Efficient Authenticated Wireless Roaming via Tunnels

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Abstract. Wireless roaming means that a mobile device is able to switch from one network cell to another while keeping the link to active services. Recent researches [13] showed that it increases the security to establish an authenticated and confidential tunnel directly to a home network which then acts as service provider respectively proxy server for further external services. In this paper we extend the trust assumptions and formal security goals for *wireless roaming via tunnels* (WRT) that were given by Manulis et al.[7].

Additonally, we propose an efficient protocol that realizes the authentication and key agreement for establishing the secure tunnel, whereby considering the delay restrictions that are given by current multimedia services like VoIP or video streaming.

Furthermore we discuss the accounting problem and present a solution that ensures a fair accounting for the foreign network.

Keywords: Wireless networks, security, key agreement, mutual authentication, accounting.

1 Introduction

Wireless LAN is a very popular communication medium today, since it allows its users to be mobile while having access to all services they usually use in a wired LAN. Recent technologies like IEEE 802.11a/g/n also allow a very high bandwidth, so that the advantages from the wired alternative become smaller and smaller.

To let wireless LAN become even more attractive, the coverage has to be improved further on, so that everyone has everywhere access to his preferred services. Of course, it is not possible to realize a single wireless LAN that covers a whole city region. That means, it is necessary to work with several smaller wireless networks that may be operated by foreign network providers. Therefore a cooperation with foreign network providers is required.

There are three problems to solve:

1. When connecting to foreign wireless LAN providers, it is important to preserve the own security.
2. While switching between two wireless LAN cells, current running services like VoIP, video or audio streaming should not be affected.

3. The foreign wireless LAN provider clearly wants to get paid for the service he provides; that means, a fair accounting must be arranged.

Imagine a whole city covered with wireless nodes from private users. Most of them have a direct connection to the internet and are able to distribute their internet link over wireless LAN. There are several companies which want to provide seamless internet access in the whole city by using the given infrastructure. These companies offer an accounting model for all private users who share their internet connectivity, so that the companies' customers may use these internet links. The task is, to provide a network protocol that authenticates the companies' customers to the companies and offers fair accounting for the private users, that share their internet connection with the customers.

Sastry et. al [13] made a new proposal for the network structure that is needed for realizing a city-wide wireless LAN access. Shortly, they propose that a foreign network provider (in the following called $\mathcal{F}$) does only relay the traffic between the mobile node (called $\mathcal{M}$) and the home network (called $\mathcal{H}$) which then acts as a proxy server for all services the mobile node wants to access. The communication between the mobile node and the home network is protected by a confidential and authenticated tunnel to improve the security. The big advantage of this solution is that the risk for the misuse of the foreign network's internet link drops to zero, because all services (including internet access) are provided by the home network. The single purpose of the foreign network $\mathcal{F}$ is to relay the tunnel data between the mobile node $\mathcal{M}$ and the home network $\mathcal{H}$.

Nevertheless, Sastry et. al did not propose a concrete implementation for this solution.

Manulis et. al [7] extended this idea with a concrete secure authentication and key establishment protocol for three parties. This protocol accomplishes mutual authentication between $\mathcal{M}$, $\mathcal{H}$ and $\mathcal{F}$, $\mathcal{H}$, which is necessary for the secure communication and can later be used for accounting purposes also. Their proposed protocol is not optimized for efficiency in terms of roaming.

We propose a new network protocol that is optimized for roaming, even when multimedia services like VoIP or video streaming are in use. This can be reached by improving the efficiency in comparison to the proposed protocol by Manulis et. al. Furthermore, we present a protocol for accounting purposes so that a commercial scenario can be realized easily.

2   Our Roaming and Accounting Solution

Before we can go over to present our new protocols EAWRT (Efficient Authenticated Wireless Roaming via Tunnels) and WRA (Wireless Roaming Accounting), we have to define the environment for both protocols formally.

That is defining the protocol participants and the used key material (section 2.1), the identifiers for instances and protocol sessions in section 2.2, our trust assumptions (i.e. who trusts who) in section 2.3, the adversary abilities (section 2.4) and last but not least the building blocks (cryptographic primitives and abbreviations) of our protocols in section 2.5.

After that we present our roaming protocol (EAWRT) in section 3 and the accounting protocol (WRA) in section 4, giving proof sketches for the correctness as well as the security of the protocols.

2.1 Protocol Participants and Key Material

The protocol participants are namely the mobile device $\mathcal{M}$, a foreign network $\mathcal{F}$ and a home network $\mathcal{H}$. The user of the mobile device $\mathcal{M}$ has got a service contract with a home network $\mathcal{H}$, which gives him access to several provided services by $\mathcal{H}$, wherever an appropriate network infrastructure is given. An appropriate network infrastructure is realized through the nodes of the foreign network $\mathcal{F}$, that provide on the one side wireless access for all $\mathcal{M}$ and on the other side a fast link to the home network $\mathcal{H}$.

We assume, $\mathcal{M}$ and $\mathcal{H}$ are in possession of a common longterm key k_{MH} that is chosen with respect to the security parameter l.

For relaying data between $\mathcal{M}$ and $\mathcal{H}$, the foreign network wants to get paid. Therefore there is another contract between each foreign network $\mathcal{F}$ and home network $\mathcal{H}$. Because there may be a lot of different home networks and even more foreign networks, it is not efficient to provide a symmetric key between each foreign network and each home network.

For that reason, each foreign network $\mathcal{F}$ and home network $\mathcal{H}$ own a Diffie-Hellman public key pair $\{SK, PK\}$ which is chosen with regard to the security parameter l.

2.2 Instances and Protocol Sessions

The number of the mobile devices $\mathcal{M}$, foreign networks $\mathcal{F}$ and also home networks $\mathcal{H}$ may be very big, so it is likely that the same $\mathcal{F}$ *or* $\mathcal{H}$ (*or* even $\mathcal{M}$) are participants in several parallel protocol sessions. We want to extend this by saying that it is possible that there are different protocol sessions with the same $\mathcal{M}$, $\mathcal{F}$ *and* $\mathcal{H}$. The number of parallel protocol sessions is denoted as q (later used in the security analysis).

We claim that there is an unlimited number of instances of $\mathcal{M}$, $\mathcal{F}$ and $\mathcal{H}$, whereby denoting an instance as $\mathcal{X}_s$ with $\mathcal{X} \in \{\mathcal{M}, \mathcal{F}, \mathcal{H}\}$ and $s \in \mathbb{N}$. Three instances $\mathcal{M}$, $\mathcal{F}$ and $\mathcal{H}$ are called partnered when they have the same session id $SID := H, AID_M, F, r_H, r_M, r_F$ whereby H, AID_M, F are the identifiers of $\mathcal{H}$, $\mathcal{M}$, $\mathcal{F}$ and r_H, r_M, r_F are randomly chosen nonces of each participant.

An instance of $\mathcal{H}$, $\mathcal{M}$, $\mathcal{F}$ in a protocol session calls ACCEPT or ABORT upon the decision if the protocol execution was successful in respect to the protocol aims.

2.3 Trust Assumptions

Before protocol execution, the mobile device $\mathcal{M}$ and the home network $\mathcal{H}$ share some credentials that allow them to do a mutual authentication, which is necessary for establishing a trusted communication tunnel. Since $\mathcal{H}$ provides a service

for $\mathcal{M}$, both parties must have a contract with each other, including on the one hand credentials and on the other hand rules for accounting and usage.

The foreign network $\mathcal{F}$ is responsible for the relay of the tunnel data between the mobile device $\mathcal{M}$ and the home network $\mathcal{H}$. Mutual authentication between $\mathcal{F}$ and $\mathcal{H}$ is required, because the foreign network $\mathcal{F}$ clearly wants to get paid for the forwarding service it provides and must therefore be aware of $\mathcal{H}$'s identity. Additionally the home network $\mathcal{H}$ wants to be sure about $\mathcal{F}$'s identity to realize a fair payment. Furthermore sharing credentials between $\mathcal{F}$ and $\mathcal{H}$ to support the accounting process may be necessary.

The mobile device $\mathcal{M}$ will be implicitly authenticated against the foreign network $\mathcal{F}$ due to the fact that $\mathcal{H}$ accepts in the protocol. The same applies for the foreign network $\mathcal{F}$ against $\mathcal{M}$, because the mobile device $\mathcal{M}$ is assured that $\mathcal{H}$ would not have been accepted when the authentication between $\mathcal{F}$ and $\mathcal{H}$ had failed.

2.4   Adversarial Model

The adversary $\mathcal{A}$ is modelled as a probabilistic polynomial time (PPT) machine and has full control over the communication and protocol invocations. $\mathcal{A}$ is allowed to do the following queries:

- **Invoke($\mathcal{X}$, m).** Upon this query, a new instance $\mathcal{X}_s$ of $\mathcal{X} \in \{\mathcal{M}, \mathcal{F}, \mathcal{H}\}$ is created. Message m is sent to the new instance, whereby the answer is directed to the adversary $\mathcal{A}$.
- **Send($\mathcal{X}_s$, m).** This query sends a message m to $\mathcal{X}_s$. When $\mathcal{X}_s$ has completed processing m, the response is sent back to $\mathcal{A}$. With the help of this query, $\mathcal{A}$'s control over the communication channel is modeled, since $\mathcal{A}$ is able to stay passive by honestly forwarding each message or to become active by modifying m or even injecting a new message.
- **Corrupt($\mathcal{X}$).** As response to this query, $\mathcal{A}$ gets the longterm key of $\mathcal{X}$. That is k_M for $\mathcal{M}$, SK_F for $\mathcal{F}$ and $\{SK_H, k_M \ \forall \mathcal{M}\}$ for $\mathcal{H}$. When $\mathcal{X}$ becomes corrupted, all instances $\mathcal{X}_s$ of $\mathcal{X}$ become corrupted too.
- **RevealKey($\mathcal{X}_s$).** If $\mathcal{X}_s$ has already accepted, the adversary $\mathcal{A}$ gets the session key as response to this query. The session key between $\mathcal{M}$ and $\mathcal{H}$ is k_{MH}, whereas the session key between $\mathcal{F}$ and $\mathcal{H}$ is denoted as k_{FH}.
- **TestKey($\mathcal{X}_s$).** The adversary may query **TestKey()** to an accepted instance of a session. The instance $\mathcal{X}_s$ chooses a random bit b and answers with a random value on $b = 0$ and with the session key $\{k_{MH}, k_{FH}\}$ on $b = 1$.

2.5   Building Blocks

Now, we itemize the cryptographic primitives that are used by the proposed protocols EAWRT (Fig. 1) and WRA (Fig. 2).

- A *cryptographic hash function* that provides preimage, second preimage and collision resistance [11]. Hash: $\{0,1\}^* \rightarrow \{0,1\}^l$. By $\mathrm{Succ}_{\mathrm{Hash}}^{\mathrm{preimage}}(l)$ we denote

the success probability for a PPT adversary to find a preimage for a given output $\in \{0,1\}^l$ of the hash function. $\mathrm{Succ}_{\mathrm{Hash}}^{\text{2nd-preimage}}(l)$ denotes the success probability for a PPT adversary to find a second preimage $\in \{0,1\}^*$ for a given preimage-hash pair $\in \langle\{0,1\}^*, \{0,1\}^l\rangle$.

– A *message authentication code* (MAC) that suffices the weak unforgeability against chosen message attacks (WUF-CMA) [4]. $\mathrm{Succ}_{\mathrm{MAC}}^{\text{wuf-cma}}(l)$ denotes the success probability over all PPT adversaries to find a MAC forgery under access to the MAC oracle. A MAC is verified with $\mathrm{ver}_{\mathrm{key}}(\text{value})$.

– A *pseudo random function* PRF: $\{0,1\}^l \times \{0,1\}^* \to \{0,1\}^*$ for key derivation. We denote the maximum advantage over all PPT adversaries (running within time l) in distinguishing the outputs of PRF from the outputs of a random oracle better than $\mathrm{Pr}=\frac{1}{2}$ by $\mathrm{Adv}_{\mathrm{PRF}}^{\mathrm{prf}}(l)$.

– A *symmetric encryption scheme with integrity protection* that suffices the indistinguishability property under adaptive chosen ciphertext attacks (IND-CCA2) [2]. We denote the advantage that an adversary is able to decrypt (dec) at least one bit without knowing the used key as $\mathrm{Adv}_{\mathrm{DEC}}^{\text{ind-cca2}}(l)$.

Furthermore, the symmetric encryption scheme satisfies weak unforgeability against chosen message attacks. The adversary's success probability to encrypt (enc) without the right key and gaining a valid ciphertext is $\mathrm{Succ}_{\mathrm{ENC}}^{\text{wuf-cma}}(l)$.

– A static *diffie-hellman key agreement* over a finite cyclic group, where the decisional diffie hellman (DDH) problem is strong. By $\mathrm{Adv}_{\mathrm{DH}}^{\mathrm{ddh}}(l)$ we denote the advantage over all PPT adversaries to recognize a valid DH tuple.

– A *digital signature scheme* that provides existential unforgeability under chosen message attacks (EUF-CMA). The signing operation is denoted by $\mathrm{sig}_{SK_?}$ and the according verification operation by $\mathrm{ver}_{PK_?}$. The maximum success probability over all PPT adversaries of finding a forgery is represented by $\mathrm{Succ}_{\mathrm{SIG/VER}}^{\text{euf-cma}}(l)$.

– A set of *database operations*: **lookup(AID_M)** searches for the given index AID_M and returns the corresponding identity ($\mathcal{M}$). **add()** inserts a new assignment: $AID_M \to \mathcal{M}$.

– A set of *verification functions*: **validate** and **verify**. **validate** checks, if a value is within a logical range. The range may be of length one (an expected value). **verify** is used, when the expected value must be cryptographically computed, e.g. when the expected value must be hashed.

3   Roaming Protocol (EAWRT)

In the following, we propose a new protocol for the wireless roaming via tunnels scenario. We introduce a more efficient protocol than Manulis et al. by abandoning on digital signatures and asymmetric encryption. Due to this, we have smaller messages and we need less computation time. Additionally we support anonymity of the mobile device.

The EAWRT protocol is shown in Figure 1. $\mathcal{M}, \mathcal{F}, \mathcal{H}$ are the identities of the participants and AID_M is the anonymous identity of $\mathcal{M}$.

$SK_i = i$, $PK_i = g^i \mod p$ are the private respectively public diffie-hellman parameter for $i \in \{F, H\}$. In detail (but not shown in the figure), there is also a big prime p that conforms to the security level l and a base g that generates $\mathbf{Z}_p^*$.

Mobile Device $\mathcal{M}$	Foreign Network $\mathcal{F}$	Home Network $\mathcal{H}$
$\{k_M, AID_M\}$	$\{SK_F := f, PK_F := g^f\}$	$\{k_M : \forall \mathcal{M}, AID_M :$
		$\forall \mathcal{M}, SK_H := h, PK_H := g^h\}$

$r_M \in_R \{0,1\}^l$ $r_F \in_R \{0,1\}^l$ $r_H \in_R \{0,1\}^l$
$tk_{FH} := PK_H^{SK_F}$ $tk_{FH} := PK_F^{SK_H}$

$\mathcal{H}, AID_M, r_M \longrightarrow$ $AID_M, r_M, \mathcal{F}, r_F \longrightarrow$

$lookup(AID_M) \to \mathcal{M} \vee ABORT$

$SID := \mathcal{H}, AID_M, \mathcal{F}, r_H, r_M, r_F$
$k_{MH} := PRF_{k_M}(SID)$
$k_{FH} := PRF_{tk_{FH}}(SID)$
MAC-1 $:= MAC_{k_{MH}}(SID|l_1)$
$E_F := enc_{k_{FH}}(r_F, \text{MAC-1})$

$\longleftarrow r_H, E_F$

$SID := \mathcal{H}, AID_M, \mathcal{F}, r_H, r_M, r_F$
$k_{FH} := PRF_{tk_{FH}}(SID)$
$\langle r_F', \text{MAC-1} \rangle := dec_{k_{FH}}(E_F)$
$validate(r_F') \to ACCEPT \vee ABORT$

$\longleftarrow \mathcal{F}, r_F, r_H, \text{MAC-1}$

$SID := \mathcal{H}, AID_M, \mathcal{F}, r_H, r_M, r_F$
$k_{MH} := PRF_{k_M}(SID)$
$ver_{k_{MH}}(\text{MAC-1}) \to ACCEPT \vee ABORT$

$AID_M := PRF_{k_{MH}}(\mathcal{M})$
MAC-2 $:= MAC_{k_{MH}}(\text{MAC-1}|l_2)$

MAC-2 $\longrightarrow$ MAC-2 $\longrightarrow$

$ver_{k_{MH}}(\text{MAC-2})$
$\to ACCEPT \vee ABORT$

$AID_M := PRF_{k_{MH}}(\mathcal{M})$
$add(AID_M \to \mathcal{M})$

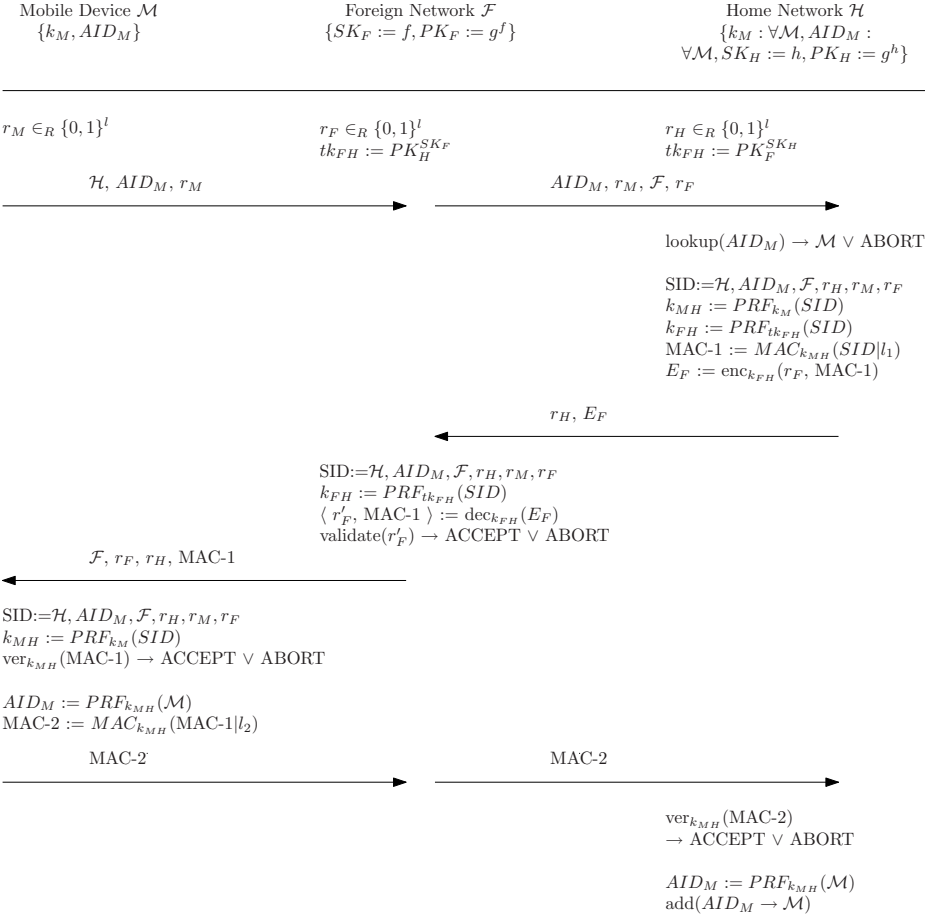**Fig. 1.** Efficient Authenticated Wireless Roaming via Tunnels (EAWRT)

3.1 Correctness of EAWRT

The authentication and key establishment protocol Π (Figure 1) is correct, when definition 1 holds.

Definition 1 (Correctness EAWRT). *In the presence of a passive adversary, Π is correct when all parties $\mathcal{M}$, $\mathcal{F}$ and $\mathcal{H}$ have accepted and the key k_{MH} between $\mathcal{M}$ and $\mathcal{H}$, as well as the key k_{FH} between $\mathcal{F}$ and $\mathcal{H}$ is identical on both sides.*

Proof (sketch). The key k_{MH} is computed as $PRF_{k_M}(SID)$, whereby k_M is a shared key between $\mathcal{M}$, $\mathcal{H}$ and SID is the session identifier (consisting of all participant identifiers and all participant nonces). As proof statement we state that k_{MH} is identical on both sides, if both parties are partnered in the protocol session and share the same key k_M.

The key k_{FH} is computed as $PRF_{tk_{FH}}(SID)$, whereby tk_{FH} is a static Diffie-Hellman key between $\mathcal{F}$, $\mathcal{H}$ and SID is the session identifier. If both instances are partnered in the protocol session, the public key of the other party is known and $PK_H^{SK_F} \equiv PK_F^{SK_H}$, then k_{FH} is identical on both sides.

The combination of both statements gives an idea for the correctness proof of EAWRT.

3.2   Security Definitions for EAWRT

Now we state the security goals that have to be achieved between the mobile device $\mathcal{M}$, the foreign network $\mathcal{F}$ and the home network $\mathcal{H}$. Between $\mathcal{M}$ and $\mathcal{H}$ mutual authentication, integrity and confidentiality is required. These goals can be obtained by using symmetric cryptographic methods based on key material which is agreed on both sides. Non-repudiation is not explicitly required, which leads to the fact that no asymmetric cryptography is necessary.

Definition 2 (Mutual Authentication between $\mathcal{M}$ and $\mathcal{H}$). *$\mathcal{A}$ wins if one of the following arises during the protocol run:*

1. *An uncorrupted instance of $\mathcal{M}$ accepts with a corrupted partnered instance of $\mathcal{H}$*
2. *An uncorrupted instance of $\mathcal{H}$ accepts with a corrupted partnered instance of $\mathcal{M}$*
3. *After having accepted, both uncorrupted partnered instances $\mathcal{M}$ and $\mathcal{H}$ hold a different session key k_{MH}.*

Definition 3 (Authenticated Key Exchange between $\mathcal{M}$ and $\mathcal{H}$). *Given a uniformly chosen bit b, a PPT adversary $\mathcal{A}$ interacts with a correct protocol Π, whereby it is not allowed for $\mathcal{A}$ to query **RevealKey()** to an accepted instance or to corrupt an instance. $Game_{\Pi}^{ake-\mathcal{M}-\mathcal{H}}(\mathcal{A}, l)$ is defined as the following interaction:*

1. *$\mathcal{A}$ interacts with instances of $\mathcal{M}$, $\mathcal{F}$, $\mathcal{H}$ without using the **RevealKey()** and **Corrupt()** query*
2. *$\mathcal{A}$ asks **TestKey()** to an instance of $\mathcal{M}$ or $\mathcal{H}$ and gets, dependent on b, a random value chosen from $\{0,1\}^l$ (if $b = 0$) or k_{MH} (if $b = 1$)*
3. *After further interaction, $\mathcal{A}$ terminates and outputs a bit b'*

$\mathcal{A}$ wins $Game_{\Pi}^{ake-\mathcal{M}-\mathcal{H}}(\mathcal{A}, l)$ if $b' = b$. The maximum probability of the adversarial advantage over the random guess of b, over all adversaries (running in time l) is

$$Adv_{\Pi}^{ake-\mathcal{M}-\mathcal{H}}(\mathcal{A},l) = \overset{max}{\mathcal{A}} \ |2Pr[Game_{\Pi}^{ake-\mathcal{M}-\mathcal{H}}(\mathcal{A},l) = b] - 1|.$$

Definition 4 (Mutual Authentication between $\mathcal{F}$ and $\mathcal{H}$). *$\mathcal{A}$ wins if one of the following arises during the protocol run:*

1. *An uncorrupted instance of $\mathcal{F}$ accepts with a corrupted partnered instance of $\mathcal{H}$*
2. *An uncorrupted instance of $\mathcal{H}$ accepts with a corrupted partnered instance of $\mathcal{F}$*
3. *After having accepted, both uncorrupted partnered instances $\mathcal{F}$ and $\mathcal{H}$ hold a different session key k_{FH}*

Definition 5 (Authenticated Key Exchange between $\mathcal{F}$ and $\mathcal{H}$). *Given a uniformly chosen bit b, a PPT adversary $\mathcal{A}$ interacts with a correct protocol Π, whereby it is not allowed for $\mathcal{A}$ to query **RevealKey()** to an accepted instance or to corrupt an instance. $Game_{\Pi}^{ake-\mathcal{F}-\mathcal{H}}(\mathcal{A}, l)$ is defined as the following interaction:*

1. *$\mathcal{A}$ interacts with instances of $\mathcal{M}$, $\mathcal{F}$, $\mathcal{H}$ without using the **RevealKey()** and **Corrupt()** query*
2. *$\mathcal{A}$ asks **TestKey()** to an instance of $\mathcal{F}$ or $\mathcal{H}$ and gets, dependent on b, a random value chosen from $\{0,1\}^l$ (if $b = 0$) or k_{FH} (if $b = 1$)*
3. *After further interaction, $\mathcal{A}$ terminates and outputs a bit b'*

$\mathcal{A}$ wins $Game_{\Pi}^{ake-\mathcal{F}-\mathcal{H}}(\mathcal{A}, l)$ if $b' = b$. The maximum probability of the adversarial advantage over the random guess of b, over all adversaries (running in time l) is

$$Adv_{\Pi}^{ake-\mathcal{F}-\mathcal{H}}(\mathcal{A},l) = \overset{max}{\mathcal{A}} \; |2Pr[Game_{\Pi}^{ake-\mathcal{F}-\mathcal{H}}(\mathcal{A},l) = b] - 1|.$$

Definition 6 (Anonymity of $\mathcal{M}$). *This goal protects the anonymity of $\mathcal{M}$ by hiding the real identity of $\mathcal{M}$ towards $\mathcal{F}$ and all protocol outsiders. A PPT adversary $\mathcal{A}$ wins if one of the following occurs, after $\mathcal{M}$ and $\mathcal{H}$ have accepted:*

1. *$\mathcal{A}$ knows the real identity of $\mathcal{M}$*
2. *$\mathcal{A}$ knows if an instance of $\mathcal{M}$ has participated in a previous accepted session*
3. *$\mathcal{A}$ recognizes an instance of $\mathcal{M}$ when it participates in a next session*

3.3   Proof Sketches for the Security of EAWRT

Having all definitions and assumptions in place, we proceed proving the security of the EAWRT protocol. To give a full security proof, we need to show that the protocol accomplishes the security goals from definition 2 to 6. Due to lack of space we only give short proof sketches and refer to [10] for the full security analysis of EAWRT.

Theorem 1 (Mutual authentication between $\mathcal{M}$ and $\mathcal{H}$). *With a WUF-CMA secure MAC, the protocol Π of EAWRT provides mutual authentication in the sense of definition 2 and*

$$Succ_{EAWRT}^{MA-\mathcal{M}-\mathcal{H}}(l) \leq \frac{3q^2}{2^l} + 2Succ_{MAC}^{wuf\text{-}cma}(l).$$

Proof (sketch). The advantage of the adversary can be reduced to the collision of the three nonces r_M, r_F, r_H (within q sessions) and the adversary's probability successfully forging MAC-1 or MAC-2.

Theorem 2 (Authenticated Key Exchange between $\mathcal{M}$ and $\mathcal{H}$). *With a pseudo random function and a WUF-CMA secure MAC, the protocol Π of EAWRT provides authenticated key exchange in the sense of definition 3 and*

$$Succ_{EAWRT}^{AKE-\mathcal{M}-\mathcal{H}}(l) \leq \frac{3q^2}{2^l} + 2Succ_{MAC}^{wuf\text{-}cma}(l) + 2qAdv_{PRF}^{prf}(l).$$

Proof (sketch). The advantage of the adversary can be reduced to the collision of the three nonces r_M, r_F, r_H, the adversary's probability successfully forging MAC-1 or MAC-2 and the success probability of distinguishing k_{MH} from a random value in all q sessions.

Theorem 3 (Mutual Authentication between $\mathcal{F}$ and $\mathcal{H}$). *With a WUF-CMA secure MAC, the protocol Π of EAWRT provides mutual authentication in the sense of definition 4 and*

$$Succ_{EAWRT}^{MA-\mathcal{F}-\mathcal{H}}(l) \leq \frac{3q^2}{2^l} + Succ_{ENC}^{wuf\text{-}cma}(l) + qAdv_{DEC}^{ind\text{-}cca2}(l).$$

Proof (sketch). The advantage of the adversary can be reduced to the collision of the three nonces r_M, r_F, r_H and the adversary's probability successfully forging an encryption E_F. Additionally, if the adversary is able to extract one bit of information out of E_F, it is possible to create a distinguisher that breaks the IND-CCA2 security. The advantage of breaking the IND-CCA2 security (q parallel sessions) is added to the success probability of the adversary.

Theorem 4 (Authenticated Key Exchange between $\mathcal{F}$ and $\mathcal{H}$). *With a static Diffie-Hellman and a IND-CCA2 secure symmetric encryption, the protocol Π of EAWRT provides authenticated key exchange in the sense of definition 5 and*

$$Succ_{EAWRT}^{AKE-\mathcal{F}-\mathcal{H}}(l) \leq \frac{3q^2}{2^l} + qAdv_{DH}^{ddh}(l) + qAdv_{DEC}^{ind\text{-}cca2}(l) + 2qAdv_{PRF}^{prf}(l).$$

Proof (sketch). The advantage of the adversary can be reduced to the collision of the three nonces r_M, r_F, r_H, the secrecy of tk_{FH} breaking the decisional Diffie-Hellman assumption, the security of E_F by beeing able to extract one bit of information about k_{FH} (IND-CCA2) and at last the pseudo randomness of k_{FH} due to beeing able to predict a random value for the used pseudo random function (PRF).

Theorem 5 (Anonymity of $\mathcal{M}$). *With a pseudo random function PRF, the protocol Π of EAWRT provides anonymity of $\mathcal{M}$ in the sense of definition 6 and*

$$Succ_{EAWRT}^{anonymity}(l) \leq \frac{3q^2}{2^l} + qAdv_{PRF}^{prf}(l).$$

Proof (sketch). he advantage of the adversary can be reduced to the collision of the three nonces r_M, r_F, r_H and the pseudo randomness of AID_M.

Combining the previous five theorems, we state security of EAWRT according to the defined security goals.

4   Accounting Protocol (WRA)

We extended the model of Manulis et al. by the need for a fair accounting. To realize that, we propose the WRA protocol, which is an extension to the normal tunnel communication between the mobile device $\mathcal{M}$ and the home network $\mathcal{H}$. Additionally to the tunnel data, which is represented by MSG and MSG2, we have added some cryptographic measures to ensure that the foreign network $\mathcal{F}$ is able to proof, how many data was relayed. As consequence, the foreign network $\mathcal{F}$ is able to bring this size of transmitted data to account, whereby neither $\mathcal{H}$ nor $\mathcal{F}$ is able to cheat.

The home network $\mathcal{H}$ acknowledges the size of the transmitted data to F via two mechanisms. Firstly as an absolute value of the transmitted bytes in a

Mobile Device $\mathcal{M}$ $\{k_{MH}\}$	Foreign Network $\mathcal{F}$ $\{k_{FH}\}$	Home Network $\mathcal{H}$ $\{k_{MH}, k_{FH}\}$

MSG $\quad\longrightarrow$

$B := \#$ transmitted bytes
$E_H := \mathrm{enc}_{k_{FH}}(B)$

$\qquad\qquad$ MSG, $E_H \quad\longrightarrow$

$B := \mathrm{dec}_{k_{FH}}(E_H) \wedge$
validate$(B) \rightarrow$ ACCEPT
$\vee$ ABORT

IF $(B \geq Base + n)$ THEN
$x \in_R \{0,1\}^l$;
$Base := B$;
$\forall\, 0 < i \leq n$:
$\quad Coin_i := \mathrm{Hash}^{n-i}(x)$;
$SIG := \mathrm{sig}_{SK_H}(B, Coin_0, SID)$
END IF

$COINS := Coin_{(B-Base)}$
$MAC := MAC_{k_{MH}}(\mathrm{MSG2}, COINS)$

$\longleftarrow \quad$ MSG2, COINS, MAC $[, SIG]$

validate(COINS) $[\wedge\ \mathrm{ver}_{PK_H}(SIG)\,]$
$\rightarrow$ ACCEPT $\vee$ ABORT

$\longleftarrow \quad$ MSG2, COINS, MAC $[, SIG]$

$\mathrm{ver}_{k_{MH}}(MAC) \wedge$
validate(COINS) $[\wedge\ \mathrm{ver}_{PK_H}(SIG)\,]$
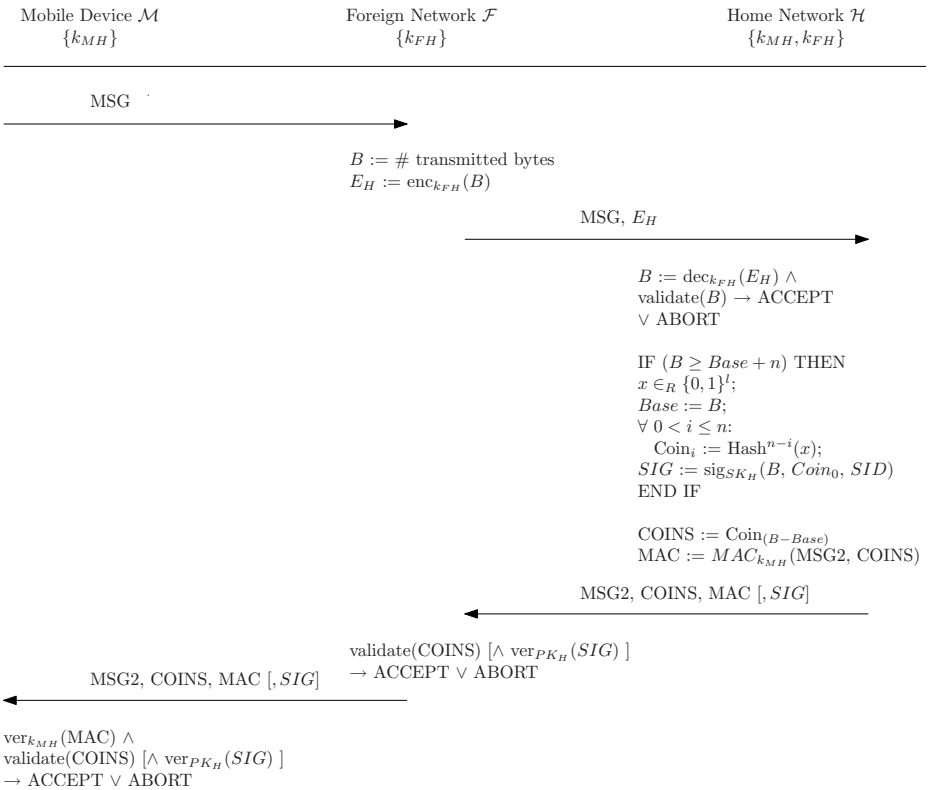$\rightarrow$ ACCEPT $\vee$ ABORT

Fig. 2. Wireless Roaming Accounting protocol (WRA)

digital signature. Secondly as an element of a hash chain, representing a value relative to the last digitally signed value.

Figure 2 shows the WRA protocol. The size of the used hash chain is denoted by n. B is the number of transmitted bytes, whereby $Base$ is the last digitally signed value of B.

4.1   Correctness of WRA

The accounting protocol is correct when definition 7 holds.

Definition 7 (Correctness WRA). *In the presence of a passive adversary, Π is correct when $\mathcal{M}$, $\mathcal{F}$ and $\mathcal{H}$ have accepted and are sure that the partnered instances hold the same value B, containing the transmitted data volume.*

Proof (sketch). We give an idea for the correctness proof of WRA in the following. If all parties have accepted, it is left to show that all parties have the knowledge of the same value B in the presence of a passive adversary. B can be represented by several values: B, COINS and SIG. $\mathcal{H}$ sends COINS with a corresponding MAC in the third message, $\mathcal{F}$ forwards these values in the fourth message. If these values have arrived at $\mathcal{M}$ and $\mathcal{M}$ accepts, it is obvious that all parties hold the same value for B.

The correctness of WRA can be proven with these considerations.

4.2   Security Definitions for WRA

Between $\mathcal{F}$ and $\mathcal{H}$ mutual authentication is required for accounting. Both sides have to be sure about the identity of the other party, so that one side can account its provided service and the other side will accept the issued bill. Integrity protection and maybe confidentiality are necessary to protect the accounting data communicated between $\mathcal{F}$ and $\mathcal{H}$.

Definition 8 (Fair Accountability). *In order to guarantee fair accountability, the foreign network $\mathcal{F}$ needs a non-repudiative acknowledgement over the size of the data, that was forwarded.*

By demonstrating this acknowledgement, the foreign network $\mathcal{F}$ can prove, how much data was relayed (at least), whereby nor the mobile device $\mathcal{M}$ neither the home network $\mathcal{H}$ are able to deny this. $\mathcal{A}$ wins if one of the following arises during the protocol run:

1. *An uncorrupted instance of $\mathcal{F}$ or $\mathcal{M}$ accepts an acknowledgement over the transmitted bytes (COINS/SIG) that was not created by $\mathcal{H}$*
2. *An uncorrupted instance of $\mathcal{F}$ or $\mathcal{M}$ accepts an invalid or replayed acknowledgement over the transmitted bytes (COINS/SIG)*

4.3 Proof Sketch for the Security of WRA

The WRA protocol fulfills the fair accountability property according to definition 8. Due to lack of space we only present a proof sketch here. The full proof of this theorem can be found in [10].

Theorem 6 (Fair Accountability of WRA)). *Given a EUF-CMA secure digital signature scheme and a cryptographic hash function, the fair accountability property of WRA (definition 8) can be broken with a probability of*

$$Succ_{WRA}^{FA}(l) \leq \frac{1}{m} Succ_{SIG/VER}^{euf\text{-}cma}(l) + nSucc_{Hash}^{preimage}(l) + Succ_{MAC}^{wuf\text{-}cma}(l).$$

Proof (sketch). Given the appearance probability of SIG as $\Pr[\text{SIG occurs}] := \frac{1}{m}$ with $1 < m \leq n$ and n the length of the used hash chains. The adversary's advantage can be reduced to forging (EUF-CMA) a signature SIG, appearing with the probability $\frac{1}{m}$, the forgery of COINS to a higher value by finding any valid preimage (maximum n) for a given value and the success probability of forging the value MAC (WUF-CMA).

5 Efficiency of EAWRT and WRA

In comparison with the WRT protocol from Manulis et al. [7], the EAWRT protocol has some obvious advantages in respect to performance, since we abandon digital signatures and asymmetric encryption. Due to this, we have notably smaller sized messages and less computation time needed. Particulary for mobile devices this approach fits good, because their computation power respectively battery power is limited.

Moreover, we are able to improve the performance from EAWRT even more by applying some precomputations. The computation of tk_{FH}, the static diffie-hellman key, is computational expensive but has to be done only one time for all protocol instances with the same $\mathcal{F}$ and $\mathcal{H}$. So, this key can be computed at the first contact between $\mathcal{F}$ and $\mathcal{H}$ and then stored for later use.

After the last message of the EAWRT protocol, $\mathcal{H}$ verifies MAC-2 by comparison with a self-computed MAC-2. This computation can be done earlier to save time. The verification MAC-2 can be computed by $\mathcal{H}$ right after sending out his message $\langle r_H, E_F \rangle$, while waiting for the last message of the protocol.

Our accounting protocol (WRA) works like an addon to the normal communication (MSG, MSG2). To each message, only one hash value (COINS) and one MAC value is added (in total 256-512 bits). Additionally, everytime our hash chain runs out of preimages, a digital signature setting a new root for the hash chain is appended.

Since digital signatures need a big amount of space (usually 1024-4096 bits without canonicalization) and computation time, it is desirable to abandon them as long as possible. Therefore the length of the hash chain n should be chosen in respect to efficiency.

6   Conclusion

In this paper, we introduced two new properties for the wireless roaming via tunnels scenario. At first, the anonymity property, which allows the user of the mobile device to stay anonymous for outsiders (including the foreign network) while roaming. This includes the unlinkability of two different sessions.

The second property is named fair accounting, which has a special meaning for this scenario. It is necessary for the foreign network, which forwards the tunnel data between the mobile device and the home network, that the home network approves the size of the transmitted data. Since the foreign network wants to get paid for relaying, the home network's confirmation of the size of the transmitted data must be non-repudiative, in other words: signed. In dispute, the foreign network can present the signatures and demand the payment.

We have presented an optimized AWRT protocol (named EAWRT), that fulfills the requirements proposed by Manulis et al. [7]. Additionally, our protocol has the anonymity property *and* is designed to be more efficient. Notably the efficiency of our protocol is important, since we want to allow near realtime services like VoIP or video chats even in roaming cases.

Moreover we showed up a solution for the accounting problem by introducing another protocol named WRA. This protocol attaches some cryptographic values to the normal communication flow and can thereby enforce fair accounting without too much overhead.

For both introduced protocols there is a full security analysis in [10].

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