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TAMPERE UNIVERSITY OF TECHNOLOGY

RIKU ITÄPURO
SMARTPHONE AS HOME NETWORK'S TRUST ANCHOR

Master of Science thesis

Examiner: Prof. Jarmo Harju
Examiner and topic approved by the
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ABSTRACT

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Today, home networks are complex, and the home owners do not necessarily want to administer all their aspects. Configuring home network devices does not differ much from configuring enterprise devices. One needs access, credentials to login and knowledge to operate the device. If the configuration is out-sourced to external parties and done remotely, those requirements need adaptation. Access to an end device from the outside must be provided, a trusted operator must be hired, and login credentials shared. For this purpose, some previously set provisioning and distribution of authentication keys is needed.

In this work, an application running on a user's smartphone represents this trusted operator. The fact that the mobile phone subscribers already are part of a reliable infrastructure is used in the study as a trusted base. To benefit from the mobile identification, it is shown how the authentication and authorization are done using an extendable authentication profile (EAP) and a SIM card. A theory to use EAP-SIM authentication at home is presented, and a simulated test bed to demonstrate that is built, tested, and analyzed. The idea is to reuse existing techniques by combining them with such new areas as homenet and delegated management. Authentication claims are transported with WPA2 Enterprise. To further avoid complexity and granularity, we only use a simple model of management network.

As a result, we show that the smartphone authentication provides a trust anchor between a configuration agent and the home network. The home network management can be controlled via the smartphone while keeping the local phone user still in control. The benefits of the SIM authentication are strong authentication and a large existing user base, while its disadvantages include dependency onto the mobile operator. Additionally, there remain challenges in keeping the SIM's identity private and in disabling unwanted re-authentications.

TIIVISTELMÄ

RIKU ITÄPURO: Älypuhelin kotiverkkojen luottamusankkurina
Tampereen teknillinen yliopisto
Diplomityö, 63 sivua, 5 liitesivua
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Kun tietoverkot kodeissa monimutkaistuvat, eivät kotikäyttäjät osaa tai halua enää ylläpitää niitä. Kotiverkkojen ylläpito ei eroa nykyisin paljon yritysympäristöistä. Käyttäjältä vaaditaan läsnäolo, tunnukset ja tietämys laitteiden operointiin. Näitä vaatimuksia täytyy soveltaa, jos ylläpito ulkoistettaisiin ja pääsy kotiverkkoihin sallittaisiin. Luotettava toimija on palkattava ja jaettava tälle tunnistautumiskeino sekä pääsy kohdelaitteelle ulkoa käsin. Tämä edellyttää ennakkotoimia ja tunnistautumisavainten jakelua.

Tutkielma kuvaa tätä toimijaa sovelluksena käyttäjän älypuhelimessa. Käyttäjä on matkapuhelinliittymällään jo osa luotettua tilaajarekisteriä, ja tätä ominaisuutta käytetään hyväksi työssä luottamuksen rakentajana. Matkapuhelintunnistuksena käytetään SIM-kortin tilaajatietoa EAP menetelmällä. EAP-SIM-pohjaisen tunnistuksen teorian tueksi esitetään käytännössä simuloitu käyttöympäristö. Periaatteena on ollut käyttää olemassaolevia tekniikoita yhdistäen niitä uusiin alueisiin, kuten homenet-määritysten kotiverkkoihin ja edustajalle ulkoistettuun hallintaan. Tunnistus- ja valtuutustietojen välittämisen hoitaa WPA2 Enterprise RADIUS ympäristössä. Välttääksemme monimutkaisuutta ja tarpeetonta hienorakeisuutta, käytämme yksinkertaista hallintaverkkomallia, jonka rajalla on kotiverkosta muuten erollaan oleva älypuhelin.

Tuloksena näytetään, että matkapuhelimella tehty tunnistautuminen luo luottamusankkurin ulkoisen edustajan ja kodin hallintaverkon välille avaten edustajalle hallintayhteyden kotikäyttäjän valvonnassa. SIM-tunnistuksen hyötyjä ovat vahva tunnistus ja laaja käyttäjäkanta. Haittoina ovat riippuvuus teleoperaattorista, käyttäjän identiteetin paljastumisen uhka ja ei-toivottu automaattinen tunnistautuminen.

PREFACE

This thesis is dedicated to my father.

I wrote this thesis during my research assistant period at TUT. It took time approximately 9 months to start these final words on preface, taking into account my part time job. Although I had some earlier experience on some of the techniques involved in this paper, other techniques were quite new to me, not to mention writing a longer science related paper. Writing and studying all this was equally fun, but now it is time to let go.

There were many people involved in the creation process of this thesis. Bilhanan Silverajan took care of introducing me in to this topic of home networking and worked as my supervising instructor. Jarmo Harju as the examiner, helped in technical proofreading and corrected some of my speling errors, but Pirkko, my friend, was the ultimate inspiration and the aid for the rest of the forgotten articles and misplaced commas. Antti, Axu, Joona, Lauri, Mava, Pekka, and Tiina among others were the uplifting spirit at work. Those pervs made my working in the Pervasive Computing unit a pleasure. At home front the one power cell, who kept me going and always encouraged me was my beloved wife Päivi.

Thank you all!

Tampere, November 18th, 2015

Riku Itäpuro

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LIST OF PROGRAMS

LIST OF ABBREVIATIONS

3GPP	3^{rd} Generation Partnership Project
AAA	Authentication, Authorization, Accounting
AKA	Authentication and Key Agreement
AuC	Authentication Center
CPE	Customer Premise Equipment
EAP	Extensible Authentication Protocol
GAA	Generic Authentication Architecture
GBA	Generic Bootstrapping Architecture, 3GPP standard for user authentication with help of shared key from operator, part pf GAA.
GSM	Global System for Mobile Communication (earlier Groupe Spécial Mobile)
HLR	Home Location Registry, ...
IEEE	Institute of Electrical and Electronics Engineers
IMSI	International Mobile Subscriber Identity
ISP	internet service provider
MNO	mobile network operator
MSISDN	Mobile Station Integrated Services Digital Network, user's phone number
RADIUS	Remote Authentication Dial In User Service, protocol and server, AAA service
SIM	Subscriber Identity Module, a smartcard. Also USIM program running in UICC card (UMTS networks)
SSID	Service Set Identifier, identifies Wi-Fi network
TMSI	Temporal Mobile Subscriber Identity
TUT	Tampere University of Technology
Wi-Fi	Wireless local network, implements IEEE 802.11 standards
WPA	Wireless Protected Access version 1
WPA2	Wireless Protected Access version 2

TERMINOLOGY

802.1X port-based access control standard

access point, AP connects wireless (Wi-Fi) clients to a wired network, used here to encapsulate EAP messages to RADIUS and to forward them to an authentication server

authentication server a server checking identity claims, for example RADIUS server

authenticator a local entity that makes the authentication (and authorization) decision for a client based on local and remote claims, part of 802.1X standard

mobile (network) operator, MNO a mobile network operator, knows the connection between a SIM-owner and SIM secrets

proxying RADIUS RADIUS server standing between a RADIUS client and an authentication server, part of RADIUS server chain

1. INTRODUCTION

Managing computer and network devices can be hard. Modern homes have become similar to small offices regarding the equipment present in them. Earlier, it was sufficient to make just minimal settings at home to a modem (cable, phone or radio) and to connect it to the home computer to get a fully working home network with internet connectivity. Today, the home network has expanded with countless devices available. Entertainment centers (AV-amplifiers, media players, game consoles), manageable network devices (switches/routers), and mobile phones represent new devices and network segments beside computers and printers. Sensors and controller devices from the Internet of Things domain bring their own increment to the device count at home. Connecting these devices to the network remains trivial, but managing the network afterwards has become challenging and complex.

There might be separate areas in homes that have different needs regarding connectivity, resources, and access. In addition, devices in separate segments may not belong to the home owner anymore, hence needing their own administrative parties. For example, an electricity company may have a sensor and controller network, which physically uses the home network, but is logically separated from the other parts of the home network. It is therefore important to keep track of who is allowed to access the different parts of the home network.

The configuration choices in networking devices take some amount of expertise that is not necessarily present at every home. There could exist a market for an external consultant service, which would remotely manage the home network. Remote management eliminates the consultant's physical presence at home and so reduces external actors' costs, but adds many questions regarding security, not only to overcome firewalls, NATs, and the disconnectivity from the Internet. Persons who are allowed to make configuration changes are today often authenticated only by a simple password and physical presence at home. If external help was present, the home owner would need more control allowing only authorized operators in, because the protection used earlier would be missing.

Finally, it is challenging to find a common, trusted entity, upon which every actor could base their trust. Mutual trust is needed to join the formerly unknown parties together safely. Summarized, the problems are the delegated network management, remote provisioning, and trust finding. At its roots, this is an authentication and authorization problem.

One model to solve these problems is to separate the management and control functions from the connectivity and routing issues. Silverajan et al. [41] proposes a model where the management is achieved through a service in a cloud. The cloud service is of type Backend-as-a-Service (BaaS) which is well suited for mobile application usage. The configuration model of devices in a home is mirrored to the cloud as a resource graph. Changes can be planned ahead in the cloud and committed (Pushed) later to the home using configuration tools running over CoAP (Constrained Application Protocol) via a local controller point located at home. CoAP is suitable for IoT devices having constrained resources.

The managers operate in the cloud with the configuration data and the cloud verifies those managers, but the question that remains is how to connect the cloud service to the home network through the local controller securely. The local controller at home would approve the changes, and a smartphone is assumed to function in the local controller role. It will operate as a bridge between the cloud and the home network. See Figure 1.1 for the design of this architecture.

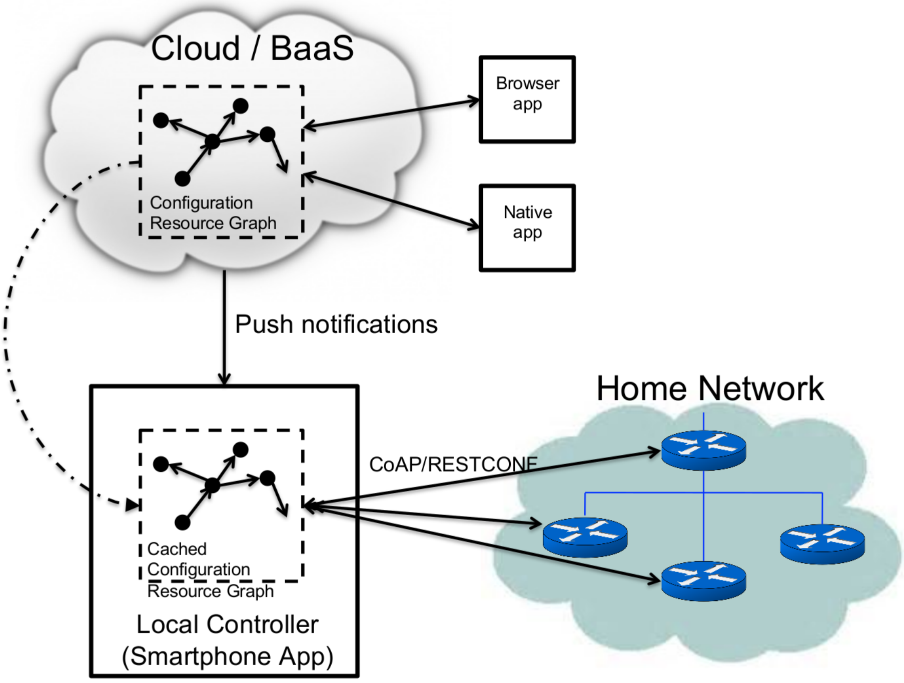
Cloud / BaaS
Configuration Resource Graph
Browser app
Native app
Push notifications
Home Network
CoAP/RESTCONF
Cached Configuration Resource Graph
Local Controller (Smartphone App)

***Figure* 1.1** *Local Controller and Collaborative Management Design*

The delegated service provider therefore does not need to have a direct data access to the home but only to the cloud-based service in order to be able to manage the home network devices. Consultant service is not the only possible delegation for a home network.

One of the security issues is the authentication and authorization from the cloud to the home network. To secure the connection from the cloud service (remote controller) to the home network, there needs to be a mutual trust between the end points, and the research problem here is how to enable the trust between the local controller and the home network as the local controller lies at the edge of the home network. The connection between the remote and local controller is assumed to already be trusted.

Any encryption between devices needs trusted key exchange beforehand, and finding and establishing trust is needed for that. That is called the key distribution problem. Public and private keys solve the key exchange part, but only partially, because the trust still must be found somewhere. The trust can be derived from the facts that already are known. The ultimate trust can be achieved by verifying the trust chains until the chain reaches a trust anchor. The trust anchor is the fact, state, or place, where the derivation of trust is no longer done, but accepted per se. Combining existing techniques, this thesis presents one possible way to bind the home network's trust to the smartphone's unique, existing secret keys inside the smart card's Subscriber Identify Module (SIM), which then would function as a trust anchor.

The above mentioned cloud solution for delegated home network management currently has a preliminary authentication and access model using pre-defined credentials for accessing the local network in general, and other credentials for secure SSH-connection from the local controller device to configuration targets [41, Chap.4]. That does not yet handle the bootstrap of the infrastructure, i.e., the first trust is taken as given.

The smartphone with its SIM and an existing key infrastructure to the mobile network operator (MNO) would later eliminate the requirement for an additional credential distribution. That issue is studied in this thesis. Although the smartphone provides an alternative authentication method with its SIM key, usual methods to authenticate are still plain username-password combinations. This security issue must be solved before delegation in the cloud can happen.

The goal presented in Figure 1.2 is to make the smartphone a central, trusted controlling point for managing purposes. The normal access between the Internet and the home network should stay unchanged. The human aspect and usability are also important, but the focus will still be on the authentication and authorization part of the home net management with smartphone as a trust anchor. The proposed model should nevertheless require less effort than the currently used methods on distributing user credentials, finding the right place for them to be inserted, and ensuring that they are written correctly. Besides those, problems such as limited connectivity are studied.

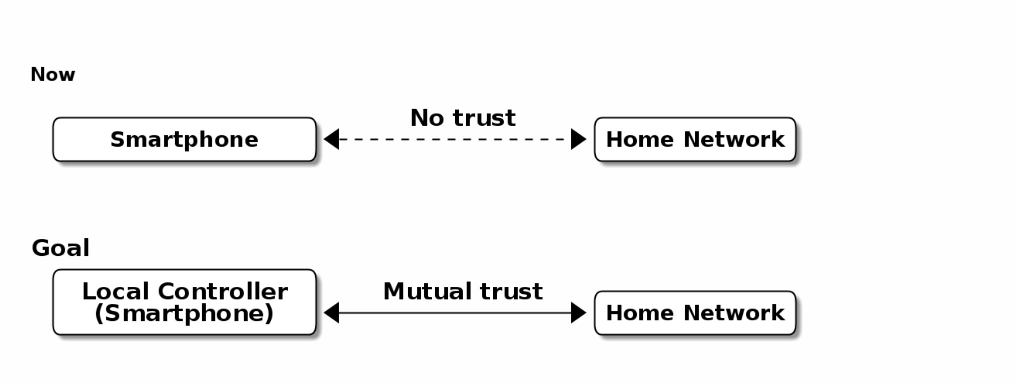

***Figure* 1.2** *Goal of the thesis*

The thesis is structured as follows: authentication–authorization model is explained in Chapter 2. Chapter 3 describes security in current home network architecture and practices for configuring it. Chapter 4 discusses methods to bring a trust anchor into the home network and explains the chosen method. One specially crafted problem is how the scenarios presented here can be tested without knowing the SIM card's secret keys and without a real phone operator involved. Those experiments are described in Chapter 5. Results are discussed in Chapter 6, and Chapter 7 concludes the thesis.

2. AUTHENTICATION, AUTHORIZATION, AND TRUST

Authentication, authorization, and accounting services (AAA) are components for access management. AAA-protocols do not dictate policies, i.e., who is granted an access or what operations a user is allowed to do. They only transport this information between a client who needs them and a server authorized to provide them. Often, the last 'A', which stands for accounting, has been neglected and also here only the first two 'A's are used and later described as AA services. Authentication (AuthN) answers the question of how to identify users and prove that they really are who they claim to be. Authorization (AuthZ) answers the question of what operations the identified users are allowed to do and enforces the usage policy. The rest of the thesis uses short terms AuthN and AuthZ.

In very small environments, AA service is built on a static backend, such as a file on a protected target that an entity wants to access. There, AuthN is checked against a credentials file, and AuthZ is given from a service specific policy file. To be more exact, the identification preceding the authentication is the part where the entity claims and presents its identity to the access controlling system. That can involve sending a username, login name, or other identifier. Authentication in turn is the part where those facts are verified. AuthZ involves checking which rights are available for the authenticated entity.

Before we introduce SIM-based authentication used throughout the thesis, protocols 802.1X, WPA2, EAP and RADIUS are described in the following sections. After this, we expand the term *trust*.

2.1 802.1X

802.1X [21] is an IEEE standard protocol for port-based access control. Ports are physical layer ports, not to be mixed with Layer-4 ports such as TCP/UDP ports. Network access through a specific physical port is restricted (controlled) from a client (called Supplicant) until the client has successfully performed AA. An 802.1X device, where the ports are located, is called authenticator. Third party in 802.1X is an authentication server.

The terms *authenticator* and *authentication server* are easily mixed, but their roles are different: an authenticator works as a gate-keeper to the ports between a supplicant and the network, while an authentication server handles the AA processes. At home the, authenticator usually lies inside the access point (AP), which functions also as a router. However, in large enterprise networks, the authenticator may be a centralized unit, and multiple access points function only as radio stations without routing or authenticator properties.

2.2 RADIUS

RADIUS is the most popular provider for the AAA-services [13, p.75]. It was used first with remote terminal and dial-up modem users, hence the name Remote Authentication Dial-In User Service. Later, it was used as a centralized AAA for networking devices such as switches and routers.

RADIUS protocol is a stateless, request-response type client-server protocol. There are four types of RADIUS messages defined in RFC2865 that are used in the AA. ACCESS-REQUEST and ACCESS-CHALLENGE cover both AuthN and AuthZ messaging, while the final RADIUS message is either ACCESS-ACCEPT or ACCESS-REJECT, based on the result given by the final RADIUS server.

Today, RADIUS has some shortcomings and fixing them is no longer reasonable as development has shifted to another AAA protocol called Diameter, which is already in use in 3GPP and 4G networks [44]. Nevertheless, as RADIUS is so wide-spread, it is still used in many places instead of Diameter. Currently, the main environment of RADIUS, besides AA in network managing, are wireless connections (Wi-Fi) in enterprises and nationwide community federations.

When local Wi-Fi groups such as “SparkNet”, “Langaton Tampere”, or “Wippies” started to form around 2005 in Finland, they used 802.1X and RADIUS for AA. Those networks did still have as an alternative AA method a captive portal technique, where the user had to first authenticate on a WWW-page before getting an access. 802.1X and RADIUS brought an external, central RADIUS server for the automatic authentication of requests, without the burden of the captive portal.

The members of the Wi-Fi groups could then use the network in any location where the same uniform SSID (Service Set Identifier) was seen. Roaming became possible if one found a familiar SSID outside the home area. Later, agreements were made between different local groups to allow roaming, and so federations were born.

As seen from the federated Wi-Fi groups, RADIUS servers can be chained to form a tree. The reasons for the chaining are load balancing and high availability, centralization of distant servers, and a federation of different domains. With a RADIUS hierarchy, the messages can be proxied to the next RADIUS server in the chain, depending on the settings on the proxying RADIUS server.

RADIUS messages are normally not protected from eavesdropping, but they have integrity fields to notice if they have been tampered with. The integrity field is called a Message Authenticator. Notice the use of the term *authenticator* in a different context here, not meaning 802.1X's authenticator. When using RADIUS to AuthN and AuthZ, Requests can only belong to ACCESS-REQUEST messages while Responses can be either an ACCESS-ACCEPT, ACCESS-REJECT, or ACCESS-CHALLENGE message. The Message Authenticator field is sent as last Attribute Value Pair (AVP) of each RADIUS message, and it can belong to either Request or Response [17, p.20].

The Request Authenticator is a 16-octet long, random number in an ACCESS-REQUEST message, but the Response Authenticator for it is achieved with a one-way MD5 digestion function. The digest is taken from the concatenation of Code, ID, Length, corresponding RequestAuth, Attributes, and a Secret, and can look like $3fef65608\ldots2a79$.

```
Response Authenticator =
     MD5(Code |ID |Length |Request Authenticator |Attributes |Secret)
```

The Secret is the shared secret which has been configured between RADIUS client-server pairs, and it protects some parts of the traffic. Different RADIUS client-server pairs may use different shared secrets, and the RADIUS server must separate them according to the client's IP address to manage proxied RADIUS requests [17].

An exception to the above-mentioned plain-text messaging are the user passwords. If the user password was to be transmitted in RADIUS, it would be sent first through an exclusive OR (XOR) function together with an MD5 digested Secret and Request Authenticator.

```
User-Password = XOR(password, MD5(Secret | Request Authenticator))
```

In the following chapters, it is discussed how the proxying servers take part in the AA decisions. Of main interest there is whether it is possible to inject or modify AuthZ information in those proxying RADIUSes in cases where AuthN and AuthZ are provided from different places [3]. A secondary goal is to universally divide AA regarding the client's domain in the federation.

2.3 WPA2

A Wireless Protected Access (WPA or WPA2) protects the traffic in a wireless, shared media, where everyone otherwise can simply listen to all the radio traffic. WPA2 enables both an authenticated access and a message encryption between a client device and a wireless access point (AP) by negotiating session keys. This happens after 802.1X has opened the virtual port in the AP for the client.

The WPA (version 1) was an early subset of then upcoming 802.11i standard, while the WPA2 is the full implementation, also denoted as IEEE 802.11i-2004. The term WPA2 is used throughout the thesis. Client software for 802.11i is called a WPA2-Supplicant, and it is used in wireless clients to communicate with the authenticator.

The WPA2 has two modes of protection: one for groups with a common, pre-shared key (WPA2-PSK, also known as WPA2-Personal) and one for individuals having their own key (WPA2-RADIUS, also known as WPA2-Enterprise). With WPA2-RADIUS, revoking individual access is easier, but client setup is slightly more complicated than on WPA2-PSK, as seen on Table 2.1.

Table 2.1 *Comparison of WPA2-PSK and WPA2-ENTERPRISE modes*

Property	WPA2-PSK	WPA2-ENTERPRISE
suitable for groups	x	
suitable for individuals		x
individual client revocation		x
client setup	easy	intermediate

2.4 EAP

New AuthN methods are invented all the time. Instead of implementing them into 802.1X, it was extended with a modular framework called EAP (Extensible Authentication Protocol) [2]. Researchers justify using EAP, as it provides flexibility independent from underlying technology, whether wireless or wired, and integration with AAA infrastructures, although it adds some overhead to AuthN [36]. Different authentication methods, such as hashed passwords, TLS certificates, or SIM/AKA using smartphone's SIM card, can be used with EAP. This work uses the EAP-SIM authentication method.

EAP describes only the messaging form, so EAP messages needs to be encapsulated inside another protocol. In Wi-Fi, between a smartphone and an AP, the EAP can be encapsulated into 802.1X protocol (as EAPOL) or into a protected EAP(PEAP) [33] before sending it into air. In a wired network, those EAP messages are translated and encapsulated into RADIUS.

The encapsulation is described in Figure 2.1 where it can be seen that the EAP messaging takes place logically between the EAP peer and the authentication server. On a lower transport layer between them, there is an EAP authenticator, which transfers EAPOL messaging into a RADIUS message.

Furthermore, EAP is used to transfer AuthN messages only. EAP includes neither AuthZ information, which is RADIUS's responsibility, nor session keys, which are negotiated by WPA2. In the end, the authenticator is responsible for opening access for the EAP peer, as 802.1x dictates.

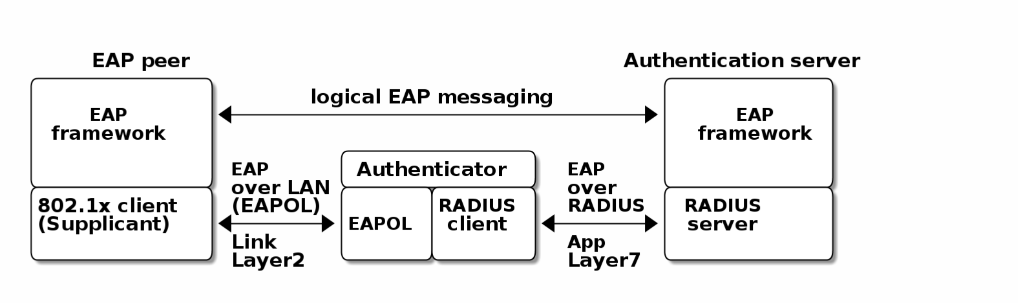

Figure 2.1 *EAP-logical layering and encapsulation*

2.5 SIM-based authentication

SIM associates a physical card used in smartphones to a subscriber of the Mobile Network Operator (MNO). SIM here means the secret keys and the application in mobile phone's SIM or USIM inside UICC (Universal Integrated Circuit Card). The secret keys are hardware-protected and only usable for applications in a SIM card. The SIM's storage also includes a unique serial number ICCID (Integrated Circuit Card Identifier) which identifies the SIM globally, and a unique IMSI (International Mobile Subscriber Identity). The IMSI is a composition of digits belonging to the Mobile Country Code (MCC, 2 digits), Mobile Network Code (MNC,2-3 digits), and Mobile Subscriber Identification Number (MSIN, 10 digits at maximum). It is not to be mixed with MSISDN (Mobile Station Integrated Services Digital Network), which is the user's full international phone number.

SIM card usage can be controlled with two passwords: PIN and PUK. PUK is used as a remedy if PIN has been entered incorrectly too many times. If the card has other applications, such as a mobile electrical signature application (see Section 3.3), they may have different keys and codes.

The passwords, keys, and cards are distributed by the MNO. They provide the mobile network connectivity to the customers of the MNO. The secret keys are used for authenticating an IMSI to an MNO, and this enables MNOs to identify their customer in the network and to charge them accordingly. The client's identity is verified when the SIM is delivered. It is assumed that the SIM card represent its owner, but in reality nothing prevents an identity thief from stealing someone's SIM card. Although the 4-digit PIN tries to prevent the usage of the stolen SIM, this is considered a weak safe [29, p.31]. The most important outcome of this distribution is the achieved trust between the client and the MNO.

AA services need to trust some entity endpoint. In case of the MNO and the SIM, they already mutually trust each other, and the SIM can be used to open access to the mobile networks. Access to Wi-Fi networks still needs a separate access credential, and that was the reason for developing EAP-SIM and later the derivatives EAP-AKA and EAP-AKA'. The goal was to combine the existing keys used in GSM (Global system for Mobile communication) in a secure way to Wi-Fi access. The general purpose EAP-methods existing in 2004 were not compatible with GSM protocols for this purpose [19, p.93]. The results of that development gave us EAP-types EAP-SIM, EAP-AKA, or EAP-AKA'(AKA-PRIME).

EAP-SIM is the original type created for GSM networks and defined in RFC4186 [18]. It is a challenge-response method and similar to AuthN used in GSM, but it adds mutual AuthN; i.e., also the network is authenticated. Beginning from 3GPP networks, the new types EAP-AKA and AKA' can be used. EAP-AKA is defined in RFC4187 [6] and uses the 3GPP's AKA (Authentication and Key Agreement) protocol. It adds to EAP-SIM additional parameters [7], such as sequence numbering from the MNO to protect replay attacks and more advanced digestion functions instead of SHA-1. Otherwise the protocol messaging is same as in EAP-SIM. Finally, there exists EAP-AKA' that enhances AKA by including a Service Set Identifier (SSID) in the key derivation function, which limits the possibility of using possibly compromised network's nodes and keys.

Using EAP-SIM means using the secret key inside a SIM card with A3/A8 algorithms to generate valid responses for the challenges coming from an MNO and to derive session keys. The algorithms A3/A8 and their possible implementations (COMP128, COMP128v2, COMPv3) are not of interest in this work. They can be MNO specific or known reference algorithms.

EAP-SIM variants provide strong AuthN, which here means two-factor AuthN. One factor is something you own (the physical SIM card) while another is something you know (the SIM card's PIN). Biometric factor, i.e., what you are, is not used here, but that would be a third possible factor. Software-based certificates, while stronger than regular passwords, do not, on the other hand, possess the properties *non-copiable* or *unique*, so they can only be considered as strong passwords and do not fulfill the requirements for two-factor AuthN. If we nonetheless were using software certificates with a method such as EAP-TLS, then the certificates (for CA and client) and the private key should still be provisioned first, which would defeat what we want to achieve in easy user experience.

Disadvantages with SIM are the dependency on the mobile operator and internet connection, although disconnectivity issues are later addressed partly in Section 4.6. Using a smartphone may cost money, either to the client or to the service provider, but the costs could be lower than using an SMS, because the network used is an IP network instead of a cellular phone network.

In many parts, SIM variants of EAP are simpler than other EAP variants to the mobile client. Table 2.2 compares the setup of Wi-Fi in clients of one existing organization to EAP-SIM. The example is taken from setting up Nokia Communicator model E90, but in general, the same options are also needed for other clients, also with laptops. It is noteworthy that plain EAP-SIM will not support identity hiding. This will be discussed further later on. If we also added PEAP to EAP-SIM (in last column of Table 2.2), the comparison would be more fair. As can be seen from the table, leaving certificates out from the environment makes the client setup easier with the price of revealing the smartphone user's identity.

2.6 Analysis of EAP-SIM protocol

A bird's-eye view to the EAP-SIM protocol messaging between the smartphone, an AP, an authentication server, and an MNO with its Home Location Registry Authentication Center (HLR_AuC) is described in Figure 2.2. The traffic is EAP on the left, RADIUS in the middle, and MAP/SS7, which is a mobile connection

Table 2.2 *WPA2-Enterprise client setup with EAP-PEAP-MSCHAPv2 and EAP-SIM*

Task: (x)="needed", (N/A)= "not available"	EAP-PEAP with MSCHAPv2	EAP-SIM	EAP-PEAP with EAP-SIM
CA settings:			
- choose CA for the RADIUS	x		x
- if CA-key not known, fetch *securely*	x		x
Other settings:			
- used EAP-method	x	x	x
- validation of RADIUS server's name	x		x
- encapsulation (WPA2/802.1X)	x		
- password	x	x(PIN)	
Identity hiding:			
- enable PEAP	x	N/A	x
- outer identity	x	N/A	x
- inner identity	x	N/A	

application running over a signaling system (SS7) used in cellular networks, on the right.

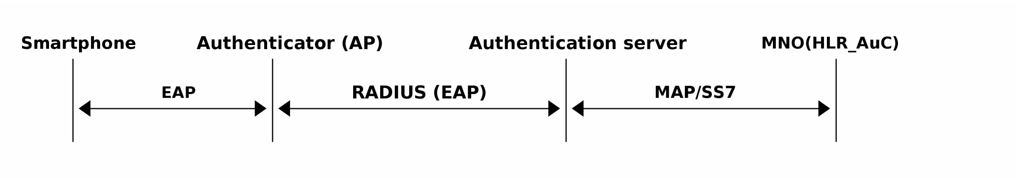

Figure 2.2 *Bird's-eye view to EAP-SIM components*

Protocol analysis of full EAP-SIM authentication is described in Figure 2.3. Important parameters for this work are IMSI, NONCE, and triplet values RAND, SRES, and Kc. From the traffic between the Supplicant (here smartphone) and the authenticator (in AP) we can see that IMSI is first used in message 3. IMSI is the identity which the authentication server would next try to challenge as part of the AuthN and for which the AuthZ would be checked.

All EAP-SIM derivatives provide mutual authentication. An operator (network) is authenticated with the help of a nonce, which is by definition "a number used only once" and can be thought of as a client's challenge to the network. The nonce is transmitted in the message 7 in Figure 2.3. The client later checks in the process 13 whether the RAND values from the operator were digested with the correct nonce and so authenticates the operator.

The client in turn is authenticated when the authentication server generates a challenge with an aid of a triplet from the MNO and the client responses to the challenge correctly after processing it with its own *Ki*. The correct answer would be SRES which the Authentication server received in message 10.

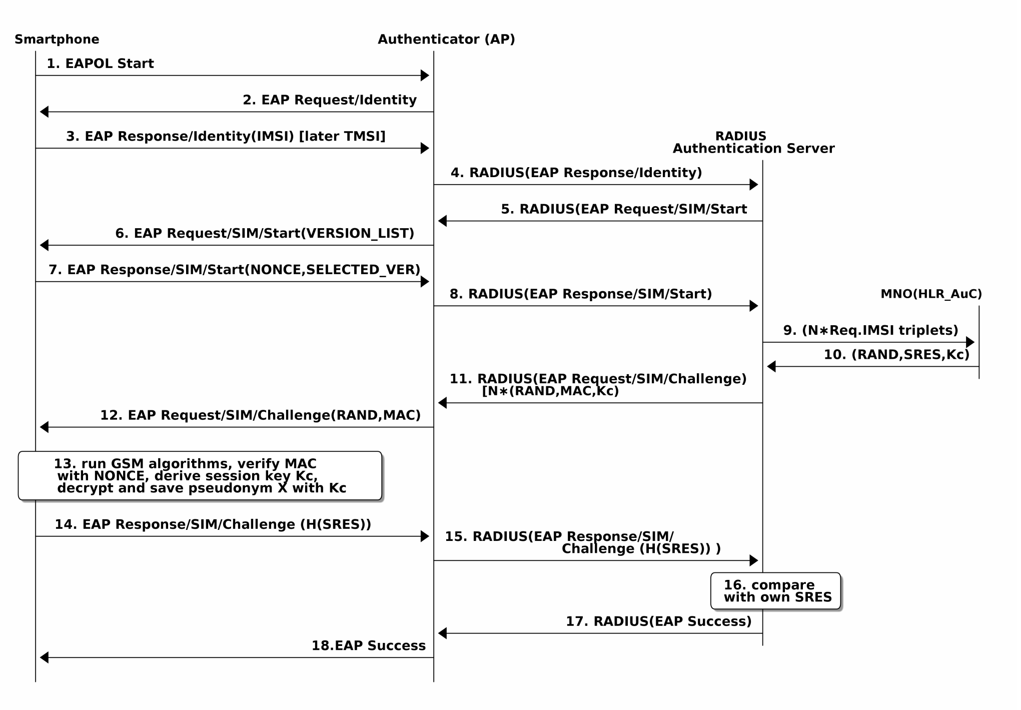
Smartphone
Authenticator (AP)
1. EAPOL Start
2. EAP Request/Identity
3. EAP Response/Identity(IMSI) [later TMSI]
RADIUS
Authentication Server
4. RADIUS(EAP Response/Identity)
5. RADIUS(EAP Request/SIM/Start
6. EAP Request/SIM/Start(VERSION_LIST)
7. EAP Response/SIM/Start(NONCE,SELECTED_VER)
8. RADIUS(EAP Response/SIM/Start)
MNO(HLR_AuC)
9. (N∗Req.IMSI triplets)
10. (RAND,SRES,Kc)
11. RADIUS(EAP Request/SIM/Challenge)
[N∗(RAND,MAC,Kc)
12. EAP Request/SIM/Challenge(RAND,MAC)
13. run GSM algorithms, verify MAC
with NONCE, derive session key Kc,
decrypt and save pseudonym X with Kc
14. EAP Response/SIM/Challenge (H(SRES))
15. RADIUS(EAP Response/SIM/
Challenge (H(SRES)))
16. compare
with own SRES
17. RADIUS(EAP Success)
18.EAP Success

Figure 2.3 *Successful EAP-SIM full authentication with RADIUS*

After mutual authentication, the AuthN phase has been completed. The authentication server completes the AuthZ by sending the authenticator either an Access-Accept or Access-Deny RADIUS message. An accept message triggers 802.1x protocol to open a virtual port in the AP and lets the WPA2 process continue exchanging WPA2 session keys.

Both parties have now retrieved the same trusted key *Kc*. The authenticator has received it directly from the RADIUS message 10, and the smartphone has generated it using its own secret *Ki* key in the process 13. Therefore the derivation of a secret session key for WPA2 is possible.

After the session has been set, the IMSI may be left out and a temporal IMSI (TMSI) can be used instead to hide the client's identity, for example, in a fast re-authentication case to reduce the risk of exposing the client's IMSI unnecessarily. Unfortunately, at that point, the IMSI has already been exposed at least once in plain text, namely in message 3.

TMSI is composed of a pseudonym and a realm part and can be a string. So, one can send `my-string-which-can-change@...operator.domain` instead of the IMSI number as an identity. It must be noted that the TMSI used here differs from the TMSI used in 3GPP networks. Those context must not be mixed, otherwise the security that they bring may decrease, i.e. one must not use the TMSI received from 3GPP as a TMSI in EAP-SIM.

2.7 Trust

Secure communication has many layers, and on its base lies trust. Only after completing the trust setting phase, it is meaningful to complete the other security layers. For example, secret keys enable encrypted communication, but the keys need to be delivered through a trusted channel first. The same applies to public key infrastructure solutions when verifying the public keys. Thus, we can see that trust really is the first layer to be fixed.

Even without trust, some form of secure asymmetric key-exchange is achievable with Diffie-Hellman key-exchange [12]. Unfortunately, it is vulnerable to Man-in-the-middle (MitM) attacks, where the protocol does not notice if messaging has gone through a third party impersonating as the corresponding messaging partner to both ends. MitM can read and decrypt encrypted messages and forward the possibly changed message with a correct-looking signature. With trust set between two devices, i.e., if they can securely authenticate each other, secret communication is achieved. Secure network configuration and credential exchange is then possible.

This trust can be used to include other components under the same trust circle in the home network. As mentioned earlier, SIM and the MNO trust each other; hence mutual authentication between them is possible. That is later shown to be an important factor. Also the key distribution problem mentioned in Chapter 1 is solved already at a SIM card distribution phase. As AuthN-AuthZ at home proceeds through the authenticator, the authenticator must use it as a derivation function to extend trust and deliver this information further.

3. HOME NETWORK ARCHITECTURE

3.1 Home network architecture and IETF

While a home network is any network located at a person's home consisting of devices and their connections, either wired or wireless, this thesis avoids using the term *homenet* in that context because homenet is reserved to Internet Engineering Task Force Working Group's (IETF WG) homenet. IETF is responsible for most internet technology standards, and WG homenet was started in year 2011. The current drive in homenet management is towards the IPv6 environment as it fulfills the future routing and addressing needs. Regarding home networks, homenet has five issues to solve: service discovery, network security, prefix configuration for routers, routing management, and name resolution [20]. As old technologies cannot be forgotten, home networks will be heterogeneous, having both old and new technology, and their interoperatibility is an important issue when planning future home networks. Segmenting a home into multiple subnets will also be part of planning homenets; for example, the home network can include areas for home members, guests, and management. It will not be uncommon to have an inexpensive second network operator subscription for backup purposes at home. Those issues are discussed in the multihoming parts of homenet WG. Lastly, end-to-end access, i.e., restriction-free access is in homenet WG's agenda. It was the key element for the Internet's success and enabled many new applications in the past, but has since then faced difficulties because of firewalls and NATs.

Securing a home network and its router's configuration can be done, for example by first limiting access to their administrative ports with static or dynamic extended access control lists (ACL) in routers. To get through administrative ports, i.e., to login and make configuration changes, there exists either an AAA or local authentication. Authorized agents can then make changes, either directly in the device or through some management protocol, such as SNMP or NETCONF (RFC6241 [14]). SNMP has been in use for over 30 years and is well supported in routers. Yet there are multiple versions for this protocol. While earlier versions (v1, v2) did not provide any encryption of messages, version 3 knows, for example, about public keys and is secure enough when used correctly. NETCONF is a modern protocol and runs over SSH or CoAP protocols, for example.

Customer Premises Equipment (CPE), such as ADSL broadband routers or set-top boxes, connect the customer's network to the operator's network. There are existing protocols for managing CPEs on the border of home network and operator. For example, TR-069 standard [49] for CPEs has been used to implement self-configuration architecture in home networks [38].

RFC7368 [5] from Arkko about IPv6 Home Networking Architecture Principles defines the borders of the home network and states that internal borders in a home network should possibly be automatically discovered. Limiting those borders to a specific interface type would make it difficult to connect different realms locally. The same document continues stating that while a home network should self-configure and self-organize itself as far as possible, self-configuring unintended devices should be avoided, and the home network user should be let to decide whether a device becomes trusted. So, these statements show that the home network environment still needs external configuration even with the proposed automation aids.

3.2 Centralization trends in management

Traditionally, configuration management of individual network devices has been done using each device's console or web interface. As the number of devices has increased, it would have been reasonable to rationalize the process by utilizing a central management, not least to prevent human errors in repetitive tasks. The reason why this has not happened in homes, is that network devices there often are too heterogeneous, bought at different times from different vendors, and therefore incompatible with each other.

To help in moving the management into a more centralized model, the home network will see the smartphone as a central managing local controller. Usually, home users already have a phone, which can be considered 'smart'. Most smartphones have Wi-Fi capabilities and writing programs for them is possible even with only a little knowledge. When we choose a smartphone to be the management point, the other benefits are numerous: a management software can be delivered and updated from the cloud to diverse smartphone types, there are many users having smartphones, and as the most important fact, the trust anchor can be set to the smartphone.

The users are already centrally located in operators' user databases in HLR-AuC. To achieve the management paradigm change to a centrally configured one, we still need to bridge the home network to that model with a trusted local controller, and then resolve the work-flow of change management.

Home network change management itself is mostly excluded from this work. For example, because of synchronization issues, it is desirable that changes in a home network are done only through a local controller, not at a local device, even if synchronizing algorithms such as Trickle [23] were used in the home network for configuration propagation. As another example, configuration also includes power level settings in devices to save electricity based on the usage profile. For example, during the nighttime or when nobody is at home, some devices do not need to be working at their maximum capacity. The details of how this is scheduled is out of scope of this thesis.

Instead, we study interfaces of AA. The main points here are the existing infrastructure (phones, internet access, Wi-Fi access points), strong authentication (two-factor), and authentication methods (EAP-SIM, EAP-AKA, EAP-AKA').

3.3 Methods for introducing trust anchor into the home network

Trust anchor information, be it a secret or some other evidence, can be delivered to a trust device via a physical transport channel separate from the actual communicating channel. The traditional way to do that is with a password inside a sealed envelope or a one-time password list that, for example, online banks use today. The secret can also be sent as an SMS. The trust anchor is part of bootstrapping, which is needed because although the smartphone and the MNO already trust each other, the trust between the smartphone and the AP, and thus the management network at home, is non-existing in the beginning, as can be seen from Figure 3.1.

In this thesis, the phone brings trust to the home network by completing a full EAP-SIM AA through the local authenticator. SIM's identity is verified by HLR AuC at the phone operator's end and AuthZ is added to it later. The verification leaves a trail on the local authenticator and opens a trust channel for a limited period of time for changes from the phone. The disconnection, i.e., the revocation of trust has only been theoretically presented, but not tested in simulated environment.

This chosen model will be fully explained in the next chapter, but before that, we introduce four alternative approaches for using SIM's unique properties besides EAP-SIM. Other techniques are Bluetooth SIM Access Profile(Bluetooth SAP), direct connection through PC/SC (Personal Computer/Smart Card), Caller ID service

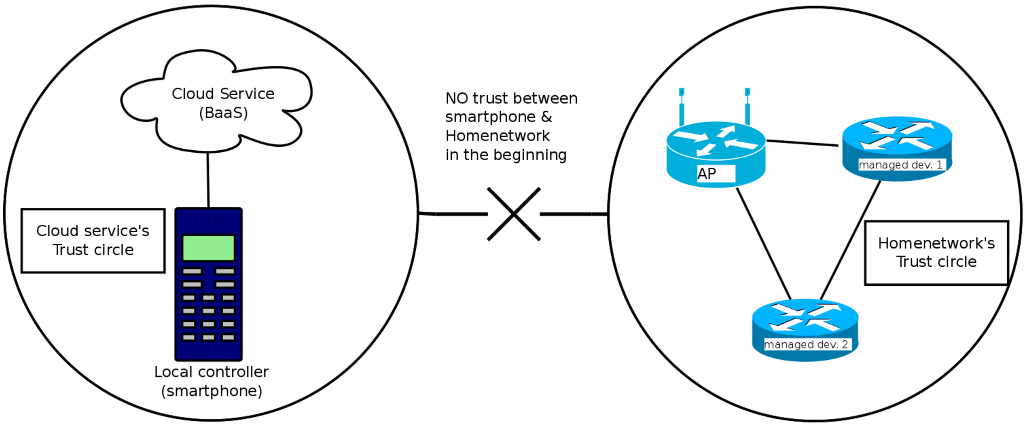
Cloud Service (BaaS)
Cloud service's Trust circle
Local controller (smartphone)
NO trust between smartphone & Homenetwork in the beginning
AP
managed dev. 1
managed dev. 2
Homenetwork's Trust circle

Figure 3.1 *Trust circles in the beginning*

from phone network, and Mobile signing service. Bluetooth SIM and PC/SC would need patching of smartphone's software to work. On the other hand, the smartphone would anyway need to download a controlling application in the beginning for advanced use, so these techniques could be studied further in another work.

Caller ID as an authentication method uses a cellular network's controlling channels. When a phone makes a call, the receiving end gets to know the caller's phone number (MSISDN) before it answers the call. That information is called Caller ID, and it has been in use successfully for some door locking implementations. It does not cost anything either the caller or the responder, because after receiving the Caller ID information, the responder can hang up the upcoming call and no call expenses are created. It can also be made safe, at least in Finland, by limiting which teleoperators are allowed to connect. That can eliminate some Caller ID forgeries.

A SIM card can also benefit from electronic signatures. European Telecommunications Standards Institute (ETSI) has defined a standard for mobile signature services (MSS) in ETSI TS 102 204. MNOs in Finland have diverse implementations for this. The universal service is called “Mobiilivarmenne”, but MNO Sonera's brand for it is “Sonera ID” while MNO Elisa calls it “Elisa Mobiilivarmenne”.

When AuthN and AuthZ comes from the outside, one possibility is to use a federated Mobile AuthN Service, which then is connected to MSSP (Mobile Signature Service Provider) with ETSI-204. The benefits of ETSI-204 federation are similar to those of a federation of Wi-Fi groups mentioned in Section 2.2. No home device needs to implement it at home, but also MNO benefits as it sees the service as just one client instead of all the possible clients. Without the federation, the mobile AuthN services would need to be multiplied with the number of the separate home networks needing authentication service.

Project Moonshot [28], is in its early phases. Its goal is to enable federated access universally to applications and services. If it works and is used together with MSSP, it may offer SIM-based SSH access to authenticator. Modifications are then needed both in the SSH server and the client. Additionally, EAP must be used through tunneling, for example, as an inner protocol of EAP-TTLS.

At this point, one might rise why these external service providers are needed. Is it not easier and simpler to just send an SMS with a password code to the smartphone, when access confirmation is needed? Mobile SIM provides a two-way AuthN part as discussed earlier. Without the need for strong AuthN, that model would indeed be simpler, but using SIM also solves the initial key distribution problem. Additionally, the mutual AuthN problem would still need to be solved: Who sent that password, and where that password should be inserted?

Mutual AuthN is important because if a fake access point were involved, the dishonest admin could lure users to take part in Man-in-the-Middle scenarios. For example, the smartphone user could start the authentication process to the AP located at the neighbor and think that he is using his own home AP. The malicious neighbor AP (MitM) allows access to the user and starts listening the traffic on the AP's network interface. At that time, MitM may capture data from the smartphone's traffic, which may include sensitive data such as username, passwords, or even configuration data. It is not very difficult to even fake an SSH-server, if the client (smartphone here) does not check the server's changed fingerprint.

4. DESIGN OF HOME NETWORK TRUST ANCHOR AND SEPARATION OF CHANGE MANAGEMENT

This chapter describes how the smartphone becomes a trust anchor for the home network and how the change management takes place after that. At its simplest, the smartphone connects with a Wi-Fi link to an AP in the home network and authenticates with a SIM card. The resulting authorized connection brings a trust relationship between the smartphone (a local controller) and the home network (managed devices) anchoring the trust to the smartphone so that the management can take place. In essence, the presence of the smartphone at home opens the gate for the management, although it needs a little interaction on behalf of the user.

4.1 Chosen AA design

A network can be divided into separate segments based on the user's role and needs, such as guest or home members segment. The segments provide a base connectivity layer and simple separation. Different services, like disk storage, can force their own policy on the application level. It is not defined here if the segmentation is made physical or virtual (VLAN, Virtual LAN). There is also a segment for devices management. An analogy to the real world would be a hotel where customers use public access corridors and doors, and service personnel privileged corridors and doors.

Router devices know, how to connect the different segments and how the path goes from segment A to segment B. Normally, they can also control access to the segments with the aid of access control lists (ACL), where the decision is made based on the current configuration or the user's role. The decision can take place at the border of the network or a specific segment.

An example of a deeper access controlling solution would be a traditional firewall and packet inspection in the interconnects of segments, but even a more complex and modern model would be the de-perimeterization trend set originally by Open

Group's Jericho Work Group [32] in 2004, that will not leave trust verification to the perimeters of the network (firewalls and application proxies), but always handles traffic as coming from an unreliable source. One implementation of de-perimeterization is Google's BeyondCorp [48], where traffic always travels through Access Control Engine and is suspected as being external, even when it originates from inside networks.

On our chosen model, on the other hand, once a user has been authorized into a management network, access will stay open for him, at least for a (predefined) limited time. So, instead of checking a user's credentials each time data is received, this model only checks where data is received from. Data received from the management network is allowed for changes. It is arguably a lighter method than to always make full AuthN and AuthZ but may suffice here, at first.

When the home network needs a secure link to the smartphone, the trust mentioned earlier is the first one needed. The trust is achieved by checking whether the smartphone can access the home management network using only its trusted SIM card providing AuthN. AuthZ in turn is compared to the existing roles of IMSI in the authenticator.

When an AP forwards an authentication request to the next RADIUS server, it can ask or receive, beside AuthN and AuthZ, other service parameters, such as provisioning. RADIUS can carry those extra attributes in its ACCESS-ACCEPT message. In essence, AuthZ part itself can be thought as one type of service provisioning. That would then allow the smartphone to connect to a specific management network and access the devices either via command line interfaces, SNMP, or similar [30, p.4]. There exist RADIUS attribute types for directing user into a specific VLAN. If those do not suffice, there are also special Vendor Specified Attributes (VSA). VSAs allow vendors to define up to 255 attributes of their own that can be used in provisioning in a homogeneous environment.

That way (3rd party) authentication server can decide which network segment the device will be put in. In our case, admin users are put in to the management network. Yet, usually RADIUS's ACCESS-ACCEPT message, which means AuthN and AuthZ were successful, puts the user in the default network, i.e., it just gives basic access, because not all end devices support those provisioning parameters.

In the first prototype it is enough to identify an authorized smartphone's SIM. The smartphone holding the authorized SIM is granted access to parts of the management network and it is authenticated strongly. User management is outsourced to the MNO, which already has provided SIM cards to users. What remains is the adding of the user's IMSI to the authorized users' list. That list can be located in diverse places, as can be seen in Section 4.2.

After authentication and authorization have succeeded, WPA2 session key creation occurs between the AP and the smartphone. The authenticator has opened a port to the smartphone for access. It specifically has opened an access to the management network for the configuration changes. The local RADIUS (if existing) and AP have a trail of a successful authentication and they know which IMSI has successfully authenticated in the home network. They also know the mapping between IMSI and temporal TMSI for cases where the smartphone later would need re-authentication.

Even though the AP now has authenticated the smartphone user, the managed devices still need to have their own access control. They may consult a local RADIUS server, which tells whether there currently is an authenticated smartphone present, and then the changes going to the management network would be allowed. Smartphone could also have received the login credentials to devices through earlier configuration information and use them after getting into the management network. This kind of AA would happen on upper, application layer (layer 7), while AA discussed here (802.1X) happens already on lower, media layer (layer 2).

4.2 AA component location scenarios

The AA components AuthN and AuthZ can be found in diverse location combinations depending on who provides those services and whether there is any caching available. Table 4.1 presents the non-inclusive list of locations of AuthN and AuthZ in 5 scenarios. The locations in the table are marked as (i) for internal or (e) for external and the scenarios are described in detail after the table. Authenticator is the entity which gives the final decision about access regardless of the location of AA and it is always internal, located at home network.

Table 4.1 *Location of AA, AuthN and AuthZ in scenarios I-V*

scene no:	AuthN	AuthZ
I	e	e
II	e	i
III	e	i/e (proxied)
IV	i	i
V	-	-

Here, the AuthN component is usually located outside the home, as the MNO provides AuthN, unless we are considering offline or recurring AuthN (in Scenario IV).

The AuthZ component may be placed more freely. It can be at the MNO (I), at home (II-IV), or at the external provider (III). The authenticator, on the other hand, must stay at home, and it always gives the final decision about the access. If the AuthZ decision is made on a remote 3rd party AuthZ server (I,III), then that server needs to have either local AuthZ data or access to cloud service's AuthZ data. Further it seems inevitable that delegating AuthZ function would simplify home network management. Because the cloud already has AuthZ data of eligible IMSI accounts, then, instead of putting logic on CPE for AuthZ, CPE could just trust the 3rd party service's AuthZ message, which in case of RADIUS is either *ACCESS-ACCEPT* or *ACCESS-REJECT*. The last scenario (V) presents the case, where the environment has not yet been bootstrapped, so neither AuthN nor AuthZ is ready yet.

The first AA-scenario is presented here thoroughly as an example. The goal is to make the smartphone trusted to the home network and later proceed to a trusted configuration change. The steps are numbered and explained in detail in Figure 4.1. The configuration change is allowed if CPE gets an ACCEPT message from MNO. Allowed users have been inserted earlier to the MNO from the Cloud.

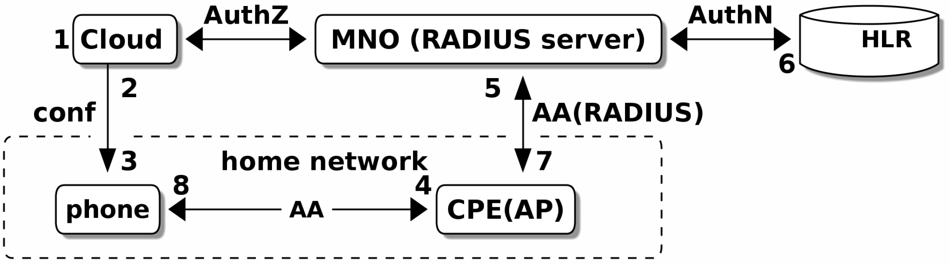

Figure 4.1 *Scenario I with 3 separate domains: Cloud, MNO and home net*

1. The model has been changed in the Cloud.
2. The Cloud sends the changes to the Local Controller (phone).
3. If the changes are privileged, they need to be approved by the phone user. The phone user must authenticate to the management network.
4. The phone user starts the authentication process to management network using EAP-SIM and reveals its IMSI.
5. A CPE (AP) forwards the authentication to an MNO's RADIUS server using RADIUS protocol.

6. The MNO has RADIUS server which uses a HLR-AuC for authentication triplets. This RADIUS continues the authentication process until the end. The MNO also asks (AuthZ phase) the Cloud whether IMSI user has an admin role. The MNO returns in a RADIUS message either *ACCESS-ACCEPT*, if user is both known AND has admin role, or *ACCESS-REJECT*, if either property fails.

7. The CPE receives this ACCEPT or REJECT. If there were other RADIUSes between the CPE and the MNO, they would have acted as proxy RADIUS servers.

8. If ACCEPTed, the smartphone is both authenticated and authorized and can now send configuration change messages to the CPE, which recognizes them as coming from an authorized network.

In the second scenario (Figure 4.2), AuthN is asked from an MNO, but AuthZ is checked from a local database. Local data comes from a data model, i.e., from the configuration data, and it will be saved in CPE or some other place within the home network. The benefit of local roles is that administrative users can be held at a local base. Even if some intruder got a positive AuthN result, the AuthZ would still deny him the access. When we think that a local role cache involves only a few IMSI numbers, this is administratively tolerable.

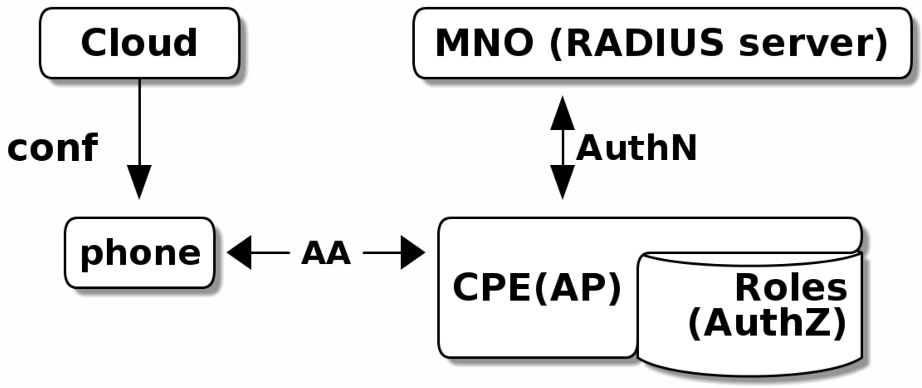

Figure *4.2 Scenario II with AuthZ in home network*

Similar to the first scenario is scenario III (Figure 4.3), but this time there is a service provider between the CPE and the MNO, so AA is fully outsourced: the local AP communicates with RADIUS protocol to the external authentication server. That in turn gets AuthN from the MNO via its own HLR-AuC gateway and AuthZ from the cloud. It can also use alternative sources for AuthN. Locally, there is a cache for roles in case of network disconnectivity.

Here the benefit is that the 3rd party authentication server may have direct contracts to many alternative MNOs, so the user is free to choose its MNO operator. As a bonus, the MNOs already delegate requests to the right operator, if they happen to get AuthN request which does not belong to them. This is similar to federated service.

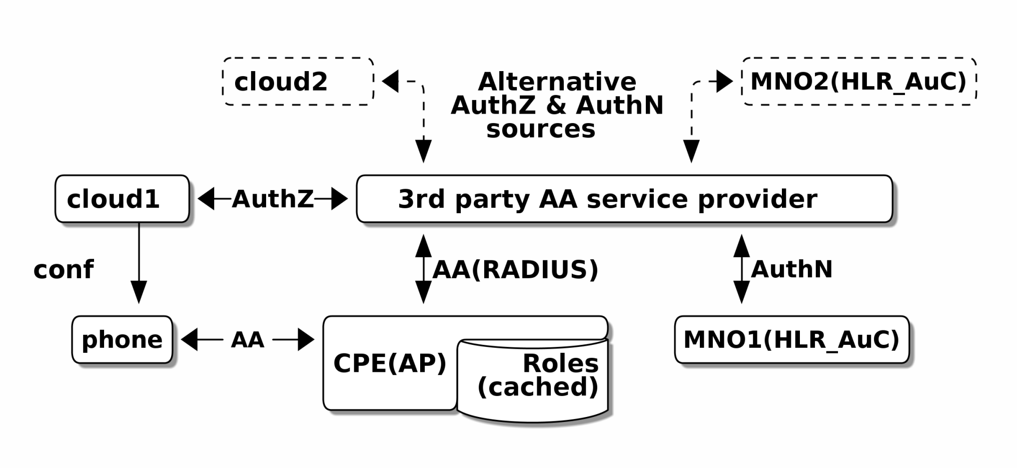

Figure* *4.3* *Scenario III with outsourced AA and backup cache for AuthZ

Allowed users are verified from the cloud's registries, and the specific IMSI is authenticated at the MNO. It may need some preparation if the SIM identities are temporary, i.e., if TMSI is used. Still, IMSI is carried out at the first message of full authentication. Later, the server would need to have mapping between IMSI and TMSI, but because only full authentication is used, there should be no problem.

If the Internet connection is down, local AA is still possible, if there has been at least one full AA round. Full authentication uses IMSI, which is the identity of the phone's SIM. Fast re-authentication on the other hand would use temporal identity TMSI, which is lighter in operation than full authentication, and is shown in Figure 4.4.

TMSI can change each time the AuthN request had been sent. Mapping of TMSI is cached on the authenticator and the round-trip, and handling at the HLR can so be eliminated. When the smartphone makes a re-authentication request with its temporal TMSI value, the CPE still knows the right mapping to IMSI authorization, so this method works even when there is no Internet connectivity. However, full authentication would not work here then because of the missing MNO.

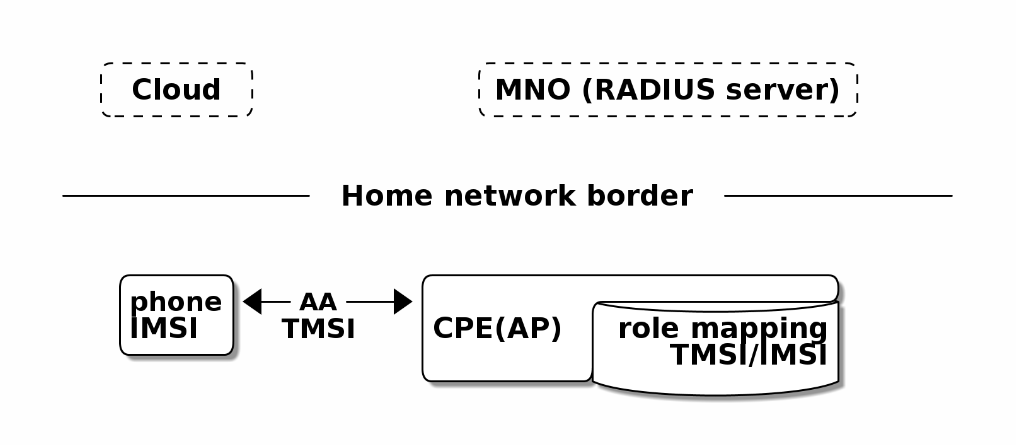

Figure 4.4 *Scenario IV with offline AA*

Scenario V represents the case when nothing has been configured in a network, there are no admin users, and APs are set to factory default. CPE has first neither trust nor roles. The scenario therefore needs pre-configuring and bootstrapping after which it can become any of the scenarios I-IV. Bootstrapping is discussed later in Section 6.7.

4.3 Modification of RADIUS messages

Our model greately benefits from the modification of RADIUS messages in proxying RADIUS, if that is possible as was mentioned in Section 2.2 (RADIUS). The modification is needed when the proxying RADIUS wants to combine an AuthN message from the MNO to AuthZ decision received from elsewhere.

RADIUS servers may implement different vocabulary in their AVP set. RFC6929 [10] points out that even when the RADIUS proxies do not understand all AVPs inside RADIUS message, they must deliver those attributes, and that allows us to use a larger set of AVPs than is in any (proxying) RADIUS server's vocabulary. By adding AVPs inside the authorization packet, we achieve extra information about the validity of the access request. That information may include a VLAN parameter or a time stamp for a forced logout. RFC2865 [40] says that the forwarding RADIUS proxy may alter the packet as it passes the proxy, but because an alteration would invalidate the packet's signature, the proxy has to re-sign the packet. In the end, proxying RADIUS can technically insert some data into bypassing messages.

4.4 Similarities with Lock-and-Key method

The method is very similar to the concept used on routers to dynamically enable access to certain parts of a network by first letting the user to log in to the router. If the access succeeds, the router dynamically adds the route to the management (or other restricted) part from the users network.

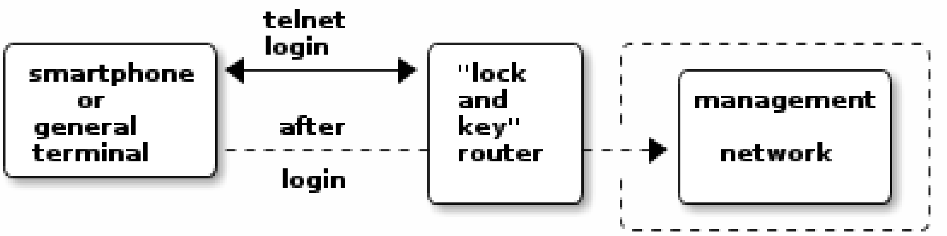

Figure 4.5 *Cisco's view of Lock-and-key access*

Device provider Cisco calls this “Lock-and-Key” access and uses dynamic access list to implement it [34, p.117]. Lock-and-key is presented on Figure 4.5. Smartphone has only limited access to the network before AA is completed, while in the Lock-and-key the other parts of network are already open, and successful login to the router opens access to even more segments through it. In other words, Lock-and-Key protects access in layer-3 and though needs first access to the router, while 802.1x's protection starts already at layer-2 between the smartphone and AP. Captive portals are similar to Lock-And-Key.

Both methods - 802.1X and Lock-and-Key (and captive portals) - can have RADIUS as an authentication server. When RADIUS is not available, for example, because the Internet is down, there almost always exists as a failover a local password method in the configurable router.

This thesis suggests a mix of these methods: EAP-SIM 802.1x WPA2 for authenticating and encrypting in the local network with SIM and Lock-and-key type modification in the AP to further access the management network. Finally, RADIUS protocol is used to transfer the parameters that the smartphone needs in communicating with devices in need of changes.

1. Smartphone connects a Router via wireless AP and needs to login.

2. Smartphone uses telnet (or ssh) to login to the ROUTER with credentials.

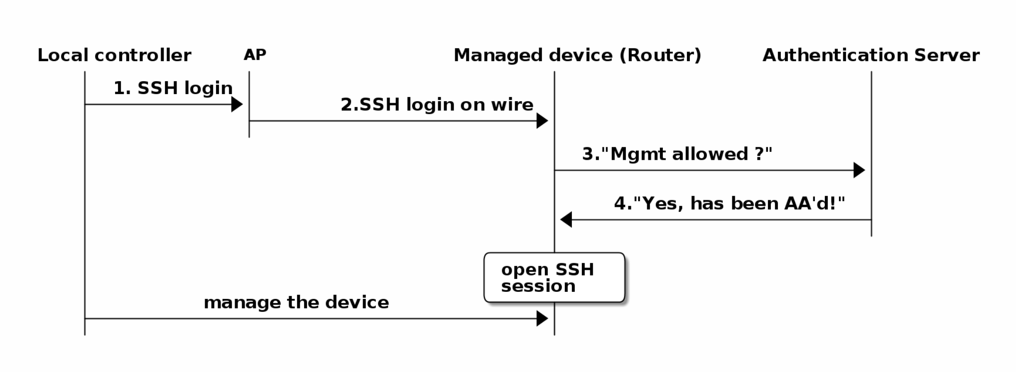

Figure 4.6 *Managed device trusts Autentication Server*

3. ROUTER (as RADIUS client) checks AA from Authentication Server (or proxy).
4. AA-server answers based on earlier SIM-authentication that this request is correct.

4.5 Chosen management model

The simple way to propagate changes from the cloud (or any outside source) is to make them come from the trusted place, here the smartphone, where an application takes care of sending them right to the end devices. This simplification has some pitfalls. If the smartphone continuously stays in the management network, then the changes coming later may not be separated from the currently approved. If we understood that the change approval belongs to the AA-process, then the later approvals would also need an AA.

The smartphone should be dropped out forcibly from the management network either right after the changes have been sent or after a predefined timeout period during which more changes can be send. That period can be called a management session. Timeout method was the original idea and should be kept in mind when the final implementation is made.

The session time and the logout can be handled in AP directly with a timer. After a specific time, AP simply drops the connection (WPA2-session) to the phone. This needs modification in the AP software, if there is no such method already.

Another solution would be for AP to listen for a command from an external AuthZ server, where a similar timer would trigger a notification event. This also requires modifications: a listening process to the AP and the timer into the AuthZ server.

Later it was learned [40] that terminating a session is not included in the original RADIUS protocol. The root cause is that messages originating from the RADIUS server are not defined in the RADIUS protocol, and so an AP as a RADIUS client cannot receive RADIUS server initiated disconnection messages. Additional extensions such as Disconnect and Change-of-Authorization (CoA) packets, also known as RADIUS Dynamic Authorization or RADIUS Disconnection Message (DM) [9], have later been brought in to the protocol by diverse vendors, but they may not all be implemented on every device. Disconnect-Request is sent to UDP port 3799, so the authenticator should also listen for that in addition to RADIUS UDP port 1812. As a side note, Diameter protocol would provide server initiated messaging.

To demonstrate how the model works, we present the case of adding a new admin user. Let us first suppose, for the sake of simplicity, that the home network has been already configured (bootstrapped) and that it is functioning properly. To further make the case simpler, let us assume that the Local Controller is the sole administrative source for the configuration changes, and ignore the cloud, because we know that there already exists a configuration framework in the cloud.

Now, let us consider what happens when the cloud operator (or the owner of the home network) tries to modify the attributes that give access to a new actor, such as a new operator, who wants to have access to separate segments of the home network. First, we need to have that segment separation change approved, and after that we want to allow the newcomer account to have access to that segment and only to that. For the first part, which is normal operation, approving would perhaps not yet be necessary, but for the second part we need some checking unless our trust to the cloud operator is ultimate.

When the CPE of the home network is about to input configuration changes which would change the balance of authors or roles, it needs to check that the change is permitted. Permission needs to be asked from a trusted point, here mobile SIM. Instead of that, the CPE checks from its own state database whether mobile SIM has been given access to the management network. This thesis justifies the management and therefore the changes to be allowed, if the smartphone user is currently logged into the management network. After the AA is ready, the smartphone has all means to connect the configured targets.

It must be noted that the smartphone can already have an association to a non-management network with Wi-Fi. If that is the case, it must first disconnect from there and then connect, i.e., do the AA in the correct management network. This implies disconnection from other services using the Wi-Fi link, because smartphones currently have only one Wi-Fi radio available and routing would still prefer Wi-Fi as a default gateway, although a possible non-Wi-Fi data link still may stay up and operational.

4.6 Disconnecting the local controller and offline changes

After the phone has been successfully connected to the management network, changes coming from the phone can reach configurable targets, for example routers. To solve the missing Internet connection problem, a simple solution would be sending a one-time password to a predefined phone via an SMS, but which entity would then check that and who would be authorized to send that message? An authenticating server which has no internet connection should have a predefined way to check that a one-time password received via SMS is correct.

One solution to this problem could be to still use a co-existing captive portal for emergency access. As the AP is programmable, it could provide this portal. Alternatively, existing programs such as *ChilliSpot* or *NoCatAuth* could be used as WWW-portals. For that to succeed, the WWW-portal would also need an open access without 802.1X port-based access control.

4.7 Summary of the chosen solution

The chosen solution to benefit from SIM is via EAP-profiles, as EAP is well known when using WPA2-Enterprise protection in Wi-Fi. Design is based on 802.1X and mobile network operator aided authentication and it is a variation of the lock-and-key design.

It is assumed that the local controller (smartphone) delivers all changes to target devices. The distribution of changes [41] is not further described here. The AP functions both as the authenticator and RADIUS client in scenarios I-IV. The authenticator receives RADIUS messages from authentication server even when there would be a separate local RADIUS server running as a proxy.

5. IMPLEMENTED SOLUTION

To prove that the proposed model works, empirical tests were done. A preliminary plan to benefit from SIM-authentication at home is presented in Figure 5.1. The real operator (MNO) and its HLR were planned to be replaced with a gateway in the home network and the real phone with its simulated counterpart. HSS would replace HLR in 3G/UMTS networks. Only the Local Controller's interaction with the home network is tested and the Cloud part set away.

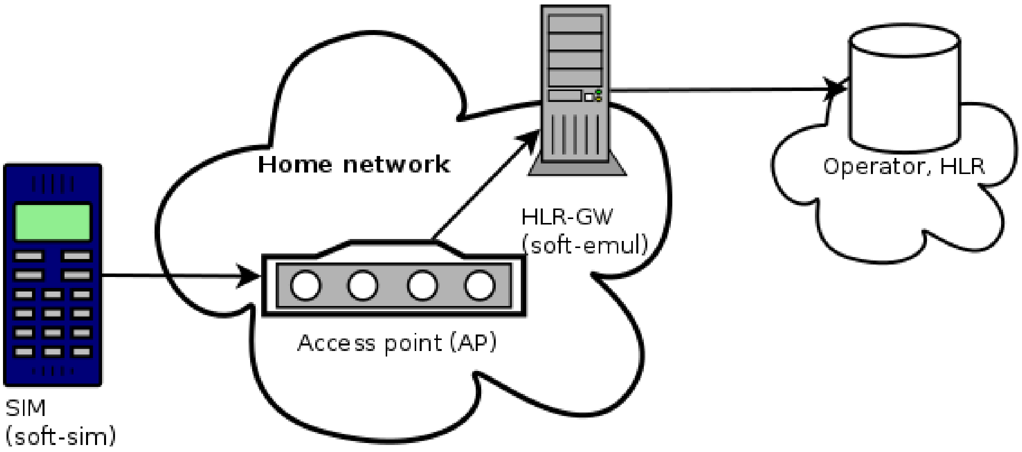

Figure 5.1 *Plan to benefit from SIM-authentication at home*

First it is shown how EAP-SIM authentication works in a simulated environment with different clients. This is further analyzed with the aid of network traces. In the end, it is shown that the changes in the management network are possible from the local controller with command line interface (CLI).

5.1 EAP-SIM authentication test bed

Physical devices used in the tests were three smartphones, a Wi-Fi access point, and a laptop. The smartphones were Nokia E70-1, Nokia E90, and Jolla. The Nokia phones featured EAP-SIM by default, but the Jolla phone missed a crucial software library and the right compilation time configuration set on its WPA-supplicant for SIM.

Jouni Malinen's software package *HostAP* [27] provides components for WPA2-Supplicant, a Wireless Access point (AP), an HLR-gateway (for GSM networks), and an EAP-endpoint with or without a RADIUS server. From those, executable binary programs wpa_supplicant, hostapd (for wired RADIUS server), and hlr_auc_gw were used. The versions of *HostAP* used in the tests were 2.2 and later 2.3, while version 2.4 was published in March 2015 and 2.5 in September 2015. The software may be distributed, used, and modified under the terms of a BSD license.

For a more realistic test, an additional hardware AP running OpenWRT firmware was used instead of hostapd's AP. OpenWRT AP worked as a RADIUS client connecting to the RADIUS server still provided by the hostapd. OpenWRT AP did not try to open EAP-messages, but just encapsulated them into RADIUS packets. RADIUS server's configuration file can be seen in Appendix 7.

The laptop's role was therefore physically split-brain; in the end, it asked for AA from itself. Figure 5.2 shows how EAP-SIM AuthN messages (dashed and solid arrowed lines) flow when using simulated WPA2-Supplicant and HLR-AuC as simulation environment.

To make thing more interesting, the laptop's WPA2-supplicant with a known software SIM part was later implemented inside Jolla. This was possible thanks to open software and similarity of Jolla's environment to the one used in the laptop. Modification involved compiling PCSC-libraries and recompiling the WPA-supplicant used in Jolla with simulator options for ARMv7 architecture.

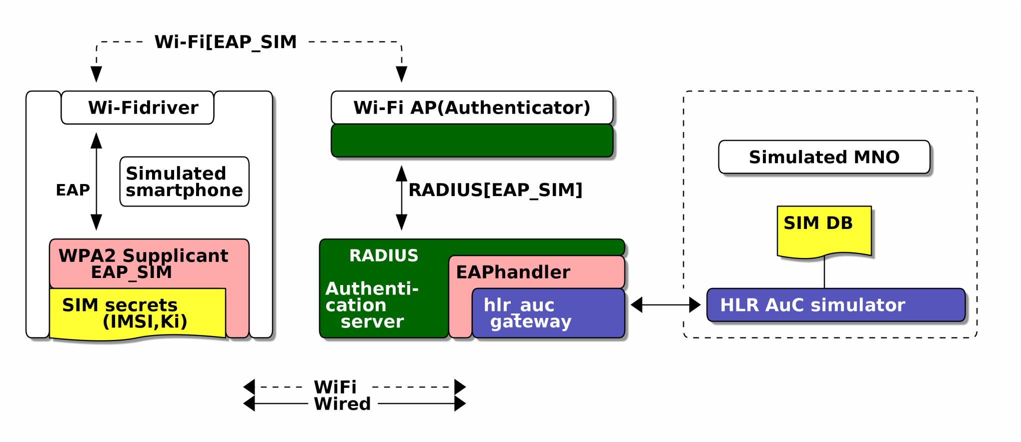

***Figure* 5.2** *EAP-SIM AuthN messaging in simulation test bed*

The algorithm used in the demo was an internal GSM-Milenage, which handles EAP-SIM beside EAP-AKA. Milenage is a reference implementation and as such suitable for operators who do not want to invent their own security algorithms. OPc and Seq parameters from Milenage were not used because they are not needed in EAP-SIM.

5.2 Detailed description of test runs

The first tests were done with hostapd as a wireless AP. Test run with Nokia E70-1 with the Symbian 60 Series OS (2006) had a non-registered SIM card. In testing the authentication, there was no indication of EAP method present in captures. The only indication of security was a message “Open System” in application logs, which only means that no pre-shared key is used. The reason for that was not found, but it may have been a problem on hostapd’s settings.

Nokia E90 with a registered SIM had better results. This time the capture was made in monitor mode, i.e., the capture interface was mon.wlan0. Traffic captures revealed some EAP traffic involving some EAP-SIM Request–Response pairs.

Capture 5.1 *E90 trying to use its internal EAP-SIM*

```
# time     from-> to    Proto len  Message
1 1.5588   e90 -> AP    EAPOL  18  Start
2 1.5589   AP  -> e90   EAP   118  Request, Identity
3 1.5607   AP  -> e90   EAP   117  Request, Identity
4 1.8055   AP  -> e90   EAP    72  Request, GSM Subscriber Identity
                                            Modules EAP (EAP-SIM)
5 1.8070   AP  -> e90   EAP    71  Request, EAP-SIM
6 1.8053   e90 -> AP    EAP    74  Response, Identity
7 1.8095   e90 -> AP    EAP   106  Response, EAP-SIM
8 1.8055   AP  -> e90   EAP    72  Request, EAP-SIM
9 1.8070   AP  -> e90   EAP    71  Request, EAP-SIM
```

When opening Responses number 6 and 7, we can see that we got to the part where a nonce, selected version, and an identity were sent from the phone (message 7 in Figure 2.3), but the RADIUS server did not know how to handle them. Even when authentication conversation did not complete fully, the authenticator still received a claim of identification from the smartphone. Yet, as there is no full AuthN, no proof of identity existed in that case. Neither the unregistered SIM nor the registered SIM could have been verified with the operator because it was locally simulated and they both therefore correctly ended the conversation as supposed to according to RFC4186 [18].

At this point, the physical phones were put aside and a simulated SIM card environment was used at the client’s side, too. After WPA2-Supplicant run on the laptop with simulated SIM card access with SIM/USIM protocols, respective EAP-SIM, logging revealed that “Hostapd will send SIM/AKA authentication queries over a UNIX domain socket to an external hlr_auc_gw. program.” This revealed, that Hostapd had successfully received the SIM card’s AuthN request and was going to forward that to the simulated HLR authentication program. Now it was time to build an environment to help automate the tests. The tests were run from a shell program (Appendix 7), which started the needed programs. It also recorded used configurations, logs, and traffic captures for later analysis.

The wireless capture of traffic between the WPA2-Supplicant and the AP was made at the WPA2-Supplicant on the wireless card. The wired capture between the AP and the RADIUS server was made at a wired card. Wireless capture was not made in monitoring mode, so not all 802.11 details in data packets were captured [52]. That was not a problem because the focus was in the EAP messaging instead of radio channel details. Additionally, the messages between the RADIUS server and the HLR were recorded. The whole conversation is first given here, and later on analyzed more thoroughly.

The packet capture of successful SIM-authentication with corresponding parts of logs at WPA2-Supplicant, RADIUS server and packet captures 802.1X, RADIUS and HLR is shown below. Communicating partners are denoted as AP and phone for Wi-Fi traffic, AP-wired and RADIUS-srv for RADIUS on wire, and finally RADIUS-hlr and HLR-AuC gw for simulated MAPS/SS7 traffic. The capture has been done at the WPA2-supplicant.

Capture 5.2 *Successful EAP-SIM Authentication*

```
No.  Time     Src      Dest      Proto    Len  Info
129  7.9830   AP-wifi  phone     EAP       23  Request, Identity
130  7.9832   phone    AP-wifi   EAP       39  Response, Identity
131  7.9887   AP-lan   RADIUS    RADIUS   235  Access-Request(1)
                                                (id=162, l=193)
132  7.9889   RADIUS   AP-lan    RADIUS   108  Access-Challenge(11)
                                                (id=162, l=66)
133  7.9908   AP-wifi  phone     EAP       38  Request, GSM
                                                Subscriber Identity
                                                Modules EAP (EAP-SIM)
134  7.9924   phone     AP-wifi  EAP       70  Response, (EAP-SIM)
135  7.9945   AP-lan   RADIUS    RADIUS   272  Access-Request(1)
                                                (id=163, l=230)
 -            RAD-hlr  HLR-AuC   socket        SIM-REQ-AUTH <IMSI> 3
 -            HLR-AuC  RAD-hlr   socket        SIM-RESP-AUTH <IMSI>,
                                                3 triplets
136  8.0024   RADIUS   AP-lan    RADIUS   256  Access-Challenge(11)
                                                (id=163, l=214)
137  8.0040   AP-wifi  phone     EAP      186  Request, (EAP-SIM)
138  8.0043   phone    AP-wifi   EAP       46  Response, (EAP-SIM)
139  8.0063   AP-lan   RADIUS    RADIUS   248  Access-Request(1)
                                                (id=164, l=206)
```

```
140  8.0065   RADIUS   AP-lan    RADIUS   202   Access-Accept(2)
                                                 (id=164, l=160)
141  8.0110   AP-wifi  phone     EAP       22   Success
142  8.0112   AP-wifi  phone     EAPOL    135   Key (Message 1 of 4)
143  8.0123   phone    AP-wifi   EAPOL    135   Key (Message 2 of 4)
144  8.0161   AP-wifi  phone     EAPOL    169   Key (Message 3 of 4)
145  8.0163   phone    AP-wifi   EAPOL    113   Key (Message 4 of 4)
```

IMSI is sent for the first time already on the second EAP message from WPA2-Supplicant to AP (compare with Figure 2.3, message 2.) This part is presented in more detail in Capture 5.3.

Capture 5.3 *First detailed indication of IMSI, captured from WPA2-supplicant*

```
Frame 129: 7.983047
    Type: 802.1X Authentication (0x888e)
    Version: 802.1X-2004 (2)
    Type: EAP Packet (0)
    Length: 5
    Extensible Authentication Protocol
        Code: Request (1)
        Id: 50
        Length: 5
        Type: Identity (1)
        Identity:
Frame 130: 7.983223
    Type: 802.1X Authentication (0x888e)
    Version: 802.1X-2001 (1)
    Type: EAP Packet (0)
    Length: 21
    Extensible Authentication Protocol
        Code: Response (2)
        Id: 50
        Length: 21
        Type: Identity (1)
        Identity: 1232010000000000
```

There is a difference between the used 802.1X versions: the AP uses version 802.1X-2004 in its request, while the smartphone uses 802.1X-2001. Here it does not have any noticeable effect.

The last line contains the important identity field received from the SIM. Its length cannot be seen directly, but when the EAP message's length (21 octets) is reduced by a fixed space needed for Code (1), ID (1), Length (2), and Type (1), it yields 16 octets for the identity. Therefore the identity is not coded as a numeral but instead as a string, and that brings more flexibility into the protocol as the identity can include alphabets, too. It also minimizes the chance for misunderstandings in case the context gets lost. When we remember from Section 2.5, that IMSI can be no longer than 15 octets, the extra prefix ’1’ has an extra meaning. Here it denotes that we are now talking about EAP-SIM identity instead of EAP-AKA or EAP-AKA’.

The EAP client’s identity is transformed at the authenticator (Figure 2.1, Chapter 2) from 802.1X’s EAPOL format into RADIUS format and sent to the RADIUS server. The captured frame between AP and Radius server is shown in Capture 5.4.

Capture 5.4 *EAP client’s identity transformed, capture from RADIUS server*

```
Frame3: 7.988616
Radius Protocol
    Code: Access-Request (1)
    Packet identifier: 0xa2 (162)
    Length: 193
    Authenticator: 055ff370b9e793c1e39d375aade8033c
    Attribute Value Pairs
        AVP: l=18 t=User-Name(1): {1232010000000000 }
        AVP: l=7 t=NAS-Identifier(32): musta
        AVP: l=27 t=Called-Station-Id(30): 66-66-B3-8A-68-B3:simtest
        AVP: l=6 t=NAS-Port-Type(61): Wireless-802.11(19)
        AVP: l=6 t=NAS-Port(5): 1
        AVP: l=19 t=Calling-Station-Id(31): 5C-51-4F-E7-FA-F4
        AVP: l=24 t=Connect-Info(77): CONNECT 54Mbps 802.11g
        AVP: l=19 t=Acct-Session-Id(44): 5491885C-00000037
        AVP: l=6 t=Framed-MTU(12): 1400
        AVP: l=23 t=EAP-Message(79) Last Segment[1]
            EAP fragment
            Extensible Authentication Protocol
                Code: Response (2)
                Id: 50
                Length: 21
                Type: Identity (1)
                Identity: 1232010000000000
        AVP: l=18 t=Message-Authenticator(80):
                                   04ea7e507d72bdb1acf515ef19ac9527
```

Here the interesting part is the first RADIUS AVP. While the encapsulated EAP fragment naturally carries the Identity=“1232010000000000” field, it was surprising that RADIUS had captured that field and filled its User-Name field with the very same “1232010000000000”. IMSI is “232010000000000” and it is prefixed with an ’1’ as explained earlier.

In the WPA2-Supplicant configuration file (see Appendix 7) both the identity and credential section had the identity field, but the latter creds block was later learnt to belong to cases where the same credentials would be used in multiple networks and therefore it would save the trouble of always rewriting that block. Another thing to be noted is that the AP has followed conventions on converting EAP into a RADIUS message, and put identity field into User-Name Attribute Value Pair (AVP), too. A similar convention can be seen when analyzing the EAP encapsulation and the message size. The last RADIUS (AVP) is Message-Authenticator, which presents limited safety against message corruption. Limited, because it uses MD5-hashing, which is not safe against malicious attackers anymore.

Meanwhile, the HLR simulator was listening requests from the Authentication server's internal EAP-handler through a local socket. Its configuration is shown in Appendix 7. There one can see the simulated Milenage parameters including SIM secrets.

The AuthN request (SIM-REQ-AUTH), which in production version would go to real HLR-AuC, included the IMSI and parameter "3", which indicates that the requester wants three triplets. While one triplet would equal a 64-bit key used for challenges, three triplets will make the key 192-bit long. Session keys are derived from this key material. Crypto analysis of Patel [35] noted in 2003 that the achieved session key security length would be not even 128 but 64 bits; however, it is not known to us whether this was taken into account in the 2005 version. The format of the triplet received is RAND:SRES:Kc.

```
Received: SIM-REQ-AUTH 232010000000000 3
Send: SIM-RESP-AUTH 232010000000000
 a5dc7c1a177ee418:fea4260f:6634b5081c74b5872b49f37fc387ddb5 \
 0faa08f223510ef6:e6d0f3f4:3d7559287e5bd2ec3fb77b1f7d097d8f \
 832475ad3e7bea2b:3fe28cc8:1be8b4f1ab247ec732d15cf63ad57390 \
```

5.3 Simulation on smartphone Jolla

Since we had source the code available, we also tried to move the simulated SIM application to the real smartphone. Jolla is a new Finnish smartphone that runs on ARMv7 processor and has its roots in Nokia's last mobile phone line that used Linux Distribution MeeGo at the beginning of 2010's. The OS is called Sailfish and it includes user interface code created by Jolla, open source base components from Mer, and some other software components, which are either free or proprietary. Mer is a community driven by merits; its name comes from the words 'Meego Reinvented', or 'meritocratic community' There are also other OSs based on Mer, such as Tizen.

Jolla's base WPA-supplicant belongs to Mer core, and it was here re-built for simulator use. The build process was done inside the MerSDK virtual machine running under Virtualbox because it provided not only a simulated Jolla environment on x86 processor architecture, but also a cross compiling environment Scratchbox, which makes porting programs to Armv7 processor easy.

To compile wpa_supplicant with EAP-SIM simulator, a PCSC component was needed. So first pcsc-lite was downloaded and cross-compiled in MerSDK. Then wpa-supplicant was compiled with correct parameters in the same place. Finally, the wpa_supplicant was stripped of debugging symbols and copied to Jolla together with the PCSC-library. Jolla phone's file hierarchy is very similar to hierarchy in the test environment's Linux, which made the operation very easy. Table 5.1 describes the components and their versions that were used in the tests.

Table 5.1 *Versions of components in tests and their architecture.*

version(s)	component	tested on (machine arch)
2.3	hostap(RADIUS-EAP)	laptop(x86_64)
2.3	hlr_auc_gw	laptop(x86_64)
2.2, 2.3	wpa-supplicant	laptop(x86_64)
2.4	wpa-supplicant	Jolla (armv7l)
1.1.9.28	Sailfish OS	Jolla (armv7l)
1-8.13	pcsc-lite	Jolla(armv7l)
1-8.13	pcsc-lite	laptop(x86_64)

5.3.1 Cross-compile the programs inside a virtual machine

MerSDK is shipped as a virtual image which runs inside Virtualbox. Starting the image opens an ssh server, which by default listens on port 2222 on localhost. One can use an SSH keypair authentication to get there. In the following example, file *mersdk* represent the private SSH key of type RSA.

```
# ssh -l mersdk -p 2222 \
    -i ~/emu/sailfish/vmshare/ssh/private_keys/engine/mersdk \
     localhost
Last login: Sun Nov 15 09:50:47 2015 from 10.0.2.2
[mersdk@SailfishSDK ~]$ uname -rm
3.6.11-10.1.17.jolla i686
```

As can be seen, the virtual machine's architecture is i686, i.e., 32-bit x86. We moved into the sandboxed armv7hl architecture (armv7hl) with sb2 command, and changed the user id into a virtualized root user. A pcsc-lite package retrieved earlier was compiled and installed.

```
[mersdk@SailfishSDK ~]$ sb2 -t SailfishOS-armv7hl -R
[SB2 sdk-build SailfishOS-armv7hl] root@SailfishSDK ~ # uname -rm
3.6.11-10.1.17.jolla armv7l
[SB2 sdk-build SailfishOS-armv7hl] root@SailfishSDK ~ # cd \
   /home/mersdk/rpmbuild/SOURCES/pcsc-lite-1.8.13
[SB2 sdk-build SailfishOS-armv7hl] root@SailfishSDK ~ # ./configure ;
[SB2 sdk-build SailfishOS-armv7hl] root@SailfishSDK ~ # make install
```

The wpa_supplicant was compiled in a similar way. The needed options were added to the configuration file before compiling.

```
CONFIG_EAP_SIM=y
CONFIG_SIM_SIMULATOR=y
CONFIG_USIM_SIMULATOR=y
CONFIG_PCSC=y
```

After wpa-supplicant was compiled and linked, it was stripped of debugging symbols to reduce its size to merely 15% of the original size.

```
# ls -s wpa_supplicant-pscs
5788 wpa_supplicant-pcsc
# strip wpa_supplicant-pcsc ; ls -s wpa_supplicant-pscs
876 wpa_supplicant-pcsc
```

Finally, the program wpa_supplicant-pcsc and a corresponding libpcsclite.so.1 library were copied to the Jolla phone, which was connected to the computer with an USB cable.

```
scp wpa_supplicant-pcsc nemo@jolla:
scp libpcsclite.so* nemo@jolla:/usr/local/lib
```

5.3.2 Running the new binary on a real smartphone

At this point, we were able to use inside the real physical smartphone this modified wpa_supplicant, which uses a configuration file instead of a SIM card. To make sure that it does not conflict with an existing wpa_supplicant on the phone, we first disabled the system version and used our version manually.

```
% ssh nemo@jolla
Last login: Sun Oct 11 17:44:37 2015 from 192.168.2.1
,---
| SailfishOS 1.1.9.28 (Eineheminlampi) (armv7hl)
’---
[nemo@Jolla ~]$ systemctl disable wpa_supplicant
```

Because the *libpcsclite* libraries are in a non-standard place (in /usr/local/lib), we had to start wpa_supplicant with the correct dynamic library path environment value; otherwise, an error occured.

```
[nemo@Jolla ~]$ export \
             WPASUPP=/home/nemo/wpa-pscs/wpa_supplicant-pcsc-stripped
[nemo@Jolla ~]$ ${WPASUPP} -v
./wpa_supplicant-pcsc-stripped: error while loading shared libraries:
libpcsclite.so.1: cannot open shared object file: No such file or
directory
[nemo@Jolla ~]$ LD_LIBRARY_PATH=/usr/local/lib ${WPASUPP} -v
v2.4 (malinen 2003-2015)
```

From this point on, the tests that earlier needed the computer could now be run on the smartphone. Even now, we did not use a real SIM card, but it probably would have been possible, if the configuration file had not given the secrets but instead a PIN to unlock the smartcard.

6. ANALYSIS, RESULTS, AND DISCUSSION

We have now gone through the theory, design, and implementation. Next, let us discuss some of the results and findings. We will concentrate on security, deployment difficulties, costs, platform issues, usability of multiple APs, and cases where we need to extend the number of SSID's. The facts collected in the thesis are once more wrapped up in Discussion section. Last, we speculate on some alternative design solutions for adding trust and management models.

6.1 Security considerations

There can be multiple ways to attack the described methods of the home network management delegation. The following subsections divide them into confidentiality (privacy), integrity, and authenticity. Accessibility is also discussed.

6.1.1 Confidentiality (privacy)

Confidentiality means that no one except the message's intended recipients may get to know the information inside the message. The purpose of the message confidentiality in the authentication phase is to hide the identity of the smartphone and possibly the delivered secrets from eavesdroppers. Hiding IMSI enhances the privacy of the smartphone user.

As discussed in Section 2.5, IMSI is sent in clear during the starting phase of 802.1X authentication. This is a privacy issue because TMSI which hides IMSI cannot be used before a session has been set up [18, p.66]. After the first full authentication, the client and the authenticator know the TMSI and can use it in further communication. The TMSI can even be re-changed using re-authentication as shown in Figure 6.1.

The authenticator is responsible for converting TMSI to IMSI if it later needs to ask for full authentication from the MNO. During that time, IMSI can be caught using a device called IMSI-catcher. The very same happens also in a regular GSM network with non-EAP traffic. IMSI can be caught by listening to the GSM network for

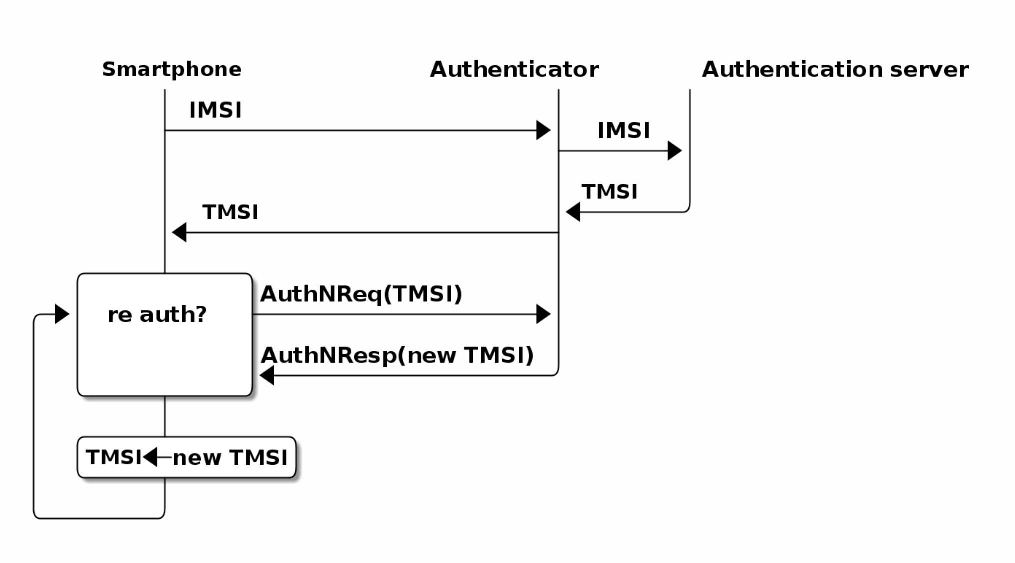

Figure 6.1 *Changing TMSI without the authentication server (or MNO)*

phones that are registering themselves to the operator when they are powering on. The fault lies in that the GSM specification does not require the mobile network to authenticate itself to the phone, and so GSM allows a man-in-the-middle attack. The attack follows when the IMSI-catcher impersonates itself as a (cellular) base station. When the smartphone tries to attach to the fake base station, the smartphone reveals its IMSI number. Further, because the base station is responsible for the chosen encryption, the base station can order the phone to not encrypt traffic at all or to use only weak encryption thus revealing all data, calls, and texts. Mitigation for IMSI-catching would be to disable GSM (2G) usage altogether from phone if that is possible [43]. Some development has been done to detect IMSI-catchers, most notably by the project AIMSICD [4].

Most EAP methods themselves do not provide identity protection, i.e., the end-user hiding. This feature can be achieved with PEAP (Protected EAP) or TTLS, which chains different EAP-methods together and protects the inner EAP with an outer EAP. The outer identity tells just the realm where AuthN can be checked, and the inner identity reveals the real identity. The inner identity is encapsulated inside the outer identity which functions as an envelope. For example, EAP-MSCHAPv2 (Microsoft's Challenge Handshake Authentication Protocol, version 2) can be used inside PEAP.

EAP-SIM would provide identity protection if it was used together with PEAP. There PEAP would anonymize the outer identification and EAP-SIM would be used in inner authentication. Currently, it is not known for the author that such an implementations exists for EAP-SIM, except for Tseng's proposition [45] for a new EAP type EAP-USIM, which would extend EAP-TLS type.

If it was possible to use anonymous identity on the outer EAP authentication, then EAP-SIM AuthZ would also have to be done at HLR AuC. AuthZ cannot otherwise be connected to the corresponding identity, and AuthN itself is not enough because it only defines the users' authenticity, not their admin roles. Thus, AuthN should work for any smartphone that has an existing contract with an MNO. It still is the responsibility of the authenticator to check AuthZ and let only admin mobile access the management network.

If SIM is used as the only EAP without EAP-PEAP, then there is no mitigation for revealing the IMSI on the first message, and this leads to a privacy issue. If there was an IMSI-catcher involved, only IMSI would be revealed. The other parameters or encryption are not in danger in EAP-SIM authentication, because EAP-SIM will stop the conversation if it does not receive the correct MNO authentication message. EAP-SIM protocol, like most of the other EAP-variants, provides a secure way to generate session parameters for a WPA2-session. These parameters are not leaked outside because they are created individually on both endpoints: at the smartphone and at the Authentication Server. Finally, the fact that the secret key Ki stays inside the SIM makes it difficult to attack the session by pretending to be the smartphone.

RADIUS messaging in the wire is vulnerable, too, because IMSI is transmitted in clear in EAP. IMSI is copied in to RADIUS's user-name attribute from the EAP's identity field. RADIUS runs over UDP, but can also be used with TCP. With TCP, RADIUS may use RadSec extension, which features TLS-based message encryption, integrity checking, and more advanced digesting functions than plain RADIUS. RadSec is also expandable and open for negotiating more secure ciphersuites that future versions of TLS might require [50]. This is more and more important today, as it already has been noted in 2005, that even SHA1 digesting has shown its weaknesses and can be manipulated. RADIUS servers usually support RadSec extension, but APs do not, so the part from the AP to RADIUS server will travel in plain unless secured otherwise.

Based on those facts, EAP-SIM cannot be considered confidential for identity during the first message exchanges, but later the identity can be hidden using temporal identity (TMSI). For other parameters, EAP-SIM is confidential. Thus, this paper considers TMSI only when using it for recurring authentication (re-auth) and offline cases in the implementation Chapter 5.

6.1.2 Integrity

The integrity issues were partly handled in Section 4.3 describing RADIUS message modification. Message digestion codes provide integrity for the RADIUS protocol. If PEAP is used, it handles integrity through its usage of TLS [33].

There is also a fraudulent authenticator problem, which is an attack against both the integrity and privacy. The authenticator may present some information to the authentication server and other to the EAP-peer. Mitigation for that would be that EAP-peer would include some characteristics of the authenticator inside its EAP-message, which the authentication server then would verify (RFC6677) [16].

6.1.3 Accessibility, DoS and scalability

Is a home network immune against (distributed) denial of service (DoS) attacks? Besides DoS, does the solution scale up from a home network to small and middle-size companies? To answer these questions, we must remember that backends (cloud and operator) are designed for thousands or even millions of users, so they hardly are limiting factors. Instead, the local authenticator is the one whose performance might suffer, which could happen because of processing loads [24].

Traditionally, RADIUS has used connectionless UDP protocol which is light-weight. Retransmission in UDP is tolerable because the user is ready to wait for several seconds for authentication to complete. Today, RADIUS can be also run over TCP, which generally has a more aggressive retransmission rate [31, Section 2.2.1]. UDP misses the reliability that TCP has, but adding an alternative UDP RADIUS server can make answering the requests faster than waiting for TCP RADIUS's reliable delivery.

6.1.4 RADIUS weaknesses and strengths in limited use cases

RADIUS protocol itself is old and not very secure as of current standards (2015) because messages are not encrypted and they are transported on datagrams (UDP). Alternative RADSEC protocol uses TLS, and is backwards compatible with RADIUS protocol, so it can be used as a secure RADIUS proxy such as *radproxy* [47].

The RADIUS protocol provides some integrity checks with Message Authenticators as described in Section 4.3. RADIUS uses MD5 hashing and shared secrets, but that is not enough. MD5 hashes were broken for the first time by brute force already 20 years ago, and today they can only be used as a data error detection tool [46, p.2]. If a malicious actor (Man-in-the-middle, MiTM) imitates a RADIUS proxy, it can try to inject false messages. Duplicate MD5-hashes (collisions) are easy to compute today (for example MD5Attack [9]) and researchers like Xie in 2013 [54] are even accelerating the speed for computing.

Because of the weaknesses of MD5 hashing, the transport needs additional protection like tunneling or IPsec. TLS can be used for encryption and its signatures for integrity checking of packet payload.

In scenario III (Figure 4.3), there was a proxying RADIUS between the authenticator and the MNO. When the MNO notifies the authenticator that a smartphone has been authenticated, then the authenticator (AP, functioning as a RADIUS-client) hooks that message and usually just grants the smartphone the access to the network. After giving access rights, other provisioning parameters can be sent with RADIUS messages, for example, a session time-out, a current admin user list, a state of OTP list, or a VLAN id.

6.1.5 Replay, re-use, re-auth, and brute-force challenges

Earlier, in RADIUS analysis, prevention of replied messages was mentioned. Reusing the same secret in different security context is also considered unsafe practise because mixing secrets between usage domains weakens the security. In GSM networks, IMSI identifies the subscriber on the first contact, and later TMSI is used for call and SMS. In EAP-SIM those values are also used. IMSI naturally is the same, but TMSI should be different for call and EAP. Haverinen [19] explains how special RAND numbers can be used to differentiate the use of TMSI in 3GPP and Wi-Fi contexts.

Re-authentication and termination can bring unexpected results. Even when sessions can be terminated, the client side may have the option of setting to login automatically, transparent and without the user's control. Automatic re-authentication after disconnection must be considered here as harmful, as well as automatic login near a suitable AP. An example of harmful behaviour was a case with the Swiss mobile operator Swisscom, which provided two networks, "Mobile" and "Mobile Eapsim" , for its customers. The latter network did not ask for the customers' permission for a connection each time, but used their smartphone's SIM automatically. Unfortunately, it also charged users for using Wi-Fi connections without users' knowledge [26].

Although a direct connection to SIM card's memory is restricted, if one can read and write data through the SIM card's API, one could still try to get information (SRES, Kc) by brute-force. Fortunately SRES and Kc are never sent in clear, but inside a digested MAC. Additionally, a SIM card can be programmed to answer only to a limited number of challenge requests, for example, 65,535 times. For normal use that would be enough, but in brute-force challenges it would soon be exhausted, and the SIM card would lock itself and not function anymore at all.

6.1.6 Hardware tampering

All this time it is assumed that hardware does not lie. In the case that the hardware has been tampered, we cannot trust its claims. For example, there have been attacks against SIM to reveal its private key after the SIM has been copied. To verify that a device has not been tampered with, a method called attestation can be used.

A device which has attestation capability such as hardware certificates or Trusted Platform Module (TPM) technology can function as a trust anchor. Such a device could be sent directly to the customer with pre-configured secrets and methods to take a place as a trust anchor. That leads us again to the key distribution problem.

6.1.7 Mitigation methods against radio capturing

To mitigate risks for radio capturing, two methods are presented: hiding of wireless network and proximity. They are not perfect, but can limit attack vectors in time and place.

Recall that the access to management network from the smartphone is needed only then when changes are made. Why then not just enable management radio network during those times? Then there would be fewer networks for users to choose from. Enabling management network could be programmed through LuCI-interface, which is a web user interface to the Unified Configuration Interface used in OpenWRT routers. Preliminary tests showed that activating new networks in an AP also disconnects the existing Wi-Fi connections and may even restart the AP, which certainly would not be wanted. Some other methods need to be invented to avoid denial-of-service when an intruder tries to connect by that method and causes continuous AP outages.

One could also think of hiding the network by disabling the advertisement of management network SSID. That is called "network cloaking". The smartphone would then need to know the exact target SSID name. Does disabling or hiding the management network bring real security, or is it just security by obscurity? Security by obscurity means here that hiding the network as a security method would filter out only some casual crackers, while at the same time it still is trivial for any serious crackers. Disabling or hiding merely gives one security layer more so it is not a real security method.

The SSID could also be always renamed, in essence to implement a one-time-only network, but then the smartphone would need to get that secret somewhere, perhaps via an SMS, and that would defeat the purpose of easy access. If that method nevertheless would be used, then hiding the one-time-only network name actually could add security. If the client knows beforehand the name of SSID (and maybe also checks AP's MAC), then AP does not reveal any information before the client has tried to connect to it, and that would minimize the time window for attacks. Because RFC5448 [7, p.12] forbids the change of the network name between full and fast authentication to prevent usage of compromised keys, the client and server should use full authentification when they notice that the network name has changed.

Hiding can also have privacy-enhancing effects. While a Wi-Fi client's normal action is to probe for SSIDs of lately visited and learned APs, anyone can analyze those probes and reveal the client's earlier locations without very much effort. Lindqvist et al. [25] present usage of hidden APs in protecting privacy of clients and preventing that scenario.

Regarding boundaries of home network, the Wi-Fi coverage gives one natural limit, which is 50 meters indoors or 100 meters outdoors, when no extenders (Wi-Fi repeaters) are in use. Proximity brings a minimal extra layer just like network cloaking for preventing attacks, as the attacker must be physically within those limits. This can be considered as an added factor in multifactor authentication or reputation, but it will not be enough, because attackers will have more sensitive radios available than normal users' devices have. In addition, if a SIM-profile was used through Bluetooth, there would also be range limits, but even shorter. Despite the claimed distance limits on Bluetooth, receiving can be extended up to one mile with a directed antenna [53].

6.2 Deployment difficulty and costs

To deploy the system, modifications must be made to the AP and the client. Additionally, a contract must be made with the MNO service provider producing AuthN.

The requirements for a home network can be as small as having a WPA2 Enterprise capable AP. Almost any AP will do, but as an exception, cable modem Bewan, which has been distributed to many homes by the cable modem operator Elisa, was found to have only WPA2-PSK mode. WPA2-enterprise setting involves configuring the IP-address of the RADIUS server providing AA and a corresponding shared secret. For the client, a Wi-Fi profile must be added: used management SSID, protection mode 802.1X (or WPA2-Enterprise), and AuthN method EAP-SIM. A smartphone can have different profiles, even with the same SSID, but then the user needs to choose manually which profile is wanted.

Additionally, the initial admin user's SIM card has to be registered as an admin user in some way in the home network configuration, i.e., the IMSI must belong to the admin group. In this implementation, no extra application is needed in the smartphone for primitive trust, but later, for more serious use, some application is needed. For added functionality, such as logging admins out, OpenWRT-based software can be used, although those functions have not yet been implemented.

While no such service is yet provided by MNOs, we estimate their costs based on Mobiilivarmenne. Using Mobiilivarmenne is currently free for clients if usage is personal, but costs for service providers are unknown. Hardware costs can mostly be eliminated because users already have smartphones and for the infrastructure, existing hardware such as APs can be used.

Using SIM for local Wi-Fi AA adds value to the smartphone ecosystem. To further divide possible costs for EAP-SIM usage is difficult. EAP-SIM always needs an MNO for the first authentication, because only the MNO and a SIM card manufacturer know the SIM's Ki and the used A3/A8 algorithm variation for GSM/3GPP/LTE authentication.

It is difficult to see if any commercial provider would implement the SIM key sharing so that the secret part would be divided into a part that implements AuthN for the user's own operator and into a part that is free to use by some other operator. Instead, the same functionality can be achieved with a dual-SIM phone, which allows inserting two SIM cards from different operators into the phone. By using a menu option in phone, or even a specific prefix code before a call, an alternate SIM card can be chosen without booting the phone. Dual-SIM thus allows change of identity and IMSI without removing the SIM card.

There also exist private GSM networks. An interesting use case of them are Chaos Computer Club's international CCC-camps [15], where the organizers provide a private GSM network for the attendees of the camp by distributing them separate

SIM cards for 2 euros. Even when a GSM network used 1.8GHz radio channel under an experimental spectrum license, GSM encryption could also be used, because the SIM card secrets were known to the organizing, private operator. On the other hand, empty GSM cards for testing can cost as much as 18 euros a piece [42].

6.3 Platform-specific issues

For clients, there is no need for public key infrastructure (PKI) unless EAP-PEAP is used. Under PEAP there is either a server certificate or an additional client certificate present. There are smartphones that do not have EAP-SIM available yet. For example, support for EAP-SIM (and -AKA) methods starts in Android only from version 4.x and in iOS from version 5.x. [22].

Generally, to support EAP-SIM with open source software in a smartphone, the needed components are *pcsc-lite* for accessing the SIM card, *wpa_supplicant* for WPA2 client, and possibly used connection manager (*connman*, *wicd*, or *Network Manager* in Linux). This is in line with what was done in testing without *pcsc-lite*, because a file backend was used instead of a SIM card.

If OpenWRT platform is used for CPE, the memory size (32MB) restricts some use. WPA2 software included in basic OpenWRT installation is small, but that does not yet include the RADIUS server part or EAP-SIM handling. Freeradius2 is not yet included in OpenWRT, and even if it was, it would also be heavily based on the current Perl environment which itself needs a lot of space. Currently, as of August 9th, 2015, Freeradius is running on version 3 and EAP-AKA is supported through a module from the hostapd project. COMP128 (versions 1, 2, and 3), which is an implementation of A3/A8 algorithms, is supported [11], and so EAP-SIM is available. Yet, Freeradius can be used as an Authentication Center (AuC). Diameter (freeDiameter) can be compiled in OpenWRT, which is good because Diameter protocol has more support on 3GPP networks than RADIUS has. If nothing else works, as a backup, an old-fashioned WWW-authentication portal can be used for offline authentication.

To enable EAP-SIM method, it is necessary to use the WPA2-Enterprise mode and, thus, RADIUS server, but at the same time, the existing Wi-Fi network at home usually has been set using WPA2-PSK. Because it was not found out how the authenticator could use the same network SSID for both WPA2-PSK (or open access) and WPA2-Enterprise, a separate SSID for dedicated management network was technically needed. Luckily, today's APs allow the setting of multiple SSIDs.

Nevertheless, if Wi-Fi was limited to only one SSID, then we would need another way to indicate that the user wants to get into the management network. Separation can be done, for example, at the client's end by using a different realm on AuthN identity. It can also be done by adding hints for a different destination to the username (username decoration) or by using a different authentication method. All these methods allow the Authentication Server to distinguish what the user wants to do; to get normal access to the home network, or to make a trust anchor claim to the management network.

If the Lock-and-key method was used instead of EAP-SIM RADIUS, then a separate management SSID would not be needed. Roles are given at authentication server or designated router after the smartphone has logged into it via the normal access network.

6.4 Usability with access points

There are three main types of wireless access points: open access points without configuration on the client's end, access points demanding one-time-only setup of a client such as WPA2-PSK or WPA2-Enterprise, and access points similar to a captive portal, where users on the first time have to login manually through webpage login. It is well known that the usability of the captive portal Wi-Fi network is a burden, because a user needs to go through a web portal login with a username-password authentication procedure, and those credentials are different for every network. Additionally, the users are often required to switch between cellular and Wi-Fi data access when they change their location, and that disrupts the network connection.

An industry brand Hotspot 2.0 (HS2.0) addresses those issues and tries to simplify the user's switch between Wi-Fi and cellular to automate the roaming experience. HS2.0 is driven by two alliances: Wi-Fi Alliance has a certification program (Passpoint) for HS2.0 compatible devices, while the Wireless Broadband Alliance has a program called Next Generation Hotspot (NGH), targeted to user experience [51].

HS2.0 enables the selection of the network based on the ownership, services and performance characteristics *before* a Wi-Fi client has been associated to a HS2.0 AP. The technology is built on IEEE 802.11u specification. In its second release version the operator will have control over which network the smartphone carries its data transmission.

Ericsson's technology journal "Review" revealed in 2012, that their HS2.0 goal is "to make roaming between Wi-Fi and 3GPP/LTE networks smoother and to bring operator-grade to Wi-Fi by putting control in operators side". More than offloading traffic, plans were to bring to Wi-Fi other services, too [39]. Developing HS2.0 a few steps further would add mobile traffic and internet off-loading onto Wi-Fi networks, and that would be the missing link in interworking those two worlds.

In HS2.0, the cellular network may signal the smartphone and propose it to switch to Wi-Fi. The smartphone then tries to find a HS2.0 capable access point and continue using Wi-Fi instead of the cellular network. In a similar way, the smartphone could receive a signal from the cellular network when controlling changes need to be approved. The smartphone would then make some tests to proof the local AP's suitability for HS2.0. If those succeed, then the cellular network would continue and order the phone to make a switch to the Wi-Fi network, authenticate there with EAP-SIM (or -AKA), and transfer services to Wi-Fi, not forgetting the transfer into the management network. This scenario could be studied further.

If HS2.0 was used here to automate the part where the smartphone needs to change from cellular to local management Wi-Fi network and back, we would probably miss the user decision part. The user, not the operator, must give his consent to access the management network, so it is important that the switch is not automatic or forced. In a way, operator aided roaming between Wi-Fi and cellular works on a different level than the trust-anchor method described here. The operator is interested in the access network, while we are interested in the side result of getting access, namely the achieved trusted access point.

6.5 Discussion

Although the core technology has been there for more than ten years and the hardware and the applications mostly support it, there can be many reasons why SIM-based methods are not in wider use. One can guess that the reasons are similar to what happened, for example, with WiMax technology, which was used for broadband network connections in rural areas. Technically, WiMax was good enough, but the demand was not so high. Additionally, lower speed technologies that were cheaper at the time, such as cellular modems, were thought to be sufficient, even when technically inferior. It could also be that the market is waiting for future products, and does not want to invest in existing technology, which can be seen as "old".

The SIM card of the smartphone, used together with Wi-Fi access to a home network, helps in verifying the changes, and for that we have presented some options. The location of AuthN and AuthZ components may vary depending on the state of the process. In the beginning, AuthN always lies outside the home network, but later it can also use a local point. AuthZ, on the other hand, may be located more freely.

Based on 802.1X standard, the management port is activated and RADIUS transfers the orders for the correct AA. The smartphone traffic is directed into its own virtual LAN segment (VLAN), which is dedicated to management. Thus, this thesis uses an old, yet simple method for solving a problem risen in a modern home network environment.

Disconnection from a normal (Wi-Fi) access network must happen before a phone can get into the management network. This means that all stateful network connections using Wi-Fi will close at that point. Smartphones do not have multiple wireless connections, but mobile data connections may stay up. Even then, the default routing in the smartphone may change.

By definition, EAP only performs the AuthN part, although the successful authentication often precedes ad hoc AuthZ if nothing else is demanded. EAP-SIM handles this part, but for AuthZ, something else is needed, and so some methods have been presented to add the right role to the authenticated identity.

In the design chapter (Chapter 4) it was questioned whether the proxying RADIUS server can read and alter the messages on their way or whether the messaging is secured by encryption, integrity hashes, and digital signatures. Later it was learned that the message's integrity is indeed protected, if only in a very light way, but not encrypted.

Altering or adding of RADIUS messages can be chosen from many attributes of RADIUS's vocabulary. They can carry extra information for provisioning in the AuthZ phase. Exactly which of them are used remains for the implementer to decide. The term *provisioning* can mean adding users to the home network with the correct attributes, such as authentication method and identification. It can also mean identifying users later and giving them more attributes and access rights dynamically. Linking a user to a SIM card is also provisioning, and that has been done earlier by the MNO.

Another problem using on-fly alteration of the AuthZ data in RADIUS ACCESS-ACCEPT message is the mapping between IMSI and TMSI identities. The authenticator does know the original user and the mapping of IMSI to TMSI, but needs AuthZ information. That can be received from the remote operator, which is easier for the authenticator, or there may be a proxying RADIUS, which resolves the AuthZ information and generates an ACCESS-ACCEPT packet. The latter, in turn, has issues with TMSI.

When a proxying RADIUS gets the temporary SIM-identity (TMSI) instead of a previously known IMSI identity, there will be a problem because the proxying RADIUS knows only the originating server for sure. The MNO in turn does not necessary know about the roles, and it can directly perform only AuthN.

It seems that AuthZ data must be mapped during the first phase of EAP-SIM AuthN, when IMSI still is available, and in some way that map must be forwarded to the proxying RADIUS servers. These issues are fully avoided only in scenario II presented in Chapter 4, where there is a local authentication server in home network. Partial avoidance can be reached if only full authentication is used, i.e., the authentication is always checked with the MNO and no fast re-authentication is used, thus eliminating the use of TMSI altogether.

6.6 Alternative management models

If we were to question or develop the given model of change propagation, the trust anchoring would also need some modifications. An alternative method is that the changes could be marked in some way, so that they need approval, and then there could be a specific change-approval message, which must be sent through the management network. That approval would be akin to *commit* in database actions, and its form could perhaps include a digest of change message as a verification. Because a smartphone is not actively listening to the CPE, it cannot input those request. Together with the chosen method, there are four planned methods to distribute changes. The first uses the smartphone as a direct commander and it is the one described throughout the thesis. The second would not involve a smartphone at all but would depend on earlier set trust. The remaining two methods would depend on more complex setups involving tokens, and are presented here just as ideas.

I) Changes are delivered from the cloud to the smartphone, which forwards them to devices located at the management network after the authentication has succeeded. This is the method chosen here and already explained.

II) Changes are delivered normally from the cloud to CPE (CPEs) without interaction with the smartphone. Such changes would not need AA at all, or changes would include credentials to login to targets. An example of a change is a modification in network segment, which does not change network topology of other domains. It is still unclear to the author which type of changes represents the majority of the requests: those that need approval, or those that may proceed without approval. An educated guess is that every change set needs to check the trust anchor's presence.

III) Besides AP, also CPE would have a direct connection to the cloud. Changes are then delivered from the cloud to the CPE functioning as a central management station without interaction with the smartphone. A digest of what is going to happen would be sent to the smartphone from the cloud over the air (OtA). The smartphone would authenticate into the management network (if not already there) and send through it the digest token it received from the cloud as an approval message to the central management station inside the home network, which would then forward the configuration changes to other devices.

IV) Variation of III is that when CPE itself is an authenticator, it could proceed on propagating changes when it receives ACCESS-ACCEPT. Otherwise it must timeout waiting for phone's AA and drop the received changes without forwarding them.

In the last two planned ways, the smartphone may receive the AuthN token with a message explaining what is going to happen in the change. As the CPE and the authenticator may be separate devices, approving happens by sending the token from the smartphone to the CPE via the management network where the authenticator gives access. Further, only the initial bootstrap as well as the change of admin roles and some dangerous combination of commands would need AA with the smartphone.

In the future, other components than the local controller might have a direct connection to the cloud. Scenario VI (Figure 6.2) is similar to Scenario I presented earlier, but now AuthZ is checked directly with the cloud by the CPE instead of the MNO. If there is no connection to the cloud, the fall-back is to work just like in Scenario II. So also this scenario needs a local store for caching admin IMSIs (roles).

6.7 Bootstrapping with and without PKI

Homenet WG proposes the use of Public Key Infrastructure (PKI) at home. The public key cryptography is processor intensive and its asymmetric keys are usually used just at the beginning of communication. There they can be used to securely negotiate symmetric keys, which allows faster cryptographic processing. The rest of this section discusses possible PKI usage.

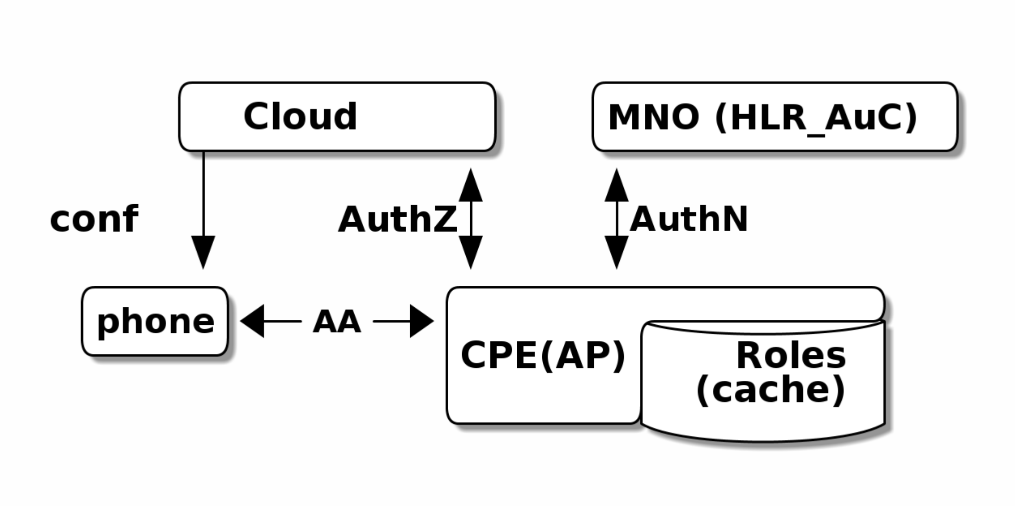

Figure 6.2 *Future, direct to Cloud connected CPE. AuthN comes from MNO*

To use PKI for trust anchoring and AuthN in an empty environment, bootstrapping protocols are first needed. The bootstrapping protocols in trust finding are used to bring the first trust anchor into an environment, and later use that anchor to attach other devices to the same trust circle.

Despite the etymology of the name bootstrapping “Lift oneself by one’s own bootstraps”, bootstrapping usually needs some input from the outside. For that, AuthN of the trust anchor device happens by checking the device’s vendor certificates. Behringer [8] proposes that one device at home should be first chosen as a trust anchor using its unique properties, and this anchored device should later become the home network’s Certificate Authority (CA) service. A smartphone would only play the user interface role, not the trust anchor role. The rest of the home network devices would apply for certificates from this trust anchor to get under the same trust circle. Key creation, key exchange, and their usage is explained in a similar draft from Pritikin [37].

This model could be expanded to a full ticket enabled AA, where time-limited tickets (tokens) for both AuthN and AuthZ exist for different services. There, the end devices first try to get an AuthN ticket, which does not yet include the AuthZ. With that ticket, the device may later apply for an AuthZ ticket, which opens the correct port to change management service from CPE. This is very similar to Kerberos AA, which is based on the Needham-Schroeder protocol. Another bootstrapping architecture is defined in GBA (General Bootstrapping Architecture) [1], which is a technical specification of 3GPP. It benefits from MNO’s or any other identity center’s knowledge of user’s SIM. In GBA, Trusted Third Party authentication center would be set up with the help of an MNO. One service would then authenticate an entity, here smartphone, and give it a time-limited ticket as a proof that the entity has been authenticated. When the entity wants to connect to the service, it again asks for a ticket from the central server, but this time for the service by presenting the authentication ticket. In return, it receives a service ticket which it can present to the desired service, which verifies the access based on the ticket.

As can be seen, no public key infrastructure (PKI) is used before the setup phase is ready. If EAP-SIM was applied in such an environment, it would be used only once, namely in the bootstrapping phase to set up the CA trust anchor. Only after that can the CA start delivering PKI. Kerberos needs shared keys, and EAP-SIM helps in providing those. The smartphone would hold a token with a validity time and would have to present that when accessing services, here the management network. The validity time would automatically disallow the management if applied after the allowed time has expired.

Trust can also be requested with the help of the device's other unique properties than SIM. Recently, devices with vendor-provided certificates inside them have appeared on the market. These bring public key infrastructure as one possible alternative for learning trusted identity. The device proves its identity by presenting a certificate which has been issued by a trusted vendor and which includes the device's public key. The private part of a key pair is inside the device's trusted hardware store and does not ever leave the hardware. Vendor trust is needed for checking the issued certificates, and so the trust verification of individual devices is merely transferred to trust verification of the vendor. Root CAs are also trust anchors and can be read in the same way from the device's read-only store. CPE could use a vendor-issued certificate for AuthN of some earlier unknown device.

7. CONCLUSION

The environment described in this thesis is modern complex home network management, whose configuration management tools are external in the cloud. The thesis concentrates on three main parts: the smartphone-driven authorization and authentication in home networks, the connection to the existing change management model from the external cloud service, and the security issues in that environment.

The trust issues between the home network and the cloud are searched through a smartphone located at the intersection of both domains. The home network's future needs, such as the change of the authority and the delegation of the configuration management, have been described. To solve those needs, a method to approve changes indirectly has been proposed. The approval follows from a successful authentication and authorization with EAP-SIM method by the smartphone, and that also sets a trust anchor to the smartphone.

For testing purposes, a real working EAP-SIM test bed with fake credentials and a fake mobile operator representing EAP-SIM authentication flow was built. A dual-role model, which binds the smartphone to the home network and grants it rights to make changes there, has been proposed. An indirect way to approve changes is achieved by linking the authorized access to the management network. After the authorization, the smartphone is free to configure the devices with its local application. Another way to convince the devices about a trusted source is to send approval tickets that can be verified on reception, but that would involve a more complex setup.

The complexity of the existing models in interworking was one motivator for the work. The research on the subject did reveal some reasons for the complexity that are difficult to overcome with simplistic methods shown here without losing security at the same time. There are some obvious weaknesses in the proposed solution, such as missing continuous authorization after management access has been granted. The application for the smartphone is yet to be fully implemented. Possible usage must carefully check the safety limits even when, for example, the RADIUS protocol still has strengths in security today. The thesis only scratches the surface of bootstrapping problems, and the issues in the home network bootstrapping need to be studied more thoroughly. One promising lead would be to use tickets in Kerberized way as in GBA.

Even though these shortcomings exist, the provisioning of manager users at home networks would still be minimized with the proposed technique, as the users already own a smartphone, which is an identifiable and trusted object. As a positive side effect, the two-factor AuthN from a hardware-based SIM would strengthen the existing security. Finally, the cloud management tools would benefit from the trust anchor on the smartphone and could be developed further to aid in resolving trust issues in future home networks.

REFERENCES

[1] "Generic Authentication Architecture (GAA); Generic Bootstrapping Architecture (GBA). TS 33.220"," 3GPP, Tech. Rep., 2014.

[2] B. Aboba, D. Simon, and P. Eronen, "Extensible Authentication Protocol (EAP) Key Management Framework," RFC 5247 (Proposed Standard), Internet Engineering Task Force, Aug. 2008. [Online]. Available: http://www.ietf.org/rfc/rfc5247.txt

[3] B. Aboba and J. Vollbrecht, "Proxy Chaining and Policy Implementation in Roaming," RFC 2607 (Informational), Internet Engineering Task Force, June 1999. [Online]. Available: http://www.ietf.org/rfc/rfc2607.txt

[4] AIMCID-community, accessed: 2015-09-02. [Online]. Available: https://github.com/SecUpwN/Android-IMSI-Catcher-Detector/wiki

[5] J. Arkko, A. Brandt, O. Troan, and J. Weil. (2014, Oct) "ipv6 home networking architecture principles". [Online]. Available: https://datatracker.ietf.org/doc/rfc7368/

[6] J. Arkko and H. Haverinen, "Extensible Authentication Protocol Method for 3rd Generation Authentication and Key Agreement (EAP-AKA)," RFC 4187 (Informational), Internet Engineering Task Force, Jan. 2006, updated by RFC 5448. [Online]. Available: http://www.ietf.org/rfc/rfc4187.txt

[7] J. Arkko, V. Lehtovirta, and P. Eronen, "Improved extensible authentication protocol method for 3rd generation authentication and key agreement (EAP-AKA')," RFC 5448 (Informational), Internet Engineering Task Force, May 2009. [Online]. Available: http://www.ietf.org/rfc/rfc5448.txt

[8] M. Behringer, M. Pritikin, and S. Bjarnason. Bootstrapping trust on a homenet. [Online]. Available: http://tools.ietf.org/id/draft-behringer-homenet-trust-bootstrap-02.txt

[9] M. Chiba, G. Dommety, M. Eklund, D. Mitton, and B. Aboba, "Dynamic Authorization Extensions to Remote Authentication Dial In User Service (RADIUS)," RFC 5176 (Informational), Internet Engineering Task Force, Jan. 2008. [Online]. Available: http://www.ietf.org/rfc/rfc5176.txt

[10] A. DeKok and A. Lior, "Remote Authentication Dial In User Service (RADIUS) Protocol Extensions," RFC 6929 (Proposed Standard), Internet Engineering Task Force, Apr. 2013. [Online]. Available: http://www.ietf.org/rfc/rfc6929.txt

[11] A. DeKok, “COMP128 implementation in FreeRADIUS,” accessed: 2015-05-10. [Online]. Available: https://github.com/FreeRADIUS/freeradius-server/blob/master/src/modules/rlm_eap/libeap/comp128.c

[12] W. Diffie and M. E. Hellman, “New directions in cryptography,” *Information Theory, IEEE Transactions on*, vol. 22, no. 6, pp. 644–654, 1976.

[13] “Chapter 3 - communication security: Remote access and messaging,” in *How to Cheat at Securing Your Network*, ser. How to Cheat, I. Dubrawsky, Ed. Burlington: Syngress, 2007, pp. 65 – 104,75. [Online]. Available: http://www.sciencedirect.com/science/article/pii/B978159749231750006X

[14] R. Enns, M. Bjorklund, J. Schoenwaelder, and A. Bierman, “Network Configuration Protocol (NETCONF),” RFC 6241 (Proposed Standard), Internet Engineering Task Force, June 2011. [Online]. Available: http://www.ietf.org/rfc/rfc6241.txt

[15] “GSM - 28C3 public wiki,” accessed: 2015-05-10. [Online]. Available: https://events.ccc.de/congress/2011/wiki/GSM

[16] S. Hartman, T. Clancy, and K. Hoeper, “Channel-Binding Support for Extensible Authentication Protocol (EAP) Methods,” RFC 6677 (Proposed Standard), Internet Engineering Task Force, July 2012. [Online]. Available: http://www.ietf.org/rfc/rfc6677.txt

[17] J. Hassell, *RADIUS*. O’Reilly, Oct 2002.

[18] H. Haverinen and J. Salowey, “Extensible Authentication Protocol Method for Global System for Mobile Communications (GSM) Subscriber Identity Modules (EAP-SIM),” RFC 4186 (Informational), Internet Engineering Task Force, Jan. 2006. [Online]. Available: http://www.ietf.org/rfc/rfc4186.txt

[19] H. Haverinen, “Interworking between wireless LAN and GSM/UMTS cellular networks: Network access control, mobility management and security considerations,” Ph.D. dissertation, Tampere University of Technology, 2004.

[20] homenet WG, “Home networking,” Jul 2011. [Online]. Available: http://datatracker.ietf.org/doc/charter-ietf-homenet/

[21] IEEE, “IEEE 802.1: 802.1X-2010 - Revision of 802.1X-2004,” 2010, accessed: 2015-05-10. [Online]. Available: http://www.ieee802.org/1/pages/802.1x-2010.html

[22] Infocomm Development Authority of Singapore, “SIM-based connection guide,” accessed: 2015-05-10. [Online]. Available: http://www.ida.gov.sg/Infocomm-Landscape/Infrastructure/Wireless/Wireless-at-SG/For-Consumer/SIM-based-Connection-Guide

[23] P. Levis, T. Clausen, J. Hui, O. Gnawali, and J. Ko, “The Trickle Algorithm,” RFC 6206 (Proposed Standard), Internet Engineering Task Force, Mar. 2011. [Online]. Available: http://www.ietf.org/rfc/rfc6206.txt

[24] S.-H. Lin, J.-H. Chiu, and S.-S. Shen, “Authentication schemes based on the eap-sim mechanism in gsm-wlan heterogeneous mobile networks,” in *INC, IMS and IDC, 2009. NCM ’09. Fifth International Joint Conference on*, "Aug" 2009, pp. 2089–2094.

[25] J. Lindqvist, T. Aura, G. Danezis, T. Koponen, A. Myllyniemi, J. Mäki, and M. Roe, “Privacy-preserving 802.11 access-point discovery,” in *Proceedings of the Second ACM Conference on Wireless Network Security*, ser. WiSec ’09. New York, NY, USA: ACM, 2009, pp. 123–130. [Online]. Available: http://doi.acm.org/10.1145/1514274.1514293

[26] F. Maissen, “Kostenfalle für Swisscom-Kunden,” accessed: 2015-05-04. [Online]. Available: http://www.srf.ch/konsum/themen/multimedia/kostenfalle-fuer-swisscom-kunden

[27] J. Malinen, “Linux WPA/WPA2/IEEE 802.1X Supplicant,” accessed: 2015-05-07. [Online]. Available: http://w1.fi/wpa_supplicant/

[28] “EAP - Moonshot Wiki,” accessed: 2015-05-10. [Online]. Available: https://wiki.moonshot.ja.net/display/Moonshot/EAP#EAP-HowMoonshotusesEAP

[29] M. Nakhjiri and M. Nakhjiri, *AAA and Network Security for Mobile Access - Radius, Diameter, EAP, PKI and IP Mobility.* Wiley, 2005.

[30] K. Narayan and D. Nelson, “Remote Authentication Dial-In User Service (RADIUS) Usage for Simple Network Management Protocol (SNMP) Transport Models,” RFC 5608 (Proposed Standard), Internet Engineering Task Force, Aug. 2009. [Online]. Available: http://www.ietf.org/rfc/rfc5608.txt

[31] D. Nelson and A. DeKok, “Common Remote Authentication Dial In User Service (RADIUS) Implementation Issues and Suggested Fixes,” RFC 5080 (Proposed Standard), Internet Engineering Task Force, Dec. 2007. [Online]. Available: http://www.ietf.org/rfc/rfc5080.txt

[32] OpenGroup. [Online]. Available: https://collaboration.opengroup.org/projects/jericho/

[33] A. Palekar, D. Simon, J. Salowey, H. Zhou, G. Zorn, and S. Josefsson, "Protected eap protocol (peap) version 2," Oct 2004. [Online]. Available: http://tools.ietf.org/id/draft-josefsson-pppext-eap-tls-eap-10.txt

[34] W. R. Parkhurst, *Cisco router OSPF.* McGraw-Hill, 1998.

[35] S. Patel, "Analysis of EAM-SIM session key agreement." [Online]. Available: https://www.ietf.org/proceedings/57/slides/eap-11.pdf

[36] F. Pereniguez, G. Kambourakis, R. Marin-Lopez, S. Gritzalis, and A. F. Gomez, "Privacy-enhanced fast re-authentication for eap-based next generation network," *Computer Communications*, vol. 33, no. 14, pp. 1682–1694, 9/1 2010.

[37] M. Pritikin, M. Behringer, and S. Bjarnason, "Bootstrapping key infrastructures," Tech. Rep., 2014, accessed: 2015-02-04. [Online]. Available: http://tools.ietf.org/id/draft-pritikin-bootstrapping-keyinfrastructures-01

[38] H. Rachidi and A. Karmouch, "A framework for self-configuring devices using tr-069," in *Multimedia Computing and Systems (ICMCS), 2011 International Conference on*, April 2011, pp. 1–6.

[39] S. Rayment and J. Bergström, "Achieving carrier-grade Wi-Fi in the 3GPP world," *Ericsson Review*, 2012, accessed: 2015-05-05. [Online]. Available: http://www.ericsson.com/res/thecompany/docs/publications/ericsson_review/2012/er-seamless-wi-fi-roaming.pdf

[40] C. Rigney, S. Willens, A. Rubens, and W. Simpson, "Remote Authentication Dial In User Service (RADIUS)," RFC 2865 (Draft Standard), Internet Engineering Task Force, June 2000, updated by RFCs 2868, 3575, 5080, 6929. [Online]. Available: http://www.ietf.org/rfc/rfc2865.txt

[41] B. Silverajan, J.-P. Luoma, M. Vajaranta, and R. Itäpuro, "Collaborative cloud-based management of home networks," in *Integrated Network Management (IM), 2015 IFIP/IEEE International Symposium on.* IEEE, 2015, pp. 786–789.

[42] "Smartjac TEST (U)SIM card webshop," accessed: 2015-05-10. [Online]. Available: http://www.smartjac.biz/webstore/samples-to-order/smartjac-test-sim-configurable-options

[43] D. A. Sokolov, "Digitale Selbstverteidigung mit dem IMSI-Catcher-Catcher," *C't*, Aug 2014, visited April 2015. [Online]. Available: http://heise.de/-2303215

[44] C. Sriharsha and S. Sandhya, “Role of DIAMETER stack protocol in IMS network architecture,” *IJITR*, vol. 3, no. 3, 2015. [Online]. Available: http://ijitr.com/index.php/ojs/article/view/642

[45] Y.-M. Tseng, “USIM-based EAP-TLS authentication protocol for wireless local area networks,” *Computer Standards & Interfaces*, vol. 31, no. 1, pp. 128 – 136, 2009. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0920548907001213

[46] S. Turner and L. Chen, “Updated Security Considerations for the MD5 Message-Digest and the HMAC-MD5 Algorithms,” RFC 6151 (Informational), Internet Engineering Task Force, Mar. 2011. [Online]. Available: http://www.ietf.org/rfc/rfc6151.txt

[47] S. Venaas, “radsecproxy,” accessed: 2015-04-22. [Online]. Available: https://software.uninett.no/radsecproxy

[48] R. Ward and B. Beyer, “Beyondcorp: A new approach to enterprise security,” *;login:*, vol. 39, No. 6, pp. 6–11, 2014. [Online]. Available: http://static.googleusercontent.com/media/research.google.com/fi//pubs/archive/43231.pdf

[49] J. Wey, J. Luken, and J. Heiles, “Standardization activities for IPTV set-top box remote management,” *Internet Computing, IEEE*, vol. 13, no. 3, pp. 32–39, May 2009.

[50] S. Winter, M. McCauley, S. Venaas, and K. Wierenga, “Transport Layer Security (TLS) Encryption for RADIUS,” RFC 6614 (Experimental), Internet Engineering Task Force, May 2012. [Online]. Available: http://www.ietf.org/rfc/rfc6614.txt

[51] Wireless Broadband Alliance, accessed: 2015-09-04. [Online]. Available: http://www.wballiance.com/key-activites/next-generation-hotspot/

[52] Wireshark community, “WLAN (IEEE802.11) capture setup.” [Online]. Available: https://wiki.wireshark.org/CaptureSetup/WLAN

[53] J. Wright, “"I Can Hear You Now - Eavesdropping on Bluetooth Headsets,” SANS, 2007, accessed: 2015-10-03. [Online]. Available: http://www.willhackforsushi.com/presentations/icanhearyounow-sansns2007.pdf

[54] T. Xie, F. Liu, and D. Feng, “Fast collision attack on MD5.” *IACR Cryptology ePrint Archive*, vol. 2013, p. 170, 2013.

APPENDIX A: SHELL, THAT STARTS PROGRAMS AND LOGS

```
#!/bin/sh -x
# Shell to start programs needed to demonstrate EAP-SIM
# authentication on simulated  PHONE and HLR AUC env.
# All used programs are from wpa (v2.3) reference package
# - wpa-supplicant
# - RADIUS-server
# - HLR-AuC
# External WPA2-RADIUS AP hardware is used
#
# options:
# -t more timestamps to xxx...
# -K include keydata to debug
# -dddd more debug
#
# usage:
#       ./apd [OPTION]...

# Variables
BASE=$HOME/gitdocs/di/testit
WPASUPPLICANT=$BASE/wpa_supplicant
HOSTAPD=$BASE/hostapd
HLR=$BASE/hlr_auc_gw
WPASUPPLICANTCONF=$BASE/wpa-simtest-owrt2.conf

# sim triplets, when EAP-SIM used
SIM=$BASE/hostapd.sim_db
#  Milenage parameters, when AKA used
MILENAGE=$BASE/hlr_auc_gw.milenage_db
# HOSTAPD parameters
# settings for hostapd include wired, eap_server, eap-handler
HOSTAPDCONF=$BASE/hostapd-jmdemo.conf
# timestamped logs and confs
TIMESTAMP=‘date +s%y%m%d-%H%M%S‘
TARGET=$BASE/demot/ap-$TIMESTAMP

mkdir $TARGET
cp $0 $HOSTAPDCONF $SIM $MILENAGE $TARGET
# reset and cleanup locks and sockets
pkill hlr_auc_gw; pkill wpa_supplicant; pkill hostapd
if [ -S /tmp/hlr_auc_gw.sock ] ; then
  rm -f /tmp/hlr_auc_gw.sock
fi
```

```
if [ -S ./eth0 ] ; then
  rm -f ./eth0
fi

### 1. HLR_AUC
# startup using SIM-triplet
# $HLR -g $SIM  >  $TARGET/hlr-debug &
# startup using MILENAGE. Works also with SIM
$HLR -m $MILENAGE > $TARGET/hlr-debug  &

### 2. HOSTAP (in RADIUS-EAP-handler mode)
ifconfig wlan0 up
# captures for RADIUS (wired, AP-RADIUS) and
# EAP (wireless, client-AP)
tshark -i eth0  -w $TARGET/eth0-pcap &
tshark -i wlan0 -w $TARGET/wlan0-pcap &
echo start hostapd
# start RADIUS in background
$HOSTAPD -Kdt $HOSTAPDCONF > $TARGET/hostapdwired-debug  &
echo "if␣$?␣==␣0␣then␣RADIUS␣server␣started␣ok"
sleep 1

### 3. WPA_SUPPLICANT
echo starting supplicant..
$WPASUPPLICANT -dK -iwlan0 -c $WPASUPPLICANTCONF \
        -D nl80211 > $TARGET/wpasupp-extapradius-debug &
### Live analysing
echo starting analyze..
cd $BASE/demot
cd ‘ls -d ap-*|tail -1‘/
sleep 1
# follow 3 log files, with color coding set in  multitail.conf
multitail -F ../multitail.conf -N 10000 -CS eap-sim -ts host*debug
   ↪ -i wpa*debug
# alternatively, start this in own window
# xterm -e $BASE/demot/anamulti &

# if tests take over  15 mins, user had fallen in sleep. Commit
   ↪ logs.
sleep 900
pkill tshark
git add $TARGET
git commit -m "apd-tty␣tests␣$TIMESTAMP␣"
```

APPENDIX B: WPA2-SUPPLICANT SETTINGS

```
# EAP-SIM with a GSM SIM or USIM
network={
  ssid="simtest"
  key_mgmt=WPA-EAP
  eap=SIM
  # If uncommented, the REAL SIM would be used instead of simulator
  # pin="1234"
  # pcsc=""
  identity="1232010000000000"    # IMSI. Can also be pseudonym
  password="90dca4eda45b53cf0f12d7c9c3bc6a89:
     ↪ cb9cccc4b9258e6dca4760379fb82581"
}

# credentials can also be presented on their own block. Not used
   ↪ here.
cred={
  imsi="1232010000000000"  # format should be <MCC> | <MNC> | ’-’ |
     ↪  <MSIN> ,
                           # i.e., 35840-123456789, so this would
                              ↪ not work.
  milenage="90dca4eda45b53cf0f12d7c9c3bc6a89:
     ↪ cb9cccc4b9258e6dca4760379fb82581"
}
```

APPENDIX C: RADIUS SERVER CONFIGURATION

```
# no wireless functionality here, only RADIUS/EAP
driver=none
# file for external AP RADIUS secrets
radius_server_clients=hostapd.radius_clients
# eap-handler enabled
eap_server=1
# mapping of eap credentials to SIM,AKA and AKA' protocols
eap_user_file=./hostapd.eap_user
# Inter-process communication with hlr_auc_gw process
eap_sim_db=unix:/tmp/hlr_auc_gw.sock
```

APPENDIX D: HLR_AUC_GW PROGRAM'S MILENAGE FILE

```
# Parameters for Milenage (Example algorithms for AKA).
# The example Ki, OPc, and AMF values here are from
# 3GPP TS 35.208 v6.0.0 4.3.20 Test Set 20.
# SQN is the last used SQN value. These values can be
# used for both UMTS (EAP-AKA) and GSM (EAP-SIM)
# authentication. In case of GSM/EAP-SIM, AMF and SQN
# values are not used, but dummy values will need to be
# included in this file.

# IMSI           Ki
   ↪ OPc                              AMF  SQN
232010000000000 90dca4eda45b53cf0f12d7c9c3bc6a89
   ↪ cb9cccc4b9258e6dca4760379fb82581 61df 000000000000
232010000000000 90dca4eda45b53cf0f12d7c9c3bc6a89
   ↪ cb9cccc4b9258e6dca4760379fb82581 61df 000000000001
232010000000000 90dca4eda45b53cf0f12d7c9c3bc6a89
   ↪ cb9cccc4b9258e6dca4760379fb82581 61df 000000000002
# e90
244052900226278 90dca4eda45b53cf0f12d7c9c3bc6a89
   ↪ cb9cccc4b9258e6dca4760379fb82581 61df 000000000003

# nokia e71, old found SIM card
244052161294281 90dca4eda45b53cf0f12d7c9c3bc6a89
   ↪ cb9cccc4b9258e6dca4760379fb82581 61df 000000000000
244052161294281 90dca4eda45b53cf0f12d7c9c3bc6a89
   ↪ cb9cccc4b9258e6dca4760379fb82581 61df 000000000001
244052161294281 90dca4eda45b53cf0f12d7c9c3bc6a89
   ↪ cb9cccc4b9258e6dca4760379fb82581 61df 000000000002

# These values are from Test Set 19 which has the AMF separation
# bit set to 1 and as such, is suitable for EAP-AKA' test.
555444333222111 5122250214c33e723a5dd523fc145fc0 981
   ↪ d464c7c52eb6e5036234984ad0bcf c3ab 16f3b3f70fc1
```