need a significant amount of these devices, and they need to be able to communicate with each other through networks.

Our information is valuable. Therefore, we need to secure the data that we capture to protect it from possible adversaries that would want to steal, alter, or delete our precious information. Information can be secured by encrypting it, which would make the data look like nonsense to adversaries that intercept it. However, before a device is capable of encrypting its outgoing information stream, it needs to agree upon some key scheme to use for the encryption-decryption process. This is done through key establishment.

There exist numerous well-tested and deployed protocols for key establishment in wireless networks. These are not, however, always well-suited for device-to-device communication where the devices are meant to be cheap and energy-efficient. Therefore, the community needs to rethink their approach when it comes to key establishment schemes for sensor networks.

Protocols for key establishment in device-to-device networks is an emerging market and involves multiple different network technologies and standards. While in the chase of creating energy efficient and universal key establishment schemes, the security analysis may not always be conducted properly or conducted at all. As the key establishment schemes become more sophisticated and complex, it may be

difficult for humans to verify that a scheme is correct and does not contain any states that may cause the scheme to misbehave.

To avoid insecure protocols being standardized and deployed, which has repeatedly happened, formal security analysis is often conducted to verify that the protocol is, in fact, correct. Over the recent years, multiple tools for formal security analysis have been developed and made available to the public. By using these tools it is possible to verify security protocols by allowing a machine to explore each possible state of the protocol to expose possible malicious behaviour. Formally security analysis is something that any protocol should be exposed to, but is surprisingly often omitted. Hence, it would be interesting to explore proposed protocols for key establishment in 6LoWPAN in a formal way to verify that they provide the alleged security stated in their proposal.

1.2 Scope and Objectives

The scope of this thesis is to give a formal security analysis of the three key establishment protocols APKES, AKES, and SAKES by using the tool Scyther. These protocols are utilizing the IEEE 802.15.4 standard in conjunction with 6LoWPAN, which allows for connecting devices to each other over the IP. In addition to formally verifying the protocols, improvements of the protocols should be suggested.

1.2.1 Objectives

This thesis has had three main objectives:

- Find and review three proposed protocols for key establishment in IEEE 802.15.4
- Perform formal security analysis of the protocols
- Propose improvements to the protocols

1.3 Methodology

The first part of this thesis presents a background study of wireless networks such as the IEEE 802.15.4 and the 6LoWPAN to understand better how they provide different types of security services. Also, various key establishment architectures have been assessed to increase the understanding of the properties that are desirable for key establishment schemes in a sensor network setting.

To be able to formally analyse key establishment protocols, a part of the thesis has involved learning how to implement and verify security protocols using the formal

security tool known as Scyther. This includes understanding the connection between security properties for key establishment and how Scyther interprets and verifies these properties.

Three protocols for key establishment without any previous formal security analysis have been chosen for this thesis. APKES were proposed as the initial paper which this thesis used as a starting point. This led the author into AKES, which is an improved version of APKES. Finally, SAKES was chosen based on its interesting architecture where it combines multiple cryptographic concepts. These protocols are reviewed and discussed to establish their various security properties, as well as security properties that they *should* possess. The protocols have been modelled and formally verified by using the Scyther tool. When Scyther checks a protocol, it returns a table of all the claimed security properties and an indication of whether the property was successfully verified or falsified. In the event of a property being falsified, the attacks have been inspected, and changes to the protocol have been made to achieve the claimed security property.

1.4 Contribution

The contribution of this thesis is, to the author's knowledge, the first published formal security analysis of APKES, AKES, and SAKES, which are key establishment protocols for 802.15.4 networks that utilize 6LoWPAN. In addition to formally verifying these protocols, the thesis also suggests improvements of the protocols, and explains their applicability for use in real world networks.

1.5 Outline

In Chapter 2, a general background is given on the Internet of Things and wireless sensor technology. It covers the general idea of key establishment, its security properties, and why it is challenging in an IoT context. The chapter also contains a brief overview of formal security analysis and the importance of conducting such analysis of modern security protocols.

Chapter 3 is an introduction to the formal security analysis tool known as Scyther. It explains how it works, and what types of security properties can be formally verified using the tool. In addition to the overall description, the chapter also contains examples of Scyther syntax, how we can model security protocols using the tool, and how to interpret the results of the verification process.

APKES, AKES, and SAKES are introduced in Chapter 4, along with their specifications and weaknesses. These are recently proposed protocols that aim to provide secure key establishment in 802.15.4 networks that utilize 6LoWPAN.

Chapter 5 describes the formal security analysis of the protocols, how the protocols have been modelled in Scyther, and how the different security properties are assessed. The chapter also contains the results of the verification process with a brief explanation.

The results of the formal security analysis are discussed and compared in Chapter 6, which also contains suggestions on how to improve the protocols. In Chapter 7, concluding remarks of the thesis and its contribution are presented. The thesis also comes with an appendix which contains the scripts of the modelled protocols, the attacks that is presented by Scyther, and an overview of the notation that is used when describing the protocols in detail.

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 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) [3, 67]. 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.

Computational devices that contain some sort of sensor may be attached to your everyday physical device, for example your potted plant. This creates a bridge between our physical world and the cyber world [43]. 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 an 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 decision to make 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 endless. 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 [32]. By 2020, the expected number of these “things” is more than 20 billion, 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) [40]. 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, that 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 analyse actions based on the received information [42, 71]. The application layer is also responsible for controlling the sensors, performing global system management, and present data for the end users 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 possibly 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 the Internet. As these devices are small, they have a limited battery life, and need to use energy in a highly efficient matter.

Protocols using the 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 IEEE 802.15.4 standard only defines the physical and data link layer of the Open Systems Interconnection (OSI) stack, which can be seen in Figure 2.1. Therefore, specifications need to be developed to utilize the possibilities provided by 802.15.4 in the upper layers. ZigBee [69], maintained by the ZigBee Alliance, is the most notable example of specifications that uses 802.15.4 as its base. Others include WirelessHART [36], MiWi [55], and ISA100.11a [39].

Layer	Data	Example technology
Application	Data	HTTP
Presentation	Data	SSL
Session	Data	RPC
Transport	Segments	TCP/UDP
Network	Packets	IP
Data link	Frames	MAC
Physical	Bits	Ethernet

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

The fundamental intention of the IEEE 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 data rate. While being smaller and more cost efficient than those found in more complex networks, devices that operate in 802.15.4 networks have a much more limited range (about 10 meters), and in most cases a throughput below 250 Kbps [34]. 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 necessarily 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) [66]. 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 desired security properties. In the most secure end of the scale we find the Advanced Encryption Standard (AES)-Counter with CBC-MAC (CCM), which is encryption using the block cipher AES with either a 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

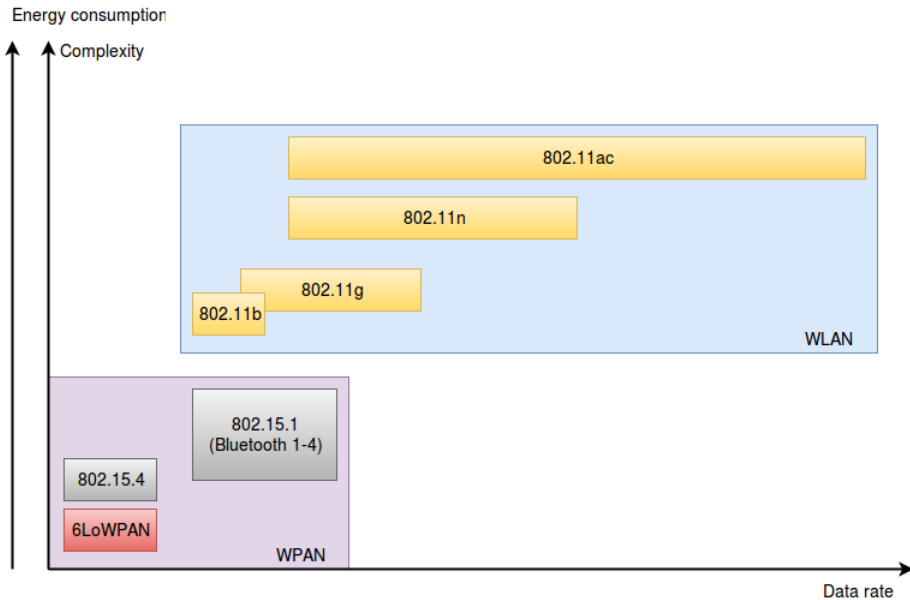


Figure 2.2: Figure of IEEE 802.15.4’s operational space compared to other wireless standards [34].

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. One of the things that the 802.15.4 standard does not specify, however, is how to deal with key establishment and key management. Therefore, these issues have to be taken care of in the higher layers.

2.3 6LoWPAN: Putting IP on Top of 802.15.4

Initially, the 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?” [56]. 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 [56]. The rejection

did not, however, stop the initiative, and a group of engineers within the Internet Engineering Task Force (IETF) started designing and developing what would later be known as 6LoWPAN.

One of the significant advantages 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 of the devices within a 6LoWPAN, as they are merely forwarding datagrams.

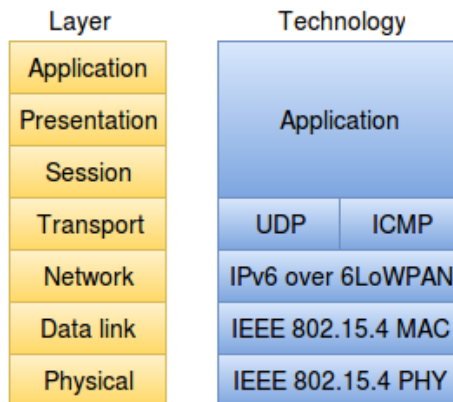


Figure 2.3: Figure of the 6LoWPAN stack, which uses the IEEE 802.15.4 physical and link layer, but adds its own adoption layer at the network layer.

6LoWPAN enables wireless 802.15.4 sensor devices to connect directly to the Internet via IPv6 by providing an adoption layer at the network layer as shown in Figure 2.3. The adoption layer provides unique functionality that fragments and compresses incoming packets to minimize header and packet size. This enables the embedded devices in 802.15.4 networks to receive the packets while using the least amount of memory and energy [46]. Its fundamental idea is that you only would only have to “pay” for what you use. The dispatch header field identifies the type of header to follow, and consists of 1 byte [56]. 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 [37]. In the special case of where a header consists solely of ones, an additional byte is added to the header, enabling a total of 320 different header types [56]. This greatly differs from IPv4 and Zigbee, which only define one monotonic header. The

use of different headers can be used to greatly minimize the header size of a packet as some types of frames may consist of smaller payloads than others, and where some header fields may be obsolete for the purpose of the frame.

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 the most reasonable approach.

2.4 Key Establishment and Key Management

As described, IoT devices communicate with each other over a network by utilizing some network protocol. There is, however, not always a guarantee 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 would enable them to perform cryptography (i.e. encryption, decryption, authentication) 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 cannot be trusted. For IoT devices and sensor networks, confidentiality and data integrity are important aspects. As previously described, IoT devices have limited resources in terms of battery life and processing abilities. This makes key establishment schemes that work well in other networks with access to more resources, such as WiFi, infeasible in an IoT scenario.

2.4.1 Cryptographic Keys

Long-Term keys

Long-term keys, also known as *static* keys, are keys that are deliberately stored on a device, as they are used multiple times for securing communication, and have no "expiration date". The shared secret key in symmetric key encryption, and the private key in public-key cryptography are examples of long-term keys.

Session Keys

Session keys are temporary keys that are used for a short period of time. By using such keys, the amount of ciphertexts encrypted with the same key is limited for an adversary to perform cryptanalysis on. Another advantage with using session keys is in the case of a node being compromised. If the protocol provides forward secrecy and known-key security (which will be described in Section 2.4.2), the data that is compromised is limited to that particular session. Session keys are not permanently stored at the client, and usually deleted after its expiration time, limiting the cost of memory, and distancing it from leaking previous session keys in the case of being compromised.

2.4.2 Security Attributes in Key Establishment Schemes

Authentication

Authentication is an important aspect of key establishment. More specifically, confirming the identity of the entity you are establishing keys with, as well as confirming that the established keys are authentic. If authentication is skipped, the protocol can be weak to so-called man-in-the-middle attacks where an adversary intercepts and relays messages between two communicating parties to learn or modify its content. There are multiple ways for parties to provide authentication based on the chosen key establishment scheme. For symmetric schemes, the inclusion of a MAC could provide authentication of the identity of the origin of a message. Schemes using public-key provides authentication through digital certificates, which are issued by a Certificate Authority (CA), and ensure the link between an identity and a public key.

For session keys, two properties are introduced, namely *implicit key authentication* and *explicit key authentication*. One of the most used ways of establishing session keys between two entities A and B is through A generating a random symmetric key, which is encrypted under B 's public key, before it is transmitted. B is then able to extract the session key that should be used for encrypting data using his private key. *Implicit* key authentication assures that only the rightful owner of the public key, which the session key is encrypted under (in this case B), is able to recover the session key. It does not, however, assure that B is in fact possessing the session key [35]. If the protocol also assures A that B has received and possesses the session key, the protocol provides a property called *key confirmation*. If a protocol provides both implicit key authentication and key confirmation, we say that the protocol overall provides *explicit* key authentication. As a side note, exactly how to define explicit key authentication is in some sense based on the glass half-full half-empty paradox. Is the knowledge of that the other party possesses everything it needs to derive the shared key enough for confirmation, or is explicit key authentication to

actually obtain something signed or encrypted using the pairwise key that you have derived. For this thesis, we will stick to the latter one as our definition of explicit key authentication.

Known-Key Security

Session keys are single-use symmetric keys that are used for a given period of the communication before being replaced and deleted from the system, 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 [30]. 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 keys of the web servers which did not support forward secrecy. The private keys could then be used to retroactively decrypt almost all traffic that had previously been recorded. One exception was servers that were utilizing one of Transport Layer Security (TLS)’s ephemeral modes, which are based on the Diffie-Hellman key exchange. The great advantage with the Diffie-Hellman key exchange is that it can be used to provide forward secrecy, making web servers that was using such versions of TLS immune against the attacks that exploited the Heartbleed bug.

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* [44]. 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. As PFS is a property related to session keys, it is not an achievable property for symmetric key schemes.

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 impersonating other entities in communication with A (masquerading as a different entity in order to establish a session key with A). KCI is, however, a very difficult security property to achieve for symmetric key protocols.

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 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 cannot be shared with any others without 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.

2.4.3 Key Establishment Architectures

Symmetric Key

Symmetric encryption is a technique for encrypting messages sent between two communicating parties, where the secret key used for encrypting the message is identical to the key used for decrypting it, as seen in Figure 2.4. Plaintext messages are processed through either a stream cipher, which encrypts the message byte by byte, or through a block cipher, which operates on a certain number of bits of the message for each round. The encryption process results in an encrypted message called a ciphertext. In schemes utilizing this form of encryption, it is essential that both parties possess the same shared secret (or key). One approach to provide both parties with the secret key is to load it into each of the parties in advance, which is inconvenient and difficult approach for a network where nodes may be joining and

leaving after network deployment. The most reasonable approach would be for two nodes to agree upon the shared secret together in a possibly unsafe environment.

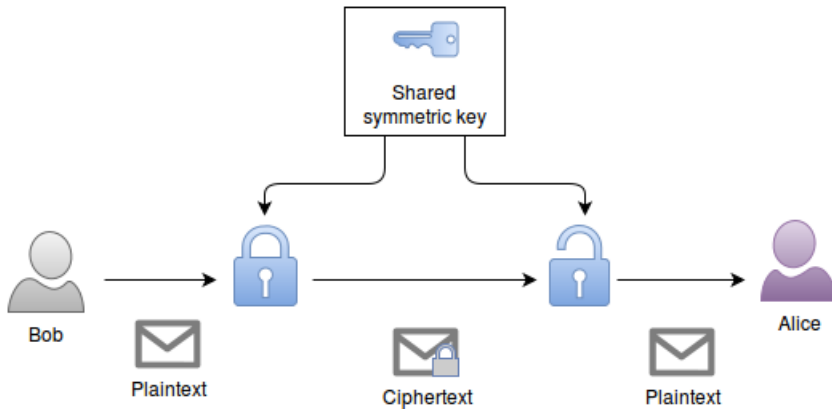


Figure 2.4: Figure of a symmetric encryption scheme, where both parties possess the same symmetric key used for encryption and decryption.

In the 1970s, Whitfield Diffie and Martin Hellman introduced the Diffie-Hellman key exchange, which allows two communicating parties to safely establish a shared secret without any prior knowledge of each other [26]. The shared secret could then be used for encrypting and decrypting messages sent between the two parties. While being a straightforward and fast way of encrypting information, symmetric encryption has a major drawback in the case of when one of the nodes is compromised. Node compromises would lead to an initially secure channel being insecure as the adversary could easily decrypt any message that it intercepts. Also, the sharing of the key is difficult to do in a secure manner. Another disadvantage with symmetric key schemes is the difficulty of authenticating the other party as they both encrypt data using the same key. 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.

Online Servers and Trusted Third Parties

By using a client-server architecture, the idea of a symmetric key that is shared between two parties can be extended to also include mutual authentication and session keys. Alice and Bob wants to establish a shared key, but they do not necessary trust each other. However, they both trust Charlie, which vouches for them both and assist them in agreeing upon a shared key to use for communication. This analogy

is also used by the Needham-Schroeder Symmetric Key Protocol, which introduces a trusted third party (often called a Key Distribution Center (KDC)) to generate and distribute a symmetric session key for Alice and Bob. When Alice wants to communicate with Bob, she notifies the server that she wants to establish a session with Bob. The server computes the session key and encrypts it twice, one time using Alice's secret symmetric key, and one time using Bob's. The secret keys of the parties are stored in advance at the server, hence making it a trusted third party.

The server then sends the encrypted session key to Alice. Alice decrypts the key encrypted with her symmetric key, and forwards the other cryptogram to Bob, which decrypts it using his key to obtain the session key. Bob sends Alice a nonce encrypted under the session key to prove to her that he has the session key, which Alice decrypts, performs a simple operation on, re-encrypts it, and sends it back to Bob, proving to him that she possesses the session key as well. However, this version of the Needham-Schroeder protocol is vulnerable to replay attacks, but can be fixed by using timestamps or include random nonces [58].

The Needham-Schroeder Symmetric Key protocol is the basis for Kerberos, which is a trusted third-party authentication service [59]. Kerberos consists of an Authentication Server (AS) and a Ticket Granting Service (TGS), often hosted in the same KDC, and an Service Server (SS) for providing services to the clients. The authentication model consists of two different credentials: *tickets* and *authenticators*. Tickets are used to securely transmitting the identity of the client between the AS and the SS, and contains information that is used to confirm that the client using the ticket is in fact the same client which it was issued to [68]. After generation, a ticket can be used multiple times until it expires. Authenticators are another type of credentials which is created by the client itself, encrypted, and passed along with the tickets sent from the client to ensure that the presented ticket is issued to it. Figure 2.5 shows the interaction between the different entities in Kerberos, and how the different tickets are passed through the authentication process.

When the client wants to contact another node in the network, it authenticates itself to the AS by providing the AS with its identity. The AS generates a Ticket Granting Ticket (TGT) and encrypts it under the client's secret key, and challenges the client: "If you can decrypt it, you are free to use the ticket to try to obtain a server ticket from the TGS". When the TGS receives a TGT, it first verifies that it is valid, and that the client is authorized to access to requested service. It then responds with a new ticket for the client to provide when requesting a service from the SS. The protocol is finalized by the client sending the server ticket to the SS, which is verified, before a confirmation message is generated and passed back to the client. If the client is able to successfully verify the confirmation message, the client and server start a session where the server provides the requested service to

the client.

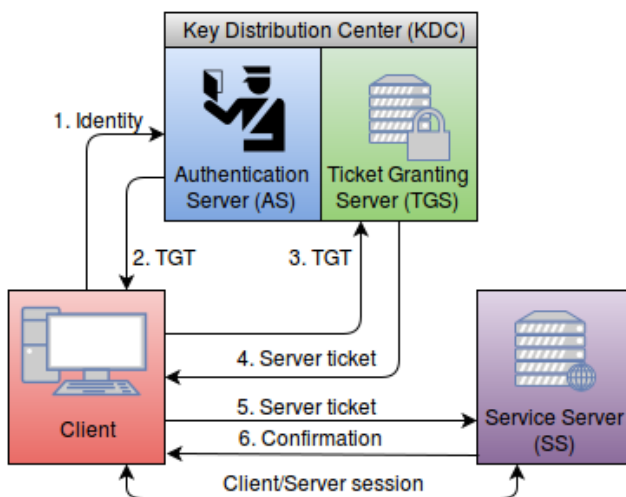


Figure 2.5: Figure of the interaction between the client, the KDC, and the SS in Kerberos.

Public-Key

As described in the section above, the Diffie-Hellman key exchange allowed two parties to agree upon a shared secret without any previous knowledge of each other. This laid the basis for public-key (or asymmetric) encryption, which consists of two keys that are generated mathematically: A private key for decryption, and a public key for encryption. In a public-key encryption system, users who want to send a message to Alice encrypt it using Alice's public key, which is published to the public. When Alice receives an encrypted message, she decrypts it using her private key, as seen in Figure 2.6.

Compared to symmetric encryption, public-key cryptography is significantly more computationally costly. However, the approach of using a public and private key for communications is more convenient than using symmetric keys. In the case of a node compromise, only one part of the communication is compromised. The adversary has your private key, and decrypt messages sent to you. It cannot, however, decrypt messages that you send to the other party as it does not possess the private key of the other party. Public-key cryptography also allows for authentication of the communicating parties by the use of digital signatures. Digital signatures are used to prove authenticity of a message, as well as proving that the message has not been modified in transmission.

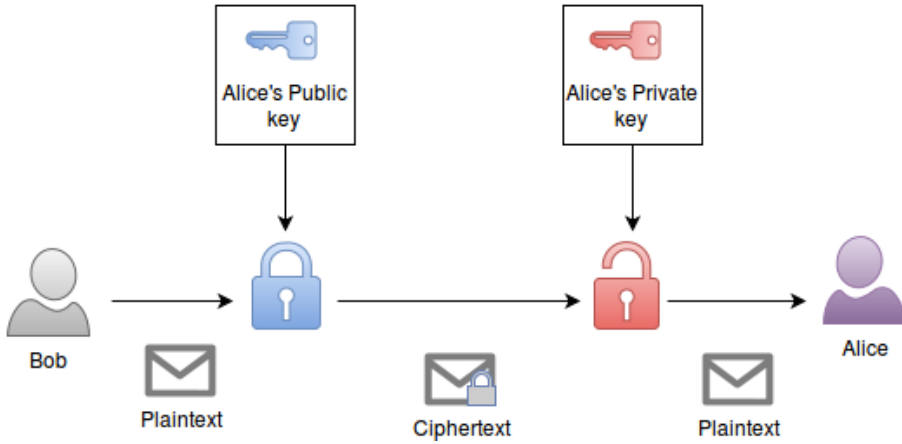


Figure 2.6: Figure of public-key encryption where a message to Alice is encrypted using her public key, and decrypted with her corresponding private key.

As mentioned, public-key cryptography is significantly more computational expensive than symmetric encryption, which has led to a hybrid solution where a symmetric session key is established and encrypted under the public key of each recipient. Such an approach reduces the computation time of encryption and decryption, giving a more efficient encryption scheme.

Public-key cryptography often involves certificates, which are used to prove ownership of a public key, and contains information about the identity of the owner, and also the digital signature of the party that has issued that particular certificate (often called a CA). When using a certificate, the sender of a message is able to confirm the identity of the recipient, by validating the certificate and the public key. The recipient may have signed the certificate himself, but the most normal approach is to have it signed by a trusted third party, namely a CA, which often are companies specializing in signing certificates and acting as a trusted third party.

2.4.4 Key Establishment Schemes

Symmetric Key

The simplest possible scheme for symmetric key establishment is the network-shared key scheme, where every node in the network possess the same symmetric key which is used for encryption and decryption between all nodes in the network [62]. While being easy to set up, a network-shared symmetric key violates all of the security properties previously described. In addition, it leaves the network vulnerable to node compromises as wireless sensor nodes often are deployed in hostile and unattended areas. This results in a network where the compromise of one node is equal to

the compromise of the entire network [46]. 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 [66].

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 has to store the symmetric key for possibly $N - 1$ nodes (called fully pairwise key schemes), where the number of nodes in the network can be high [62]. 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 [66]. When using pairwise keys, it is possible to provide a certain level of authentication, hence avoid unknown key-share attacks if implemented correctly, as well as key control, given that the two parties use a key exchange protocol where both are contributing to the key. The other properties, however, are not able to achieve using pairwise key establishment schemes.

Random pairwise keys is another scheme in the hunt for pairwise key schemes that maintains a modest level of memory consumption. Assume a “pool” of all the possible pairwise keys that can be created between the nodes in the network. Each node obtains a certain portion of these keys chosen at random (If A gets the pairwise key to B, B naturally also obtains the key for communicating with node A). By randomly delegating keys for different links between nodes, the idea is that there should be a possible path from A to C with high probability, even if they do not possess the key for direct communication, they are able to establish a multi-hop path between them by using the other nodes in the network [49]. This approach eliminates the need for storing $N - 1$ keys in each node, and is also more compromise resilient than pairwise key schemes as the adversary would only obtain a part of the pairwise keys used in the network if it compromises a node.

Online Servers and Trusted Third Parties

As mentioned, Kerberos is the most notable example of authentication systems utilizing a trusted third party, and it is implemented in most major operating systems such as Microsoft Windows, and systems running Unix such as OS X and Ubuntu. In IEEE 802.11, which is the standard for Wireless Local Area Network (WLAN) communication networks, protocols such as Wi-Fi Protected Access (WPA) and Wi-Fi Protected Access II (WPA2) may utilize the Extensible Authentication Protocol (EAP) as their authentication framework, which provides methods for negotiating multiple different key establishment and authentication schemes.

Public-Key

Of the different public-key cryptosystems in use today, the Rivest-Shamir-Adleman (RSA) cryptosystem is the most commonly used, which provides key generation, key exchange, and authentication [70]. RSA is not that often used for actually encrypt data sent between two parties as it is a relatively slow algorithm. Therefore, it is more convenient to encrypt a shared symmetric key under the parties' public keys to use for encryption of data. RSA provides authentication, while other properties involving session keys rely on the protocol used for establishing such keys. The ElGamal cryptosystem, which is based on the Diffie-Hellman key exchange, is another example of a system that is usually operated as a hybrid system utilizing both symmetric keys (for encryption) and public-key cryptography (for establishing symmetric keys).

Elliptic Curve Cryptography (ECC) systems utilize the algebraic structure of elliptic curves over finite fields, and can be used to both generate asymmetric key pairs and digital signatures, as well as providing key establishment [11]. Elliptic Curve Diffie-Hellman (ECDH), which is also based upon the Diffie-Hellman key exchange is, perhaps, the most notable scheme. One of the benefits with ECC over more commonly used public-key algorithms such as RSA is the reduced key size, which leads to greater memory and energy savings, while providing approximate the same level of security (ECC-160, which has a key size of 160 bits, is equivalent to RSA-1024 in terms of cryptographic strength) [5]. When operating in a mode that uses *ephemeral* keys, which are temporary keys generated in a key establishment process, ECDH provides security properties such as key control, known-key security, and forward secrecy. ECDH does not, however, provide authentication, which has to be addressed separately for example by using the Elliptic Curve Digital Signature Algorithm (ECDSA).

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 [40]. Sensor nodes running 6LoWPAN are powerful enough to implement cryptography standards such as AES-128, providing such nodes with a satisfactory level of encryption [64]. However, there exist 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 [46]. 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 MACs, which leads to higher requirements for storage

space, overhead in messages, and increased energy consumption.

Based on these issues, the research community looked to public-key cryptography, which had previously been considered an unsuitable solution for key establishment and key management in WSNs and other IoT related networks [33, 70]. While improving the security over symmetric key encryption, and also providing easier authentication and higher scalability, regular public-key protocols have issues related to energy consumption due to higher computational complexity, as well as being significantly more time consuming [31]. However, computer hardware specifications improves on a yearly basis, as more transistors are placed on data chips, and the processors are becoming more powerful and energy efficient. Public-key cryptography algorithms such as Rabin’s Scheme, NtruEncrypt and ECC all have proven promising results when implemented efficiently for wireless platforms [40], and especially ECC and its implementation of ECDSA have reduced the time spent on constructing a digital signature from 34 seconds in 2005, to 0.5 seconds in 2009 [64]. There is not, however, any current scheme that provides a clear advantage over others, symmetric or asymmetric, as they all have different advantages and disadvantages.

Following the line of thought where hardware specifications continuously improve, devices are also getting smaller as new “doors” are opened based on the accessibility of better hardware. Currently, companies such as Samsung and Sony are filing patents for so-called “smart” contact lenses, which are allegedly capable of taking pictures of the user’s current view, and transmitting the data wirelessly to another device [54, 72]. Processing units on something as small as a contact lens, which has to be transparent and not “bulky” to provide minimum distress on the eye, introduces a whole new level of demands to the energy efficiency of the components. As the data that is transferred from the lens obviously has to be secured in some way (having your “eyes” hacked does not sound especially tempting), we can only assume that the concept of symmetric key establishment is something that will be relevant in the distant future. Therefore, the rest of this thesis will have a special focus on symmetric key establishment.

2.5 Formal Security Analysis

As security protocols grow 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 Public-Key Protocol from 1978 [57]. 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 (referred to as the Needham-Schroeder 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 [12]. 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 [52]. 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, 50]. 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 [22]. 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. Models can be defined into two different groups: Computational and symbolic models. Computational models are detailed and cryptographic, while symbolic models are more abstract and simple.

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 [23]. 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.

Computational models are another way of mathematically model security protocols, mainly used by cryptographers, hence it holds a more mathematical approach compared to the symbolic model, and is also said to be more realistic and detailed. Messages are represented as bitstrings, which are sent into cryptographic primitives (can be seen as “functions”) where they are computed on bit-by-bit, and come out as

bitstrings [9]. Adversaries in computational models are modelled as powerful arbitrary and probabilistic Turing machines. They do not, however, account for physical attacks such as fault attacks, which may be more important as the device-to-device communication increases in the future. Security proofs offered by computational models are often acknowledged as powerful, but often difficult, long, and prone to errors [14]. For constructing proofs, symbolic models are much more efficient as they can more easily be automated to explore the entire problem space.

The Dolev-Yao model is a symbolic and formal intruder model used to prove the security properties of cryptographic protocols. Symbolic analysis considers cryptographic primitives as “black boxes” based on the assumption of perfect cryptography. The black boxes are used to construct terms, which represents the computational operations that the adversary is allowed to perform [9]. 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 [23]. The model is built upon three primary assumptions: Perfect cryptography, complete control of network, and abstract terms [27]. Firstly, the Dolev-Yao model assumes that the cryptography is perfect, essentially meaning that the cryptographic system cannot 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 [63]. The falsification process in model checking is to formally assess the security properties of the protocol in order to discover examples that disprove 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 exhaustively 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 property is fulfilled.

2.6 Related Work

Over the last decade, formal security analysis using tools have been more popular, and there exists numerous examples of key establishment protocols that have been formally verified using tools such as Scyther.

One of the pioneers on formal security analysis is the author of the Scyther tool, Cas Cremers, which has formally verified multiple protocols such as the Internet Key Exchange (IKE) protocols IKEv1 and IKEv2 [19]. In addition to these, Cremers and Horvat performed formal security analysis of the proposed protocols in the ISO/IEC 11770 standard [21], where they discovered unreported weaknesses in the protocols related to authentication. There exists several analyses involving Authenticated Key Exchange (AKE) protocols which use a stronger adversary than what the regular Dolev-Yao model provides, where protocols such as Yahalom, HMQV, DH-ISO and Naxos are verified in [22].

This thesis focuses on key establishment protocols for wireless networks such as the IEEE 802.15.4 standard. The IEEE 802.16e standard, also known as WiMAX, has been formally analysed in [2]. Key establishment schemes targeted on 802.15.4 networks, and especially 6LoWPAN, have not been the focus of formal security analysis. As the requirements for key establishment schemes in WSNs differs from well-known standards such as 802.11 and WiMAX, the focus of such schemes has been more of efficiency and usability with respect to energy and complexity, rather than verifying that they are secure for all possible scenarios.

Chapter 3

Symbolic Security Analysis Using Scyther

There exist multiple state-of-the-art tools for performing formal analysis of security protocols, for example Avispa [4], ProVerif [8], Tamarin Prover [53], and Scyther [15]. This thesis uses Scyther as its tool for conducting formal security analysis. It is chosen on suggestions from C. Boyd and B. Hale, and also on a review of popular formal security analysis tools in [61]. Another reason for choosing Scyther is its relatively easy syntax that resembled syntax from well-known programming languages. Tamarin was also considered, but it requires that protocols are modelled using multiset rewriting and first-order expressions [29, 53]. 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 pattern refinement algorithm that enables unbounded verification, falsification, and characterization [17]. 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 [24]. The blueprint can be modelled by Scyther, where the entities are converted into roles, the messages are converted into send and receive events,

and the security requirements into claim events. These terms are explained in the sections to follow. Scyther performs complete characterization of a protocol, where roles are broken down into 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 can execute. These traces are then grouped into patterns, which are partially ordered, symbolic sets of events [16]. 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 no attack exists, 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 [17, 22]. 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 [18]. 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 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 a blueprint that describes what the protocol is allowed 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 [16]. The execution of a role is referred to as a *run*, and defines a unique instance of the protocol with respect to local constraints and the binding between the role and the actual agent acting out the role's 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, 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 illustrate the threat. If the protocol developer is unsure of what types of claims should be stated for each role, Scyther has support for so-called verification of automatic claims, where Scyther will provide general claims such as secrecy for keys and values, and authentication of communicating parties.

Another of the major novelties in Scyther is the possibility for performing so-called multi-protocol analysis, which essentially means analysing multiple protocols that

co-exist in the environment. Such an analysis has previously been infeasible because of an incredibly wide state-space, but thanks to Scyther’s unique algorithm that operates on an unbounded state-space, it allows for 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 Long-term Key Reveal (LKR) rules, which are 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 Security Protocol Description Language (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 a protocol we call Test, 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 any specific behaviour.

```
protocol Test(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 role U, we can define a simple behaviour as shown in Listing 3.2, where U generates a random nonce R_u and sends it to V, before receiving a message from V containing the random nonces R_u and R_v . 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. The received Rv value is stored as the
    variable Rv.
};

```

Listing 3.2: Terms can be generated, 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. The received Ru nonce is stored as the variable Ru.
  send_2(V, U, Ru, Rv); # Send message to U containing the
    received nonce Ru and the freshly generated Rv.
};

```

Listing 3.3: Events in Role V usually corresponds 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, and public-key cryptography. Scyther also allows for declaring user specific types and macros, which are abbreviations of complex expressions. 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 of 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 by Scyther. If the protocol is not instructed with any security claims, Scyther is able to generate general claims for claiming secrecy for keys and values that are sent between roles, as well as authentication for communicating parties, 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 [23]. 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 agents where the secret property is successfully kept hidden from the adversary. For our example protocol, we can claim that the two values R_u and R_v 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 2.4.2), 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 [21]. In order to use Scyther's SKR claims, the compromise edition has to be used, and the 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 party stating the claim (U) that if the protocol is completed successfully, then the communicating party (V) has previously executed the protocol [51]. This does not necessarily mean that U knew he was interacting with V, nor does it mean that V 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 [51]. 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 also believes 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 [51]. 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 exchanged data values correspond to all of those in the 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 were 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 [25]. The *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 disrupt the current protocol execution [23]. 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 its 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 over variables that are 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 [20].

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 has reached a point where authentication is claimed (U has completed the protocol run with V), where Ru is the variable that is claimed to be exchanged during this part of the run [65]. 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 a certain part of the protocol run, for example some variable inside the message. Occurrence of a *commit* signal in U's protocol run means 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 [65]. 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 running and commit claims 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. Compromise 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 an 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 [6].

Section 2.4.2 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 modelled by enabling {LKR, Actor} in Scyther's adversary compromise model. Forward secrecy is the security property where previous communication is protected in the case of compromise of the long-term key, and is enabled in the adversary model by specifying {LKR, Aftercorrect} or {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 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

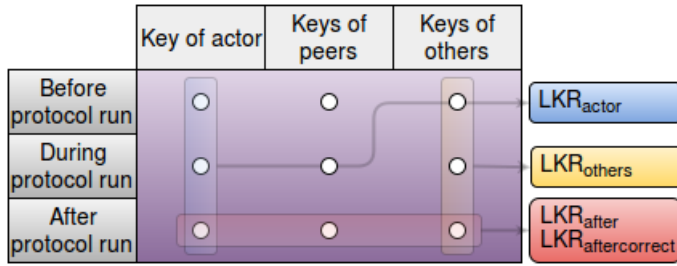


Figure 3.1: Mapping of LKR rules. Rows display when the compromise occurs, columns display whose data gets compromised, and the boxes captures the capabilities of the different adversaries, which are labelled to the right [6].

security property 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 quickly understand and assess the security of a protocol. If we continue our example of the protocol Test 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 stating 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 [17]. 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 one of 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 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 R_u and R_v 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	
TEST	U	TEST,U1	Alive	Ok	Verified	No attacks.
		TEST,U2	Weakagree	Ok	Verified	No attacks.
		TEST,U3	Niagree	Ok	Verified	No attacks.
		TEST,U4	Nisynch	Ok	Verified	No attacks.
		TEST,U5	Commit V,Ru	Ok	Verified	No attacks.
V		TEST,V1	Alive	Ok	Verified	No attacks.
		TEST,V2	Weakagree	Ok	Verified	No attacks.
		TEST,V3	Niagree	Ok	Verified	No attacks.
		TEST,V4	Nisynch	Ok	Verified	No attacks.

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

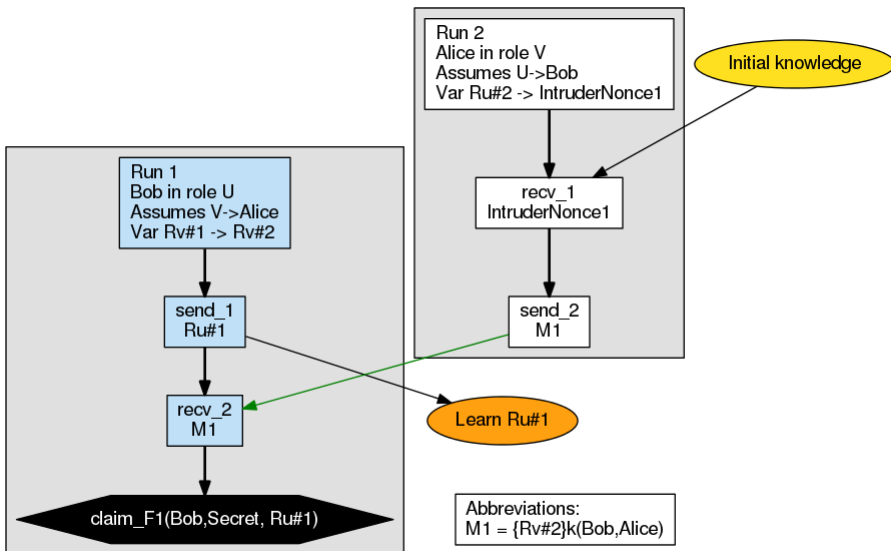
Claim				Status	Comments	Patterns	
TEST	U	TEST,F1	Secret Ru	Fail	Falsified	Exactly 1 attack.	1 attack
		TEST,F2	Secret Rv	Fail	Falsified	Exactly 1 attack.	1 attack

Figure 3.3: Results of a verification process using Scyther where 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(s)* or *Exactly X attack(s)*. In the first case, X attacks were 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 illustration of the attack as a graph. Figure 3.4 shows an example of such a graph. The top box for each vertical alignment of boxes describes the run, which is confined inside the grey boxes. It contains a description with the identifier of the run, instance type (i.e. what type of role it is running as), which agents it assumes it is communicating

with, and also what fresh values that are generated and instantiated in the run [20]. Boxes symbolises events in the different runs, connected by arrows which symbolises ordered constraints. Incoming arrows do not indicate that the messages is sent directly in this step, but is merely an ordering stating that this message can only be received *after* something else has happened. For example, in Figure 3.4, the `recv_2` event in Run 1 can only happen after Bob has sent his message in the `send_1` event and Alice has sent her message in the `send_2` event.



Scyther pattern graph for the TEST protocol, claim TEST,F1 in role U.

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

Arrows in Scyther graphs can be coloured differently. Red arrows indicate that the sent message does not correspond to the received message, which means that the adversary used some information from the sent message in order to construct the one that is received [20]. Green arrows indicate that the sent message is identical to the received message. The last possible color (other than black, which does not carry any specific information) is yellow. Yellow arrows indicate that the two parties agree upon the message that is exchanged between the two, but do not agree upon who was the sender and receiver during the exchange.

When a message is sent, it is instantly obtained by the adversary. Initial knowledge (or intruder knowledge) corresponds to the intuition that the intruder is able to generate fresh values of any type, which it in Figure 3.4 uses to generate the nonce that is sent in the `send_2` event. The green oval shape indicates where the adversary

obtains the information which falsifies the claim, which in this example is the `Ru` value that is sent in plaintext. The two last boxes in the graph are the black box at the bottom of `Run 1` which contains the claim that is falsified by Scyther, and the white box to its right which contains abbreviations of the messages that are passed between roles to increase the readability of the graph.

Chapter 4

Three Protocols for Key Establishment in 6LoWPAN

In this chapter, three proposed protocols for key establishment in 6LoWPANs will be introduced. The chapter also contains an assumption of the different security properties that would be natural to assume for the respective protocols, and a summary of the protocols' immediate weaknesses. The notation that is used for describing the presented protocols can be reviewed in Appendix C.1.

4.1 General Properties

Multiple properties are common for all of the protocols that this thesis addresses. These properties are more general than regular key establishment properties and cover a wide area of different schemes and attacks.

Key scheme As mentioned in Section 2.4.4, multiple versions of key establishment schemes exist. The network-wide shared key and pairwise keys are commonly used for symmetric key schemes, while public-key schemes is another option where encryption and decryption is done using separate, but mathematically tied, keys. Session keys are symmetric keys which are used for a single session, and never to be used again. These are often used in conjunction with public-key cryptography.

Replay protection Replay protection is a general property for a network which prevents an adversary from capturing a data frame and injecting (*replaying*) at a later time. Fortunately, the IEEE 802.15.4 security sub-layer is capable of filtering out replayed frames and thereby preventing injection [46].

Resilience against node compromises In 6LoWPANs, nodes are potentially deployed in hostile areas, which gives an adversary another way into the node, in addition to regular hacking. Therefore, it is important for key establishment schemes to discover and avoid establishing sessions with compromised nodes. 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. For schemes using pairwise schemes, however, only communication going between a node pair would be compromised in the case where an adversary obtains the secret pairwise keys of the node. For schemes utilizing public-key schemes, only information going *to* the compromised node would be vulnerable, as the attacker only possesses the private key which can be used to decrypt information that is encrypted using the corresponding public key.

Key revocation When a node is compromised for a public-key scheme, this usually includes the adversary to obtain the private key of the device. Key revocation is to retire the public key of this device by marking them as revoked, to avoid that other devices encrypts data using the compromised node's public key.

Tamper resistance Devices in 6LoWPANs are often deployed in hostile areas, where attackers may physically tamper with the devices. This is an issues that is not easily resolved, but can be avoided by constructing tampering resilient devices. For physical tampering with the device to be avoided, it has to be hermetically sealed, as well as providing strong cryptography for keeping the key secret from side-channel attacks and hostile testing. Devices used in 6LoWPANs are considered to be small, cheap, and with a limited battery supply. Hence it is difficult to provide sufficient countermeasures against tampering, and not a preferable solution [1]. Therefore, it is important for the network being able to provide node compromise resilience while storing the minimum amount of sensitive keying material on the devices.

Denial of Service (DoS) attacks DoS attacks are essentially flooding an entity with more requests than it is able to handle to force it to break down. In a key establishment setting, this would be to overwhelm a device with key establishment requests. The goal of a DoS attack in a 6LoWPAN could be to drain the device for battery, but also to keep the device from establishing keys with other devices in the network.

Wormhole attacks As explained, DoS attacks actively target an entity to deny it from providing a service or performing a certain operation. Wormhole attacks are more passive attacks, where the adversary announces itself as the best path between two nodes *A* and *B* to trick the network into choosing the path through the adversary. By announcing an exceptional good path between two nodes, the adversary creates a non-existent path between the two nodes referred to as a *wormhole*. Now the attacker can turn a link in the network on and off at its own choosing, and also drop specific frames, for example those initiating key establishments. How to avoid such attacks is the topic of current research [47].

4.2 Adaptable Pairwise Key Establishment Scheme (APKES)

The Adaptable Pairwise Key Establishment Scheme (APKES) is a proposed scheme by Krentz et al. for handling key establishment and key management in 6LoWPANs [46]. It is currently implemented in the operating system Contiki, which is targeted at the sensor network community. Table 4.1 displays which general security properties that the scheme provides. As previously described in Section 2.3, 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 6LoWPANs.

Key scheme:	Pairwise symmetric keys
Replay protection:	Yes, 802.15.4 security sublayer
Node compromise resilient:	Yes, with EBEAP
Key revocation:	No
Tamper resistant	No
DoS resilient:	Yes
Wormhole resilient:	No

Table 4.1: Overview of which general security properties that APKES satisfies.

Figure 4.1 illustrates how APKES is implemented at the link layer along with the 802.15.4 security sublayer. In its implementation, APKES introduces three special messages which are used in the key establishment process, namely **HELLO**, **HELLOACK**, and **ACK** [46]. These are defined as 802.15.4 command messages, which are only processed by the data link layer (i.e. they are not passed to upper layers). Hence APKES can establish pairwise keys for networks building on 802.15.4 independently from the protocols running in the upper layers.

4.2.1 Allowing “Pluggable” Schemes to Increase Universality

APKES provides a “pluggable” key establishment scheme for 6LoWPANs using pairwise keys, where the developer of a 6LoWPAN picks an appropriate key establishment scheme and delegates APKES into handling the key establishment with other nodes [46]. As there is no general scheme for 6LoWPANs, the use of pluggable schemes enhance 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 the communicating nodes, and APKES will handle both key establishment and key management. Examples of pluggable schemes that have been suggested for APKES are Localized Encryption

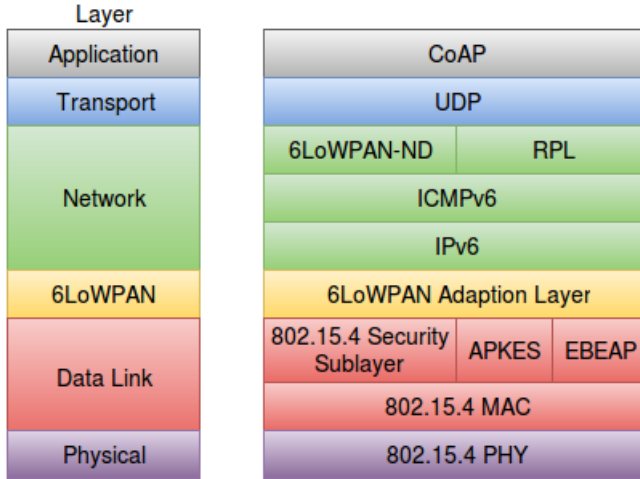


Figure 4.1: APKES is positioned in the data link layer in the 6LoWPAN stack, expanding the 802.15.4 security sublayer [46].

and Authentication Protocol (LEAP) [73], Blom’s Scheme [10], and random pairwise keys [13]. In the case of random pairwise keys, path key establishment has to be implemented in addition to APKES.

4.2.2 Avoiding Denial of Service Attacks

During the key establishment process, a responding node goes from not being a neighbour to a tentative neighbour, before ending up as a permanent neighbour, given that the key establishment was successfully executed. The change of neighbour status is implemented to prevent DoS attacks on nodes by flooding them with messages for starting key establishments (HELLO messages). Flooding a device with HELLO requests would force it to reply to each message (denoted as HELLOACK), potentially draining its battery. Also, injecting and replaying these responses could aid an attacker in draining the network-nodes for batteries. Upon receiving a HELLO message, the responder (B) checks if the initiator (A) is already a neighbour, and that it has available space in its list of tentative neighbours, which is limited to M_t neighbours.

APKES modifies the security sub-layer of 802.15.4 to instantly discard data frames that arrive from non-permanent neighbours, only accepting HELLOs, HELLOACKs, or ACKs from these neighbours. By limiting the number of tentative neighbours, B is protected against a DoS attack consisting of consecutive HELLO messages. Such requests are discarded without being processed when the number of tentative neighbours exceeds M_t . The list of tentative neighbours is processed for each HELLO, where neighbours whose expiration time has expired are deleted.

4.2.3 Node Compromise Resilience

The Easy Broadcast Encryption and Authentication Protocol (EBEAP) is a suggested protocol for authenticating broadcast frames in 6LoWPANs that use APKES as their key establishment scheme, and is implemented along with APKES in the data link layer. EBEAP does not have any direct influence of the key establishment process, but runs in cooperation with APKES to provide node compromise resilience to the network. When APKES is run in conjunction with EBEAP, compromised nodes are only able to decrypt broadcast frames of its neighbours, but are not capable of impersonating the compromised node. However, EBEAP and its contribution is outside of the scope of this thesis.

4.2.4 Protocol Specification

Key establishment in APKES consists of a three-way handshake, as described in Figure 4.2

1. When a node A in a 6LoWPAN running APKES wants to establish contact with other nodes, it broadcasts an unauthenticated HELLO message containing a random nonce N_A .
2. Upon receiving a HELLO, B computes a random nonce N_B , as well, and stores the concatenation of the two.
3. B then waits for a random time T_w . The waiting period is introduced to avoid flooding A with responses, as there may be an unknown number of nodes that received the broadcasted HELLO message.
4. After T_w , B loads its key $K_{B,A}$ from the pluggable key scheme, and uses this key to authenticate a HELLOACK message containing the generated N_B nonce and the received N_A by computing a MIC. MICs are generated by the 802.15.4 security sublayer, through the use of CCM* operation mode in a block cipher. CCM* is a modified version of the regular CCM which allows for the payload of the frame to be encrypted using AES with a 128-bit key [46]. CCM* has additional capabilities, where the sender can choose whether to encrypt or authenticate the data.
5. B uses $K_{B,A}$ to authenticate the HELLOACK, and sends it to A . Afterwards, B derives the pairwise key $K'_{B,A}$ for future communication with A , by plugging $K_{B,A}$ it into the AES algorithm along with the two nonces.
6. When A receives a HELLOACK message, it verifies the attached MIC by extracting its key $K_{A,B}$ from the pluggable scheme and computing the MIC for the concatenation of N_A and N_B .

7. A then computes the pairwise key for further communication with B by plugging $K_{A,B}$ into the AES algorithm. A also checks that the N_A value has not been tampered with, and that it is equal to the value it initially sent in its HELLO broadcast.
8. The three-way handshake ends with A sending an ACK to B that is authenticated using the pairwise key $K'_{A,B}$.
9. When B receives the ACK, it verifies the MIC by using its derived pairwise key $K'_{B,A}$. After this process, A and B have successfully agreed upon a shared pairwise key where $K'_{A,B} = K'_{B,A}$, which is to be used for encrypting all future communication between the two nodes.

Three-way handshake in APKES

```

    A : Generate  $N_A$  randomly
    A → * : HELLO $\langle N_A \rangle$ 
    B : Generate  $N_B$  randomly. Wait  $T_w \leq M_w$ 
    B :  $K_{B,A}$  from pluggable scheme
    B → A : HELLOACK $\langle N_A, N_B \rangle K_{B,A}$ 
    B :  $K'_{B,A} = AES(K_{B,A}, N_A || N_B)$ 
    A :  $K_{A,B}$  from pluggable scheme
    A :  $K'_{A,B} = AES(K_{A,B}, N_A || N_B)$ 
    A → B : ACK $\langle \rangle K'_{A,B}$ 

```

Figure 4.2: Figure of the messages sent between communicating parties during APKES' three-way handshake.

4.2.5 Assumptions of Security Properties

One focus of APKES is to provide authentication of parties during the key establishment process. By inspecting the messages that are exchanged between the two sides in Figure 4.2, we observe that no encryption is involved in the handshake, but messages are authenticated by the use of MICs. These MICs are either computed using $K_{A,B}$ (the pre-shared secret) or $K'_{A,B}$ (the established pairwise key). Therefore, we can assume that entity authentication has to hold for the two communicating parties.

As mentioned in Section 2.4.2, *implicit* and *explicit* key authentication are two of the other attributes within authentication. For a three-way handshake such as

the one used by APKES, the initiator achieves implicit key authentication, while the responder (B) achieves explicit key authentication. As the pairwise key is computed from the two nonces that are shared between A and B , and the secret from the pluggable scheme (which we assume is secure), both know that the only parties that can compute the pairwise key are those possessing the pre-shared secret, giving them both implicit key authentication. B also receives an ACK which is authenticated using the pairwise key $K'_{A,B}$, effectively meaning that A has computed the pairwise key. B can confirm this by verifying the attached MIC, hence B can be said to achieve explicit key authentication of A . From A 's point of view, however, it has no confirmation of that B has in fact computed the pairwise key, other than it knows that B has to in order to verify the authenticity of the ACK. Also, as APKES is a key establishment scheme, the established key is of course assumed to be secret from the adversary.

4.2.6 Weaknesses and Challenges with APKES

Storing frame counters in case of reboot

APKES establishes a shared symmetric key between nodes, which is used to encrypt and decrypt data that is sent between them. One issue that the protocol does not address is the case where, for some reason, the node is forced to do a reboot. To avoid replay attacks, a node needs to keep control of the frame counters of the nodes it communicates with. These frame counters need to be swapped from the RAM of the device to a non-volatile storage over time. Such storages are for most 802.15.4 devices flash memory, making the swapping process both energy and time consuming [45]. In the Contiki operating system (where APKES is currently implemented), reboot commands are issued whenever processes get stuck or when the battery of the device is replaced [28]. In the case of a reboot without storing the frame counter, neighbouring nodes would just discard all messages from the node as the frame counter would start at zero, and the frames would be considered replayed. Another issue with storing anti-replay data is that APKES does not remove information of disappeared neighbours (nor does it discover that a node has left the neighbourhood), which may unnecessarily seize a large part of the node's memory over time.

Deadlock with previous neighbours after reboot

In addition to the weaknesses related to frame counters and storing anti-replay protection data, APKES has issues related to its usage of temporary and permanent neighbours. As mentioned, the life cycle of a neighbour node ranges from not being associated at all to becoming a temporary neighbour, and finally a permanent neighbour during the key establishment process. However, APKES discards HELLO messages from permanent neighbours to prevent DoS attacks. This means that if a neighbour reboots, it goes into a deadlock with former neighbours, where it is

not able to establish any new keys with these nodes as its HELLOs would silently be discarded [45]. The broadcasting of HELLOs occurs immediately after the node is booted up, which means that after the node is up and running, it will not attempt to connect to any new neighbours that may have been deployed afterwards. One can argue that it is the responsibility of the post-deployed nodes to establish contact with “early birds”, but deployed nodes should nevertheless be able to discover new nodes at runtime.

4.3 Adaptable Key Establishment Scheme (AKES)

Key scheme:	Symmetric and session keys
Replay protection:	Yes
Node compromise resilient:	Yes, with EBEAP
Key revocation:	No
Tamper resistant	No
DoS resilient:	Yes
Wormhole resilient:	No

Table 4.2: Overview of which general security properties that AKES satisfies.

The Adaptable Key Establishment Scheme (AKES) aims to improve and fix the weaknesses that were introduced in APKES and is currently implemented in the Contiki operating system [45]. Its primary goal is to establish session keys between devices in a 6LoWPAN while being able to withstand reboots and movement from one network to another. The general security properties that AKES satisfies As described in Section 4.2.6, APKES suffered from issues when restarting the device, and it was unable to provide mobility for the devices. Most of these problems can be solved by one “simple” adjustment: Establishing session keys between nodes instead of long-term keys. By establishing session keys, MICs from previous sessions would be invalidated, which enables the node to delete data used for providing replay protection (such as frame counters), and will also filter out old frames. Also, this removes the problem related to frame counters being reset after a reboot, as mentioned in Section 4.2.6.

AKES builds on the approach from APKES, where the underlying scheme is pluggable, and provides AKES with the secret that is pre-shared between the nodes. Before an 802.15.4 node can run AKES, addressing information (which uniquely identifies a node within an 802.15.4 network and is used by the pluggable scheme when establishing the shared secret) and keying material has to be preloaded into it. AKES also has access to the same command frames HELLO, HELLOACK, and ACK, which are used to establish session keys, and only processed by the data link layer.

Figure 4.1 describes where APKES is implemented in the 6LoWPAN stack, and as AKES is merely an improvement over APKES, it is implemented in the same layer as APKES and the 802.15.4 Security Sublayer.

4.3.1 Renewing a Session

As in APKES, AKES also utilizes a differentiation between non-neighbours, temporary neighbours, and permanent neighbours. When a node sends a HELLO, it obtains a temporary node status at the receiver. This status will be changed to a permanent neighbour upon receipt of an authentic ACK message as part of the final step in the session key establishment. Keep in mind that one of the issues with APKES was the deadlock state rebooted nodes would start in with previously permanent neighbours.

In AKES, a permanent neighbour who transmits a HELLO message will obtain status as a temporary neighbour in addition to its old permanent neighbour status until the ACK is received. After receiving the ACK, the permanent neighbour status is deleted, and the temporary neighbour is turned into a permanent one, which effectively renews the session between the two nodes. When a permanent neighbour (i.e. a session key) is established, the neighbour is assigned an expiration time when the key becomes invalid. The lifetime of a session is, however, prolonged for each received, authentic frame from the particular session, and can also be extended by issuing individual commands.

4.3.2 Preventing Deadlocks and Removing Neighbours

AKES introduces two tasks for preventing deadlocks and increasing mobility for devices while still keeping DoS attacks in mind: Periodically pinging its permanent neighbours to delete disappeared nodes, and discover new neighbours by routinely broadcasting HELLOs. When a session with a neighbour expires, the node issues an authenticated UPDATE command and sends it to the node, which potentially responds with an UPDATEACK. A received UPDATEACK leads to both parties of the session extending the lifetime of their key, while in the absence of such an acknowledgement, it will try for a few more times before eventually giving up and deleting the neighbour from its view of the network.

Trickle, which is an algorithm for distributing information in WSNs [48], is adopted by AKES for discovering new neighbours in a routine matter. The challenge is to define *how* often the node should broadcast HELLOs to discover new nodes and changes to the network topology, which Trickle aims to solve by applying different network statistics into its algorithm.

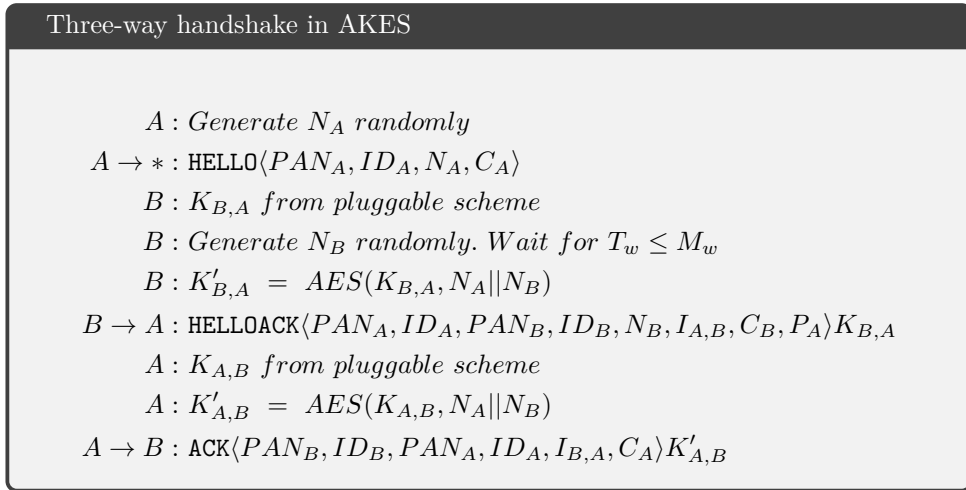


Figure 4.3: Figure of the messages sent between communicating parties during AKES' three-way handshake.

4.3.3 Protocol Specification

In AKES, the key establishment process consists of a three-way handshake where the two nodes establish a session key, as described in Figure 4.3.

1. Initially, the node A broadcasts a HELLO message to its neighbours containing a randomly generated nonce value N_A along with the identity of the node, its Personal Area Network (PAN) address, and the frame counter C_A . The HELLO broadcast is authenticated using EBEAP [46], which is a protocol for authenticating broadcast frames in 6LoWPANs, or a pre-distributed group session key.
2. When B receives a HELLO transmission, it generates a random nonce as well, denoted as N_B .
3. It then proceeds to request the shared secret $K_{B,A}$ from its pluggable scheme, and uses this secret to derive the pairwise session key $K'_{B,A}$ as $AES - 128(K_{B,A}, N_A || N_B)$.
4. B then crafts a HELLOACK response which is sent to A containing N_B . The HELLOACK is authenticated by adding a MIC generated with $K'_{B,A}$, in addition to B 's PAN address, identity, and other values related to frame counters and EBEAP authentication.

5. In the response, B attaches a field P_A as well to indicate whether or not A is currently registered as a permanent neighbour of B , and is also capable of piggybacking group session keys. If the P_A field is set, A can choose to abort the session key establishment, which would be normal if the HELLO was just a routine broadcast.
6. Upon receiving the HELLOACK, A validates the attached MIC by computing the pairwise session key $K'_{A,B}$ in the same manner as B .
7. A then completes the three-way handshake by creating an ACK which is authenticated using the pairwise session key $K'_{A,B}$ and sent to B .
8. When B receives the ACK, it verifies the attached MIC using its own session key. After this, future communication between A and B is encrypted using the shared pairwise session key until it expires.

4.3.4 Assumptions of Security Properties

AKES focuses on secure session key establishment between nodes in a 6LoWPAN. As it primarily builds on APKES, we can assume that the same security properties should hold for AKES as well. However, there are some deviations. In AKES, the responding party B uses the generated session key $K'_{B,A}$ to generate the MIC that is sent in the HELLOACK response. By doing so, A can verify that B has in fact computed the session key, which can be interpreted as *explicit* key authentication. Forward secrecy is often affiliated with session keys, but as the session keys are generated from a symmetric key, forward secrecy is not achievable for AKES.

4.3.5 Weaknesses and Challenges with AKES

Addressing information has to be loaded into the node at start-up

As previously mentioned, APKES introduced some protocol weaknesses that AKES aims to fix. While repairing most of these issues, AKES is still not perfect. For example, all addressing information (i.e. the PAN identifier, short address, and other parameters used for identifying nodes in 6LoWPANs) has to be preloaded into the node. The IEEE 802.15.4 standard has support for auto-configuring such address information at runtime, but these protocols require that the 802.15.4 security is up and running before being able to execute [45]. AKES modifies the security sublayer of 802.15.4, which means that AKES is running before the 802.15.4 addressing protocols are running, hence they are not applicable with AKES. When AKES establishes session keys with a node, it sends the node's address and identity to the pluggable scheme in order to obtain the shared secret. This means that if AKES did not have the address of the node when it was booted up, it is not able to establish keys with

it. Therefore, AKES does only support mobility for devices that are known to the node at startup.

4.4 Secure Authentication and Key Establishment Scheme (SAKES)

The third, and last protocol which will be discussed in this thesis is the Secure Authentication and Key Establishment Scheme (SAKES). SAKES aims to provide secure authentication and key establishment for nodes in a device-to-device network running on 6LoWPAN [38]. The general security properties that are provided by the scheme is presented in Table 4.3. Previous described protocols such as APKES and AKES enables devices to communicate directly with each other without any previous authentication have taken place. The architecture in SAKES as seen in Figure 4.4 consists of end devices, 6LoWPAN routers, 6LoWPAN border routers, and remote servers providing services to the devices. End devices are typically sensors, with very limited computational power. Border routers and conventional 6LoWPAN routers are more powerful entities which can perform lightweight public key cryptography operations.

Key scheme:	Asymmetric, Symmetric, and Session keys
Replay protection:	Yes
Node compromise resilient:	No
Key revocation:	No
Tamper resistant	No
DoS resilient:	No
Wormhole resilient:	Yes

Table 4.3: Overview of which general security properties that SAKES satisfies.

Border routers, also known as “edge routers”, are in addition responsible for handling communication between the end devices and the Internet (as well as other IP-based networks), act as a broker between local data exchanged between the end devices, and generate and maintain the 6LoWPAN subnet [60]. In SAKES, the border router is responsible for authenticating end devices and 6LoWPAN routers to each other, as well as generating ephemeral public-key pairs for the router to use in session key establishment. In addition to these tasks, the border router is also responsible for periodically distribute symmetric shared keys to its registered nodes.

The use of different entities with more computational power than a regular sensor device allows SAKES to provide a key establishment scheme utilizing both pairwise symmetric keys and lightweight public key cryptography. SAKES assumes that the nodes within the network are stationary and pre-registered in the border router’s

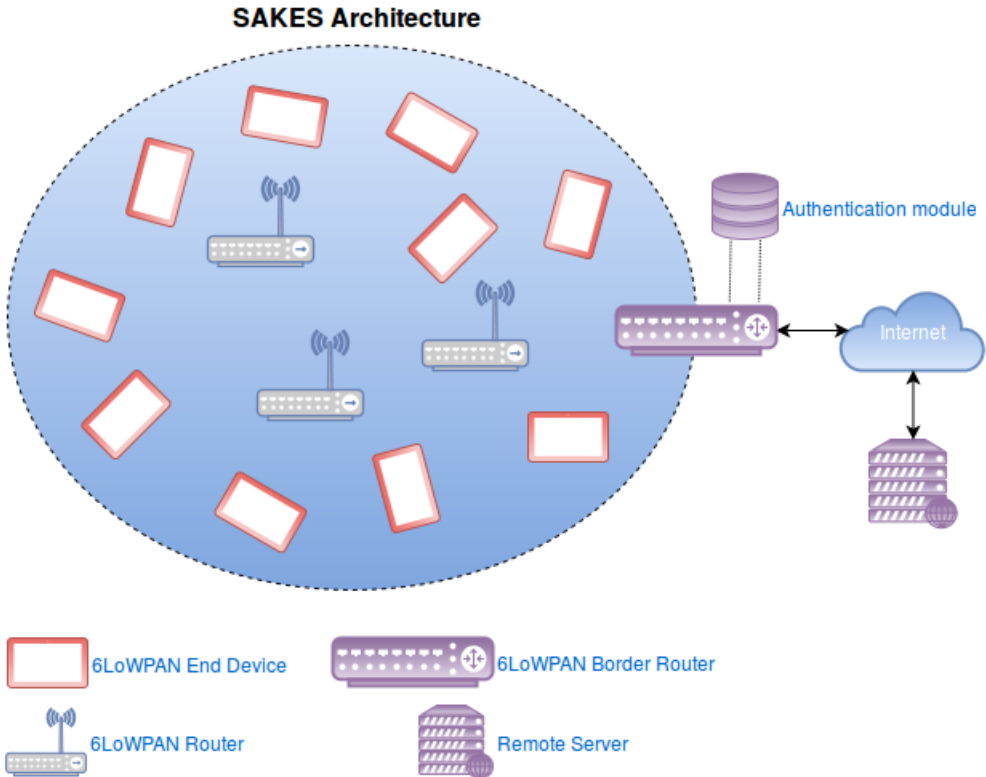


Figure 4.4: Figure of the architecture for a 6LoWPAN using SAKES for authentication and key establishment [38].

authentication module, which is a trusted entity between the remote server and the 6LoWPAN. While not defined anywhere in the specification, we assume that this includes possessing the public key of the border router.

Before a device is able to communicate with the remote server, it needs to authenticate itself to the server, as well as confirming that the nearest 6LoWPAN router is an authentic and valid gateway on its way to the server. The authentication module of the border router handles the authentication process, by authenticating a request sent by the end device to the router, which relays it to the edge router. This request contains the identity of the end device, the router, and the remote server. If the entities are registered in the authentication module, the border router notifies both the end device and the router with a confirmation of the other party's identity. SAKES utilizes, as mentioned, a lightweight public key approach where the border router also generates an ephemeral public key pair for the router, which is to be used

for session key establishment with the remote server.

Session key establishment between the end device and remote server is done by the router acting on behalf of the end device and the server. For establishing the session key, SAKES utilizes a form of Diffie-Hellman key agreement by exchanging public keys with the remote server, before distributing the key securely to the end device.

4.4.1 Protocol Specification

SAKES consists of two phases: Authentication and session key establishment. Figure 4.5 describes the messages exchanged between the end device (A), the 6LoWPAN router (B), and the border router (C) in the authentication phase of SAKES.

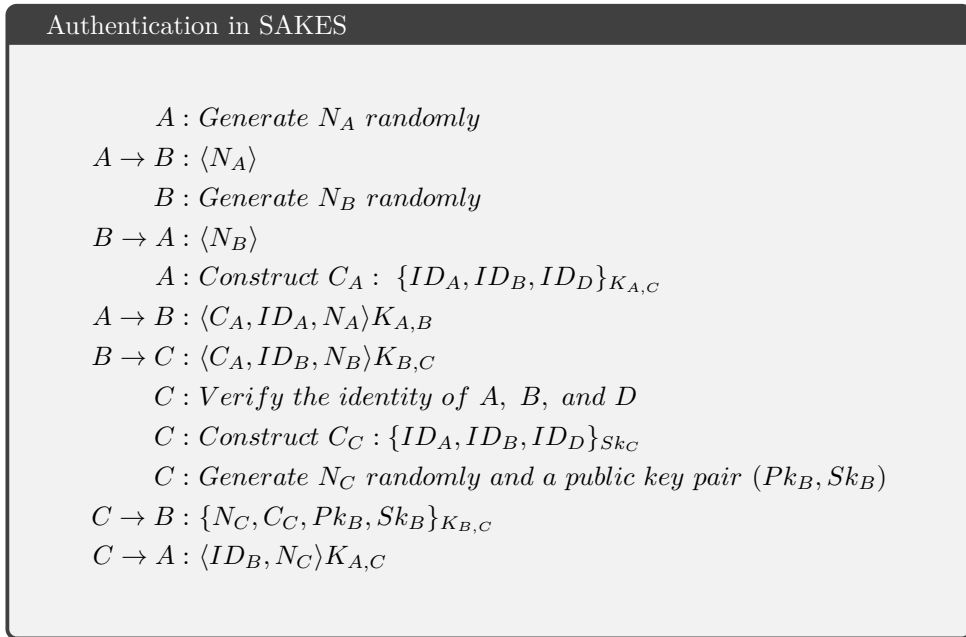


Figure 4.5: Figure of the messages sent between the end device (A), router (B), and border router (with authentication module) (C) in SAKES' authentication phase.

1. A starts the authentication phase by generating a random nonce N_A , which it transmits to its closest router B .
2. The router responds by generating its own random nonce N_B , and sends this back to A .

3. The identities of the end device, the nearest router of the end device, and the remote server the device wants to connect to is then encrypted into the ciphertext C_A by A with the symmetric key $K_{A,C}$, which is shared between the end device and the border router. A also then sends this ciphertext along with its identity and previously computed nonce to the router after adding a MAC of the message using the symmetric key $K_{A,B}$.
4. Upon receiving the request from A , B authenticates the MAC of the message by using its copy of the secret key $K_{A,B}$, and adds its nonce N_B to the message. The request is authenticated by B , who generates a MAC using $K_{B,C}$ and relays it to the border router C .
5. When the request is received by C , it verifies the attached MAC by using its copy of the symmetric key that it shares with B . It then decrypts the ciphertext created by A containing the identity of the end device, the router, and the remote server by using the symmetric key $K_{A,C}$.
6. The border router then checks with its authentication module whether the message is sent by the end device A , and if the identity of its nearest neighbour router B is correct. If these checks are successful, the border router creates a signed message C_C containing the identities of the end device, router, and remote server. It also generates a public key pair (Pk_B, Sk_B) based on ECC, and random nonce N_D .
7. It then sends two messages: one to the router, and one to the end device. The message sent to B contains the nonce N_D , the signed message C_C containing the verified identities of the request, and the public key pair for B to use in the key establishment phase. To provide secrecy for the generated key pair, the entire message is encrypted under the shared symmetric key $K_{B,C}$ to ensure that the key pair is only accessible to B .
8. The end device A also receives a confirmation message from C containing the identity of the router, as well as the random nonce N_D to prevent replaying. The message is authenticated using a MAC with the shared secret $K_{A,C}$ as the key to ensure its authenticity.

After both the end device and the router receives their confirmation messages and successfully verifies their authenticity, the authentication process is believed to be completed. The next step in SAKES is for the router B to establish a session key with the remote server D on behalf of the end device A , as the end device often has limited computational power. The messages sent between the entities in the key establishment phase of SAKES can be seen in Figure 4.6.

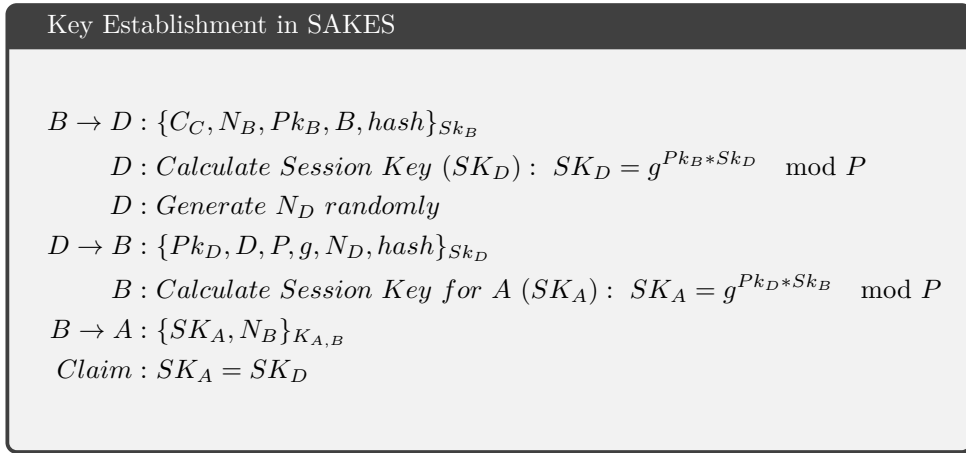


Figure 4.6: Figure of the messages sent between communicating parties in SAKES' key establishment between the end device (A), the 6LoWPAN router (B), and the remote server (D). In SAKES, the session key is established between the router and the server before the router distributes it to the end device.

1. The router crafts a request containing the obtained signed proof from the border router, its identity, and the random nonce N_B , and also adds its temporary public key Pk_B . B computes a hash of the message and appends it as well, before signing it and sending it to the remote server D . By signing the message using its corresponding private key Sk_B , B allows the remote server to verify the authenticity of the message by using the attached public key Pk_B .
2. When the server D receives the request, it verifies the signature of the message. It then proceeds to check the authenticity of the signed proof in the message that the authentication module in C created by applying its copy of C 's public key Pk_C .
3. The computation of the session key SK_D in SAKES is displayed in Equation 4.1, allegedly utilizing a version of the Diffie-Hellman key agreement. In the equation, g and P are two cryptographic numbers, respectively a generator and a prime modulus, while the exponents are the public key of the router B and the private key of the server D .
4. After generating the session key, D constructs a message to B containing its public key, a random nonce N_D , and the two cryptographic numbers g and P . A hash of the message is attached as well, before it is signed using the remote server's private key Sk_D , and sent to B .

$$SK_D = g^{Pk_B * Sk_D} \pmod P \quad (4.1)$$

5. Upon receiving the response from the remote server, B computes the hash for the message and compares it to the attached hash value, as well as verifying that the signature matches the public key.
6. The session key for the end device is computed as in Equation 4.2, using the received cryptographic numbers g and P , and the public key of D and B 's ephemeral private key.

$$SK_A = g^{Pk_D * Sk_B} \text{ mod } P \quad (4.2)$$

7. In order to distribute the session key securely to the end device A , the key is encrypted along with the nonce N_B under the symmetric key $K_{A,B}$, and sent to A .
8. After the end device successfully decrypts and retrieves its session key, future communication between A and D will be encrypted using the session key.

4.4.2 Assumptions of Security Properties

SAKES uses an authentication module located in the border router to authenticate end devices and routers before granting them a signed proof to use in the key establishment process. Authentication is one of the most fundamental security properties in a key establishment, and therefore it is fair to assume that SAKES should provide authentication between end devices, routers, and border routers. The key establishment process is merely conducted between the router and the remote server, where the remote server has no knowledge of the end device while the border router is absent from this phase. Therefore, we assume that authentication in this process is claimed between the end device and the router, and between the router and the remote server.

As SAKES makes use of both pairwise keys and public key pairs, the generated session keys should, of course, be claimed to be secret. Also, the private key of the ephemeral key pair generated the authentication module should be secret to ensure the secrecy of the generated session key. In modern key establishment schemes, the Diffie-Hellman key agreement process can be used to provide forward secrecy for communicating parties. In SAKES, the remote server holds a long-term public key pair, while the border router generates a fresh ephemeral key pair for each session. Nevertheless, forward secrecy should be a desirable property for protocols that leverage Diffie-Hellmen.

4.4.3 Weaknesses and Challenges with SAKES

The major downside with SAKES is that the authors have misunderstood the concept of Diffie-Hellman key agreement. If we look closer at the two equations that derive

the alleged identical session keys, we observe that they are in fact unequal. The mathematical equation for Diffie-Hellman is listed in Equation 4.3 below.

$$(g^a \bmod p)^b \bmod p = (g^b \bmod p)^a \bmod p \quad (4.3)$$

In SAKES, the private key of the remote server and the ephemeral public key of the router are used to calculate the session key at the server's side. However, the router uses its ephemeral private key and the public key of the server to compute the session key, which gives us two different session keys as shown in Equation 4.4.

$$(g^{Pk_B} \bmod p)^{Sk_D} \bmod p \neq (g^{Pk_D} \bmod p)^{Sk_B} \bmod p \quad (4.4)$$

As for the computation of the key, the remote server has a fixed public key pair which is used for generating every session key, while the router uses a freshly generated key pair that it gets from the border router. The Diffie-Hellman key agreement relies on the mathematical challenge in computing discrete logarithms (i.e. finding x when presented with g^x), and having half the key fixed for each session key can potentially leak information about the secret key over time.

Also, the authors seem to have misused the notation of MAC in the key establishment phase, where they generate MACs using publicly known keys such as Pk_B and Pk_D instead for a shared secret key, which is the conventional way of applying such functions. Lastly, the protocol specifications uses private keys to sign the messages that are exchanged during the key establishment, but the public keys that should be used to verify the signed messages are not published at any secure server. Also, the public key that should be used to verify the signature is sent within the signed message, which can remind of a self-signed certificate. While the identities of the end device and the router are verified through the signed message C_C created by the authentication module, it does not verify that the public key pair used for the key establishment is the same that was generated by the border router.

Formal Security Analysis of Three Key Establishment Protocols

5.1 Modelling Security Properties

As mentioned in Section 2.4.2, key establishment schemes desire certain security properties. In the verification of the security protocols of this thesis, the following properties are verified: *Entity authentication*, *Implicit key authentication*, *Explicit key authentication*, *Known-key secrecy*, *Key control*, and *Secrecy of key*. As mentioned in Section 2.4.2, symmetric key establishment schemes are not resilient against KCI attacks and do not provide forward secrecy. These properties are nevertheless included in the models as SAKES uses a lightweight version of public-key cryptography and the type of Diffie-Hellman key agreement to establish session keys.

Entity authentication Entity authentication between nodes corresponds to the security claim of aliveness, and can also be verified through stronger claims such as weak agreement. This property can only be violated if the adversary can inject or tamper with messages that are transmitted over the network, which we assume that the adversary in a 6LoWPAN is.

Implicit key authentication Implicit key authentication is modelled through the settings of the adversary compromise model described in Section 3.3. The property is modelled by allowing the adversary to obtain the long-term keys and impersonate anyone except for the nodes that are supposedly establishing keys.

Explicit key authentication Is achieved when the protocol satisfied both implicit key authentication and key confirmation. Explicit key authentication is modelled through the security claim for non-injective agreement denoted as `ni-agree`, but can also be modelled by using `running` and `commit` claims.

Known-key security By revealing session keys to the adversary after usage (i.e. the session key is expired, and will never be used again) known-key security can

be modelled. This is done by setting the *Session-key reveal* rule in the adversary compromise model.

Key control Scyther has no support for verifying key control. Therefore, this security property has to be checked by hand.

Secrecy of key To model a key (or any other property) as secret, the `secrecy` claim is used in Scyther.

Forward secrecy Both PFS and wPFS are related to active adversaries and is modelled through the adversary compromise model, which can be configured to leak the long-term private key which the session keys are derived from.

Key compromise impersonation KCI is also a property related to an active adversary and is, therefore, available through the adversary model where the adversary can be allowed to obtain the long-term private key of the actors.

5.2 Formal Security Analysis of APKES

APKES is modelled as two roles, the initiator A and the responder B , agreeing upon a pairwise key through the message exchange that is presented in Figure 4.2. There is not specified any concrete type of pluggable scheme (i.e. the scheme where APKES obtains the shared secret between two nodes). Hence, we assume that whatever scheme is used is secure. In the model, the shared secret derived from the pluggable scheme has been modelled using Scyther's built-in support for shared symmetric keys, where the two nodes A and B both possess the shared secret at start-up.

APKES states that the N_A value has to be checked whether or not it has been tampered with before the pairwise key can be derived on the initiating side. This can be verified by modelling the protocol to agree upon the N_A value during the protocol execution, and committing to this. In addition, we model agreement over the pairwise key by using a `Running` claim in role B after receiving the `ACK` authenticated with the pairwise key, and `Commit` claims in both roles to claim explicit key authentication on the pairwise key. As B authenticates the `HELLOACK` by using the shared secret, we do not claim that the pairwise key is created before A receives the `HELLOACK` from B . The Scyther model of APKES can be viewed in its entirety in Appendix A.1.

5.2.1 Security Claims

By taking a starting point in the protocol specification from Section 4.2.4 and the alleged security properties from Section 4.2.5, the protocol is modelled as an SPDL-script, which can be verified by Scyther. Listing 5.1 describes the various security

claims that are chosen for A . In these claims; we verify that the other party in the protocol is authentic and that the pairwise key is secret. Claims for non-injective synchronization and agreement is also added to verify that the protocol executes as expected. The security claims for role B in APKES are stated in Listing 5.2. Compared to the claims for A , B does not contain the `Commit` claim for the variable N_A , as the `Running`, `Commit` approach is used in role A to provide agreement (i.e. confirm that the nonce has not been altered by B) over the nonce N_A . We also claim non-injective synchronization and data agreement.

```
claim(A, Alive);
claim(A, Weakagree);
claim(A, Niagree);
claim(A, Nisynch);
claim(A, Commit, B, Na);
claim(A, Secret, PairwiseKey);
claim(A, Commit, B, PairwiseKey);
```

Listing 5.1: Security claims for role A in APKES.

```
claim(B, Alive);
claim(B, Weakagree);
claim(B, Niagree);
claim(B, Nisynch);
claim(B, Secret, PairwiseKey);
claim(B, Commit, A, PairwiseKey);
```

Listing 5.2: Security claims for role B in APKES.

5.2.2 Adversary

In the description of APKES, no particular adversary is mentioned. We assume that such a protocol would be used for key establishment in 6LoWPANs, which are potentially deployed in hostile areas. Therefore, we can assume that the adversary would be able to observe, inject, and tamper with messages that are sent over the network. As APKES does not utilize any session keys, but rather agreeing upon a fixed long-term key, we model the adversary in a Dolev-Yao way without giving it any active capabilities other than being able to obtain the long-term keys of nodes not participating in the current key establishment process.

5.2.3 Results

Figure 5.1 shows the verification result from running the model of APKES through Scyther in the presence of the adversary described above. Scyther was able to perform

an unbounded verification of the model where all claims but one were successfully verified. APKES provides valid entity authentication, explicit key authentication for role B (implicit for A), and holds the non-injective synchronization property, which means that every message in the protocol is executed as expected, even in the presence of the adversary. When looking at the characterization of the protocol, there exist only one executable trace for each of the roles. Hence, there does not exist any malicious behaviour that can force the modelled protocol to misbehave. The attack proposed by Scyther on *Commit B*, $\{N_A, N_B\}k(A, B)$ is not a direct attack on the protocol, but shows that it is not possible to achieve explicit key authentication for the role A , as it has no knowledge of if B has computed the pairwise key.

Claim				Status	Comments	Patterns	
APKES	A	APKES,A2	Alive	Ok	Verified	No attacks.	
		APKES,A3	Weakagree	Ok	Verified	No attacks.	
		APKES,A4	Niagree	Ok	Verified	No attacks.	
		APKES,A5	Nisynch	Ok	Verified	No attacks.	
		APKES,A6	Commit B,Na	Ok	Verified	No attacks.	
		APKES,A7	Secret $\{N_A, N_B\}k(A, B)$	Ok	Verified	No attacks.	
		APKES,A8	Commit B, $\{N_A, N_B\}k(A, B)$	Fail	Falsified	At least 1 attack.	1 attack
		B		APKES,B3	Alive	Ok	Verified
APKES,B4	Weakagree			Ok	Verified	No attacks.	
APKES,B5	Niagree			Ok	Verified	No attacks.	
APKES,B6	Nisynch			Ok	Verified	No attacks.	
APKES,B7	Secret $\{N_A, N_B\}k(A, B)$			Ok	Verified	No attacks.	
APKES,B8	Commit A, $\{N_A, N_B\}k(A, B)$			Ok	Verified	No attacks.	

Figure 5.1: Result of verifying APKES' security claims using Scyther.

5.3 Formal Security Analysis of AKES

AKES is modelled almost like its predecessor, but with additional content that is used to allow mobility for the devices. As AKES is used for establishing session keys, the SKR claim is used emphasize that the key is, in fact, a session key. The

pluggable scheme is assumed to be secure and is modelled as a symmetric key shared between the two communicating parties using Scyther’s built-in symmetric key support. Appendix A.2 contains the model in its entirety. APKES was not able to provide explicit key authentication of role B for the initiator A . In AKES, however, the received `HELLOACK` is authenticated using the session key. Therefore, we model a `Running` claim (not present in Listing 5.3 or 5.4 - See Appendix A.2) to indicate that the role B has computed the key at this point and a `Commit` claim to state that the two parties agree that the session key has been derived.

5.3.1 Security Claims

From the protocol specification in Section 4.3.3 and the assumed security properties in Section 4.3.4, the security claims that are claimed to hold for the two roles in AKES are listed in Listing 5.3 and Listing 5.4. In addition to claiming authentication for the other party, we also argue that the protocol has been executed as intended by adding claims for non-injective synchronization and agreement.

```
claim(A, SKR, SessionKey);
claim(A, Alive);
claim(A, Weakagree);
claim(A, Niagree);
claim(A, Nisynch);
claim(A, Commit, B, SessionKey);
```

Listing 5.3: Security claims for role A in AKES.

```
claim(B, SKR, SessionKey);
claim(B, Alive);
claim(B, Weakagree);
claim(B, Niagree);
claim(B, Nisynch);
claim(B, Commit, A, SessionKey);
```

Listing 5.4: Security claims for role B in AKES.

5.3.2 Adversary

The adversary in this model is nearly the same adversary as the one introduced in the verification of APKES. However, to model session keys, the adversary is allowed to obtain all session keys whose identifier differs from the current protocol execution.

5.3.3 Results

Figure 5.2 shows the result of running the model of AKES through Scyther in the presence of the adversary presented above, where AKES is verified for an unbounded state space and all the claimed security properties are successfully verified. AKES provides provable authentication for both roles, as well as explicit key authentication. In addition, AKES is proved to hold the non-injective synchronization and data agreement claims which state that the protocol was executed as intended. When looking at the characterization of AKES, only one possible trace is returned for each role, which means that there exists only one way to execute the protocol.

Claim				Status	Comments	
AKES	A	AKES,A2	SKR $\{Na,Nb\}k(A,B)$	Ok	Verified	No attacks.
		AKES,A3	Alive	Ok	Verified	No attacks.
		AKES,A4	Weakagree	Ok	Verified	No attacks.
		AKES,A5	Niagree	Ok	Verified	No attacks.
		AKES,A6	Nisynch	Ok	Verified	No attacks.
		AKES,A7	Commit $B,\{Na,Nb\}k(A,B)$	Ok	Verified	No attacks.
		B	B	AKES,B3	SKR $\{Na,Nb\}k(A,B)$	Ok
AKES,B4	Alive			Ok	Verified	No attacks.
AKES,B5	Weakagree			Ok	Verified	No attacks.
AKES,B6	Niagree			Ok	Verified	No attacks.
AKES,B7	Nisynch			Ok	Verified	No attacks.
AKES,B8	Commit $A,\{Na,Nb\}k(A,B)$			Ok	Verified	No attacks.

Figure 5.2: Result of verifying AKES' security claims using Scyther.

5.4 Formal Security Analysis of SAKES

From the protocol specification in Section 4.4.1 and the assumed security properties in Section 4.4.2, SAKES have been modelled into four roles: *A* (End device), *B* (Router), *C* (Border router), and *D* (Server). The authentication phase is carried out between *A*, *B*, and *C* before *B* and *D* establish the session key, which is distributed from the router *B* to the end device *A*. As the protocol specification presented in

the original protocol proposal can be considered inconsistent; some assumptions have been made in the model.

The verification of the original protocol in its entirety takes over 72 hours to complete on a workstation equipped with an Intel Core i7 processor with four cores and 12 GB RAM (The experiment was aborted at this point). Therefore, it has been infeasible to formally verify the complete protocol in one round, and the two phases have been separated into two different models to be able to provide some insight on the weaknesses of SAKES. The two models are available in Appendix A.3.1 and A.3.2.

5.4.1 Authentication Phase

Security Claims

The end device A is only in direct communication with the router B and the border router C , which is why authentication is only claimed for these two roles as seen in Listing 5.5. We add claims for non-injective synchronization and agreement to find attacks where the messages are not exchanged as intended.

```
claim(A, Alive, B);
claim(A, Alive, C);
claim(A, Weakagree, B);
claim(A, Weakagree, C);
claim(A, Niagree);
claim(A, Nisynch);
```

Listing 5.5: Security claims for role A during the authentication phase in SAKES.

Listing 5.6 contains the claims that are stated for role B (i.e. the 6LoWPAN router) in SAKES during the authentication phase. The router is originally interacting with all the other entities in the network, but during the authentication, it only interacts with the end device A , and the border router C . Hence we are claiming authentication for only these roles. In addition, we state that the ephemeral key Sk_B , which is generated by the border router during the authentication phase and which is to be used in the key establishment, is secret. To verify that the role behaves as intended, we add claims for non-injective synchronization and agreement.

```

claim(B, Secret, Sk);
claim(B, Alive, A);
claim(B, Alive, C);
claim(B, Weakagree, A);
claim(B, Weakagree, C);
claim(B, Niagree);
claim(B, Nisynch);

```

Listing 5.6: Security claims for role B during the authentication phase in SAKES.

The border router *C* does only participate in the authentication phase with *A* and *B*; hence, we claim authentication for these two parties. In addition, we add claims for non-injective synchronization and agreement to state that the protocol was executed as expected as seen in Listing 5.7.

```

claim(C, Alive, A);
claim(C, Alive, B);
claim(C, Weakagree, A);
claim(C, Weakagree, B);
claim(C, Niagree);
claim(C, Nisynch);

```

Listing 5.7: Security claims for role C during key establishment in SAKES.

Adversary

For the authentication phase in SAKES, we assume a Dolev-Yao adversary who is capable of eavesdropping, delete messages, compute cryptographic analysis on intercepted messages, forge new messages from its knowledge, and insert them into the network.

Results

Figure 5.3 shows the result of verifying SAKES' authentication phase, where multiple of the claimed security properties are falsified. Scyther can verify that SAKES provides entity authentication for the end device, router, and border router, but fails to provide stronger notions of authentication such as weak agreement for the end device. Also, the authentication phase in SAKES does not provide non-injective synchronization nor non-injective data agreement for either of the three roles. The attacks presented below are described more thoroughly in Section 6.5, and improvements are suggested to achieve the claimed security properties.

Claim				Status	Comments	Patterns	
SAKES_AUTH	A	SAKES_AUTH,A1	Alive B	Ok	Verified	No attacks.	
		SAKES_AUTH,A2	Alive C	Ok	Verified	No attacks.	
		SAKES_AUTH,A3	Weakagree B	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_AUTH,A4	Weakagree C	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_AUTH,A5	Niagree	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_AUTH,A6	Nisynch	Fail	Falsified	At least 1 attack.	1 attack
B	SAKES_AUTH,B1	Secret Sk	Ok		No attacks within bounds.		
		SAKES_AUTH,B2	Alive A	Ok	No attacks within bounds.		
		SAKES_AUTH,B3	Alive C	Ok	No attacks within bounds.		
		SAKES_AUTH,B4	Weakagree A	Ok	No attacks within bounds.		
		SAKES_AUTH,B5	Weakagree C	Ok	No attacks within bounds.		
		SAKES_AUTH,B6	Niagree	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_AUTH,B7	Nisynch	Fail	Falsified	At least 1 attack.	1 attack
C	SAKES_AUTH,C1	Alive A	Ok	Verified	No attacks.		
		SAKES_AUTH,C2	Alive B	Ok	Verified	No attacks.	
		SAKES_AUTH,C3	Weakagree A	Ok	Verified	No attacks.	
		SAKES_AUTH,C4	Weakagree B	Ok	Verified	No attacks.	
		SAKES_AUTH,C5	Niagree	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_AUTH,C6	Nisynch	Fail	Falsified	At least 1 attack.	1 attack

Figure 5.3: Result of verifying SAKES' authentication claims using Scyther.

- SAKES_AUTH, A3 & A4 Weakagree B & C: The attacks proposed by Scyther that falsifies the Weakagree claims for the end device leverage the last message that is sent between the end device and the edge router, and can be seen in Appendix B.1. When the border router receives the relayed request from the router, it has to confirm the identity of the router to the end device. There are, however, flaws in the messages that are exchanged, which enables an adversary to use the request created by the end device and the nonce generated by the

router to change a different end device’s perception of its closest router.

- **SAKES_AUTH, A6 & B7 & C6 Nisynch:** Neither A , B , or C hold the non-injective synchronization property. If we study the attack proposed in Appendix B.2, we see that the adversary is using the same approach as in the attack on the **Weakagree** above. In the original protocol description of SAKES, the adversary can combine the information sent in the second and third message into a message that is sent directly to the border router. Such an alternation is the message flow is not allowed in the model of the protocol, and hence the **Nisynch** properties are falsified.
- **SAKES_AUTH, A6 & B7 & C6 Niagree:** Scyther also proposes attacks targeting the non-injective agreement claims. These attacks are of the same flavour as the attacks aimed at the **Nisynch** property above, and the claims are falsified as the adversary is able to combine information in observed messages into valid new messages. Generation of new messages leads to a different set of data items. Hence, the protocol can agree upon the data that is exchanged throughout the protocol.

5.4.2 Key Establishment Phase

In order to model the key establishment phase in SAKES, it is assumed that the Diffie-Hellman key agreement is done correctly by letting B and D share their secret key to the power of the generator g . Also, it is assumed that when the authors use a notion of “decrypting the ciphertext encrypted with the private key of X ”, they mean that the message is signed using the private key of X and that the signature can be verified by applying the corresponding public key. When it comes to the notation of MACs, an assumption is that the alleged MAC that is sent between the router and the server that do not share any symmetric key is simply a hash of the message.

Originally, the server distributes the generator g and the prime modulus P to the router. This means that a new message needs to be introduced to allow for the Diffie-Hellman procedure to be executed correctly. If the router B either has these two cryptographic numbers preloaded in its memory or if the numbers get distributed from the border server, then the router can send g^{Sk_B} to the server in its first message. As the original protocol specification got the Diffie-Hellman part wrong, the models presented in this section assume that the router has access to both g and P before initiating the key establishment process with the remote server D . Therefore, these two elements have been omitted from the key establishment phase in the model presented in this thesis.

Also, the border router C generates an ephemeral public-key pair for the router to use in the key establishment process. This, however, leads to challenges when separating the two phases. Thus, the ephemeral key pair is modelled as the regular public-key pair of the entity B . We can argue that this is appropriate as the trusted authentication module has authenticated the ephemeral key pair, and transmitted to B under the secret symmetric key $K_{B,C}$.

To improve the accuracy of the analysis, the generated session key has been split into two separate keys, namely `SessionKeyA` and `SessionKeyD`. `SessionKeyA` is a fresh session key generated by the router B and transported to A to model the distribution of the session key from the router to end device. `SessionKeyD` is the key that is computed in the Diffie-Hellman key agreement between the router and the remote server. As it is not possible to directly model a Diffie-Hellman exponentiation in Scyther, session keys are computed by using the two hash functions $g1$ and $g2$. More specifically, instead of transmitting g^{Sk_B} , the router sends $g1(Sk_B)$ to the remote server, which returns $g1(Sk_D)$ to B . The session key is then derived by applying these two terms in a new hash function $g2$: $g2(g1(Sk_B), Sk_D)$. This gives an *under-approximation* of that the two computed session keys are equal.

Security Claims

The session key establishment in SAKES is conducted between the router B and the server D before the session key is distributed from the router to the end device A . We assume that A and B have authenticated each other before the key establishment process is engaged. Listing 5.8 shows the claims that are stated for the end device in the key establishment phase of SAKES. Since the only message that is sent between the two contains the session key, which is encrypted with their shared symmetric key $K_{A,B}$, we assume that the session key is secret by using the SKR claim. In addition, claims for non-injective synchronization and agreement have been added to ensure that the protocol is executing as expected based on the model.

```
claim(A, Niagree);
claim(A, Nisynch);
claim(A, SKR, SessionKeyA);
```

Listing 5.8: Security claims for role A during key establishment in SAKES.

As the router generates the session key on behalf of the end device B , we also state that the session key should be secret at the router side using the SKR claim as seen in Listing 5.9. As the router interacts with the remote server D , we also add claims for entity authentication. Finally, claims for non-injective synchronization and data agreement are added to verify that the protocols behave as specified in the

protocol model.

```

claim(B, Alive , D);
claim(B, Alive , B);
claim(B, Weakagree , D);
claim(B, Weakagree , B);
claim(B, Niagree);
claim(B, Nisynch);
claim(B, SKR, SessionKeyA);
claim(B, SKR, SessionKeyD);

```

Listing 5.9: Security claims for role B during key establishment in SAKES.

For the remote server, authentication is claimed only between it and the router which it establishes session keys with. The end device is indirectly authenticated through the proof that is signed by the authentication module in the border router, but this is not modelled as a direct authentication claim in this model. The generated session key is claimed to be secret using the **SKR** notation. In addition, we also claim non-injective synchronization and agreement for the role as seen in Listing 5.10.

```

claim(D, Alive , B);
claim(D, Weakagree , B);
claim(D, Niagree);
claim(D, Nisynch);
claim(D, SKR, SessionKeyD);

```

Listing 5.10: Security claims for role D during key establishment in SAKES.

Adversary

For the key establishment phase, we assume a Dolev-Yao adversary who is capable of eavesdropping, delete messages, compute cryptographic analysis on intercepted messages, forge new messages from its knowledge, and insert them into the network. It is allowed for the adversary to obtain the session keys for all sessions whose identifier differs from the current session's identity. As SAKES utilizes a form of Diffie-Hellman key agreement, it is also assumed that the protocol should possess forward secrecy, especially since the half of the key is fixed as the remote server uses a permanent public key pair.

5.4.3 Results

The results of verifying the model of the key establishment phase in SAKES using Scyther is presented in Figure 5.4. Entity authentication of both the router and the server is provided and verified in the key establishment process but is falsified for the end device. Stronger notions of authentication such as *Weakagree* for the end device *A* and the server *D* are falsified for the router *B* in this model. Both non-injective synchronization and data agreement are falsified for the end device and the router in the key establishment phase.

Claim	Status	Comments	Patterns
SAKES_KEYS A SAKES_KEYS,A1 Niagree	Fail	Falsified At least 1 attack.	1 attack
SAKES_KEYS,A2 Nisynch	Fail	Falsified At least 1 attack.	1 attack
SAKES_KEYS,A3 SKR SessionKeyA	Ok	No attacks within bounds.	
B SAKES_KEYS,B1 Alive D	Ok	Verified No attacks.	
SAKES_KEYS,B2 Alive A	Fail	Falsified At least 1 attack.	1 attack
SAKES_KEYS,B3 Weakagree D	Fail	Falsified At least 1 attack.	1 attack
SAKES_KEYS,B4 Weakagree A	Fail	Falsified At least 1 attack.	1 attack
SAKES_KEYS,B5 Niagree	Fail	Falsified At least 1 attack.	1 attack
SAKES_KEYS,B6 Nisynch	Fail	Falsified At least 1 attack.	1 attack
SAKES_KEYS,B7 SKR SessionKeyA	Ok	No attacks within bounds.	
SAKES_KEYS,B8 SKR $g2(g1(sk(B)),sk(D))$	Ok	No attacks within bounds.	
D SAKES_KEYS,D1 Alive B	Ok	Verified No attacks.	
SAKES_KEYS,D2 Weakagree B	Ok	Verified No attacks.	
SAKES_KEYS,D3 Niagree	Ok	No attacks within bounds.	
SAKES_KEYS,D4 Nisynch	Ok	No attacks within bounds.	
SAKES_KEYS,D5 SKR $g2(g1(sk(B)),sk(D))$	Ok	No attacks within bounds.	

Figure 5.4: Result of verifying SAKES' key establishment claims using Scyther.

- **SAKES_KEYS, A1 & A2, Niagree & Nisynch:** The attack on the non-injective synchronization and the data agreement claims for the end device *A* is shown in Figure B.4 in Appendix B. Non-injective synchronization and data agreement are falsified because the adversary can generate its response to the message

that is sent between the router B and the remote server D . This attack occurs because the remote server does not authenticate itself to the router, which can be problematic. Given that the remote server's public key is not published (not mentioned in the specifications), then there is not possible for the router to verify that the received response does, in fact, originate from the trusted remote server D . Another important part of this attack, is that there is no linkage between the message that is sent from the router to the server and the response that is received following this message.

- **SAKES_KEYS, B2 & B4, Alive A & Weakagree A:** Entity authentication is for the end device is falsified by Scyther. However, if the attack in Figure B.3 in Appendix B is inspected, we see that it does not involve the end device at all. In the model of the key establishment phase, the end device does not contribute to the protocol, and hence, it is impossible for the router to determine whether the end device has ever participated in the protocol runs at all. This attack will be examined more carefully in the next subsection.
- **SAKES_KEYS, B4, Weakagree D:** Scyther also discovers an attack on the weakagree claim of the remote server at the router, as seen in Figure B.5 in Appendix B. This attack indicates that the adversary can impersonate the remote server D , and forge response messages that are sent to the router during the key establishment phase. As the responses are not authenticated, nor contains a linkage to the previous request, there is no way for the router to detect if the message originates from the remote server, nor which request it is tied to.
- **SAKES_KEYS, B5 & B6 Niagree & Nisynch:** The attacks targeted at the non-injective synchronization and data agreement claims are identical. This is essentially the same attack as the one Scyther proposed on the **weakagree** claim above, which can be reviewed in Figure B.5 in Appendix B. In this attack, the adversary can use the computed part of the session key $g1(Sk_B)$ in a new message that is sent from the remote server D to the router B that differs from what was initially sent, as the response from the server is not authenticated or linked to a request.

Deeper analysis of the entity authentication of the end device at the router

Above, Scyther discovered an attack that falsified the entity authentication of the end device (**SAKES_KEYS, B2 & B4, Alive A & Weakagree A**). Apparently, there is no evidence for that the end device has ever run the protocol. However, the end device is the entity that kicks off the protocol, but due to a large state-space, the key establishment model is not able to capture this. Therefore, this part of the protocol is analysed more carefully. By isolating the two roles A and B in the key

establishment, another model is presented in Appendix A.3.3. This captures the interaction between the end device and the router and includes the exchanging of the two nonces N_A and N_B from the authentication phase.

In this model, the interaction between the router and the remote server in establishing the session key is omitted. Instead, the router generates a fresh key, without giving it any specific properties. This key is used to illustrate the last part of the key establishment phase, where the router distributes the computed session key to the end device.

Claim				Status	Comments	Patterns	
SAKES_KEYS	A	SAKES_KEYS,A1	Alive B	ok	Verified	No attacks.	
		SAKES_KEYS,A2	Weakagree B	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_KEYS,A3	Niagree	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_KEYS,A4	Nisynch	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_KEYS,A5	SKR SessionKeyA	ok		No attacks within bounds.	
B	SAKES_KEYS,B1	SAKES_KEYS,B1	Alive A	ok	Verified	No attacks.	
		SAKES_KEYS,B2	Weakagree A	Fail	Falsified	Exactly 1 attack.	1 attack
		SAKES_KEYS,B3	Niagree	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_KEYS,B4	Nisynch	Fail	Falsified	At least 1 attack.	1 attack
		SAKES_KEYS,B5	SKR SessionKeyA	ok		No attacks within bounds.	

Figure 5.5: Result of verifying SAKES' the key distribution between the router B and the end device A in the key establishment phase.

The results of using Scyther to verify this model is presented in Figure 5.5 below. As observed, this part of the protocol is able to provide entity authentication of the end device, which was falsified in the model that captured the entire key establishment phase. This is because in the model only focusing on the end device and the router contains the nonce N_A , which indicates that the end device must have run the protocol at some point. We observe that stronger notions of authentication such as Weakagree are falsified, as well as non-injective synchronization and data agreement. These attacks will be addressed in Section 6.5 in Chapter 6. Also, the freshly generated session key is distributed securely to the end device.

Therefore, it is fair to assume that the key establishment phase of SAKES actually

provides entity authentication when it is protocol is verified in a complete model containing the entire protocol execution.

5.5 Incompleteness in the Analysis of SAKES

As the SAKES protocol proved to be computational and time expensive to verify on the available equipment, it has been divided into two separate protocols for the analysis to provide some insight into SAKES security. Therefore, the mutual authentication that is achieved between A , B , and C in the authentication phase is not transferable to the key establishment phase. The separation may or may not cause some of the attacks that are discovered because of lack of authentication, and could also lead to attacks that bypass the analysis undiscovered.

5.6 General Limitations in the Analysis

Even though Scyther is a powerful tool for formal security analysis, there are particular types of attacks that Scyther is not able to model. Replay attacks, where the adversary saves a captured frame for injecting it into the network at a later time, are not possible to model in Scyther. Both AKES and APKES claim to avoid replay attacks through the 802.15.4 security sub-layer and the use of frame counters to discover frames that have been previously observed [45, 46]. SAKES claims to prevent replay attacks by adding nonces and MACs to prevent messages from being tampered with and to ensure freshness [38]. However, the presented analyses do not verify such security properties.

Chapter 6

Discussion

In this chapter, the results from the formal analysis will be evaluated and compared. If an attack were discovered in the analysis, possible improvements and alternatives will be suggested.

6.1 Evaluation of Authentication Properties

Table 6.1 shows the security properties related to authentication for the three protocols that have been verified by Scyther. In the section for entity authentication, we assume that successful verification of the weakest property in the hierarchy of authentication properties, Aliveness, is enough to earn a checkmark in the column. However, Aliveness has to hold for the role in the claims of all the other roles, meaning that all roles that claim aliveness for role *A* have to be successfully verified to obtain the check mark. In cases where the property is not applicable, for instance claiming entity authentication for role *C* in APKES or AKES, a dash is inserted. The authentication phase in SAKES only includes *A*, *B*, and *C*, while the key establishment phase includes the claim for entity authentication of role *D*.

Protocol	Entity authentication				Implicit key authentication				Explicit key authentication			
	Of A	Of B	Of C	Of D	Of A	Of B	Of C	Of D	Of A	Of B	Of C	Of D
APKES	✓	✓	–	–	✓	✓	–	–	×	✓	–	–
AKES	✓	✓	–	–	✓	✓	–	–	✓	✓	–	–
SAKES	✓	✓	✓	✓	✓	✓	–	✓	×	×	–	×

Table 6.1: Table of the security properties for authentication that are satisfied in the different protocols. ✓ indicates that that the property is verified, × that the property is falsified, and – that the property is inapplicable for the protocol.

APKES is only able to achieve explicit key authentication for the responding role *B* because the HELLOACK that is sent from *B* to *A* is authenticated by using the shared secret from the pluggable scheme. AKES fixes this by computing the session

key before sending the HELLOACK and use the session key to compute the MAC. Hence it achieves explicit key authentication. As for SAKES, the session key cannot be computed without the other side of the key establishment sending its secret key to the power of the generator. There is not, however, any message passing proving that the session key is in fact computed, and therefore, no explicit key authentication is provided by either party, which means that during its key establishment process, SAKES is only able to provide implicit key authentication. A is included in this process even though it is not directly computing the key, but receives it from the router B .

6.2 Evaluation of Key Secrecy Properties

Table 6.2 shows the results related to the secrecy of the computed keys in the various schemes. In all three schemes, the computed key is verified to be secret, which is the most valuable property in key establishment schemes. Key control is not directly modelled and verified, but can be verified manually by confirming that each side in the key establishment phase has to contribute to the computation of the key. Known-key security is modelled by allowing the adversary to obtain session keys from other sessions than the current one. The importance of verifying this property is so that there is not possible to compute future session keys from knowledge of previous ones. AKES holds for this property, as well as SAKES, while APKES does not claim this property as it computes a static key rather than session keys.

Protocol	Secrecy of key	Key control	Known-key security	Forward Secrecy	Key compromise impersonation
APKES	✓	✓	–	–	–
AKES	✓	✓	✓	–	–
SAKES	✓	✓	✓	×	×

Table 6.2: Table of the security properties for secrecy that are satisfied in the different protocols. ✓ indicates that that the property is verified, × that the property is falsified, and – that the property is inapplicable for the protocol.

As explained in Section 2.4.2, forward secrecy is a property where the compromise of the long-term key used to generate session keys does not lead to compromise of previous sessions. The Diffie-Hellman key agreement is one of the most well-known schemes that provide forward secrecy. SAKES leverages this type of agreement, and therefore it should provide forward PFS or at least wPFS.

When looking at Table 6.2, this is not the case based on the models that this thesis presents. If we observe the protocol more closely, we see that the server has, in fact, a fixed public key pair (Pk_D, Sk_D) , and does not generate anything fresh for each session. This means that if the key pair of the remote server is compromised,

all previous sessions would be compromised as well, given that the adversary has recorded the messages passed in previous protocol runs AKES generates session keys as well, but as these keys are computed using a symmetric key, it is infeasible for the protocol to achieve forward secrecy. Forward secrecy is not, however, a claimed secrecy property of either APKES nor AKES.

6.3 Comparison

6.3.1 APKES versus AKES

Both infrastructures focus on device-to-device communication without any in-between routers to forward messages. AKES is merely an improvement over APKES, which addresses its known issues. From the results in Table 6.1 and Table 6.2, we see that the security properties provided in both protocols are almost identical, but as we know: AKES generates session keys. The advantage with AKES is its support for mobility regarding handling reboot of nodes and deleting disappeared neighbours to save precious storage space on devices that these protocols target.

Also, AKES uses its derived session key to authenticate the message providing the initiating party with its nonce, which eventually ends in the protocol achieving explicit key authentication. Overall, AKES is naturally the best choice of the two based on its security properties and built-in mechanisms which gives it more robustness when deployed in a dynamic 6LoWPAN.

6.3.2 AKES versus SAKES

Both AKES and SAKES are protocols for establishing session keys in 6LoWPANs, but the infrastructure for the following protocol includes both 6LoWPAN routers and border routers, as well as a remote server which the devices connect to. Based on the security properties in Table 6.1 and Table 6.2, we see that both protocols provide the same security properties. However, based on the Scyther analysis presented in Section 5.3 and Section 5.4, AKES seems to be the protocol that is most carefully designed. Multiple attacks are introduced that target different phases of SAKES, which may indicate that the suggested protocol is not a preferable protocol to use for key establishment in your next 6LoWPAN.

Apart from the attacks discovered in the analysis, SAKES has a more thorough authentication hierarchy, where the trusted authentication module authenticates each device and router in the network for each session key establishment. Authentication in AKES is solely based on that if the node is capable of establishing keys using the shared secret, it is authenticated.

It's hard to recommend SAKES over AKES as a protocol to use in a 6LoWPAN as it is wrong in its original proposed form, and since its complexity leads to a security analysis where the model had to be split into separate phases. They are also proposed for different infrastructures. However, AKES can successfully establish session keys for device-to-device communication, and is also implemented and tested in the Contiki operating system [45].

6.4 Suggested Improvements for APKES

Use the pairwise session key to authenticate the HELLOACK APKES does provide verifiable and secure key establishment. One improvement, however, could be to use the pairwise session key to authenticate the HELLOACK that is sent between B and A in Figure 4.2, instead of the shared secret. By doing so, the scheme would achieve explicit key authentication of B to A as well, and behave much like AKES while still generating a pairwise symmetric key.

6.5 Suggested Improvements for SAKES

Flaws for SAKES have been discovered in the formal analysis presented in this thesis. This section aims to propose possible improvements to the protocol.

6.5.1 Achieve Authentication in the Authentication Phase by Returning Nonces

As presented in Section 5.4.1, certain authentication claims fail in SAKES. Two of them are weak agreement claims in role A for the router B and the border router C . These can be fixed by adding the nonce N_A , which was initially generated by the end device to the response that is sent from the border router to the end device for confirming the identity of the router B . Listing 6.1 shows how this is implemented in the improved model of SAKES, which can be found in Appendix A.4.1. When the following improvements are implemented, all claimed security properties are verified as seen in Figure 6.1.

```

# Previous:
send_6(C, A, B, Nc, MAC(B, Nc, k(A, C))); # In role C
recv_6(C, A, B, Nc, MAC(B, Nc, k(A, C))); # In role A

# Fix:
send_6(C, A, B, Na, Nc, MAC(B, Na, Nc, k(A, C))); # In role C
recv_6(C, A, B, Na, Nc, MAC(B, Na, Nc, k(A, C))); # In role A

```

Listing 6.1: Fix to the SAKES protocol to provide weak agreement for the end device in the authentication phase. The changes to the protocol are highlighted with blue.

The next step is to achieve non-injective synchronization and data agreement for the authentication phase. As discovered in the attacks from Section 5.4.1, the issue lies in two messages. The first message is the request that is created at the end device and sent to the router. To avoid that the request can be reused in pair with an unrelated nonce N_{B2} from another session, we have to add the received nonce N_{B1} in the initial request as seen in Listing 6.2. By adding this nonce, the protocol achieves both non-injective synchronization and data agreement for the end device A and the border router C , as seen in Figure 6.1.

```

# Previous:
send_3(A, B, {A, B, D}k(A,C), A, Na, MAC); # In role A
recv_3(A, B, {A, B, D}k(A,C), A, Na, MAC); # In role B

# Fix:
send_3(A, B, {A, B, D}k(A,C), A, Na, Nb, MAC); # In Role A
recv_3(A, B, {A, B, D}k(A,C), A, Na, Nb, MAC); # In Role B

```

Listing 6.2: Fix to the SAKES protocol to provide non-injective synchronization and data agreement for the end device and the border router during the authentication phase. The changes to the protocol are highlighted in blue.

Lastly, the protocol lacks non-injective synchronization and data agreement for the router B . When the router relays the request from the end device to the border router, it receives a signed proof of identities and an ephemeral public key pair from the border router. There is not, however, confirmation of that this is the intended response to that particular request. It may be possible that the returned identities and key pair are actually from a different session, hence the protocol is not able to fulfil the two claims non-injective synchronization and data agreement for the router B . If the border router C is instructed to return the nonce N_B that was generated

by the router and sent with the request, the router can verify that the response corresponds to the initial request, and not a different session. Listing 6.3 shows how this improvement can be added to the message which has been verified as seen in Figure 6.1.

Claim				Status	Comments
SAKES_AUTH	A	SAKES_AUTH,A1	Alive B	Ok Verified	No attacks.
		SAKES_AUTH,A2	Alive C	Ok Verified	No attacks.
		SAKES_AUTH,A3	Weakagree B	Ok Verified	No attacks.
		SAKES_AUTH,A4	Weakagree C	Ok Verified	No attacks.
		SAKES_AUTH,A5	Niagree	Ok Verified	No attacks.
		SAKES_AUTH,A6	Nisynch	Ok Verified	No attacks.
		B	SAKES_AUTH,B1	Secret Sk	Ok
SAKES_AUTH,B2	Alive A		Ok	No attacks within bounds.	
SAKES_AUTH,B3	Alive C		Ok	No attacks within bounds.	
SAKES_AUTH,B4	Weakagree A		Ok	No attacks within bounds.	
SAKES_AUTH,B5	Weakagree C		Ok	No attacks within bounds.	
SAKES_AUTH,B6	Niagree		Ok	No attacks within bounds.	
SAKES_AUTH,B7	Nisynch		Ok	No attacks within bounds.	
C	SAKES_AUTH,C1	Alive A	Ok Verified	No attacks.	
	SAKES_AUTH,C2	Alive B	Ok Verified	No attacks.	
	SAKES_AUTH,C3	Weakagree A	Ok Verified	No attacks.	
	SAKES_AUTH,C4	Weakagree B	Ok Verified	No attacks.	
	SAKES_AUTH,C5	Niagree	Ok Verified	No attacks.	
	SAKES_AUTH,C6	Nisynch	Ok Verified	No attacks.	

Figure 6.1: Result of verifying the fixed version of SAKES' authentication claims using Scyther.

```

# Previous:
send_5(C, B, {Signed-Proof, Pk, Sk, Nc}k(B, C)); # In role C
recv_5(C, B, {Signed-Proof, Pk, Sk, Nc}k(B, C)); # In role B

# Fix:
send_5(C, B, {Signed-Proof, Pk, Sk, Nb, Nc}k(B, C)); # In
  role C
recv_5(C, B, {Signed-Proof, Pk, Sk, Nb, Nc}k(B, C)); # In
  role B

```

Listing 6.3: Fix to the SAKES protocol to provide non-injective synchronization and data agreement for the router B during the authentication phase. Changes to the protocol are highlighted in blue.

6.5.2 Add Nonces in the Key Establishment Phase to Limit Malicious Behaviour

Above, the adding of nonces in the authentication phase was suggested to improve the level of authentication and protect the protocol against misbehaviour. This idea should also be transferred to the key establishment phase. When inspecting the protocol specification for SAKES, which can be reviewed in Figure 4.6, we observe that the nonce N_A , which the end device creates for each session request, is not returned to the end device along with the session key.

The formal security analysis of SAKES in Section 5.4 revealed attacks on the authentication of the end device during the key establishment, which can be reviewed in Figure 5.5. When inspecting the protocol, we observe that the protocol lacks the same type of message linking as explained above. More specific, the nonce that is generated by the end device at the start-up of the protocol, N_B , is not returned along with the session key.

```

# Previous:
send_3(B, A, {Nb, SessionKeyA}k(A, B)); # In role B
recv_3(B, A, {Nb, SessionKeyA}k(A, B)); # In role A

# Fix:
send_3(B, A, {Na, Nb, SessionKeyA}k(A, B)); # In role B
recv_3(B, A, {Na, Nb, SessionKeyA}k(A, B)); # In role A

```

Listing 6.4: Fix to the SAKES protocol to provide non-injective synchronization and data agreement for the end device A during the key distribution. Changes to the protocol are highlighted in blue.

Not returning the N_A nonce along with the session key removes the mapping between the request and the session key, effectively meaning that the end device is unable to detect which session the received session key belongs to. By adding this nonce as seen in Listing 6.4 above, the model presented in Appendix A.3.3 would achieve both non-injective synchronization and data agreement for the end device as seen in Figure 6.2.

However, the attack on the **Weakagree** claim in A is still present in Figure 6.2, and can be seen in Figure B.6 in Appendix B. The attack claims to fake the sending of the nonce N_B from the router to the end device. In the subsection on improving the authentication phase that was discussed previously in this section, weak agreement was provided for the end device, the router, and the border router. As the attack found in the model of the isolated interaction between the end device and the router targets a message that was sent in authentication phase of the protocol, it may be that the attack is a consequence of the separation of the two phases, and not a direct attack on the protocol itself.

Claim				Status	Comments	Patterns
SAKES_KEYS	A	SAKES_KEYS,A1	Alive B	Ok	Verified	No attacks.
		SAKES_KEYS,A2	Weakagree B	Fail	Falsified	At least 1 attack. 1 attack
		SAKES_KEYS,A3	Niagree	Ok	Verified	No attacks.
		SAKES_KEYS,A4	Nisynch	Ok	Verified	No attacks.
		SAKES_KEYS,A5	SKR SessionKeyA	Ok	Verified	No attacks.
B	SAKES_KEYS,B1	SAKES_KEYS,B1	Alive A	Ok	Verified	No attacks.
		SAKES_KEYS,B2	Weakagree A	Fail	Falsified	Exactly 1 attack. 1 attack
		SAKES_KEYS,B3	Niagree	Fail	Falsified	At least 1 attack. 1 attack
		SAKES_KEYS,B4	Nisynch	Fail	Falsified	At least 1 attack. 1 attack
		SAKES_KEYS,B5	SKR SessionKeyA	Ok		No attacks within bounds.

Figure 6.2: Result of verifying the model of the key distribution in SAKES' using Scyther with a mapping between session and session key.

6.5.3 Return the Proof to the Router to Confirm the Identity of the Server

In Section 5.4.3, the results of Scyther’s verification of the key establishment model was presented. As discussed, the two phases in SAKES has been divided into two separate models due to the large state-space. In the results, both claims for non-injective synchronization and data agreement for the router B were falsified, in addition to the **Weakagree** claim of the server D in B ’s claims. A theory was presented where these attacks were suggested to originate from the lack of mapping between the request to the server and its response, and also the absence of authentication of the server to the router.

To protect the protocol from an adversary that can forge the responses from the server, a suggestion was to include both the proof generated by the border router C and the nonce N_B in the response from the server, which can be done as seen in Listing 6.5.

```
# Previous:
send_3(D, B, {Nd, g1(Sk(D), MAC}k(sk(D)))}; # In role D
recv_3(D, B, {Nd, g1(Sk(D), MAC}k(sk(D)))}; # In role B

# Fix:
send_3(D, B, {Nb, Nd, Signed-Proof, g1(Sk(D), MAC}k(sk(D)))};
# In role D
recv_3(D, B, {Nb, Nd, Signed-Proof, g1(Sk(D), MAC}k(sk(D)))};
# In role B
```

Listing 6.5: Fix to the SAKES protocol to provide authentication of the remote server D to the router B in the key establishment phase.

When running the model with the changes above in Scyther, the results in Figure 6.3 is returned. As we see, the protocol achieves both non-injective synchronization and data agreement, as well as weak agreement for the server D . We observe that the claims for non-injective synchronization and data agreement for A , as well as aliveness and weak agreement in B , are failing. However, these were previously addressed in the fix proposed in Subsection 6.5.2, where a possible solution was introduced and verified. When seeing these two results as one, all the claims in the protocol are essentially confirmed after the presented fixes.

Claim				Status	Comments	Patterns
SAKES_KEYS	A	SAKES_KEYS,A1	Niagree	Fail	Falsified	At least 1 attack. 1 attack
		SAKES_KEYS,A2	Nisynch	Fail	Falsified	At least 1 attack. 1 attack
		SAKES_KEYS,A3	SKR SessionKeyA	Ok		No attacks within bounds.
B		SAKES_KEYS,B1	Alive D	Ok	Verified	No attacks.
		SAKES_KEYS,B2	Alive A	Fail	Falsified	At least 1 attack. 1 attack
		SAKES_KEYS,B3	Weakagree D	Ok		No attacks within bounds.
		SAKES_KEYS,B4	Weakagree A	Fail	Falsified	At least 1 attack. 1 attack
		SAKES_KEYS,B5	Niagree	Ok		No attacks within bounds.
		SAKES_KEYS,B6	Nisynch	Ok		No attacks within bounds.
		SAKES_KEYS,B7	SKR SessionKeyA	Ok		No attacks within bounds.
		SAKES_KEYS,B8	SKR g2(g1(sk(B)),sk(D))	Ok		No attacks within bounds.
D		SAKES_KEYS,D1	Alive B	Ok	Verified	No attacks.
		SAKES_KEYS,D2	Weakagree B	Ok	Verified	No attacks.
		SAKES_KEYS,D3	Niagree	Ok		No attacks within bounds.
		SAKES_KEYS,D4	Nisynch	Ok		No attacks within bounds.
		SAKES_KEYS,D5	SKR g2(g1(sk(B)),sk(D))	Ok		No attacks within bounds.

Figure 6.3: Result of verifying the model of the key distribution in SAKES’ using Scyther where the server returns both the proof and the nonce N_B .

6.5.4 Generate Ephemeral Keys at Both Sides in the Diffie-Hellman Key Agreement

SAKES uses the private key of an ephemeral key pair at the router side and the private of the server to generate the session key in a Diffie-Hellman manner. The reason for generating the key pair in the first place is to use them in the computation of the session key. Another usage is to sign the messages that are sent between the router and the server using the private key, and verify them with the public key.

Generating public key pairs is a time-consuming process for a server, especially if it has to do so for each session, and if the network of end devices that request services is large. Therefore, random nonces could be generated in addition to improve the security of the session keys that are generated in the key establishment phase. This

approach will also allow for maintaining the signing capability of the server and the router.

Generating random nonces is relatively inexpensive compared to generating public key pairs. Let both B and D generate one nonce each, N_{B2} and N_{D2} , to use in the key establishment phase. When B sends its request to D , it also sends $g^{N_{B2}}$ to the server. At the server side, the server sends $g^{N_{D2}}$ in return to B , and computes the session key as $(g^{N_{B2}})^{N_{D2}}$. The advantage of this approach is that it provides forward secrecy. In the case where the server is compromised, the adversary is not able to decrypt previous sessions since the nonces used to generate the session keys are fresh on both sides each time.

6.5.5 Use Elliptic Curve Diffie-Hellman and the Elliptic Curve Digital Signature Algorithm

Another suggestion is to use the ECDH in conjunction with the ECDSA [41] in the key establishment phase. ECDH uses ECC public key pairs in the Diffie-Hellman key agreement. However, as the protocol generates an ephemeral public key pair for the router to use in each key establishment session, we need to handle authentication and integrity of the messages in addition. Authentication can be achieved by using the ECDSA to sign the messages that are exchanged.

The protocol specifications of SAKES states that the key pair generated by the authentication module C is an ECC key pair, while no information is given about how the public key pair of the server D is derived. As the server is assumed to be a computationally powerful entity, it is fair to assume that it is capable of generating an ECC public key pair as well.

As mentioned in Section 2.4, public-key cryptography is more computationally expensive than symmetric cryptography, meaning that the energy consumption on the devices is significantly higher. However, given the architecture of SAKES, where more powerful routers utilizes public-key cryptography to generate the session key, it may be a feasible approach to use ECDH and ECDSA in the key establishment.

Chapter 7

Conclusion

In this thesis, the first formal security analyses of three proposed protocols for key establishment in IEEE 802.15.4 networks that utilize 6LoWPAN are presented. The protocols have been investigated, reviewed, and formally analysed using the tool Scyther. Scyther, the selected tool for verifying these protocols, has also been examined and explained in detail to aid the reader in understanding the importance of verifying the correctness of security protocols, and how this can be done using computer software. Key establishment, different schemes, and the desirable properties in key establishment have also been thoroughly assessed and explained to support the analysis and to explain the modelling choices.

Outcomes

There exist multiple architectures for key establishment schemes, namely those based on symmetric and asymmetric encryption, as well as those that leverage online key servers and trusted third parties. This thesis has identified some of the reasons for choosing a symmetric key establishment scheme over key servers and public-key cryptography. It has also discussed the possibility of using a hybrid system where the infrastructure allows for having more powerful devices in the 6LoWPAN to handle the heavier computation. However, as technological progress often leads to smaller devices and new business opportunities, symmetric key establishment schemes are suited for future applications because of their low complexity and low energy consumption.

Based on the results that been presented, AKES seems to be a valid and usable scheme for establishing keys in a 6LoWPAN, but as the analysis has not covered replay attacks, there may still be undiscovered vulnerabilities. Both APKES and AKES have been formally verified for an unbounded state space and have been proven to be correct schemes that may have an appropriate role in a real-life network. AKES, however, holds advantages over APKES when it comes to providing mobility in networks, which can be assumed to be a requirement for modern device-to-device

communication in dynamic networks.

Flaws have been presented and explained in the SAKES protocol, along with suggested changes that can improve the protocol. The improved protocol have then been formally verified using Scyther. However, due to the design of SAKES, it has been infeasible to provide an analysis of the protocol in a single model. Therefore, the protocol has been divided into two separate models targeting the authentication and key establishment phases. Because of this separation, the security analysis is not entirely complete, and there may exist attacks that went undiscovered through the formal analysis presented in this thesis. SAKES provides an interesting authentication phase, which holds advantages over the two other protocols, given that the authentication module used in the scheme is trusted and secure. These advantages include a more robust authentication system and protection against wormhole attacks.

Future Work

As the formal security analysis of SAKES was separated into two components with each formally verified individually, it raises the question of undiscovered attacks on the protocol. One way to verify this unanswered question is to use a more powerful computer to search through the state-space of the protocol, for example, NTNU's super-computer Vilje.

Also, as this thesis presents multiple fixes that may improve the usability of SAKES as a key establishment protocol in 6LoWPANs, a compelling case for future work would be to implement the protocol in a real-world network to analyse its suitability as a future key establishment protocol in a 6LoWPAN. This work would include more extensive security analysis and also an analysis of the energy consumption of the different entities in SAKES to verify whether standard technologies can run the protocol in an efficient matter.

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Appendix

Scyther Scripts



This appendix contains the Scyther scripts that have been developed to formally verify APKES, AKES, and SAKES.

A.1 Scyther Script of Adaptable Pairwise Key Establishment Scheme (APKES)

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

usertype Index; # User defined type Index
hashfunction MIC; # Message Integrity Code

macro PairwiseKey = {Na, Nb}k(A, B);

macro Message1 = (Na, AddressA);
macro Message2 = (Na, Nb, Iab, AddressB);
macro Message2-MIC = MIC(Message2, k(A,B));
macro Message3 = (Msg, Iba);
macro Message3-MIC = MIC(Message3, PairwiseKey);

const Msg; # ACK-message.
const AddressA; # A's Short Address
const AddressB; # B's Short Address
const Iab: Index; # A's index in B's list of neighbours
const Iba: Index; # B's index in A's list of neighbours

protocol APKES(A, B)
{
  role A
  {
    fresh Na: Nonce;
```

```

var Nb: Nonce;

# HELLO
send_1(A, B, Message1);

# HELLOACK
recv_2(B, A, Message2, Message2-MIC);
claim(A, Running, B, PairwiseKey); # Agree upon the value of
Na

#ACK
send_3(A, B, (Message3, Message3-MIC));

claim(A, Alive); # Entity authentication
claim(A, Weakagree); # Weak agreement, A and B believe they
are communicating with each other
claim(A, Niagree); # Non-injective agreement
claim(A, Nisynch); # Non-injective synchronization
claim(A, Commit, B, Na); # Claim that the recv2 value of Na
has not been changed from the send_1 value of Na
claim(A, Secret, PairwiseKey); # Secrecy of key
claim(A, Commit, B, PairwiseKey); # Explicit key
authentication
}

role B
{
  fresh Nb: Nonce;
  var Na: Nonce;

  # HELLO
  recv_1(A, B, Message1);
  claim(B, Running, A, Na); # Agree upon the value of Na

  # HELLOACK
  send_2(B, A, Message2, Message2-MIC);

  # ACK
  recv_3(A,B, Message3, Message3-MIC);
  claim(B, Running, A, PairwiseKey);

  claim(B, Alive);
  claim(B, Weakagree);
  claim(B, Niagree);
  claim(B, Nisynch);
}

```

```

    claim(B, Secret, PairwiseKey);
    claim(B, Commit, A, PairwiseKey);
  }
}

```

Listing A.1: Scyther script of Adaptable Pairwise Key Establishment Scheme (APKES)

A.2 Scyther Script of Adaptable Key Establishment Scheme (AKES)

```

/*
  Adaptive Key Establishment Scheme (AKES)
*/

hashfunction MIC; # Message Integrity Code

const Msg; # ACK message
const PANa; # A's Personal Area Network (PAN) Id
const PANb; # B's Personal Area Network (PAN) Id
const IDa; Agent; # A's extended, short or simple address
const IDb; Agent; # B's extended, short or simple address
const Ca; # B's frame counter of the last accepted frame from A
const Cb; # A's frame counter of the last accepted frame from B
const Pa; # Flag indicating whether or not A is currently one of
  B's permanent neighbours
const AddressA; # A's Short Address
const AddressB; # B's Short Address
const Iab; # A's index in B's list of neighbours (EBEAP)
const Iba; # B's index in A's list of neighbours (EBEAP)

macro SessionKey = {Na, Nb}k(A,B); # Where k(A,B) is the key from
  the plugged-in scheme
macro Message1 = (Na, PANa, IDa, Ca);
macro Message2 = (Nb, PANa, IDa, PANb, IDb, Iab, Cb, Pa);
macro Message2-MIC = MIC(Message2, SessionKey);
macro Message3 = (Msg, PANb, IDb, PANa, IDa, Iba, Ca);
macro Message3-MIC = MIC(Message3, SessionKey);

protocol AKES(A, B)
{
  role A
  {
    fresh Na: Nonce;
    var Nb: Nonce;

```

```

send_1(A, B, Message1); # HELLO
recv_2(B, A, Message2, Message2-MIC); # HELLOACK
claim(A, Running, B, SessionKey); # Claim that the session key
    is computed
send_3(A, B, Message3, Message3-MIC); # ACK

claim(A, SKR, SessionKey); # Secrecy of session key
claim(A, Alive); # Entity authentication
claim(A, Weakagree); # Weak agreement
claim(A, Niagree); # Non-injective agreement
claim(A, Nisynch); # Non-injective synchronization
claim(A, Commit, B, SessionKey); # Secrecy of session key
}

role B
{
fresh Nb: Nonce;
var Na: Nonce;

recv_1(A, B, Message1); # HELLO
claim(B, Running, A, SessionKey); # Claim that the session key
    is computed
send_2(B, A, Message2, Message2-MIC); # HELLOACK
recv_3(A, B, Message3, Message3-MIC); # ACK

claim(B, Running, A, SessionKey);
claim(B, SKR, SessionKey);
claim(B, Alive);
claim(B, Weakagree);
claim(B, Niagree);
claim(B, Nisynch);
claim(B, Commit, A, SessionKey); # Explicit key authentication
}
}

```

Listing A.2: Scyther script of Adaptable Key Establishment Scheme (AKES)

A.3 Scyther Scripts of Secure Authentication and Key Establishment Scheme (SAKES)

A.3.1 SAKES - Authentication

```

/*
Secure Authentication and Key Establishment Scheme (SAKES) –
Authentication phase
*/

hashfunction MAC;

macro Message1 = Na;
macro Message2 = Nb;
macro Message3-Cipher = {A, B, D, Na}k(A, C);
macro Message3 = Message3-Cipher, A, Na;
macro Message3-MAC = MAC(Message3, k(A, B));
macro Message4 = Message3-Cipher, B, Nb;
macro Message4-MAC = MAC(Message4, k(B, C));
macro Message5-Signed = {A, B, D}sk(C); # The authentication
module at the border router verifies the identities and signs
them in a proof to be used in the key establishment phase
macro Message5 = {Message5-Signed, Pk, Sk, Nc}k(B, C); #
Distributes the proof and key pair to the router. Encrypted
using symmetric key.
macro Message6 = B, Nc;
macro Message6-MAC = MAC(Message6, k(A,C)); # Confirms the
identity of the router to the end device.

protocol SAKES-AUTH(A, B, C, D) {

role A {
# 6LoWPAN End Device (A)

fresh Na: Nonce;
var Nb, Nc: Nonce;
var Pk, Sk;

send_1(A, B, Message1); # Initial "Hello" from end device
recv_2(B, A, Message2); # Closest router responds.
send_3(A, B, Message3, Message3-MAC); # End device crafts a
request with the router and its desired server.
recv_6(C, A, Message6, Message6-MAC);

claim_A1(A, Alive, B); # Entity authentication
claim_A2(A, Alive, C); # Entity authentication

```

```

claim_A3(A, Weakagree, B);
claim_A4(A, Weakagree, C);
claim_A5(A, Niagree); # Non-injective data agreement
claim_A6(A, Nisynch); # Non-injective synchronization
}

role B {
  # 6LoWPAN Router (B)

  fresh Nb: Nonce;
  var Na, Nc: Nonce;
  var Pk, Sk;

  recv_1(A, B, Na);
  send_2(B, A, Message2);
  recv_3(A, B, Message3, Message3-MAC);
  send_4(B, C, Message4, Message4-MAC);
  recv_5(C, B, Message5);

  claim(B, Secret, Sk);
  claim(B, Alive, A);
  claim(B, Alive, C);
  claim(B, Weakagree, A);
  claim(B, Weakagree, C);
  claim(B, Niagree);
  claim(B, Nisynch);
}

role C {
  # 6LoWPAN Border Router (C)

  fresh Nc: Nonce;
  var Na, Nb: Nonce;

  const Pk: Function;
  secret Sk: Function;
  inversekeys (Pk, Sk);

  recv_4(B, C, Message4, Message4-MAC);
  send_5(C, B, Message5);
  send_6(C, A, Message6, Message6-MAC);

  claim_C1(C, Alive, A);
  claim_C2(C, Alive, B);
  claim_C3(C, Weakagree, A);

```

```

claim_C4(C, Weakagree, B);
claim_C5(C, Niagree);
claim_C6(C, Nisynch);
}

role D {
# Remote Server (D)
}
}

```

Listing A.3: Scyther script of the authentication phase in SAKES

A.3.2 SAKES - Key Establishment

```

/*
Secure Authentication and Key Establishment (SAKES) – Session
Key Establishment
*/
usertype key; # User defined type
hashfunction HASH; # Un-keyed hash function
hashfunction g1, g2; # Hash functions to model Diffie–Hellman
var A, B, C, D: Agent; # Identities of the different entities

macro Proof = {A, B, D}sk(C); The identities of the end device,
router and remote server are verified and signed by the
authentication module in the border router
macro Message1 = (Proof, B, Nb, g1(sk(B)));
macro Message1–HASH = HASH(Message1);
macro Message1–Signed = {Message1, Message1–HASH}sk(B);
macro Message2 = (Nd, g1(sk(D)));
macro Message2–HASH = HASH(Message2);
macro Message2–Signed = {Message2, Message2–HASH}sk(D);
macro SessionKeyD = g2(g1(sk(B)), sk(D));
macro Message3 = {Nb, SessionKeyA}k(A,B);

protocol SAKES–KEYS(A, B, C, D) {
role A {
# 6LoWPAN End Device (A)

var Nb: Nonce;
var SessionKeyA: key;

recv_3(B, A, Message3);

claim(A, Niagree);
}
}

```

```

    claim(A, Nisynch);
    claim(A, SKR, SessionKeyA);
}

role B {
  # 6LoWPAN Router (B)

  fresh Nb: Nonce;
  var Nd: Nonce;
  fresh SessionKeyA: key;

  send_1(B, D, Message1, Message1-HASH, Message1-Signed);
  rcv_2(D, B, Message2, Message2-HASH, Message2-Signed);
  send_3(B, A, Message3);

  claim(B, Alive, D); # Entity authentication of D
  claim(B, Alive, A); # Entity authentication of A
  claim(B, Weakagree, D); # Weak agreement of D
  claim(B, Weakagree, A); # Weakagreement of A
  claim(B, Niagree); # Non-injective agreement
  claim(B, Nisynch); # Non-injective synchronization
  claim(B, SKR, SessionKeyA); # Session key reveal of the fresh
  key that is distributed from the router to the end device
  claim(B, SKR, SessionKeyD); # Session key reveal of the
  session key that is established between the router and the
  server
}

role C {
  # 6LoWPAN Border Router (C)
}

role D {
  # Remote Server (D)
  fresh Nd: Nonce;
  var Nb: Nonce;

  rcv_1(B, D, Message1, Message1-HASH, Message1-Signed);
  send_2(D, B, Message2, Message2-HASH, Message2-Signed);

  claim(D, Alive, B);
  claim(D, Weakagree, B);
  claim(D, Niagree);
  claim(D, Nisynch);
  claim(D, SKR, SessionKeyD);
}

```

```

    }
  }

# Helper protocol to model the Diffie–Hellman approximation
protocol @exp(DH) {
  role DH {
    var x,y: Agent;

    recv_!DH1(DH, DH, g2(g1(sk(x)),sk(y)));
    send_!DH2(DH, DH, g2(g1(sk(y)),sk(x)));
  }
}

```

Listing A.4: Scyther script of the key establishment phase in SAKES

A.3.3 SAKES - Key Establishment - Interaction Between A and B

```

/*
  Secure Authentication and Key Establishment (SAKES) –
  Interaction between end device and router in key
  establishment phase
*/

usertype key;
hashfunction HASH;
hashfunction MAC;
hashfunction g1, g2;
var A, B, C, D: Agent;

macro Proof = {A, B, D}sk(C); # The identities of the end device,
  router and remote server are verified and signed by the
  authentication module in the border router C
macro Message1 = (Na, MAC(A, Na, k(A,B))); # Provide the router
  with the end device’s nonce. MAC added because we assume that
  the authentication phase has authenticated all parties.
macro Message2 = (Nb, MAC(B, Nb, k(A,B))); # Provide the end
  device with the router’s nonce. MAC added because we assume
  that the authentication phase has authenticated all parties.
macro Message3 = (Proof, B, Nb, g1(sk(B)));
macro Message3–HASH = HASH(Message3);
macro Message3–Signed = {Message3, Message3–HASH}sk(B);
macro Message4 = (D, Nd, g1(sk(D)));
macro Message4–HASH = HASH(Message4);
macro Message4–Signed = {Message4, Message4–HASH}sk(D);

```

```

macro Message5 = {Nb, SessionKeyA}k(A,B);

protocol SAKES-KEYS(A, B, C, D) {

  role A {
    # 6LoWPAN End Device (A)

    fresh Na: Nonce;
    var Nb: Nonce;
    var SessionKeyA: key;

    send_1(A, B, Message1);
    rcv_2(B, A, Message2);
    rcv_3(B, A, Message5);

    claim(A, Alive, B); # Entity authentication of B
    claim(A, Weakagree, B); # Weak agreement of B
    claim(A, Niagree); # Non-injective agreement
    claim(A, Nisynch); # Non-injective synchronization
    claim(A, SKR, SessionKeyA); # Secrecy of the fresh session
    key
  }

  role B {
    # 6LoWPAN Router (B)

    fresh Nb: Nonce;
    var Na, Nd: Nonce;
    fresh SessionKeyA: key; # The session key is modelled as a
    fresh key to verify the secrecy between the end device and
    the router

    rcv_1(A, B, Message1);
    send_2(B, A, Message2);
    send_3(B, A, Message5);

    claim(B, Alive, A);
    claim(B, Weakagree, A);
    claim(B, Niagree);
    claim(B, Nisynch);
    claim(B, SKR, SessionKeyA);
  }

  role C {
    # 6LoWPAN Border Router (C)

```

```

}

role D {
  # Remote Server (D)
}
}

```

Listing A.5: Scyther script of the interaction between the end device and the router in SAKES

A.4 Scyther Scripts of the Improved SAKES

A.4.1 Improved Authentication Phase

```

/*
Secure Authentication and Key Establishment Scheme (SAKES) –
Authentication – Improved
*/

hashfunction MAC; # Message Authentication Code

macro Message1 = Na;
macro Message2 = Nb;
macro Message2-MAC = MAC(Nb, k(A,B));
macro Message3-Cipher = {A, B, D, Na}k(A, C);
macro Message3 = Message3-Cipher, A, Na, Nb; # Adding Nb achieves
Nisynch and Niagree for A and C
macro Message3-MAC = MAC(Message3, k(A, B));
macro Message4 = (Message3-Cipher, B, Nb);
macro Message4-MAC = MAC(Message4, k(B, C));
macro Message5-Signed = {A, B, D}sk(C);
macro Message5 = {Message5-Signed, Pk, Sk, Nb, Nc}k(B, C); #
Adding Nb achieves Nisynch and Niagree for B
macro Message6 = B, Na, Nc; # Adding Na achieves Weakagree for B
and C in A
macro Message6-MAC = MAC(Message6, k(A,C));

protocol SAKES-AUTH(A, B, C, D) {
  role A {
    # 6LoWPAN End Device (A)

    fresh Na: Nonce;
    var Nb, Nc: Nonce;
    var Pk, Sk;

```

```

send_1(A, B, Message1);
recv_2(B, A, Message2);
send_3(A, B, Message3, Message3-MAC);
recv_6(C, A, Message6, Message6-MAC);

claim(A, Alive, B); # Entity authentication of B
claim(A, Alive, C); # Entity authentication of C
claim(A, Weakagree, B); # Weak agreement of B
claim(A, Weakagree, C); # Weak agreement of C
claim(A, Niagree); # Non-injective agreement
claim(A, Nisynch); # Non-injective synchronization
}

role B {
  # 6LoWPAN Router (B)

  fresh Nb: Nonce;
  var Na, Nc: Nonce;
  var Pk, Sk;

  recv_1(A, B, Na);
  send_2(B, A, Message2);
  recv_3(A, B, Message3, Message3-MAC);
  send_4(B, C, Message4, Message4-MAC);
  recv_5(C, B, Message5);

  claim(B, Secret, Sk); # Secrecy of the received ephemeral
  private key
  claim(B, Alive, A);
  claim(B, Alive, C);
  claim(B, Weakagree, A);
  claim(B, Weakagree, C);
  claim(B, Niagree);
  claim(B, Nisynch);
}

role C {
  # 6LoWPAN Border Router (C)

  fresh Nc: Nonce;
  var Na, Nb: Nonce;

  const Pk: Function;
  secret Sk: Function;
  inversekeys (Pk, Sk);
}

```



```

recv_4(B, C, Message4, Message4-MAC);
send_5(C, B, Message5);
send_6(C, A, Message6, Message6-MAC);

claim(C, Alive, A);
claim(C, Alive, B);
claim(C, Weakagree, A);
claim(C, Weakagree, B);
claim(C, Niagree);
claim(C, Nisynch);
}

role D {
  # Remote Server (D)
}
}

```

Listing A.6: Scyther script of the improved authentication phase in SAKES

A.4.2 Improved Key Establishment Phase

```

/*
  Secure Authentication and Key Establishment (SAKES) – Session
  Key Establishment – Improved
*/
usertype key;
hashfunction HASH;
hashfunction g1, g2;
var A, B, C, D: Agent;

macro Proof = {A, B, D}sk(C); The identities of the end device,
  router and remote server are verified and signed by the
  authentication module in the border router C
macro Message1 = (Proof, B, Nb, g1(sk(B)));
macro Message1-HASH = HASH(Message1);
macro Message1-Signed = {Message1, Message1-HASH}sk(B);
macro Message2 = (Nd, Proof, Nb, g1(sk(D)));
macro Message2-HASH = HASH(Message2);
macro Message2-Signed = {Message2, Message2-HASH}sk(D);
macro SessionKeyD = g2(g1(sk(B)), sk(D));
macro Message3 = {Nb, SessionKeyA}k(A,B); # Should also return
  the Na value in a full-size model.

protocol SAKES-KEYS(A, B, C, D) {

```

```

role A {
  # 6LoWPAN End Device (A)
  # Na should be linked from the authentication phase in a full
  -size model.
  var Nb: Nonce;
  var SessionKeyA: key;

  recv_3(B, A, Message3);

  claim(A, Niagree);
  claim(A, Nisynch);
  claim(A, SKR, SessionKeyA);
}

role B {
  # 6LoWPAN Router (B)
  fresh Nb: Nonce; # Nb should be linked from the
  authentication phase in a full-size model
  var Nd: Nonce;
  fresh SessionKeyA: key;

  send_1(B, D, Message1, Message1-HASH, Message1-Signed);
  recv_2(D, B, Message2, Message2-HASH, Message2-Signed);
  send_3(B, A, Message3);

  claim(B, Alive, D);
  claim(B, Alive, A);
  claim(B, Weakagree, D);
  claim(B, Weakagree, A);
  claim(B, Niagree);
  claim(B, Nisynch);
  claim(B, SKR, SessionKeyA);
  claim(B, SKR, SessionKeyD);
}

role C {
  # 6LoWPAN Border Router (C)
}

role D {
  # Remote Server (D)
  fresh Nd: Nonce;
  var Nb: Nonce;

```

```

recv_1(B, D, Message1, Message1-HASH, Message1-Signed);
send_2(D, B, Message2, Message2-HASH, Message2-Signed);

claim(D, Alive, B);
claim(D, Weakagree, B);
claim(D, Niagree);
claim(D, Nisynch);
claim(D, SKR, SessionKeyD);
}
}

//Computation from Message 2
protocol @exp(DH){
  role DH {
    var x,y: Agent;

    recv_!DH1(DH, DH, g2(g1(sk(x)),sk(y)));
    send_!DH2(DH, DH, g2(g1(sk(y)),sk(x)));
  }
}

```

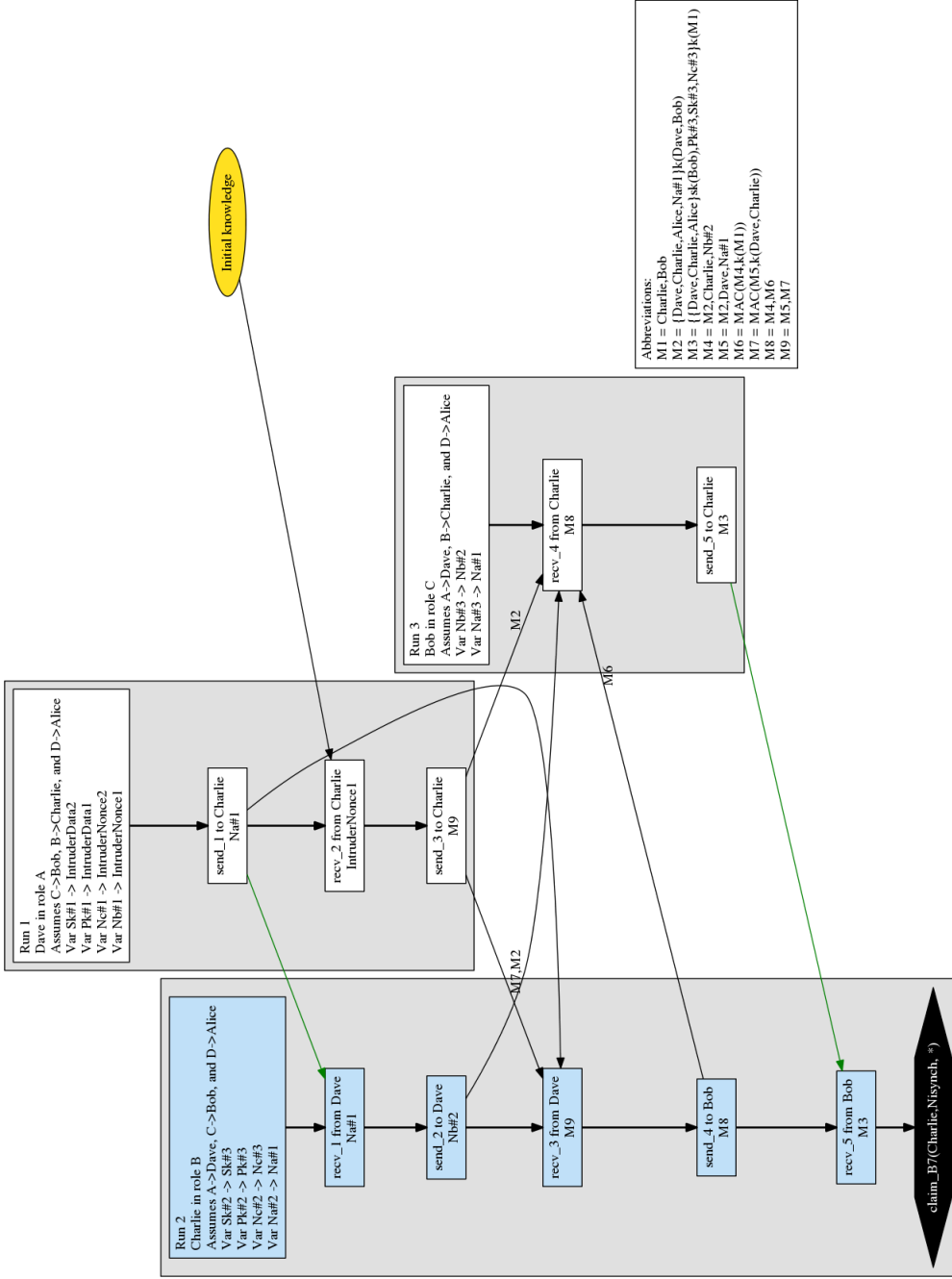
Listing A.7: Scyther script of the improved key establishment phase in SAKES

Appendix **B**

Scyther Attack Diagrams

When Scyther discovers an attack on a protocol property, it generates an attack graph (or diagram). The following attacks are listed in this appendix:

- **B.1 - SAKES:** Attack on the weak agreement property of A in the authentication phase. Here, the adversary can combine different protocol runs in to trick A into believing it is receiving the nonce N_B from B , when it is, in fact, sent by an adversary $Dave$ that has previously observed the nonce from B .
- **B.2 - SAKES:** Attack on the non-injective synchronization property of B in the authentication phase. Here, the nonce that A receives from B differs from what B is sending in this protocol run.
- **B.3 - SAKES:** Falsification of the alive property of A in role B in the key establishment phase. In this model, the session key is distributed from B to A . However, due to the separation of the two phases, A is never actively participating in the protocol. Hence, B is not able to verify that A has ever run the protocol.
- **B.4 - SAKES:** Attack of the non-injective agreement and synchronization property of A in the key establishment phase. In this attack, the adversary is able to forge a response from D to B in the key establishment phase.
- **B.5 - SAKES:** Attack on the weak agreement property of D in role B in the key establishment phase. In this attack, information from two request messages from B is combined into the message received by D .
- **B.6 - SAKES:** Attack on the weak agreement property of B in role A in the interaction component between A and B . This is a special attack that targets the set-up of the authenticated nonces, and may not be an attack of the protocol itself as the authentication phase have been corrected by the improvements that have been presented.



Seyther pattern graph for the SAKES-AUTH protocol, claim SAKES-AUTH.B7 in role B.

Figure B.2: Graph of the discovered attack on the Nisynch property of the roles A, B, and C from A’s point of view in the authentication phase of SAKES.

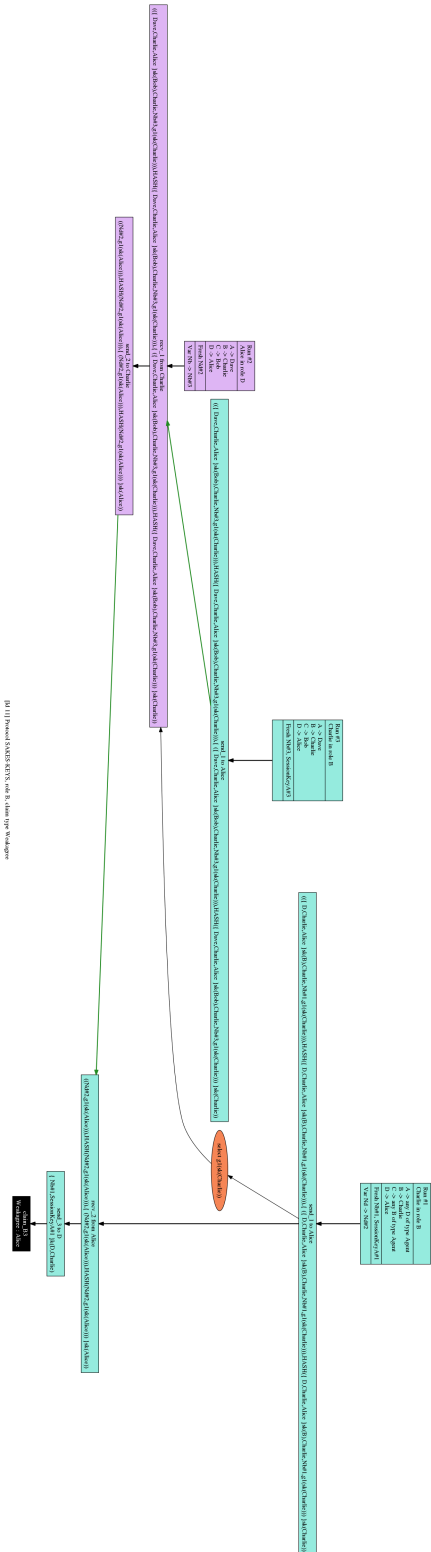


Figure B.5: Graph of the discovered attack on the weak agreement property of D in role B in the key establishment phase of SAKES.



Figure B.6: Graph of the discovered attack on the weak agreement property of B in role A in the key establishment phase of SAKES.

Appendix **C** Notation

C.1 Notation

Notation used in protocol specifications

Symbol	Meaning
A, B, C, D	Nodes A, B, C, D
$\langle \dots \rangle$	Unauthenticated message
$\langle \dots \rangle_k$	Authenticated message with key k
$\{ \dots \}_k$	Message encrypted with key k
$A \rightarrow B$	Message sent from A to B
$A \rightarrow *$	Message broadcasted from A
(Pk_{node}, Sk_{node})	Public key pair for a node
ID_{node}	Identity of a node
$AES(k, m)$	AES encryption of message m with key k
N_{node}	Cryptographic nonce generated by a node
$X Y$	Concatenation of two terms X and Y