Security and Resilience for TAGA: a Touch and Go Assistant in the Aerospace Domain

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Abstract—There is currently a drive in the aerospace domain to introduce machine to machine communication over wireless networks to improve ground processes at airports such as refuelling and air conditioning. To this end a session key has to be established between the aircraft and the respective ground unit such as a fuel truck or a pre-conditioning unit. This is to be provided by a ‘touch and go assistant in the aerospace domain’ (TAGA), which allows an operator to pair up a ground unit and an aircraft present at a parking slot with the help of a NFC system. In this paper, we present the results of our security analysis and co-development of requirements, security concepts, and modular verification thereof. We show that by, and only by, a combination of advanced security protocols and local process measures we obtain secure and resilient designs for TAGA. In particular, the design of choice is fully resilient against long-term key compromises and parallel escalation of attacks.

I. INTRODUCTION

Machine to machine (M2M) communication over wireless networks is increasingly adopted to improve speed, efficiency and accuracy of service and maintenance processes at airports, ports, and manufacturing plants. This does not come without security challenges: often these processes are safety-critical, and often, multi-instance attacks against them would disrupt critical infrastructures. One example are the ground processes at an airport. When an airplane has landed and reached its parking slot at the apron many processes such as refuelling and air conditioning are performed. These processes determine the turnaround time, i.e. the time an airplane needs to remain parked at the apron. Most ground operations that require a control loop are currently based on human-to-human communication, i.e. an operator at the ground machine and another in the aircraft. M2M communication between the ground unit and the aircraft will simplify such ground operations. Moreover, the use of wireless connections is a must-have due to the harsh conditions of the apron and increased flexibility.

Hence, there is ongoing activity on how to integrate secure M2M communication between ground units and an aircraft during turnaround. It is planned to use IEEE 802.11 WLAN as wireless channel, and to secure the data exchanged by AES-CCMP analogously to WPA2. However, the challenge remains of how to set up a session key securely in this setting where one party is mobile, the other is at different locations, and there is no notion of global trust.

A use case within the project XXX is currently underway that advocates a touch and go assistant in the aerospace domain (TAGA) to solve this challenge. The idea behind TAGA is that a key can be established by pairing a ground unit and an aircraft both present at the same parking slot based on their proximity — a bit similar to pairing a bluetooth device to a vehicle infotainment system but over a greater distance and truly secure. To this end, each aircraft and ground unit is to be equipped with a TAGA controller that contains a secure element for cryptographic operations and an NFC reader (accessible from an outside control panel). Moreover, the operator of each ground unit is to be provided with a passive NFC card. Altogether, this allows them to transport messages for key establishment from the ground unit, to the aircraft, and back by means of taps with the NFC card against the respective NFC reader. The ‘TAGA walk’ can conveniently be integrated into the operator’s usual path to the aircraft and back while connecting up the respective supply hose.

The advantage of such local key establishment is that there is no need to exchange the identities of the airplane and ground units beforehand, and that there is no need for a central trusted party that provides for key management. Thereby the flexibility and trust assumptions of the current paper- and human-based ground processes can be maintained. However, in contrast to local pairing of infotainment devices, TAGA is safety-critical and the design must be amenable to formal verification to meet current safety and security norms in the aerospace domain.

Our Contribution: We have conducted a security analysis and co-developed security and resilience requirements, security concepts, and a modular verification pattern of how to establish that the requirements are met by a security concept. We have also provided informal proofs of all our results. To our knowledge this is the first systematic analysis, design space exploration, and verification method for local key establishment. We hope the results can also serve as a blueprint for other settings of M2M communication. In more detail, our contributions are:

1) We concisely define the TAGA use case, and show how it can be integrated into current processes for air conditioning and fuelling. We make precise which overall guarantee the setup of a ground service with M2M communication must meet. We also provide an interface to safety analysis by identifying five categories of attacks, what potential safety impact they can cause, and which preconditions concerning key establishment the attacker has to reach to mount them. Throughout it becomes clear: While, as usual, it is crucial
that the established key remains secret from the attacker a new challenge critical to key establishment for M2M communication is that the key is indeed shared between the parties that are (or will be) physically connected.

(2) We explore whether we can obtain secure plain TAGA, where the underlying key establishment (KE) protocol is unauthenticated, and hence, does not require any PKI. It is well-known that such protocols cannot be secure against active adversaries but that, like the Diffie-Hellman key exchange, they can guarantee security in the presence of passive adversaries. Hence, the challenge lies in whether we can implement the TAGA transport in a way so that it provides an authentic message exchange. We show that this is indeed possible but it comes at a cost, which involves key management local to the airport, distance bounding the communications of the readers, and a high dependence on ground staff. On the positive side, our designs for plain TAGA come with the advantage that they ensure resilience against parallel escalation of attacks.

(3) We investigate authenticated TAGA (a-TAGA), which is based on an authenticated KE (AKE) protocol and PKIs governed locally by airports, and airlines respectively. It is well-known that AKE protocols can securely establish a key in the presence of active adversaries. We show that it is straightforward to implement secure a-TAGA when we relax the definition of security in a way that only guarantees location agreement rather than alignment with the operator’s TAGA walk. The new definition still enables the correct setup of ground processes. However, we are faced with another challenge now: Our setting requires that a-TAGA must be highly resilient against long-term key compromises (LTKC).

We identify three notions of LTKC resilience and show how each can be met by a combination of advanced properties of AKE protocols and local process measures.

Altogether, we obtain several designs that are secure and resilient. The design of choice combines a-TAGA with an authentic local channel, and is fully resilient against LTKCs and parallel escalation of attacks. The remainder of the paper is structured according to the three parts. Related work can be found in App. A and the notation we use for KE protocols is explained in App. B. The proofs are provided in the remainder of the appendix.

II. GROUND SERVICES WITH M2M COMMUNICATION

A. The TAGA Use Case

1) Actors and Setting: TAGA pairing takes place when an aircraft (AC) A has its turnaround at an airport H. Then A is parked at a parking slot L of H, and a secure zone is established around A, to which only authorized personnel have access. When a ground unit (GU) is to provide a ground service S to A then the operator Op of G carries out TAGA pairing as part of setting up the GU for the service. To this end, each AC and GU is equipped with a NFC reader, and the operator holds a passive NFC card. By means of NFC taps with the card the operator can transfer messages for key establishment from the GU to the AC and back. Once TAGA pairing is successfully concluded A and G share a session key for secure M2M communication on service S over WLAN.

One AC can perform the TAGA process with several GUs in parallel, and one service might require several GUs. However, each card, operator, and GU are involved in at most one TAGA process at a time. Each AC is owned by an airline A, and each GU is governed by an airport H. It is usual that an airport H does not operate the ground services itself, but has entrusted an airport service provider P with the handling thereof. Each AC and GU is equipped with a controller that computes the TAGA functionality. The controller is equipped with the NFC reader and a secure element, which supports secure key storage and cryptographic operations for key management.

2) TAGA Pairing Process: TAGA pairing is based on a three-pass key establishment (KE) protocol, where the third
pass is a key confirmation step. It is illustrated in Fig. 2 for the case when the Diffie-Hellman (DH) key exchange is used as the underlying protocol. Let $A$ be the AC, $G$ be the GU, and $Op$ be the operator of $G$.

**First message pass.** $Op$ initiates TAGA by an initial NFC tap with her NFC card $C$ at $G$’s controller. Thereby the first message $M_1$ is written to the card. $M_1$ contains information necessary for establishing the key together with the ID of $G$ and the service $S$ that $G$ wishes to provide. $Op$ carries $M_1$ stored on $C$ to the AC. There she carries out a mid NFC tap, during which message $M_1$ is transferred to $A$’s controller.

**Second message pass.** The AC checks whether the connection should be granted. In the positive case, $A$ generates message $M_2$, which is written onto the NFC card, also during the mid NFC tap. $M_2$ contains information necessary for establishing the key together with the ID of $A$ and access data to $A$’s WLAN such as the SSID. It also contains a ciphertext to grant key confirmation to $G$. The operator then carries the card with $M_2$ back to $G$. There she transfers $M_2$ from the card to $G$’s controller by a final NFC tap.

**WLAN and third message pass.** $G$ is now able to connect to $A$’s WLAN. A third message is passed over the WLAN connection to achieve key confirmation to $A$.

3) **Ground Services with TAGA:** We explain the process flow for air conditioning with secure M2M communication, and TAGA pairing integrated into the setup phase. Examples for fuelling with one and two trucks are provided in App. C.

The process flow for air conditioning is shown in Fig. 3. During the setup phase TAGA pairing is naturally integrated into the path that the operator needs to trace for the physical setup. First, the operator performs the first NFC tap at the pre-conditioning unit, and then walks to the AC carrying the air supply hose. After he has connected the hose to the AC’s supply port the operator performs the second NFC tap at the AC, and then walks back to the pre-conditioning unit. There he performs the third NFC tap, and switches on the air supply.

The pre-conditioning unit and AC are now ready to carry out the actual air conditioning during the M2M phase. First, the unit sends a request to receive data from the AC. This e.g. includes the desired temperature, the airflow parameters suitable for the AC, and readings of temperature sensors. The physical process is then controlled by the pre-conditioning unit based on temperature readings continuously communicated from the AC. When the desired temperature is reached the unit notifies the AC, and the service enters the disconnect phase. During this final phase the communication session is closed, and the operator disconnects the supply hose.

**B. Correct Setup of Ground Services**

The setup of a ground service must guarantee that the AC and each of the participating GUs are both physically connected as well as linked by a secure cyber channel. We now make precise this guarantee, based on definitions of secure channel and process flow for a ground service.

1) **Cyber Connection and Secure Channel:** A (cyber) connection owned by a GU or AC for (M2M communication on) service $S$ is defined by a tuple $(cid, DP, K, S)$ where $cid$ is the identifier of the connection, $DP$ is a data confidentiality and integrity protocol (such as AES-CCMP), and $K$ is a session key (such as established by TAGA). Hence, two parties that own matching connections can exchange data on $S$ over the connection $cid$ transformed by $DP$ using $K$ as the key. We say a GU $G$ and an AC $A$ share a secure channel for (M2M communication on) service $S$ if $G$ and $A$ both own a connection $(cid, DP, K, S)$ such that (1) $DP$ is secure, and (2) $K$ is freshly generated and only known to $G$ and $A$. When $DP$ and $cid$ are clear from the context we also write $(K, S)$ for a secure channel.

2) **Process Flow for a Ground Service:** A process flow $F$ for a ground service $S$ (with M2M communication) is a tuple $(n_F, A_F, P_F)$, where $n_F$ specifies the number of required GUs, $(A_F, P_F)$ is a partial order of actions to be carried out by the participating actors (GUs, AC, operators, perhaps crew), and $P_F$ is a multiset of parking positions relative to the AC such that $P_F$ is of size $n_F$. $P_F$ specifies where the $n$ GUs are parked during the process (e.g. [right wing, left wing] or [mid, mid]). We require $P_F$ to be a multiset rather than a set since a service can involve several GUs at one relative position, and
in practice it is important to avoid unnecessary precision (such as defining sub-positions). Given GUs $G_1, \ldots, G_n$ such that each $G_i$ is located at the same parking slot, we denote the multiset of their relative positions by $pos\{\{G_1, \ldots, G_n\}\}$.

We assume the actions of each participant are divided into a setup phase, a M2M phase, during which the actual service is carried out, and a disconnect phase. We require that $(A_F, <_F)$ guarantees: (1) A ground coordinator ensures that exactly $n_F$ GUs for service $S$, say $G_1, \ldots, G_{n_F}$, are at the parking slot such that $pos\{\{G_1, \ldots, G_{n_F}\}\} = P_F$. (2) When, in the view of an operator $Op$, the setup phase is completed then the GU $Op$ operates is physically connected up for service $S$ to $A$. (3) When, in the view of a GU $G$, the setup phase is completed then $G$ has a cyber connection for service $S$. (4) When, in the view of an AC $A$, the setup phase is completed then $A$ has exactly $n_F$ cyber connections for service $S$.

3) Correct Setup of Ground Service: Let $L$ be a parking slot, on which a turnaround process takes place. We denote the one AC that is present at $L$ by $AC(L)$. Let $F$ be a process flow for service $S$. We say $F$ guarantees Correctness of Setup to a GU $G$ if, whenever $G$ engages into the M2M phase of $F$ at a parking slot $L$ then

1) $pos\{\{G\}\} \in P_F$ and $G$ is physically connected for service $S$ to $AC(L)$, and

2) $G$ shares a secure channel for service $S$ with $AC(L)$.

We say $F$ guarantees Correctness of Setup to an AC $A$ if, whenever $A$ engages into the M2M phase of $F$ at a parking slot $L$ then there are $n_F$ GUs $G_1, \ldots, G_{n_F}$ at $L$ with $pos\{\{G_1, \ldots, G_{n_F}\}\} = P_F$ such that

1) $A$ is physically connected for service $S$ to and only to the GUs $G_1, \ldots, G_{n_F}$, and

2) $A$ shares a secure channel for service $S$ with and only with each of the GUs $G_1, \ldots, G_{n_F}$.

We say $F$ guarantees Correctness of Setup if it guarantees this to both, GUs and ACs.

C. M2M Attack Categories and Safety Impact

Let $L$ be a parking position, $A$ be the AC at $L$, and $G_S$ a GU to provide service $S$ at $L$. Assume the attacker intends to cause harm at $L$ by undermining the M2M communication between $A$ and $G_S$. There are five categories of attacks the attacker can aim for. Each category comes with different preconditions he needs to achieve first. We say the attacker has reached a state from which he can mount a ...
Example 4 (Fuelling with two trucks). Assume fuelling with two trucks is carried out. Assume the truck under the left wing is already connected (both physically and in cyber) while the truck under the right wing is still being set up and the fueller currently opens the tank. Now assume that by an Imp2AC attack the attacker pretends the right truck is also fully set up. Then (in the case of automatic control) the AC will open the fuel valves, order fuel, and the left truck will start pumping fuel. However, the right operator is at the open tank, and a highly unsafe situation has been reached.

d) Imp2GU with Mismatch Diversion: When an attacker mounts a Imp2GU attack it might be beneficial for him to divert the AC by matching it up with another GU. One reason is to thereby ensure that the impersonation attack remains undetected for longer; another reason is that without a successful session the AC might not be affected at all, perhaps because it controls a valve that it will not open otherwise.

Example 5 (Fuelling). When fuelling the pilot has to open the valves of the tanks before the fuel flow can start. Hence, as long as A does not have a successful session for fuelling the Imp2GU attack will be detected early on: the fuel pump of GS will stop almost immediately due to backflow. However, if the attacker conducts a ‘location mismatch of AC attack’ in parallel then A will open the fuel valves, and the attacker can make GS load fuel based on a forged order. Fortunately, in this case there is no safety impact as explained in Example 2.

e) Location Mismatch of GU: We have just seen that mismatch attacks can be used as a diversion. The next example illustrates that they can be safety-critical in their own right.

Example 6 (Air Conditioning). Let A’ be an AC at another parking position L’ with ongoing air conditioning service. Assume A’ is a large plane (e.g. an A380), and A is a smaller plane (e.g. an A319). Moreover, assume the attacker has obtained the state for location mismatch of GS where GS is speaking to A’. Hence, A’ will communicate its parameters for airflow to GS while GS’s air supply hose is connected to the smaller A. Since the airpacks of A are smaller than those of A’ airflow parameters suitable for A’ can be damaging for A: the air pressure is likely to be too high and the cooling process too fast. As a consequence pipes of A can be damaged as explained in Example 1.

f) and g) Service Mismatch: A service mismatch will likely be noticed as soon as M2M communication starts. The messages will not follow the protocol the AC, and respectively GU expects, and hence errors will be raised: e.g. the AC provides temperature readings while the GU expects a fuel order. However, a service mismatch could still be employed as a diversion to support another attack: when the only goal is that the party to divert has established a channel for the service (because only then it will open a valve), or when the service is such that there usually is a delay between the point when the channel is established and the start of the M2M communication.

III. PLAIN TAGA

1) Preliminaries:
NFC System, Sessions, and Taps: An NFC system (for T AGA) is a triple \( N = (R_{GU}, C, R_{AC}) \), where \( R_{GU} \) is the reader at the GU, \( C \) is the NFC card, and \( R_{AC} \) is the reader at the AC. We assume readers are equipped with a status display.

An NFC data exchange session (NFC ssn) is an event \( \delta \) of a reader or card \( D \), during which \( D \) establishes an NFC link with another party, say \( D' \), exchanges data with \( D' \) (in the view of \( D \)), and then closes the link. If \( D \) encounters an error during any of these steps then \( \delta \) is unsuccessful otherwise it is successful. In the latter case, we denote \( \delta \) by \( \text{partner}(\delta) \), and the trace of received and sent messages by \( \text{msg}(\delta) \). Often the data exchange will consist of a pair of messages \( m_r \) and \( m_s \) such that \( m_r \) is received by \( D \) and \( m_s \) is sent by \( D \). We denote \( m_r \) by \( \text{msg}_r(\delta) \) and \( m_s \) by \( \text{msg}_s(\delta) \). If \( D \) is a reader it will signal on its display whether an NFC ssn has been completed successfully or not (e.g. green or red light).

An NFC tap is an event \( \tau \) of an actor \( O \), during which \( O \) brings a card \( C \) close to a reader \( R \) and verifies whether \( R \) displays that it has completed an NFC ssn successfully. We say \( \tau \) is successful if \( O \) observes a positive confirmation, and unsuccessful otherwise. We denote \( \gamma \) by \( \text{card}(\tau) \) and \( R \) by \( \text{reader}(\tau) \).

Given an NFC tap \( \tau \) of an actor \( O \) and an NFC ssn \( \gamma \) of a reader \( R \), we say \( \tau \) and \( \delta \) coincide when \( \text{reader}(\tau) = R \) and \( O \) perceives the feedback that \( \delta \) displays upon completion of \( \tau \) as the reply to his tap \( \tau \). We then write \( \tau \approx \delta \). Note that when \( \tau \) and \( \delta \) coincide it is a priori not given that \( R \) has indeed communicated with \( \text{card}(\tau) \), even when \( R \) confirms a successful exchange. Given NFC tap or ssn events \( \epsilon_1, \epsilon_2 \), we write \( \epsilon_1 < \epsilon_2 \) when \( \epsilon_1 \) occurs earlier in time than \( \epsilon_2 \).

TAGA Process and Sessions: A concrete TAGA process is defined by a triple \( T = (P, N, M) \), where \( P \) is a KE protocol, \( N \) is a NFC system, and \( M \) is a set of process measures.

A (TAGA) session of a GU \( G \) is a tuple \( (S, \gamma_{ini}, \gamma_{fin}, K) \), where \( S \) is the service of \( G \), \( \gamma_{ini} \) and \( \gamma_{fin} \) are successful NFC ssns of \( G \)'s reader such that \( \gamma_{ini} \approx \gamma_{fin} \), and \( K \) is a key.

A (TAGA) session of an AC \( A \) is a tuple \( (\alpha_{mid}, S, K, st) \), where \( \alpha_{mid} \) is a successful NFC ssn of \( A \)'s reader, \( S \) is a service, \( K \) is a key, and \( st \in \{c, u\} \), \( st \) indicates the status of whether \( A \) has already received the finish message (sent via WLAN for key confirmation) or not: \( c \) stands for confirmed, and \( u \) stands for unconfirmed respectively.

A (TAGA) session of an OP \( O \) is a tuple \( (\tau_{ini}, \tau_{mid}, \tau_{fin}) \), where \( \tau_{ini} \), \( \tau_{mid} \), and \( \tau_{fin} \) are successful NFC taps of \( O \) such that \( \tau_{ini} < \tau_{mid} < \tau_{fin} \). (2) \( \text{card}(\tau_{ini}) = \text{card}(\tau_{mid}) = \text{card}(\tau_{fin}) \). (3) \( \text{reader}(\tau_{ini}) = \text{reader}(\tau_{fin}) \) is a GU reader, \( \text{reader}(\tau_{mid}) \) is an AC reader, and \( 5 \) is there is no other NFC tap \( \tau_{opp} \) of \( O \) such that \( \tau_{ini} < \tau_{opp} < \tau_{mid} \). Moreover, we assume that the OP's actions are well-defined as spelled out in Def. [15].

2) Concept and Security: The original idea behind T AGA is this: Since T AGA takes place in a secure zone it seems plausible that by a good choice of NFC system and, perhaps, additional process measures we can ensure that the T AGA transport guarantees an authentic message exchange (regarding both origin and message authenticity). On the one hand, this means that we can employ an unauthenticated KE protocol such as the basic DH exchange to securely establish a key, and T AGA will not depend on any PKI. On the other hand, this allows for a precise alignment of setting up the secure channels and the physical connections. More precisely, we hope to achieve a notion of security for T AGA that not only asserts the existence of secure keys but also that the NFC ssns and OP taps coincide in the expected way.

Definition 1. Let \( T \) be a TAGA process.
We say \( T \) guarantees secure TAGA I to a GU \( G \) if, whenever \( G \) has a session \( (S, \gamma_{ini}, \gamma_{fin}, K) \) then
1) there is an OP with a session \( (\tau_{ini}, \tau_{mid}, \tau_{fin}) \) such that \( \tau_{ini} \approx \gamma_{ini} \), and \( \tau_{fin} \approx \gamma_{fin} \).
2) there is an AC \( A \) with a session \( (\alpha_{mid}, S, K, \ldots) \) such that \( \tau_{mid} \approx \alpha_{mid} \), and
3) \( K \) is a fresh key known only to \( G \) and \( A \).

Similarly, we say \( T \) guarantees secure TAGA I to an AC \( A \) if, whenever \( A \) has a session \( (\alpha_{mid}, K, S, c) \) then
1) there is an OP with a session \( (\tau_{ini}, \tau_{mid}, \tau_{fin}) \) such that \( \tau_{mid} \approx \alpha_{mid} \).
2) there is a GU \( G \) with a session \( (S, \gamma_{ini}, \gamma_{fin}, K) \) such that \( \tau_{ini} \approx \gamma_{ini} \) and \( \tau_{fin} \approx \gamma_{fin} \), and
3) \( K \) is a fresh key known only to \( G \) and \( A \).

We say \( T \) guarantees secure TAGA I to both parties, GUs and ACs.

We first confirm that secure TAGA I indeed entails correct setup when the physical setup is aligned with the TAGA walk.

Definition 2. A process flow \( F \) for ground service \( S \) is suitable for secure TAGA I if \( F \) guarantees: When a TAGA walk has been completed between a GU \( G \) of type \( S \) and an AC \( A \) then \( G \) is physically connected to \( A \) for \( S \).

Theorem 1. Let \( F \) be a process flow for some ground service, and \( T \) be a TAGA process such that \( F \) includes \( T \). If \( F \) is suitable for secure TAGA I then \( T \) satisfies secure TAGA I then \( F \) guarantees correctness of setup.

To show that secure TAGA I can indeed be obtained as sketched above we first need to make precise what it means for the TAGA transport to guarantee an authentic message exchange. Our notion of channel authenticity asserts that if there is a GU session then there must be an AC session with matching messages as well as an operator session whose taps coincide with the NFC ssns of the GU session, and that of the AC session respectively. And we require the analogue for the other direction.

Definition 3. Let \( N \) be an NFC system, and \( M \) be a set of process measures.
We say \( N \) under \( M \) guarantees channel authenticity to a GU \( G \) if, whenever \( G \) has a session \( (S, \gamma_{ini}, \gamma_{fin}, \ldots) \) then there is some OP with a session \( (\tau_{ini}, \tau_{mid}, \tau_{fin}) \), and some AC with a session \( (\alpha_{mid}, \ldots) \) such that
1) \( \tau_{ini} \approx \gamma_{ini} \), \( \tau_{mid} \approx \alpha_{mid} \), and \( \tau_{fin} \approx \gamma_{fin} \), and
2) \( \text{msg-s}(\gamma_{\text{init}}) = \text{msg-r}(\alpha_{\text{mid}}), \) and \( \text{msg-s}(\alpha_{\text{mid}}) = \text{msg-r}(\gamma_{\text{fin}}) \).

Similarly, we say \( N \) under \( M \) guarantees channel authenticity to an AC \( A \) if, whenever \( A \) has a session \( (\alpha_{\text{mid}}, \ldots) \) then there is some OP with a session \( (\tau_{\text{init}}, \tau_{\text{mid}}, \ldots) \), and some GU with a session \( (S, \gamma_{\text{init}}, \ldots) \) such that

1) \( \tau_{\text{init}} \approx \gamma_{\text{init}}, \) and \( \tau_{\text{mid}} \approx \alpha_{\text{mid}}, \) and
2) \( \text{msg-s}(\gamma_{\text{init}}) = \text{msg-r}(\alpha_{\text{mid}}). \)

We say \( N \) under \( M \) guarantees channel authenticity iff \( N \) under \( M \) guarantees this to both parties, GUs and ACs.

Definition 4. We say a KE protocol \( P \) is secure for plain TAGA when \( P \) guarantees secrecy and key freshness in the presence of passive adversaries.

Theorem 2. A TAGA process \( T = (P, N, M) \) guarantees secure TAGA I if \( P \) is secure for plain TAGA, and \( N \) under \( M \) guarantees channel authenticity.

3) The Challenge of Channel Authenticity: We now illustrate that it is rather challenging to obtain channel authenticity. Even though TAGA takes place in a secure zone, where only authorized personnel have access, the attacker has various indirect ways of compromising the TAGA transport, and combining them to MitM or other attacks.

Threats against the TAGA Channel:

Swapping the Card. During a break a GU operator might reside in a less restricted area. An attacker with pickpocketing capability could use this as a window of opportunity to swap a counterfeit card for the TAGA card (carried by the operator throughout the day). Since pickpocketing can include social engineering such a card swap cannot be ruled out entirely even when the card must be worn physically attached to the operator, e.g. by a lanyard. (A lanyard is a cord or strap worn around the neck or wrist for security.)

Eavesdropping. Another threat is that the attacker eavesdrops on the NFC exchange between the card and the GU or AC reader. While the nominal range of NFC communication is only 5-10 cm the range of eavesdropping can be considerably larger. In [1] Finke and Kelter first demonstrate that the communication between a ISO-14443 reader and tag can be eavesdropped from 1-2 meters using a large loop antenna. If a device is sending in active mode (like the GU and AC reader) then it can even be eavesdropped on from a distance of up to 10 m [2]. Moreover, based on simulation Kfir and Wool predict an eavesdropping distance of tens of meters when an active antenna is used [3]. At a parking slot, a large antenna could be hidden in large luggage, sports equipment, prams, wheelchairs, cages for pets, or instruments. A large antenna could even be hidden in clothing of an operator such as a prepped safety vest swapped for the real one in a cafeteria. Hence, it seems impossible that eavesdropping can be ruled out by practically enforceable measures in our setting.

Planting a Leech and Skimming. An important component in relay attacks against electronic payment systems is a leech, which is a device that fakes a reader to a card. The leech is smuggled into a victim’s pocket or bag so that it is close to her payment card. The leech can then power up the tag of the card, and communicate with it while remaining undetected. The communication can be relayed by WLAN or cellular connection via an attacker’s laptop to and from a real payment terminal. A leech can also be employed as a skimmer to read out a tag (without writing to it).

The success of a leech depends on whether it is indeed able to activate the victim’s card. This can be improved by employing a ‘tuned leech’ with a range beyond the nominal 5-10 cm, e.g. by increasing the power of transmission and/or using larger antenna. This has been shown to be possible: In [3] Kfir and Wool predict a distance of 40-50 cm by simulation, and in [4] Kirschenbaum and Wool have experimentally confirmed a skimming range of about 25 cm. In our setting, we cannot rule out that an attacker is able to plant a leech device to skim or masquerade to the TAGA card: Similarly to card swapping an attacker could smuggle a leech device into an operators pocket while he is on a break.

Malware Leech. A particular threat in our setting is that a standard device with NFC capability carried by authorized personnel is converted into a leech by malware. For example, during the TAGA transport the operator might carry a smartphone with NFC capability with her. An attacker with standard hacking capability could compromise the smartphone, e.g. by planting malware on the device via a Trojan app or a spear phishing email to the operator. While this allows for purely remote attacks, in contrast to a hardware leech, the success of a malware leech is constrained by the standard device’s nominal range, and the operator being in the habit of storing it close enough to the card.

Ghost Attacks. The other important component in relay attacks against electronic payment systems is a ghost, which is a device that fakes a card to a reader. TAGA seems protected from ghost attacks by two factors: First, only authorized personnel can get close to the TAGA readers. Second, TAGA employs passive cards, and one would expect that for a ghost to communicate with a GU or AC reader it would have to be within their nominal activation range. However, in [3] Kfir and Wool show how to build an active ghost, which considerably increases the possible distance to the reader. The idea is that the ghost transmits in a non-standard way using its own power but so that to the reader the transmission is indistinguishable from that of a passive tag’s. Based on simulation they predict a distance of up to 50 m for bi-directional communication. To our knowledge this has not yet been experimentally confirmed but it shows that a priori we cannot exclude ghost attacks. A ghost could either be remote or it could be infiltrated similarly to a leech device, in which case it can act from a closer distance.

Attack Examples: We now give examples of how these attack vectors can be combined to carry out MitM attacks against a simple NFC system. The first attack shows that the combination of eavesdropping and card swapping is all the attacker needs to obtain full MitM capability.

Attack 1 (MitM by Swap & Eavesdrop). Let \( A \) be an AC and
$G$ be a GU at parking slot $L$ so that $G$ is to service $A$. In preparation, the attacker swaps his own prepped card $C_I$ for the operator’s card as described above. Moreover, the attacker sets up NFC eavesdropping capability, and his own WLAN access point $AP_I$ in the range of $L$. Both $C_I$ and $AP_I$ are prepped with a fixed ephemeral key $(r_G, R_G)$, and an ssid $ssid_I$ for the attacker’s WLAN.

The attack then proceeds as depicted in Fig. 5. The card $C_I$ carries out the first tap as usual. However, with the second tap the counterfeit card writes the attacker’s public key $R_I$ to $A$ rather than $G$’s public key $R_G$. Similarly, with the third tap the card writes $R_I$ and $ssid_I$ to $G$ rather than $A$’s public key $R_A$ and ssid $ssid_A$. Hence, $G$ computes session key $K_{GI}$ based on $r_G$ and $R_I$, and $A$ computes session key $K_{IA}$ based on $r_A$ and $R_I$. To be able to compute the same keys the attacker needs to get $R_G$ and $R_A$ onto his access point $AP_I$. Since the card only has a passive NFC interface he relies on eavesdropping to do so. Once he has computed $K_{GI}$ and $K_{IA}$ he can establish the corresponding channels and mount a MitM attack.

If the attacker has difficulties in setting up eavesdropping capability he can skim the keys $R_A$ and $R_G$ from the card by a leech device instead. The leech could be planted on the operator at the same time when the card is swapped, e.g. in a classical ‘pour drink over shirt’ attack.

The next attack demonstrates that a MitM attack might be possible purely from remote, without having to break integrity or authenticity of the card. We assume that the operator is in the habit of carrying her smartphone with NFC capability in her pocket, and storing the TAGA card in the same pocket next to the smartphone while she walks from the GU to the AC, and similarly for the way back. This is a natural assumption: the operator typically needs both hands to carry the supply hose and might not like the dangling of a lanyard.

**Attack 2 (MitM with Hacked Smartphone).** Let $A$ be an AC and $G$ be a GU at parking position $L$ so that $G$ is to service $A$. In preparation, the attacker hacks the smartphone of the operator of $G$, say $P_I$, and sets up his WiFi point $AP_I$ in the range of $L$. We assume that the TAGA card is a simple store NFC card with a register Reg1 assigned for the first message, and a register Reg2 for the second.

The first NFC tap proceeds as usual, and writes $G$’s message into register Reg1 of the card. After the tap the operator puts the card into her pocket next to her hacked phone $P_I$. This triggers the NFC module of $P_I$, upon which it reads the contents of Reg1 (with $G$’s public key) and then overwrites them with the attacker’s own key $R_I$. Hence, when the operator arrives at the AC and performs the (supposedly) second NFC tap the AC reads the attacker’s key $R_I$. The second message pass is manipulated in the analogous fashion. The attacker can easily relay the public keys $R_G$ and $R_A$ from the hacked smartphone to his access point $AP_I$. Now he can establish the corresponding channels, and act as MitM.

We have implemented this attack against the current prototypical implementation of TAGA. It works reliably as long as the operator observes her habit of storing the TAGA card in the same pocket next to her phone. If a more complex card than a simple store card is employed this attack can be prevented by the card keeping state of the taps, and implementing input/output checks. However, such measures can be overcome by a multi-session attack.

**Attack 3 (Multi-Session Variation).** When the phone $P_I$ first interacts with the card it will now perform three read/writes instead of one: the first impersonates the AC and reads $G$’s public key; the second impersonates the GU during the final tap and concludes the current session of the card; the third starts a fresh session, where $P_I$ impersonates the GU and writes the attacker’s key $R_I$. The next tap will be carried out with the real AC in the appropriate state. The AC has no means to notice that the attacker has skipped to a new session and will accept $R_I$ as the GU’s key. On the way back the attacker can proceed in the analogous fashion, and plant successfully his own key $R_I$ for the AC’s key.

Finally, we illustrate that if the attacker manages to install a ghost then he can very easily stage attacks. In particular, Imp2AC attacks only require one ‘fake tap’.

**Attack 4 (Imp2AC by Ghost).** Let $D_I$ be a remote or infiltrated ghost device that can reach the AC reader. Then $D_I$ can establish an NFC link with the AC, and masquerade as a TAGA card: $D_I$ writes the attacker’s key $R_I$ to the AC, and obtains the AC’s key $R_A$ in return. The resulting DH session key allows him to mount an Imp2AC attack against the AC.

4) **Designs for the NFC System:**

*Distribution Model:* The swap attack highlights that authenticity of the card is an important requirement. Hence,
is advisable that there is not just a pool of TAGA cards that are distributed daily to the operators but that a distribution model is in place that allows for better accountability. The following two models offer themselves.

In the **OP-bound model** each GU operator is equipped with their personal card, which she can use on any GU that she is authorized to operate. This model is particularly suitable when airport staff are already provided with multi-functional access cards, into which TAGA can be integrated as one of several applications. The card will usually contain a public/private key pair that is bound to the identity of the operator and a certificate for the public key signed by the airport.

In the **GU-bound model** each GU is equipped with its own TAGA card. The card can be cryptographically bound to the GU reader so that the GU can only be operated with its own card, and, conversely, the card will only work with the GU that owns it. To this end a shared symmetric key can be pre-installed on both the card and the GU reader in a secure environment. During operative times the respective operator is responsible for handling the card while during non-operative times it is stored within the GU or within a secure compartment next to the GU reader.

### Securing the NFC Links between GU and Card:

Both of the models have the advantage that they come with long-term cryptographic keys that allow us to add mutual authentication and to secure the NFC links between the GU and the card. More precisely, when a new TAGA session is initiated with the first tap then the GU and card will run an AKE protocol to mutually authenticate each other and establish a session key. The session key will be used to secure the data exchange during the first tap as well as the final tap. In the GU-bound model authentication can be anchored in the symmetric key pre-installed on the card and GU reader. In the OP-bound model this can be based on the public/private key pairs on the card and likewise on the GU reader and a PKI local to the airport.

### Detection of AC Masquerading:

Ensuring that the NFC exchange between the GU and the card is authenticated has the advantage that AC masquerading (i.e. attacks where a leech device masquerades as the AC) can be detected.

A TAGA session of a card $C$ now consists of three steps: First, $C$ performs an authenticated NFC exchange with a GU, say $G$. Second, $C$ carries out an unauthenticated NFC exchange with, presumably, the AC. Third, $C$ carries out an authenticated NFC exchange with, and only with, $G$ again. The implementation will ensure that the card does not accept any other sequence of exchanges (apart from being reset by an authenticated GU). Hence, if the operator carries out the tap with the AC successfully then the second exchange cannot have resulted from a leech device because there can only be one successful unauthenticated exchange. If a leech device masquerades as the AC while the operator walks to the AC then her tap with the AC will not be successful and she will abort the TAGA session at the GU.

### Securing the NFC Link between Card and AC:

Since the card and AC reader do not share any long-term keys (unless we break the ‘plain’ paradigm) the NFC exchange between the card and the AC cannot be secured with regards to origin authenticity. However, we can still protect the exchange from data modification as we now explain. Due to its channel characteristics it is generally assumed that NFC is not susceptible to man-in-the-middle attacks, in particular when run in the active-passive mode. For example, compare [2] for a precise argument.

**Assumption 1.** It is practically impossible to carry out a man-in-the-middle attack over NFC in the active-passive mode.

When the card and AC engage in the mid tap then they can first run an unauthenticated KE protocol such as the basic DH exchange and establish a session key to secure their data exchange. While this will a priori not establish that the AC securely communicates with the card, based on Ass. [1] this will hold if, in addition, we can ascertain that the card is engaged in the same NFC link as the AC during the time. The other direction is analogous.

**Distance Bounding:** The features discussed so far still leave open that an attacker carries out remote attacks such as relay attack to undermine the NFC link between GU and card, or a ghost attack to masquerade as a card to the AC. This can be prevented by distance bounding protocols [5], which guarantee an upper bound on the distance of the card to the reader. To this end the reader measures the round-trip time of cryptographic challenge/response pairs it poses to the card. In our setting, the GU reader must bind this to the authentication of the card to prevent distance hijacking [6]. Similarly, the AC reader must bind this to the ephemeral DH key of the card for the analogous reason.

**Secure Proximate Zone:** While distance bounding makes sure that the AC and GU reader only communicate with a device close by process measures we can ensure that only a TAGA card carried by an operator comes closed to the reader. Together, this will ensure that we obtain the coincidence between operator taps and NFC ssns of card, AC, and GU as required for channel authenticity.

**Definition 5.** Let $d$ be the precision of the distance bounding protocol. $M$ guarantees secure proximate zone, if the following holds: no NFC device other than a card hold by an operator who presumes this to be a TAGA card is brought within distance $d$ of the GU reader, and AC reader respectively.

Altogether, we arrive at a specification of NFC systems for the GU-bound model, and the OP-bound model respectively. We denote the first by $N_{GU}$, and the second by $N_{OP}$.

**Theorem 3.** The NFC systems $N_{GU}$ and $N_{OP}$ can be implemented so that under process measures that include ‘secure proximate zone’ they guarantee channel authenticity.

5) **Multi-Instance Resilience and Discussion:** To sum up, we have obtained secure plain TAGA based on the following insight: While the large secure zone established around an AC during turnaround leaves the TAGA channel open to many indirect attacks we can bootstrap channel authenticity from
binding the card to the GU (either one-to-one or via a PKI local requests only from a small proximate zone and guaranteeing that this proximate zone is secure in a strong sense.

Corollary 1. The TAGA processes $T_{GU} = (DH, N_{GU}, M)$ and $T_{OP} = (DH, N_{OP}, M)$ both guarantee secure TAGA I.

Moreover, these TAGA processes come with a strong notion of multi-instance resilience. Let $T$ be a TAGA process, and let $T_1, T_2, \ldots, T_n$ be $n$ instances of $T$. For each $i \in [1, n]$, $G_i$ be the GU, $A_i$ the AC, and $O_i$ the GU operator respectively. We say the instances $T_1, \ldots, T_n$ are in parallel if the respective GUs, ACs, and GU operators are distinct: i.e. for all $i, j \in [1, n]$, $G_i = G_j$ implies $i = j$, and analogously for the ACs, and GU operators.

Definition 6. We say a secure TAGA process $T$ guarantees resilience against parallel scaling of attacks if the effort for the attacker to successfully attack $n$ parallel instances of $T$ grows linearly with $n$ wrt a factor of physical effort the attacker has to spend (e.g. work force, breach of a physical security measure, compromise of personnel).

Theorem 4. $T_{GU}$ and $T_{AC}$ are resilient against parallel scaling of attacks (assuming that system integrity of the GU, AC, and card is resilient in the same way).

On the downside, plain TAGA comes with the caveat that its security heavily depends on the GU operator. Any security proof will rest on the premise that the operator observes procedures such as verifying that the AC has successfully received the tap, and aborting TAGA at the GU when an error occurs. Moreover, if a GU operator is compromised she can always mount a MitM attack in the following way: While she carries out the GU taps with the authentic card as usual she performs the AC tap with her own counterfeit card and uses a leech device to masquerade to the authentic card as AC reader. The latter can be carried out secretly in her pocket sometime during the TAGA walk. Of course, the GU operator is already a trusted party wrt safety of the turnaround. Nevertheless, from a security viewpoint it seems unorthodox to make her a trusted third party in the key establishment. For example, this has disadvantages when it comes to IT forensics and liability claims. A similar problem arises when ground units of different providers with different security levels are to participate in TAGA: Plain TAGA assumes that all ground units are equally trustworthy.

IV. AUTHENTICATED TAGA

1) Preliminaries: In the setting of authenticated TAGA, every AC $A$ has a long-term key pair $(W_A, w_A)$, where $W_A$ is the public key and $w_A$ is the private key. Moreover, $A$ holds a certificate for its public key $W_A$, which is issued by the airline $A$ that owns $A$ (or an entity commissioned by $A$). We denote the certificate by $cert_A(A, W_A, T_A, V_A)$, where $T_A$ is the aircraft type of $A$, and $V_A$ specifies the validity period of the certificate.

Analogously, every GU $G$ has a long-term key pair $(W_G, w_G)$, and a certificate for its public key $W_G$, which is issued by the airport $H$ that harbours $G$ (or an entity commissioned by $H$). We denote the certificate by $cert_H(G, W_G, S_G, V_G)$, where $S_G$ is the service type of $G$ and $V_G$ is the validity period of the certificate.

Moreover, we assume that every AC has installed the root certificates of those airports it intends to land, and each GU has installed the root certificates of those airlines it is authorized to handle. Since a GU is specific to its airport, and an AC knows at which airport it is currently parked (available from its electronic flight system) we require that when an AC verifies a GU certificate received during TAGA it will check that the airport within the certificate agrees with its own location.

Notation 1. For short notation of certificates we often leave away the issuing party, type of aircraft or service, and/or validity period when this is implicitly clear from the context.

2) Concept and Security: We say a TAGA process $(P, N, M)$ is authenticated when $P$ is an authenticated KE (AKE) protocol. While authenticated TAGA allows us to establish secure keys without having to rely on channel authenticity without the latter we cannot expect to reach Secure TAGA I: We lose the guarantee that the OP taps and NFC ssns of the GU and AC coincide in the expected way. However, we can reach another notion of security for TAGA that, together with a straightforward requirement on the setup process, allows for a match between cyber channels and physical connections as required for secure setup.

Secure TAGA II guarantees that when a GU $G$ and an AC $A$ successfully complete a TAGA session then they are located at the same parking slot. This can be established by the underlying AKE protocol in terms of data agreement when the GU and AC provide their location as input to the protocol. The requirement on the setup process is that the GU confirms that its physical setup is complete over the established cyber channel. The AC can then conclude that it is also physically connected to its communication partner: $G$ has confirmed it is ready, and since $G$ is located at the same parking slot as $A$, it must indeed be connected to $A$ and not to some other AC.

Definition 7. Let $T$ be a TAGA process.

We say $T$ guarantees Secure TAGA II to a GU $G$ if, whenever $G$ has a session $(S, \gamma_{fin}, \gamma_{fin}, A, K)$ then

1) $A$ has a session $(\alpha_{mid}, S, G, K, \ldots)$,
2) $K$ is a fresh key known only to $G$ and $A$, and
3) $A$ is located at the same parking slot as $G$.

Similarly, we say $T$ guarantees Secure TAGA II to an AC $A$ if, whenever $A$ has a session $(\alpha_{mid}, S, G, K, \gamma_{fin}, A, K)$ then

1) $G$ has a session $(S, \gamma_{fin}, \gamma_{fin}, A, K)$,
2) $K$ is a fresh key known only to $A$ and $G$, and
3) $G$ is located at the same parking slot as $A$.

We say $T$ guarantees Secure TAGA II iff $T$ guarantees Secure TAGA II to both parties, GUS and ACs.

Definition 8. A process flow $F$ for ground service $S$ is suitable for secure TAGA II if it guarantees: (1) When a GU of type $S$
has completed its physical setup it confirms to the end point of its cyber channel for S that it is ready. (2) Before an AC engages into service S it waits until each end point of its cyber channels for S has confirmed that it is ready.

**Theorem 5.** Let F be a process flow for some service, and T be a TAGA process such that F includes T. If F is suitable for secure TAGA II and T satisfies secure TAGA II then F guarantees correctness of setup.

To implement the requirement of Def. 8 the GU control needs to “know” when the physical setup is complete. This can be realized by means of a ‘ready button’ at the GU to be pressed by the operator on completion of the setup. Alternatively, a ‘ready signal’ can be triggered when the GU’s machinery (such as air supply or fuel pump) is activated by the operator, which is typically the last action of a GU setup.

To reach Secure TAGA II we only need to choose an AKE protocol that satisfies standard secrecy and authentication properties, and extend it so that it also guarantees agreement on service and location. GUs and ACs can communicate their location explicitly as the number of the parking slot they are located at. In this case the parking slot needs to be provided by the GU operator, and pilot respectively, via a user interface. Alternatively, GUs and ACs can communicate their location in terms of GPS coordinates. This has the advantage that the data can be provided automatically by their positioning system. Due to safety distances that need to be kept between ACs on the tarmac we expect that this will be sufficiently precise to verify whether a GU and AC are on the same parking slot.

**Definition 9.** A KE protocol P is secure for authenticated TAGA when P satisfies secrecy, key freshness, opposite type, and agreement on peer, service and location in the presence of active adversaries. (C.f. App. C)

**Theorem 6.** Given any N and M, (P, N, M) guarantees secure TAGA II if P is secure for authenticated TAGA.

Fig. 6 shows TAGA based on the **Fully Hashed Menezes-Qu-Vanstone protocol (FHMQV)** \cite{7, 8}. For TAGA we include service and location into the key confirmation step, yielding FHMQVCLS. FHMQV is one of the strongest protocols regarding security, resilience and efficiency, and comes with a security proof.

**Corollary 2.** Given any N and M, (FHMQVCLS, N, M) guarantees secure TAGA II.

3) The Challenge of LTKC: Let A be an AC. We say the attacker has obtained a long-term key compromise (LTKC) of A if he has managed to get hold of credentials that authenticate A: A public/private key pair ($W_A, w_A$) and a valid certificate $cert(A, W_A)$, which asserts that $W_A$ belongs to A. The definition for a GU G is analogous.

There are many different ways of how an attacker might obtain a LTKC of a party X. One way is to obtain the private key of X and use the existing certificate belonging to X. Another way is that the attacker tricks the certification authority (CA) into issuing a certificate for a key pair he has generated himself, perhaps for an entity that does not even exist. This is more indirect but often easier to obtain; e.g. when the private keys are generated within hardware security modules and never exported from there. Finally, if the attacker manages to get hold of the private key of the respective CA then he can generate as many valid certificates for self-generated key pairs as he likes. All these cases have been shown to be possible for real key management applications, e.g. by exploiting vulnerabilities in the APIs of the employed hardware security modules \cite{9, 10}.

Given a LTKC of an entity X it is clear that the attacker can impersonate X to other entities. In classical AKE settings this will only impact on X’s resources or on peers that communicate specifically with X (based on X’s identity). However, in our setting of local key establishment, a LTKC of an AC, say $A_I$, has wider consequences: Given any GU G that is to service the AC at some parking slot L, the attacker can impersonate $AC(L)$ to G using the credentials of $A_I$ (c.f. App. C Fig. 10). Given a LTKC of a GU, say $G_I$, the impact is locally contained: The attacker can exploit the compromised certificate of $G_I$ only within the realm of $G_I$’s airport. This is because the AC will check that the GU certificate is issued for the airport that it is currently parked at (c.f. Section IV-1).
Say entity $X$ has a LTKC. While, on the level of KE protocols, it cannot be prevented that the attacker can impersonate $X$ to any other participant, it is important to realize that, in general, impersonation is not the only attack he can mount based on the LTKC of $X$. He might also be able to exploit the credentials of $X$ to impersonate any other party to $X$, or to mount an attack that violates authentication rather than secrecy. In the full version we show an example where, based on a LTKC of a GU $G_1$, the attacker can stage a MitM attack against any AC serviced by $G_1$. Another example shows how, given a compromise of any airline’s root key pair, the attacker can reach a ‘Imp2GU with mismatch diversion attack’ against any two TAGA instances that happen about the same time at some airport. Fortunately, advanced AKE protocols such as the FHMQV are resilient against LTKCs in a way that restores the expected correspondence between LTKC and impersonation.

**Definition 10.** Let $P$ be a protocol that is secure for a-TAGA. $P$ guarantees an AC $A$ LTKC resilience for a-TAGA if $P$ guarantees secrecy, key freshness, opposite type and agreement on peer, service and location to $A$ even when $A$ has a LTKC. The definition for a GU $G$ is analogous. $P$ is resilient for a-TAGA when $P$ guarantees this to both parties, ACs and GUs.

**Lemma 1.** Let $P$ be a protocol that is secure and LTKC resilient for a-TAGA. Assume we lift the correctness assumption that long-term key pairs of ACs and GUs are secure.

1) If a GU has a session $(S, A, K)$ and the attacker knows $K$ then $A$ must have a LTKC.

2) If an AC has a session $(S, G, K, \ldots)$ and the attacker knows $K$ then $G$ must have a LTKC.

4) Resilience against LTKCs: While advanced AKE protocols tame the effects of LTKCs, on the protocol level, it is not possible to prevent an attacker from impersonating the entity with the LTKC to others. Neither is our setting amenable to fast and trustworthy certificate revocation and certificate status verification. The reason is twofold: First, this would require that all airlines and airports mutually trust each other and apply equivalently strong security management to detect and report LTKCs. Second, fast verification of the certificate status would require online connectivity of at least the airport — a disadvantage compared to the current paper- and human-based processes. Instead, in our setting of local key establishment we can harden TAGA against LTKCs by adding physical and local process measures.

We require that TAGA at least guarantees basic LTKC resilience: while when an AC $A$ and GU $G$ carry out TAGA together they must mutually trust each other and the key management processes of $A$’s airline and $G$’s airport they will never be affected by a security incidence of another airline or airport. Airport-reliant resilience is stronger in that an airport and the local AC $A$ do not require to trust the key management processes of $A$’s airline at all. This also answers to the situation when the internal certificate revocation process of an airline might not reach its aircraft in time. Full resilience ensures that TAGA has a second line of defense and does not rely on long-term credentials as long as the local measures are not compromised. We now make precise the three notions of resilience and provide examples of how they can be met.

**Definition 11.** Let $T$ be a a-TAGA process that guarantees secure TAGA II. We say $T$ guarantees $x$ LTKC resilience, where $x \in \{\text{basic, airport-reliant, full}\}$ if, whenever an instance of $T$ is carried out between a GU $G$ and an AC $A$ at a parking slot $L$ then $T$ guarantees secure TAGA II to $G$ and $A$ even when

1) for $x = \text{basic}$, all ACs and GUs other than those in the domain of $A$ and $G$ have a LTKC.

2) for $x = \text{airport-reliant}$, all ACs and all GUs other than those in the domain of $G$ have a LTKC.

3) for $x = \text{full}$, all ACs and GUs have a LTKC.

a) Basic LTKC Resilience: To reach basic LTKC resilience we only need to ensure that the attacker cannot make the GU accept a certificate that does not agree with the domain of the AC actually on site.

**Definition 12.** A measure $M$ guarantees agreement of AC domain if, when a GU has a session $(S, A, K)$ at a parking slot $L$ then $A$ is of the same airline and type as $AC(L)$.

**Theorem 7.** Let $T = (P, N, M)$ be any TAGA process such that $P$ is secure and LTKC resilient for a-TAGA and $M$ guarantees agreement of AC domain. Then $T$ guarantees basic LTKC resilience.

Agreement of AC domain can be implemented by a simple measure that makes use of the awareness of the GU operator: while the GU has no means to verify that the received AC certificate (and information therein) belongs to the AC present at the parking slot, clearly, the operator has sight of the AC. Hence, she is able to verify that visually observable features of the AC such as its type and airline agree with the information received by the GU.

**Measure 1** (‘Two Eyes’ Verification of AC (2EV)). Assume the TAGA controller of the GU is equipped with a display and two input buttons: one to confirm, and the second to stop the process and raise an alarm. Then the last NFC tap can be extended by human verification as illustrated in Fig. 7. First, the operator transfers the second message by NFC tap to the GU’s controller as usual. Recall that this message contains an AC certificate $\text{cert}_A(A, W_A, T_A, V_A)$, where $A$ is the airline
Lemma 1. Another attack will always require a $\text{LT}_{\text{TKC}}$ of the $\text{GU}$ can detect pure Imp2GU attacks. This is so because by $\text{LT}_{\text{TKC}}$ resilience will be reached if we make sure that the $\text{GU}$ operator and perform the visual verification as well. If yes, then she will confirm the process; otherwise she will stop the process and raise an alarm.

Unintended errors of the $\text{GU}$ operator can be kept small: they can be trained to keep awareness by injection of false alarms (similar to security screening at airports). It is also possible to implement this with dual-control.

Measure 2 (‘Four Eyes’ Verification of $\text{AC}$ (4EV)). For increased security a member of the $\text{AC}$ crew can accompany the $\text{GU}$ operator and perform the visual verification as well.

Fact 1. 2EV and 4EV guarantee agreement of $\text{AC}$ domain.

b) Airport-reliant $\text{LT}_{\text{TKC}}$ Resilience: Airport-reliant $\text{LT}_{\text{TKC}}$ resilience will be reached if we make sure that the $\text{GU}$ can detect pure Imp2GU attacks. This is so because by Lemma 1 another attack will always require a $\text{LT}_{\text{TKC}}$ of the $\text{GU}$ domain.

Definition 13. A measure $M$ guarantees detection against pure Imp2GU if, whenever a $\text{GU}$ $G$ has a session $(S, A, K)$ at a parking slot $L$ and the attacker knows $K$ then $G$ detects his and aborts the session (before any safety-critical process settings are started) as long as $AC(L)$ does not have any session $(S, G', K', c)$ for some $G'$ and $K'$ such that the attacker knows $K'$.

Theorem 8. Let $T = (P, N, M)$ be any $\text{TAGA}$ process such that $P$ is secure and $\text{LT}_{\text{TKC}}$ resilient for $\text{a-TAGA}$ and $M$ guarantees detection against pure Imp2GU. Then $T$ guarantees airport-reliant $\text{LT}_{\text{TKC}}$ resilience.

There are several ways to implement detection against pure Imp2GU. The following measure translates the standard scheme of challenge/response authentication into the concept of physical challenge/cyber response: The $\text{GU}$ sends a challenge via the physical connection, e.g. encoded in a pattern of pulsating airflow, which the $\text{AC}$ must answer via the cyber channel. Thereby the physical connection is directly bound into the KE process.

Measure 3 (Physical Challenge/Cyber Response (PC/CR)). Assume that the airpacks of the $\text{AC}$ are equipped with mass airflow sensors that can detect a pattern of airflow changes and report it to the $\text{AC}$ controller. Then a phase of physical challenge response can be included between the setup phase and the M2M phase as illustrated in Fig. 8. $G$ generates a random number of a fixed size, say $N_G$, and encodes this into a pattern of pulsating airflow. $A$ reads the physical signal by the airflow sensors and decodes it back into a number, say $N_{\text{read}}$. Then $A$ responds by sending $N_{\text{read}}$ back to $G$ via the cyber channel. $G$ checks whether $N_{\text{read}} = N_G$. If this is true then $G$ concludes that it speaks to $AC(L)$; only the $\text{AC}$ that is physically connected to the $\text{GU}$ could have known $N_G$. If the numbers don’t agree $G$ stops and raises an alarm.

Lemma 2. PC/CR guarantees detection against pure Imp2GU.

The space of nonces must be sufficiently large to reduce the risk of guessing attacks: Even when the attacker cannot receive the physical signal he can always guess the nonce $N_G$ and send it back via a cyber channel he has established with the $\text{GU}$ by an impersonation attack. This brings about a trade-off between security and efficiency. For example: Say the physical channel allows a binary encoding of numbers in terms of high and low airflow (e.g. using stuffing to synchronize). Say an encoded bit requires $2$ seconds to be transmitted, and a challenge shall maximally take $10$ (or $20$) seconds to be transmitted. Then one can use a space of $32$ (or $1024$) nonces, and the attacker has a $1/32$ (or $1/1024$) chance to guess correctly.

c) Full $\text{LT}_{\text{TKC}}$ Resilience: Full $\text{LT}_{\text{TKC}}$ resilience can be reached if the $\text{TAGA}$ process guarantees channel authenticity as a second line of defense without relying on any central key management. We only need to make sure that the underlying AKE protocol is suitable for this in the following sense:

Definition 14. Let $P$ be a protocol that is secure for $\text{a-TAGA}$. $P$ guarantees $\text{LT}_{\text{TKC}}$ resilience against local eavesdropping (eav-$\text{LT}_{\text{TKC}}$ resilience) for $\text{a-TAGA}$ if, whenever an instance of $P$ is run between a $\text{GU}$ $G$ and an $\text{AC}$ $A$ then, even when both $G$ and $A$ have a $\text{LT}_{\text{TKC}}$, $P$ guarantees secrecy, key freshness, opposite type, and agreement on peer, service and location to $G$ and $A$ against an attacker that can only eavesdrop on their current session of $P$ (but actively intervene in all other sessions as usual).

Corollary 3. Let $T = (P, N, M)$ be a $\text{TAGA}$ process such that $P$ is secure and eav-$\text{LT}_{\text{TKC}}$ resilient for $\text{a-TAGA}$, and $M$ under $M$ guarantees channel authenticity without relying on any central key management. Then $T$ guarantees full $\text{LT}_{\text{TKC}}$ resilience.

Fact 2. $N_{\text{GU}}$ under $M_T$ guarantees channel authenticity without relying on any central key management.

5) Resilient Designs:

Theorem 9. For $i \in [1, 4]$ let $T_i = (\text{FHMQV}_{\text{CLS}}; N_i, M_i)$ where $N_i$ and $M_i$ are as in Table 2. For each $i \in [1, 5]$, $T_i$ is secure and guarantees the properties as shown in row $i$.

For $\text{TAGA}$ designs (3) or (4) are most suitable. Our modular approach makes them amenable to be proved formally within
a symbolic or cryptographic proof framework [11].

APPENDIX A
RELATED WORK

AKE Protocols and Resilience: Resilience against LTKC has mainly been studied in the context of foundational research on authenticated DH protocols. The threat of a key compromise impersonation (KCI) attack where an attacker impersonates another party to the actor with the LTKC has been considered early on in [13], and KCI resilience (KCIR) has been identified as a desirable attribute for AKE protocols to guarantee [14]. It has also become standard to consider KCIR and other advanced properties such as forward secrecy and unknown key-share by state-of-the-art protocol checkers such as the TAMARIN prover [15].

However, automatic symbolic analysis is still not amenable to protocols that use multiplication in the DH group and addition of exponents such as the AKE protocols with implicit authentication. The MQV [16], and its development to FHMQV [7], [8] have arguably the best combination of resilience properties while in particular the FHMQV also developed for efficiency. The FHMQV comes with a security proof in a cryptographic security model [7], [8].

The theory of post-compromise security has been advanced in [17] and [13]. Following [13] our definition of LTKC resilience considers all security goals of the protocol. Moreover, we build on the result therein that LTKC resilience of agreement properties follows from KCIR when the protocol includes a key confirmation step. Our property eav-LTKC resilience seems to be new. It is close to the well-known property of forward secrecy (e.g. [14]). Although for practical protocols the two properties will typically coincide, in general, they seem incomparable: it seems possible to construct an artificial protocol for which the two notions will differ.

NFC Related Attacks and Distance Bounding: We have already discussed in Section 3 how research has shown that the nominal guarantees of NFC can be overcome by an attacker. Distance bounding protocols have been introduced to verify the physical proximity or location of a device [19], [5], [20]. While there are now many designs out there and the EMV Contactless Specifications for Payment Systems (Version 2.6, 2016) has included relay resistance protocols new attacks against them have also been devised (e.g. [6], [21]). To counter this the formal verification community has also provided techniques to verify such protocols [6]. While this work has focused on the protocols themselves our work considers how their guarantees can be used in an overall security concept that employs them.

APPENDIX B
KEY ESTABLISHMENT PROTOCOLS

Diffie-Hellman Protocols: (Authenticated) Diffie-Hellman (DH) protocols assume a cyclic group $G$ of prime order $n$, and a generator $P$ of $G$ such that the decisional Diffie-Hellman problem is hard in $G$. The domain parameters $G$, $n$, and $P$ can be fixed or sent as part of the first message. We use small letters to denote elements of the field $Z_n^*$, and capital letters for elements of $G$. A key pair in the protocols consists of a public key $T$, which is a group element, and a private key $t$, which is an element of the field $Z_n^*$ such that $T = tP$. Given an entity $X$, we denote their ephemeral key pair by $(R_X, r_X)$, and their long-term key pair by $(W_X, w_X)$ respectively. Group operations are written additively ($A + B$, or $cA$) consistent with notation for elliptic curve cryptography. Let $H$ be a $t$-bit hash function, where $t = \log_2 n)/2$.

Moreover, let $KDF_1$ and $KDF_2$ be key derivation functions, $mac$ be a message authentication code, and $sign$ a signature scheme. We write $m_1 \| m_2$ for the concatenation of two messages $m_1$ and $m_2$.

Security Properties: (captured as injective agreement between the runs of the two parties [22]).

We say a KE protocol guarantees to an AC

...Secrecy if, whenever $A$ completes a run of the protocol, apparently with GU $G$, then no party other than $A$ and $G$ can compute the session key.

...Key Freshness if, whenever $A$ completes a run of the protocol, and computes $K$ as the session key, then there is at most one other run of the protocol in which $K$ is the resulting session key.

...Opposite Type if, whenever $A$ completes a run of the protocol, apparently with GU $G$, then $G$ is indeed a GU.

...Agreement on Peer if, whenever $A$ completes a run of the protocol, apparently with GU $G$, and computes $K$ as the session key, then $G$ has a unique run in which $K$ is the resulting session key, and in this run $A$ is the apparent peer.

...Agreement on Service if, whenever $A$ completes a run of the protocol, apparently with GU $G$ and for carrying out service $S$, and computes $K$ as the session key, then $G$ has a unique run in which $K$ is the resulting session key, and in this run $S$ is the apparent service to be carried out.

Agreement on Location if, whenever $A$ completes a run of the protocol, apparently with GU $G$, then $G$ is at the same location as $A$.

The guarantees to GU $G$ are defined analogously. We say a protocol guarantees security property $X$ when it guarantees $X$ to both parties, ACs and GUs.

APPENDIX C
GROUND PROCESSES: FUELLING

Fuellng: Fig. 9 shows a process for fuelling in a setting where the fuel is obtained from an underground pipeline via a fuel truck. The fueller’s first step is to connect the input fuel hose of the truck to a hydrant in the ground. Moreover, the fueller needs to connect the output fuel hose of the truck to the fuelling port of the AC. The fuelling ports are typically

| Protocol | Security | Efficiency |
|----------|----------|------------|
| LTKC     | New      | Full       |

**TABLE I**
RESILIENT AUTHENTICATED TAGA
positioned under the wings of the plane, and this step often involves that the fueller uses a lift integrated in the truck to take him up with the hose to one of the wings. In addition, safety measures are carried out: before the AC is hooked up to the fuel hose a ground wire is laid from the fuel truck to the AC, and before the fuelling starts the fuel is checked for contamination. TAGA pairing is integrated as follows: The first and second NFC taps are aligned with connecting up the ground wire, and the third tap is carried out after the fuel hose is connected up. Finally, the fueller activates the fuel pump. At the AC, the pilot (or automatic control) waits until the secure channel is established and he has the okay from the fueller (or the fuel truck via the secure channel) that the fuel hose is connected up.

At the AC, the first action of the M2M phase is that the pilot (or automatic control) opens up the valves of the tanks, and activates the automatic fuel system. The M2M process makes use of the fact that most ACs already have an automated fuelling system: given a specified amount of fuel, the fuelling system distributes incoming fuel automatically into the various sections of the tank, monitors the amount of fuel already received, and automatically shuts the valves of the tank when the specified amount has been reached. As usual backflow will stop the fuel pump of the truck. During the M2M phase the AC can communicate several fuel orders to the fuel truck so that the fuel can automatically and precisely be topped up according to an increase in the weight of the plane. When the final weight is known and the final fuel amount reached the AC notifies the fuel truck that the service is complete. After an analogous reply by the truck the service enters the disconnect phase. In the latter the communication session is closed and the physical setup is reversed.

**Fuelling with Two Trucks:** Large ACs such as the A380 usually employ two fuel trucks to fuel from the left and right wing in parallel. Then two parallel sessions of the above process must be run. The following synchronization point between the two fuelling sessions is required: the pilot (or automatic control) only opens the valves of the tank system after two secure channels are established and both fuellers (or fuel trucks) have confirmed that the physical connection of the fuel hose on their side is ready.

**Appendix D**

**Relating to Section III**

**Definition 15.** We assume that each reader displays the status of the tap it received (i.e. initial, mid, final), and that the operator’s actions are well-defined in the following sense:

1. The operator taps an AC only as part of the mid tap of a TAGA session.

2. If during a TAGA walk the operator observes that the display of the GU or AC reader does not confirm the action she expected to carry out (e.g. the tap is (repeatedly) unsuccessful or the GU reader returns ‘first tap’ while the operator expected this to be the final tap) then she will reset the TAGA controller at the GU before carrying out any further taps.

**Proof of Theorem 1** This is straightforward from the definitions.

**Proof of Theorem 2** By Channel Authenticity to $G$, there is some OP with a session $(\tau_{ini}, \tau_{mid}, \tau_{fin})$ and some AC with a partial session $(\alpha_{mid}, S', K', u)$ such that $\tau_{ini} = \gamma_{ini}$, $\tau_{mid} = \alpha_{mid}$, and $\tau_{fin} = \gamma_{fin}$, and $\text{msg}(\gamma_{ini}) = \text{msg}-r(\alpha_{mid})$ and $\text{msg}(\alpha_{mid}) = \text{msg}(\gamma_{fin})$. Hence, $S = S'$, and $G$ and $A$ will compute $K$, and $K'$ respectively, based on the same DH public keys. Hence, we also have $K = K'$, $K$ is fresh and only known to $A$ and $G$.

By Channel Authenticity to $A$, there is some OP with a partial session $(\tau_{ini}, \tau_{mid}, \ldots)$ and some GU $G$ has a partial session $(\gamma_{ini}, \ldots)$ such that $\tau_{ini} = \gamma_{ini}$, $\tau_{mid} = \alpha_{mid}$, and $\text{msg}(\gamma_{ini}) = \text{msg}-r(\alpha_{mid})$. Since $A$ has obtained the Finish message someone other than $A$ knows the key $K$. By secrecy
under passive adversaries only \( G \) can know the key. Hence, \( G \) has sent the Finish message and must have a complete session \((x, y, z, K)\). By freshness \( G \) does not use the same key twice, and hence \( x = S \), and \( y = \tau_{ini} \). By Authenticity to \( G \) there must be a TAGA walk \((\tau_{ini}, \tau_{mid}'_1, \tau_{fin}'_1)\) such that \( z = \tau_{fin}'_1 \). Then clearly also \( \tau_{mid}' = \tau_{fin}' \). Hence, matching OP session also exists.

Proof of Theorem \( 3 \). Theorem \( 3 \) follows from Lemma \( 3 \) and Lemma \( 4 \) below. The first proves that when a NFC system guarantees certain properties to be defined below then under the measure ‘secure proximate zone’ it will guarantee channel authenticity. The second lemma then argues that \( N_{GU} \) and \( N_{OP} \) satisfy these properties. Before proving the lemmas we need more definitions and intermediary facts.

More definitions: If a reader \( R \) has a NFC ssn \( \delta_x \), and a card \( C \) has a NFC ssn \( \gamma_y \), and \( R \) and \( C \) communicate with each other during these NFC ssns then we write this by \( \delta_x \rightarrow \gamma_y \).

A (TAGA) session of a card \( C \) is a tuple \((\sigma_{ini}, \sigma_{mid}, \sigma_{fin})\) where \( \sigma_{ini}, \sigma_{mid}, \sigma_{fin} \) are successful NFC ssns of \( C \) such that (1) \( \sigma_{ini} < \sigma_{mid} < \sigma_{fin} \), and (2) \( msr-r(\sigma_{ini}) = msr-s(\sigma_{mid}) \), and \( msr-r(\sigma_{fin}) = msr-s(\sigma_{fin}) \).

Between OP taps and reader NFC ssns and sessions: Due to ‘secure proximate zone’ and distance bounding we can infer operator taps from NFC ssns of the GU and AC reader, and vice versa:

**Proposition 1.** Let \( N \) be a NFC system with distance bounding, and assume ‘secure proximate zone’ holds.

1) If a GU or AC reader \( R \) has a NFC ssn \( \delta_x \) and \( \text{partner}(\delta_x) \) is proximate during \( \delta_x \) then there is an operator tap \( \tau_x \) such that
   a) \( \text{card}(\tau_x) = \text{partner}(\delta_x) \), and
   b) \( \tau_x \approx \delta_x \).

2) If there is an operator tap \( \tau_x \) and reader(\( \tau_x \)) is a GU or AC reader \( R \) then \( R \) has a NFC ssn \( \delta_x \) such that
   a) \( \text{card}(\tau_x) = \text{partner}(\delta_x) \), and
   b) \( \tau_x \approx \delta_x \).
   c) If \( R \) is a GU reader then \( C \) is authentic.

Proof. (1) This follows from ‘secure proximate zone’.

(2) Since the operator visually verifies that the reader has successfully completed an NFC exchange (e.g. green light) \( \delta_x \) exists. By distance bounding and ‘secure proximate zone’ the exchange must have indeed been carried out with the operator’s card. If the reader is a GU the GU will check authenticity of the card, and the NFC exchange will fail if it is not (e.g. red light).

**Proposition 2 (Taps and reader sessions).**

1) If there are operator taps \( \tau_x \) and \( \tau_y \) and a GU session \((S, \gamma_{ini}, \gamma_{fin}, \ldots)\) such that \( \tau_x \approx \gamma_{ini} \) and \( \tau_y \approx \gamma_{fin} \) then there must be an operator session \((\tau_x, \tau_{mid}, \tau_y)\) for some \( \tau_{mid} \).

2) If there is an operator tap \( \tau_{ac} \) and an AC session \((\alpha_{mid}, \ldots)\) such that \( \tau_{ac} \approx \alpha_{mid} \) then there must be an operator session \((\tau_{ini}, \tau_{ac}, \ldots)\) for some \( \tau_{ini} \).

Proof. (1) By Def. \( 2 \) the operator will immediately abort the GU session if \( \tau_x \) wasn’t the first tap of a TAGA session \((\tau_x, \ldots)\). Since \( G \) receives the last NFC ssn the latter must be true. By definition of TAGA session of OP, clause (5), the next tap the operator will carry out is with the AC. By Def. \( 2 \) the tap is either successful or the operator will immediately abort \( G \)’s session. Since \( G \) receives the last NFC ssn the former must be true. But then \( \tau_{mid} \) exists as required.

(2) This follows from Def. \( 2 \).

**Guarantees of the NFC System:** The following are guarantees that the NFC system must provide to the GU, card, and AC.

**Definition 16 (Guarantees to GU).** Let \( N \) be a NFC system. We say \( N \) guarantees ‘authenticity of initial tap to a GU \( G \)’ if, whenever \( G \) has a session \((S, \gamma_{ini}, \ldots)\) then there is an authentic card \( C \) with a session \((\sigma_{ini}, \ldots)\) such that

1) \( \gamma_{ini} \approx \sigma_{ini} \) and \( msg(\gamma_{ini}) = msg(\sigma_{ini}) \), and
2) \( C \) is proximate to \( G \) during \( \sigma_{ini} \).

We say \( N \) guarantees ‘authenticity of final tap to a GU \( G \)’ if, whenever \( G \) has a session \((S, \gamma_{ini}, \gamma_{fin}, \ldots)\) then there is an authentic card \( C \) with a session \((\sigma_{ini}, \sigma_{mid}, \sigma_{fin})\) such that

1) \( \gamma_{ini} \approx \sigma_{ini} \) and \( msg(\gamma_{ini}) = msg(\sigma_{ini}) \),
2) \( \gamma_{fin} \approx \sigma_{fin} \) and \( msg(\gamma_{fin}) = msg(\sigma_{fin}) \), and
3) \( C \) is proximate to \( G \) during \( \sigma_{ini} \) and \( \sigma_{fin} \).

**Definition 17 (Guarantees to Card).** Let \( N \) be a NFC system. We say \( N \) guarantees ‘authenticity of initial tap to a card \( C \)’ if, whenever \( C \) has a session \((\sigma_{ini}, \ldots)\) then there is some GU \( G \) with a session \((S, \gamma_{ini}, \ldots)\) such that

1) \( \gamma_{ini} \approx \sigma_{ini} \) and \( msg(\gamma_{ini}) = msg(\sigma_{ini}) \), and
2) \( C \) is proximate to \( G \) during \( \sigma_{ini} \).

We say \( N \) guarantees ‘authenticity of mid tap to AC with \( C \)’ if, whenever \( C \) has a session \((\sigma_{ini}, \sigma_{mid}, \ldots)\) and \( \text{partner}(\sigma_{mid}) \) is an AC \( A \) then \( A \) has a session \((\alpha_{mid}, \ldots)\) such that

\( \alpha_{mid} \approx \sigma_{mid} \) and \( msg(\alpha_{mid}) = msg(\sigma_{mid}) \).

**Definition 18 (Guarantees to AC).** Let \( N \) be an NFC system. We say \( N \) guarantees ‘proximity of NFC peer to an AC \( A \)’ if, whenever an AC \( A \) has a session \((\alpha_{mid}, \ldots)\) then \( \text{partner}(\alpha_{mid}) \) is proximate to \( A \) during \( \alpha_{mid} \).

We say \( N \) guarantees ‘authenticity of mid tap to an authentic card to an AC \( A \)’ if, whenever \( A \) has a session \((\alpha_{mid}, \ldots)\) then \( \text{partner}(\alpha_{mid}) \) is an authentic card \( C \) then \( C \) has a session \((\sigma_{ini}, \sigma_{mid}, \ldots)\) such that

\( \alpha_{mid} \approx \sigma_{mid} \) and \( msg(\alpha_{mid}) = msg(\sigma_{mid}) \).

**Lemma 3.** Let \( N \) be an NFC system, and \( M \) a set of process measures such that \( N \) implements distance bounding and the guarantees to GU, card, and AC of Def. 16, 17, 18 and \( M \) guarantees ‘secure proximate zone’. Then \( N \) under \( M \) guarantees Channel Authenticity.

Proof. Guarantee for GU: Assume \( G \) has a session \((S, \gamma_{ini}, \gamma_{fin}, \ldots)\). Then by ‘authenticity of final tap to \( G \)’ there is an authentic card \( C \) with a session \((\sigma_{ini}, \sigma_{mid}, \sigma_{fin})\) such that the NFC ssns and exchanged messages are matching.
i.e.: \( \gamma_{\text{ini}} \leftrightarrow \sigma_{\text{ini}}, \ \gamma_{\text{fin}} \leftrightarrow \sigma_{\text{fin}}, \ \text{msg}(\gamma_{\text{ini}}) = \text{msg}(\sigma_{\text{ini}}) \), and \( \text{msg}(\gamma_{\text{fin}}) = \text{msg}(\sigma_{\text{fin}}) \). Moreover, \( \alpha \) is proximate to \( G \) during \( \sigma_{\text{ini}} \) and \( \sigma_{\text{fin}} \).

By Prop. \( \text{I}(1) \) there are successful operator taps \( \tau_{\text{ini}}, \ \tau_{\text{fin}} \) such that \( \text{card}(\tau_{\text{ini}}) = C \) and \( \tau_{\text{ini}} \approx \gamma_{\text{ini}} \), and \( \text{card}(\tau_{\text{fin}}) = C \) and \( \tau_{\text{fin}} \approx \gamma_{\text{fin}} \), respectively. Then by Prop. \( \text{I}(2) \) there is an operator with a session \( (\tau_{\text{ini}}, \tau_{\text{mid}}, \tau_{\text{fin}}) \) for some \( \tau_{\text{mid}} \).

Further, by definition of OP session we obtain \( \text{reader}(\tau_{\text{mid}}) = A \) for some AC \( A \) and \( \text{card}(\tau_{\text{mid}}) = C \). Hence, by Prop. \( \text{I}(2) \) \( A \) has a successful NFC ssn \( \alpha_{\text{ac}} \) such that \( \text{partner}(\alpha_{\text{ac}}) = C \) and \( \tau_{\text{mid}} \approx \alpha_{\text{ac}} \). Let \( \sigma_{\text{ac}} \) be defined by \( \alpha_{\text{ac}} \leftrightarrow \sigma_{\text{ac}} \). \( \sigma_{\text{ac}} \) takes place after \( \gamma_{\text{ini}} \) (and hence \( \sigma_{\text{ini}} \)) and before \( \gamma_{\text{fin}} \) (and hence \( \sigma_{\text{fin}} \)). Hence, we conclude that \( \sigma_{\text{ac}} = \sigma_{\text{mid}} \). Then by ‘authenticity of mid tap with AC to \( C \) \( A \) must have a session \( (\alpha_{\text{mid}}, \ldots) \) and \( \text{msg}(\alpha_{\text{mid}}) = \text{msg}(\sigma_{\text{mid}}) \). Finally, by definition of session of a card it is straightforward to check that the messages of the \( A \) session match those of the \( G \) session.

**Guarantee for AC:** Assume \( A \) has a session \( (\alpha_{\text{mid}}, \ldots) \). Then by ‘proximity of NFC peer to \( A \)’ partner(\( \alpha_{\text{mid}} \), say \( C \), is proximate. Then by Prop. \( \text{I}(1) \) there is a successful operator tap \( \tau_{\text{ac}} \) such that \( \tau_{\text{ac}} \approx \alpha_{\text{mid}} \) and \( \text{card}(\alpha_{\text{ac}}) = C \). Then by Prop. \( \text{I}(2) \) there is an operator with a session \( (\tau_{\text{ac}}^{\text{ini}}, \tau_{\text{ac}}^{\text{mid}}, \tau_{\text{ac}}^{\text{fin}}) \) for some \( \tau_{\text{ac}}^{\text{ini}} \). By definition of OP session \( \text{reader}(\tau_{\text{ac}}^{\text{ini}}) \) is a GU \( G_{\text{ac}} \), and \( \text{card}(\tau_{\text{ac}}^{\text{ini}}) = C \).

By Prop. \( \text{I}(2) \) \( G_{\text{ac}} \) has a successful NFC ssn \( \gamma_{\text{ac}}^{\text{ini}} \) such that \( \text{partner}(\gamma_{\text{ac}}^{\text{ini}}) = C \), \( \tau_{\text{ac}}^{\text{fin}} \approx \gamma_{\text{ac}}^{\text{ini}} \), and \( C \) is authentic. Let \( \alpha_{\text{ac}}^{\text{ini}} \) be defined by \( \gamma_{\text{ac}}^{\text{ini}} \leftrightarrow \sigma_{\text{ac}} \).

Since \( C \) is authentic by ‘authenticity of mid tap with authentic card to \( A \)’ \( C \) has a session \( (\sigma_{\text{ini}}, \sigma_{\text{mid}}, \ldots) \) such that \( \alpha_{\text{ac}}^{\text{ini}} \leftrightarrow \sigma_{\text{ac}} \) and \( \text{msg}(\alpha_{\text{ac}}^{\text{ini}}) = \text{msg}(\sigma_{\text{mid}}) \). By ‘authenticity of first tap to \( C \)’ there is some GU \( G \) with a session \( (S, \gamma_{\text{ini}}, \ldots) \) such that \( \gamma_{\text{ini}} \leftrightarrow \sigma_{\text{ini}} \), \( \text{msg}(\gamma_{\text{ini}}) = \text{msg}(\sigma_{\text{ini}}) \), and \( C \) is proximate to \( G \) during \( \sigma_{\text{ini}} \). By definition of session of a card we also obtain that the messages of \( \alpha_{\text{mid}} \) and \( \gamma_{\text{ini}} \) are matching.

Moreover, by Prop. \( \text{I}(1) \) there is a successful operator tap \( \tau_{\text{ini}} \) such that \( \text{card}(\tau_{\text{ini}}) = C \) and \( \tau_{\text{ini}} \approx \gamma_{\text{ini}} \). Hence, it only remains to show that \( \tau_{\text{ini}} \approx \tau_{\text{ini}}^{\text{ac}} \). To the contrary assume this not to be the case. Then by definition of OP session, clause (5) \( \tau_{\text{ini}} < \tau_{\text{ini}}^{\text{ac}} \), and hence \( \sigma_{\text{ini}} < \sigma_{\text{ini}}^{\text{ac}} \). But this leads to a contradiction: since \( \tau_{\text{ini}} \approx \sigma_{\text{ini}} \) and \( \sigma_{\text{ini}} \) immediately precedes \( \sigma_{\text{ini}}^{\text{ac}} \) on \( C \), we must have \( \sigma_{\text{ini}}^{\text{ac}} < \sigma_{\text{ini}} \).

**Lemma 4.** \( N_{\text{GU}} \) and \( N_{\text{OP}} \) implement distance bounding and meet the guarantees of Def. \( \text{I}(6) \) \( \text{I}(7) \) \( \text{I}(8) \).

**Proof.** We only provide the argument for \( N_{\text{GU}} \). The proof for \( N_{\text{OP}} \) is analogous just based on an argument based in public key authentication instead. Distance bounding is given as explained in Section \( \text{I}(4) \).

Guarantees to GU: At the first tap the GU reader runs an AKE protocol based on \( K_{\text{GC}} \) shared between the GU and the authentic card. Moreover, it will run a distance bounding protocol to ensure that the co-owner of \( K_{\text{GC}} \) is close by. The communication is secured by the established session key, say \( K \). At the third tap the GU reader runs an AKE protocol based on \( K \), including distance bounding to ensure the co-owner of \( K \) is close by. This binds the third tap to the first as required.

Guarantees to card: At the initial tap the card runs an AKE protocol based on \( K_{\text{GC}} \) shared only with the GU. Since the GU will only communicate with a card when it can successfully prove its proximity, the card knows that if it has a successful first NFC ssn then it communicates with a proximate GU. Again the communication itself is secured by the established session key.

The mid tap will be protected by a key established via the basic DH exchange. Hence, if the mid tap is indeed carried out with an authentic AC then by Ass. \( \text{I} \) the communication is secured and the messages are matching.

Guarantees to AC: ‘Proximity’: This is guaranteed by the distance bounding protocol, and because the communication is secured by DH such that the owner of the DH public key is proximate. Authenticity when the tap is carried out with an authentic card follows because the communication is secured, and the card only accepts unauthenticated communication as part of its mid tap.

**Proofs of Section \( \text{III}(5) \)**

**Proof of Theorem \( \text{I} \)** To undermine a T AGA instance an attacker has to compromise channel authenticity. To this end the attacker either needs to undermine authenticity of the card, compromise the local GU operator, or infiltrate in person the secure zone during turnaround. For N-OP: Even if the attacker obtains a public/private key pair and can prepare a counterfeit card, they will still need to swap it with the operators card. For N-GU: Even if they obtain a master key (and update ability) they still need to swap the card within the GU.

**APPENDIX E**

**RELATING TO SECTION \( \text{IV} \)**

**Proof of Theorem \( \text{J} \)** This is straightforward to check.

**Proof of Theorem \( \text{K} \)** This is straightforward from the definitions.

**Proof of Theorem \( \text{L} \)** Assume a T AGA process between \( G_{\text{L}} \) and \( A_{\text{L}} \) at \( L \).

If \( G_{\text{L}} \) has a session \( (S, A, K) \) then by key confirmation someone knows the key. This must be an honest party or the attacker. If the attacker does not know \( K \) then agreement is guaranteed, and hence, \( A \) has a matching session at the same location as required. If the attacker knows \( K \) then by Lemma \( \text{I} \) \( A \) must have a LTKC. By ‘agreement of AC domain’ \( A \) must be of the same airline and type as \( A_{\text{L}} \).

If \( A_{\text{L}} \) has a session \( (S, G, K, c) \) then by key confirmation someone knows the key. The first case is as above. If the attacker knows \( K \) then by Lemma \( \text{I} \) \( G \) must have a LTKC. By certificate verification \( G \) is a GU of the local airport.

**Proof of Theorem \( \text{M} \)** Assume a T AGA process between \( G_{\text{L}} \) and \( A_{\text{L}} \) at \( L \).

If \( G_{\text{L}} \) has a session \( (S, A, K) \) and the attacker knows \( K \) then the attack will be detected and the session aborted, or
$A_L$ has a TAGA session $(S, G, K', c)$ for some $G'$, $K'$ such that the attacker knows $K'$. In the latter case by Lemma 1 $G'$ must have a LTTC. By certificate verification $G$ is a GU of the local airport. If the attacker does not know $K$ then the usual argument applies.

If $A_L$ has a TAGA session $(S, G, K, c)$ and the attacker knows $K$ then by Lemma 1 $G$ must have a LTTC. By certificate verification $G$ is a GU of the local airport. Otherwise the usual argument applies.

**Proof of Lemma 2** Let $G$ be a GU with a session $(S, A, K)$ at parking slot $L$, and assume $G$ has sent the challenge. Say $G$ obtains the correct answer. We may show that the attacker does not know $K$ unless $AC(L)$ has a compromised session on $S$.

Let $A_L = AC(L)$. Only $A_L$ could have known the nonce, and sent it on. Hence, $A_L$ has a session $(S, G', K', c)$ for some $G'$, $K'$ during which it has responded to the challenge. If the attacker knows $K'$ then nothing has to be proved. If the attacker does not know $K'$ then $A_L$ has the session with an honest party, who would not forward $A_L$’s reply to $G$. Hence $K = K'$. And hence, the attacker does not know $K$ as required.

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**ACKNOWLEDGMENT**

This work has been conducted within the ENABLE-S3 project that has received funding from the ECSEL Joint Undertaking grant agreement no 692455. This joint undertaking receives support from the European Union’s Horizon 2020 Research and Innovation Programme and Austria, Denmark, Germany, Finland, Czech Republic, Italy, Spain, Portugal, Poland, Ireland, Belgium, France, Netherlands, United Kingdom, Slovakia, and Norway.

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