”ALEXANDRU-IOAN CUZA” UNIVERSITY IAȘI

FACULTY OF COMPUTER SCIENCE

BACHELOR’S THESIS

Consequences of using temporary variables in RFID authentication

proposed by

Andrei-Alexandru Patrașcan

Session: july, 2025

Scientific coordinator

Prof. Dr. Țiplea Ferucio Laurențiu

”ALEXANDRU-IOAN CUZA” UNIVERSITY IAȘI

FACULTY OF COMPUTER SCIENCE

Consequences of using temporary variables in RFID authentication

Andrei-Alexandru Patrașcan

Session: july, 2025

Scientific coordinator

Prof. Dr. Țiplea Ferucio Laurențiu

Anexa II

Avizat,

Îndrumător Lucrare de Licență

Prof. Dr. Țiplea Ferucio Laurențiu.

Data: ..... Semnătura: .....

Declarație privind autenticitatea conținutului lucrării de licență

Subsemnatul **Patrașcan Andrei-Alexandru** domiciliat în **România, jud. Bacău, com. Filipești, sat Hârlești, str. Zorilor, nr. 180**, născut la data de **22 martie 1999**, identificat prin CNP **1990322046190**, absolvent al **Universității „Alexandru Ioan Cuza" din Iași, Facultatea de Informatică** specializarea **Informatică**, promoția 2025, declar pe propria răspundere, cunoscând consecințele falsului în declarații în sensul art. 326 din Noul Cod Penal și dispozițiile Legii Educației Naționale nr. 1/2011 art. 143 al. 4 și 5 referitoare la plagiat, că lucrarea de licență cu titlul **Consequences of using temporary variables in RFID authentication** elaborată sub îndrumarea dlui **Prof. Dr. Țiplea Ferucio Laurențiu**, este autentică, îmi aparține și îmi asum conținutul său în întregime.

De asemenea, declar că sunt de acord ca lucrarea mea de licență să fie verificată prin orice modalitate legală pentru confirmarea autenticității, consimțind inclusiv la introducerea conținutului său într-o bază de date în acest scop. Declar că lucrarea de față are exact același conținut cu lucrarea în format electronic pe care profesorul îndrumător a verificat-o prin intermediul software-ului de detectare a plagiatului.

Am luat la cunoștință despre faptul că este interzisă comercializarea de lucrări științifice în vederea facilitării falsificării de către cumpărător a calității de autor al unei lucrări de licență, de diplomă sau de disertație și în acest sens declar pe proprie răspundere că lucrarea de față nu a fost copiată, ci reprezintă rodul cercetării pe care am întreprins-o.

Data: ..... Semnătura: .....

Anexa III

Declarație de consimțământ

Prin prezenta declar că sunt de acord ca lucrarea de licență cu titlul „**Consequences of using temporary variables in RFID authentication**”, codul sursă al programelor și celelalte conținuturi (grafice, multimedia, date de test, etc.) care însoțesc această lucrare să fie utilizate în cadrul Facultății de Informatică.

De asemenea, sunt de acord ca Facultatea de Informatică de la Universitatea „Alexandru-Ioan Cuza” din Iași, să utilizeze, modifice, reproducă și să distribuie în scopuri necomerciale programele-calculator, format executabil și sursă, realizate de mine în cadrul prezentei lucrări de licență.

Absolvent **Andrei-Alexandru Patrașcan**

Iași, data: ..... Semnătura: .....

Contents

Motivation

The choice towards studying RFID schemes and their security came for multiple reasons.

This technology is widely adopted in various industries and in a continuous advancement, meaning it is of prime importance that secure and private protocols are implemented for it. The applications for this fascinating technology are vast, they provide near-instant authentication for multiple tags at the same time, meaning it can be used in the medical field, for supply chains, in the automotive and construction industry and where it all started, in a military context. They provide access control from authentication of staff to providing access to ski lifts. With this rapid deployment of this technology, multiple issues have emerged. Solid protocols for RFID would help in establishing a productive and secure environment.

A typical RFID scheme is in a context where achieving security properties is difficult. The tags come with multiple constraints like processing power and limited memory and some of them can only work when interacting with a reader. This means that the RFID protocols need to strike a balance between lightness of operations and a solid security parameter. This balancing act means that mature and proven cryptographic primitives are not always available, which sparked my interest in this study domain. The tags are also cheap devices that are not tamper-proof, meaning new difficulties in developing solid protocols concerning how memory is used.

Lastly the development of RFID schemes often primarily focus on the security of the schemes while the privacy takes a secondary role, this also motivated the creation of this work.

All these limitations and the possible applications and directions of study of RFID schemes lead to a challenging but rewarding field of study.

Introduction

In a world that grows more and more a reliability on smart devices the need for secure and private protocols grows with it. One such technology that makes this possible is RFID. RFID is the acronym of **Radio Frequency Identification** and it designates a wireless technology that uses radio signals aiming to identify objects and persons by the means of devices (tags) attached to them.

During World-War II, the British wanted to distinguish between enemy and their own returning aircraft. To achieve this, they placed transponders on their aircraft which would respond to queries from the base stations. This was called the Identity Friend or Foe (IFF) system, which is considered to be the first use of RFID.

Since then RFID technology has been applied to a number of technical and scientific fields. In medicine RFID tags are used in blood transfusion and analysis. Patients can wear a RFID tag attached to a wristband that contains information about their medical attributes. A RFID reader scans the tags attached to blood bags and finds the appropriate one for a specific patient.

In the aeronautics industry, RFID tags are used for the supply chain. Boeing, for instance, tags ship crates containing aeronautical components. An advance report is sent to the depots regarding the contents of these tags and the information is later verified on delivery.

In the automotive industry, the tags can be attached to parts of a car and tracked during assembly. Each customer has their own preferences for their car and RFID tags can be used to track components and avoid incorrect placements.

RFID also has many applications in the construction industry [6], from automated tracking of pipe spools to tracking the location of buried assets. The tags can serve the purpose of identifying if a valve is the correct one, at the correct pressure and in the correct location.

This work covers a mutual identification RFID scheme and studies primarily the

privacy property of it. The contribution of this thesis consists of presenting how an adversary would interact and break privacy in a multitude of circumstances. These conditions are determined by the choice and capabilities of the used tags.

The structure is as follows: the first chapter presents the necessary theoretical material about RFID schemes and classes of adversaries. The second chapter covers the protocol to be studied. The third chapter shows how an attacker interacts with a scheme for different classes of tags and provides the theoretical proofs. Lastly the forth chapter presents the case study on the attacks from chapter 3 for the block-order-modulus protocol, the effects on privacy and protocol development. It shows how the claimed security properties do not hold in the context of tag corruption.

Use of AI

The short following section covers the use of artificial intelligence. AI has had major impact on the educational process and a section presenting the use of this tool contributes to the work's academic integrity.

The development of this work included the use of AI in one regard, that of strictly consulting on the available works relevant to the subject at hand. This has been done for the purpose of achieving a holistic view of the subject.

Chapter 1

Security and Privacy in Vaudenay's RFID model

1.1 RFID Schemes

A typical RFID system includes three components: a coil (or antenna), a transceiver (with a decoder) and a transponder (a radio-frequency tag) embedded with unique information. The antenna emits radio signals in order to activate the tag and to read or write data on it. Antennas establish the communication between the transceiver and the tags. They can be packaged with the transceiver and the decoder in order to become a reader.

The tags are passive transponders identified by a unique ID. Their technical parameters often are: memory, power supply, shape, size and the presence of a microprocessor. For many applications the tags need to be very small and cheap so their attributes are deeply constrained. A tag most often:

- is passive: because it has no batteries it can operate only when queried by the reader and can only respond for a short time after;
- has limited memory: a few kilobits of memory;
- has limited computational ability, can only perform basic calculations: hash calculations [7], pseudorandom generation [8], symmetric encryption [9]. Some elliptic-curve arithmetic and public-key cryptography may fit, but remain expensive so far;

- provides no physical security: each tag can be opened (corrupted) and thus revealing its memory;
- communicates at up to a fixed distance: the tag has a range of a few meters.

In RFID, *Moore's law* cannot be directly applied. In fact, the main goal of RFID transponders producers is to keep prices down and so the performance takes a secondary, less important role.

The reader is composed by one or more transceivers and a backend processing system (sometimes in the literature the reader denotes just the transceiver). The reader is able to accommodate multiple tags at the same time although a high number of them can lead to substantial delays for authentication.

The server is the component that handles the complex cryptographic calculations and eases the load on readers whenever possible. The traditional protocols included fixed reader positions and assumed secure (wired) communication. However in practical applications the communication between server and reader is also done via *Radio-Frequency Signals*.

RFID protocols are used most often for two goals: to identify tags (by recovering their unique ID) and to authenticate tags (to make sure a tag is legitimate, i.e. registered in the database).

A frequently used and accepted model for security and privacy for RFID schemes is *Vaudenay's model*, proposed in [2].

RFID schemes: A RFID scheme is formed by a triple:

- a setup scheme for the reader: **SetupReader(λ)**: generates a pair of keys: K_P and K_S for the reader depending on the security parameter λ. The public key is released to the public and the secret key is stored on the reader database.

-a setup scheme for the tag: **SetupTag(ID)** $\rightarrow$ **(K, S)**: K is the tag's secret and S denotes the initial state of the tag. Furthermore if the tag is legitimate the values ID and K are stored on the memory of the reader.

-an interactive protocol: **Ident**, between the reader and the tag, at the end of communication the reader will output a value ($\perp$, correct ID, incorrect ID) indicating the success of an authentication. For mutual authentication schemes the tag returns ok for a legitimate reader or $\perp$ (falsum) otherwise.

Formally: $Ident[\mathcal{T}_{ID} : S; \mathcal{R} : sk_{\mathcal{R}}, DB; * : pk_{\mathcal{R}}] \rightarrow [\mathcal{T}_{ID} : out_{\mathcal{T}_{ID}}; \mathcal{R} : out_{\mathcal{R}}]$. This is interpreted as: the identification protocol "Ident" starts with tag $\mathcal{T}_{ID}$ from state S, the

reader R having the secret key $sk_{\mathcal{R}}$ and the access to database DB, and public key $pk_{\mathcal{R}}$ being shared to both parties. After a successful computation it leads to $\mathcal{T}_{ID}$ returning $out_{\mathcal{T}_{ID}}$ and $\mathcal{R}$ yielding $out_{\mathcal{R}}$.

The *correctness* of a RFID scheme means that after each successful execution of the interactive protocol between the reader and a legitimate tag, the reader outputs the tag's identity with overwhelming probability. For mutual authentication schemes correctness also includes that the tag outputs ok with overwhelming probability for a legitimate reader.

1.2 Adversaries and oracles

Adversaries: An adversary is often characterised by what action they can perform, i.e. the oracles they can query, the goals of their attack (also known as the game they are playing) and by the way they can interact with a system. An adversary is a PPT (probabilistic polynomial time) algorithm.

A tag can be either *drawn* or *free*, this means that it is in reach or not of the adversary. A virtual tag is a temporary identifier for a tag when it is drawn.

Below are the 8 oracles defined in Vaudenay's model:

1. $CreateTag^b$*(ID)*: created a new tag, legitimate (b=1) or illegitimate (b=0) with the unique ID. This oracle uses SetupTag(ID) and if the tag is legitimate then the reader updates its database. The reader searches the database in order to authenticate tags.

2. *DrawTag(*$distr$*)* $\rightarrow (vtag_1, b_1, ..., vtag_n, b_n)$: selects at random n tags following the distribution $distr$ and draws them to be used by the adversary. The oracle provides an array of virtual identifiers $(vtag_1, ..., vtag_n)$ as the adversary needs to reference them. and the bits b_k meaning authentic or not.

A hidden table Γ is kept by the oracle containing the association between the temporary identifiers and the real IDs. This will be revealed after an attack experiment to determine if it was successful.

3. *Free(vtag)*: the vtag is eliminated from the set of drawn tags (that the attacker uses). This makes it unreachable to the adversary.

4. *Launch* $\rightarrow \pi$: the reader launches a new protocol instance π.

5. *SendReader(*m, π*)* $\rightarrow (m')$: sends the reader a message m and receives as response the message m' as part of the protocol π.

6. *SendTag(*m, π*)* $\rightarrow (m')$: sends the tag a message m and receives as response the

message m'. If m is empty the response is the first message transmitted by the tag for a given protocol.

7. *Result(π)*: After the protocol has ended on the reader side, the oracle outputs 1 if the tag was authenticated and 0 otherwise.

8. *Corrupt(vtag)*: Outputs the current internal state of the tag temporary named vtag.

1.3 Classes of adversaries

Depending on how these oracles are used/the capabilities of the attacker, four kinds of adversary are defined:

1. *STRONG*: class of adversary who have access to all the oracles, with no limitations on how the Corrupt(vtag) oracle is used. Thus a strong adversary can get the state of a tag and still query other oracles for tag $\mathcal{T}$.

2. *DESTRUCTIVE*: adversaries who never use a tag after a Corrupt(vtag) oracle is called, i.e. the tag is destroyed.

3. *FORWARD*: adversaries that once they call Corrupt(vtag) oracle, can only call the same oracle i.e the corruption of tags are left at the end of the attacking phase.

4. *WEAK*: adversaries who have no access to the Corrupt(vtag) oracle, the internal memory of the tags remains a secret.

Another way to consider adversaries is by their access to the Result(π) oracle. If they have it, they are considered to be *wide* adversaries, otherwise they are called *narrow*. Since the access to the Corrupt() and the Result() oracles is quite orthogonal, four new distinct adversarial models are distinguished: *narrow-strong*, *narrow-destructive*, *narrow-forward* and *narrow-weak*.

1.4 Security

The security definition of the *Paise-Vaudenay model* [11] encompasses attacks where the adversary aims to impersonate or forge a legitimate tag $\mathcal{T}$ or the reader $\mathcal{R}$.

Tag authentication: The definition of tag authentication is based on a security experiment $Exp^{\mathcal{T}-aut}_{\mathcal{A}_{sec}}$ where a strong adversary must make a legitimate reader $\mathcal{R}$ identify $\mathcal{T}_{ID}$. To exclude trivial attacks, the attacker $\mathcal{A}_{sec}$ must compute some of the protocol

messages, not just forward them from $\mathcal{T}_{ID}$ to $\mathcal{R}$ or corrupt $\mathcal{T}_{ID}$. $Exp^{\mathcal{T}-aut}_{\mathcal{A}_{sec}}$ = 1 denotes that $\mathcal{A}_{sec}$ wins the security experiment.

Consider an adversary in the class STRONG. They win if there is an instance of the protocol run by the reader where a legitimate tag is authenticated but done so when the specific steps of the protocol are followed out of order (interleaved). If the probability of the adversary to win is negligible then a RFID scheme is considered secure for tag authentication.

Definition 1: An RFID system achieves tag authentication if for every strong adversary $\mathcal{A}_{sec}$, probability Pr[$Exp^{\mathcal{T}-aut}_{\mathcal{A}_{sec}}$ = 1] is negligible.

For a mutual authentication scheme the same property also needs to be respected for the tag authenticating the reader.

Reader authentication: The definition of reader authentication is based on a security experiment $Exp^{\mathcal{R}-aut}_{\mathcal{A}_{sec}}$ where a strong adversary must impersonate $\mathcal{R}$ to a legitimate tag $\mathcal{T}_{ID}$. To exclude trivial attacks, the attacker $\mathcal{A}_{sec}$ must compute some of the protocol messages, not just forward them from $\mathcal{R}$ to $\mathcal{T}_{ID}$. $Exp^{\mathcal{R}-aut}_{\mathcal{A}_{sec}}$ = 1 denotes that $\mathcal{A}_{sec}$ wins the security experiment.

Definition 2: An RFID system achieves reader authentication if for every strong adversary $\mathcal{A}_{sec}$, probability Pr[$Exp^{\mathcal{R}-aut}_{\mathcal{A}_{sec}}$ = 1] is negligible.

1.5 Privacy

Vaudenay's notion of privacy captures anonymity and unlinkability and focuses on the privacy loss in the wireless link. It is based on the existence of a simulator $\mathcal{B}$, called a **blinder**, that can simulate the reader and the tags without knowing their secrets.

The simulation aspect of the blinder catches the case of an adversary that can't use the transmitted messages, they only know how the protocol interacts and the actual data traffic is simulated. By contrasting this attacker with an adversary that eavesdrops, denies or changes messages, several conclusions can be drawn about the leakage of data and the privacy of a protocol.

The privacy definition can be formalized by a privacy experiment $Exp^{prv-b}_{\mathcal{A}_{prv}} = b'$ defined by an adversary of class P, a security parameter s and $b \in_R \{0,1\}$. In the first phase of the experiment, the reader is initialized (using SetupReader(1^s)). The public key is available to $\mathcal{A}_{prv}$ and $\mathcal{B}$. $\mathcal{A}_{prv}$ interacts with the protocol according to its

constraints. If b = 1, all queries to Launch, SendReader, SendTag and Result oracles are handled by $\mathcal{B}$. Moreover, the blinder can surveil all the other oracles. In phase two, the adversary cannot call the oracles any longer but is given the hidden table Γ of the DrawTag oracle. Finally, $\mathcal{A}_{prv}$ returns bit b'.

Informally, $Pr[Exp^{prv-b}_{\mathcal{A}_{prv}}]$ denotes the probability that an adversary $\mathcal{A}_{prv}$ can guess the bit b, meaning whether they interact with the real oracles or through a blinder $\mathcal{B}$.

Definition 3: Let P be one of the adversary classes specified above. An RFID system is **P-private** if for every adversary $\mathcal{A}_{prv}$ of P there exists a probabilistic polynomial time algorithm $\mathcal{B}$ (blinder) such that the advantage $Adv^{prv}_{\mathcal{A}_{prv}} = |Pr[Exp^{prv-0}_{\mathcal{A}_{prv}} = 1] - Pr[Exp^{prv-1}_{\mathcal{A}_{prv}} = 1]|$ of $\mathcal{A}_{prv}$ is negligible. $\mathcal{B}$ simulates the oracles: Launch, SendReader, SendTag and Result to $\mathcal{A}_{prv}$ without having access to the reader's secret key or database. It is considered the all oracle queries $\mathcal{A}_{prv}$ makes and the responses received are also available to $\mathcal{B}$.

Privacy is defined by the ability of the adversary to infer relations about the identifiers of a tag from the protocol messages. If a scheme is resistant to all P-private adversaries (belonging to P class, with all P specific access) then the scheme achieves P-privacy.

An adversary $\mathcal{A}$ is *trivial* if there is a negligible difference between the chances of an adversary that interacts with the system to win and the chances of a blinded adversary.

All security and privacy notions defined in the Paise-Vaudenay model are linked the following way:

Strong	$\Rightarrow$	Destructive	$\Rightarrow$	Forward	$\Rightarrow$	Weak
$\Downarrow$		$\Downarrow$		$\Downarrow$		$\Downarrow$
Narrow-Strong	$\Rightarrow$	Narrow-Destructive	$\Rightarrow$	Narrow-Forward	$\Rightarrow$	Narrow-Weak

Remark: The following relation between them is clear: $Weak \subseteq Forward \subseteq Destructive \subseteq Strong$.

This means that if a particular class of privacy is proven to be impossible for a given set of parameters then the protocol can only achieve a weaker class. For example if destructive privacy is unachievable then the protocol can still be narrow-destructive private or forward private.

Chapter 2

Authentication in a RFID protocol

2.1 Introduction

The chosen paper's authentication [1] is presented in the following chapter. The protocol makes use of a diagonal block local transpose key matrix (DBLTKM) encryption algorithm for its property of expanding the key size of the encryption without the need of extensive resources. It assures a balance between security and lightness of operations. Another component is the self updating encryption order (SUEO) and its role is to boost security. Lastly a adaptive modulus (AM) algorithm is deployed to weaken the correlation between the plaintext and the ciphertext.

These three algorithms are used to form the block-order-modulus variable matrix encryption algorithm, dubbed the AM-SUEO-DBLTKM algorithm.

2.2 Protocol structure

Paper [1] proposes 3 corollaries based on block matrix properties and modulo operations that establish the basis for the primitives (A, B and C).

A. **Diagonal block local transpose key matrix (DBLTKM)**

For two square matrices A_1 and A_2: if $A_1 \times t_1$ mod(p) = c_1 and $A_2 \times t_2$ mod(p) = c_2 exist then:

$$\begin{pmatrix} A_1 & \\ & A_2 \end{pmatrix} \times \begin{pmatrix} t_1 \\ t_2 \end{pmatrix} mod(p) = \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

Updating the order of the first matrix along the main diagonal yields multiple key matrices of different sizes thus expanding the key size. For the fact that it uses

2 matrices A_1 and A_2 as its building blocks the tag does not need to keep multiple separate keys in its memory. In order to expand the potential ways of building the key matrix, the transpose of A_1 and of A_2 are also being used as building blocks along the main diagonal.

B. **Self updating encryption order (SUEO)**

For 2 square matrices A_1 and A_2: if $A_1 \times t$ mod(p) = c_1 and $A_2 \times c_1$ mod(p) = c_2 exist and $A_2 \times t$ mod(p) = c_3 and $A_1 \times c_3$ mod(p) = c_4 exist then:

$$c_2 \neq c_4$$

Using the property of non-commutativity of matrices, one can change the order of the multiplications to get different ciphertexts. This change is equivalent to having multiple keys for encryption but with this result security can be improved without using additional storage space.

C. **Adaptive modulus (AM)**

For 2 square matrices A and B and $A \times B = I$ (identity matrix) mod(p) then:

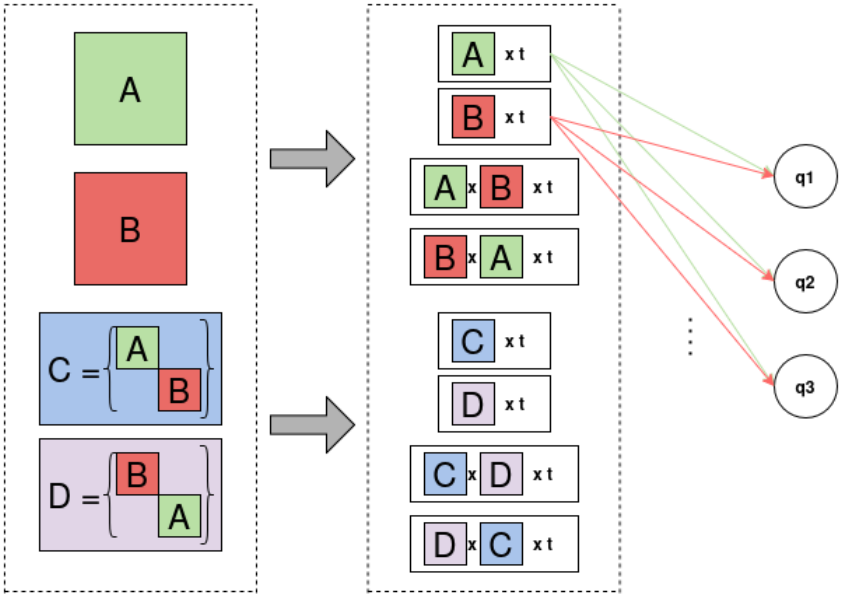
B is the modulus p-inverse matrix of A and the modulus q-inverse of A,

for a q integer divisor of p.

Thus the change in modulus still yields an inverse and the decryption process can still happen but the correlation between the ciphertext and the plaintext is weakened.

D. **AM-SUEO-DBLTKM**

The above three components can be used for an encryption and decryption algorithm. The following figure represents an example with two key matrices and three integer divisors of modulus p.



2.3 Specific steps of the authentication protocol

Notation of the authentication protocol

Notation	Meaning
N_t	Nonce generated by the tag
N_r	Nonce generated by the reader
S	Secret value
S_d	Secret value that determines the construction of the block key matrix
S_p	Secret value that determines the encryption order
S_c	Secret value that determines the selection of modulus
p	Modulus
q	q ∈ f(p), f(p) is the set of integer divisors of p
N	Total number of key matrices
Z_{DBLTKM}	Total number of elements in the DBLTKM index table
Z_{SUEO}	Total number of elements in the SUEO index table
Z_{AM}	Total number of elements in the AM index table
A, A_{new}	Initial and updated encryption matrices
B, B_{new}	Initial and updated decryption matrices

Table 2.1: Notation used in the description of the protocol

Protocol details

1. The reader sends a query to the tag. This activates tags without batteries.

2. The tag uses its internal pseudo-random number generator to get nonce N_t. After that the tag uses the encryption matrix A and the modulus p to encrypt $N_t||S$.

3. The tag sends the message E($N_t||S$, A, p) to the reader.

4. The reader decrypts E($N_t||S$, A, p) and obtains the secret S. If S can be found in its internal database, the reader has authenticated the tag successfully and accepted nonce N_t, else the protocol is stopped. After that, the reader generates nonce N_r and uses A and p to encrypt $N_r||S$.

5. The reader sends E($N_r||S$, A, p) to the server.

6. The server decrypts E($N_r||S$, A, p) and obtains secret S. A query on S means a successful authentication of the reader in which case the server accepts N_r. Contrarily the protocol is stopped. The server generates the new secret values S_d, S_p, S_c and uses A and p to encrypt $N_r||S_d||S_p||S_c$.

7. The server sends E($N_r||S_d||S_p||S_c$, A, p) to the reader.

8. The reader decrypts E($N_r||S_d||S_p||S_c$, A, p) and obtains N_r. If the received value N_r matches the saved value N_r then the reader authenticates the server. In this case the new secret values S_d, S_p, S_c are accepted, if not, the protocol is stopped. Afterwards the reader uses A and p to encrypt $N_t||S_d||S_p||S_c$.

9. The reader sends E($N_t||S_d||S_p||S_c$, A, p) to the tag.

10. The tag decrypts E($N_t||S_d||S_p||S_c$, A, p) and obtains N_t. If the value N_t received matches the saved value N_t then the tag authenticates the reader. Following that the new secret values S_d, S_p, S_c are accepted, if not, the protocol is stopped. Subsequently fresh protocol parameters are calculated: mod(S_d, Z_{DBLTKM}) to determine the construction of diagonal block key matrix, mod(S_p, Z_{SUEO}) to determine the encryption order, mod(S_c, Z_{AM}) to determine the choice of the new modulus. With the newly constructed key matrix A_{new}, new modulus q and encryption order, the tag encrypts $N_t + 1||ID$.

11. The tag sends E($N_t + 1||ID$, A_{new}, q) to the reader.

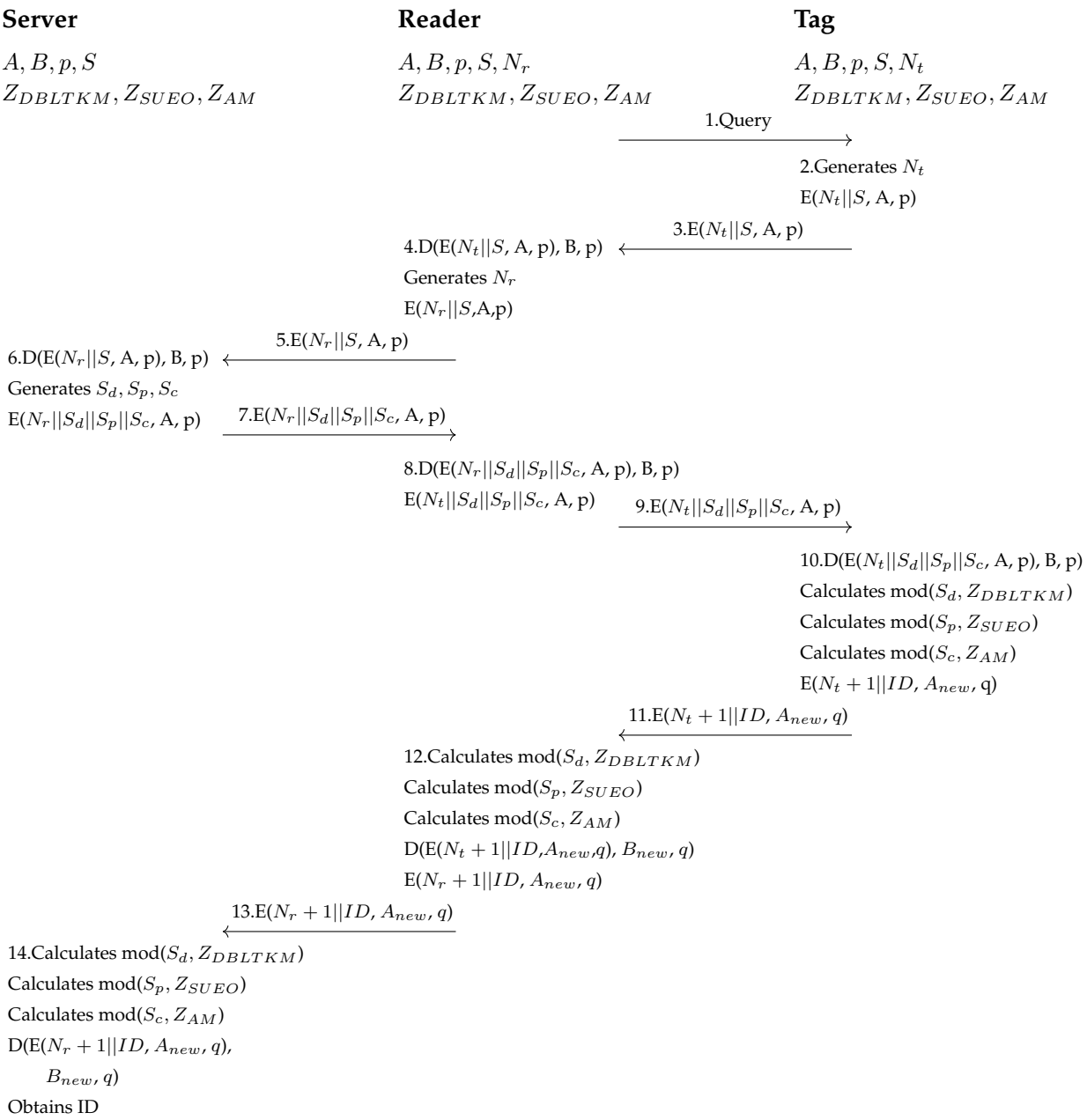
12. Reader calculates mod(S_d, Z_{DBLTKM}), mod(S_p, Z_{SUEO}), mod(S_c, Z_{AM}) itself. Then it decrypts E($N_t + 1||ID$, A_{new}, q) using the newly calculated B_{new} and q. If the received value N_t matches the saved value N_t, ID is obtained. The reader uses A_{new} and q to encrypt $N_r + 1||ID$.

13. The reader sends E($N_r + 1||ID$, A_{new}, q) to the server.

14. Server calculates mod(S_d, Z_{DBLTKM}), mod(S_p, Z_{SUEO}), mod(S_c, Z_{AM}) itself. It decrypts E($N_r + 1||ID$, A_{new}, q) using the newly calculated B_{new} and q. If the received value N_r matches the saved value N_r, the server obtains ID.

Protocol scheme

The two way AM-SUEO-DBLTKM-RFID authentication protocol



Chapter 3

The use of temporary variables

3.1 Temporary variables definition

A tag's memory can be classified in two ways: **permanent**/persistent or **temporary**/volatile. The permanent memory contains the state values of the tag, while the temporary memory is composed by temporary/volatile variables used in calculations. Temporary variables can be further split into local temporary variables: used for a single step of the protocol and global temporary variables: used to store values for a future step of the protocol.

As the definitions imply, the global temporary variables have a longer lifetime than local temporary variables. They are used to store information that is later verified against received values to aid in the process of authentication. The use of them needs to be done with great care as corruption of tags can occur and by that an adversary can access information that would thwart privacy.

3.2 Temporary state disclosure and its effects on privacy

Types of corruption: Under tag corruption the temporary tag state is disclosed depending on the concrete scenario. In general it is under one of the following cases:

1. corruption discloses *the full state*: the permanent and the temporary memory (this is referred as "Temporary State Disclosure")

2. corruption discloses *just the permanent state*, leaving the values in the temporary memory still a secret.

The vulnerability through corruption has been highlighted for the first time in

[10]. Later [3] extends the definition to cover PUF-based RFID protocols as well.

The subsequent section outlines the results of [10] and analyzes their relevance to Vaudenay's model.

Theorem 1: *There is no RFID system in Vaudenay's model that achieves both reader authentication and narrow-forward privacy under temporary state disclosure.*

This result is based on the following lemma:

Lemma 1: If every narrow-forward adversary $\mathcal{A}_{prv}$ has a blinder $\mathcal{B}$ such that $Adv^{prv}_{\mathcal{A}_{prv}}$ is negligible then $\mathcal{B}$ can be used for a blinded adversary $\mathcal{A}^{\mathcal{B}}_{sec}$ such that $Pr[Exp^{\mathcal{R}-aut}_{\mathcal{A}^{\mathcal{B}}_{sec}} = 1]$ is non-negligible.

Proof for Theorem 1: The definition of privacy requires the existence of a blinder such that there is no difference between an adversary that uses the protocol messages and a blinded adversary $\mathcal{A}^{\mathcal{B}}$. This is equivalent to an adversary that cannot distinguish between $\mathcal{B}$ and the real oracles. Lemma 1 states that if privacy is achieved there is such a blinder that can impersonate the reader with non-negligible probability. Thus, $\mathcal{B}$ contradicts reader authentication (Definition 2).

The result of Theorem 1 and the proof for Lemma 1 are deducted in the following:

Step 1. There is assumed that there is a scheme that achieves both reader authentication and narrow-forward privacy. This will lead to a contradiction.

Step 2. Narrow-forward privacy means an adversary $\mathcal{A}_{prv}$ and a blinded adversary $\mathcal{A}^{\mathcal{B}}_{prv}$ with no discernible advantage between them. $\mathcal{A}^{\mathcal{B}}_{prv}$ simulates the Launch, SendReader and SendTag oracles. The blinded adversary is used for an attacker for reader authentication, $\mathcal{A}^{\mathcal{B}}_{sec}$.

Step 3. The construction of $\mathcal{A}^{\mathcal{B}}_{sec}$ is shown in Algorithm 1 and the win condition for $\mathcal{A}^{\mathcal{B}}_{sec}$ is established (Eq. 1 to be non-negligible).

The construction for a blinded adversary against reader authentication is presented in algorithm 1.

$\mathcal{A}^{\mathcal{B}}_{sec}$ uses the blinder as a black box to simulate the messages between the reader and the tag. $\mathcal{A}_{sec}$ succeeds if $\mathcal{T}_{ID}$ accepts $\mathcal{B}$ as reader $\mathcal{R}$. Formally to break reader authentication:

$Pr[Exp^{\mathcal{R}-aut}_{\mathcal{A}^{\mathcal{B}}_{sec}} = 1] = Pr[Ident[\mathcal{T}_{ID} : S_0^{\mathcal{T}_{ID}}; \mathcal{A}^{\mathcal{B}}_{sec} : -; * : pk_R] \rightarrow [\mathcal{T}_{ID} : real; \mathcal{A}^{\mathcal{B}}_{sec} : .]]$ (Equation 1) ($S_0^{\mathcal{T}_{ID}}$ denotes the initial tag state) needs to be non-negligible.

Algorithm 1 Adversary $\mathcal{A}_{sec}^{\mathcal{B}}$ against reader authentication

1: CreateTag(ID)
2: $vtag \leftarrow$ DrawTag(ID)
3: $\pi \leftarrow$ Launch() ▷ simulated by $\mathcal{B}$
4: $m_1 \leftarrow SendReader(-, \pi)$ ▷ simulated by $\mathcal{B}$
5: i $\leftarrow 1$
6: **while** $i < stepsOfProtocol$ **do**
7: $\quad m_{2i} \leftarrow SendTag(m_{2i-1}, vtag)$ ▷ simulated by $\mathcal{B}$
8: $\quad m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$ ▷ simulated by $\mathcal{B}$
9: $\quad i \leftarrow i + 1$
10: **end while**
11: $out_{\mathcal{T}_{ID}} \leftarrow SendTag(m_{final}, vtag)$ ▷ computed by $\mathcal{T}_{ID}$

Step 4. A proof that $\mathcal{A}_{sec}^{\mathcal{B}}$ has non-negligible odds to win the security game i.e. Eq. 1 is non-negligible. This is a proof by contradiction as well. Equation 1 being negligible (i.e. achieving reader authentication) means a non-negligible $p_{\perp}$ that $out_{\mathcal{T}_{ID}} = \perp$. The consequence is that $\mathcal{A}_{prv}$ has a non-negligible advantage in distinguishing the real oracles from the simulated ones, contradicting privacy.

The construction of $\mathcal{A}_{prv}$ is shown in Algorithm 2.

The adversary for privacy $\mathcal{A}_{prv}$ corrupts $\mathcal{T}_{ID}$ just before it receives the last message, m_{final}. Next, $\mathcal{A}_{prv}$ performs the computation $\mathcal{T}_{ID}$ would have done for m_{final}. A result of $out_{\mathcal{T}_{ID}} = real$ denotes that the protocol interacted with the real oracles (and the algorithm returns 0), otherwise the calls were made through $\mathcal{B}$ (and the algorithm returns 1).

$\mathcal{A}_{prv}$ is a narrow-forward adversary because during the experiment there were no Result(π) calls and once a Corrupt(vtag) was called no other oracle was queried.

Algorithm 2 Narrow-forward adversary $\mathcal{A}_{prv}$

CreateTag(ID)
$vtag \leftarrow$ DrawTag(ID)
$\pi \leftarrow$ Launch()
$m_1 \leftarrow SendReader(-, \pi)$
i $\leftarrow 1$
while $i < stepsOfProtocol$ **do**
    $m_{2i} \leftarrow SendTag(m_{2i-1}, vtag)$
    $m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$
    $i \leftarrow i + 1$
end while
$S^{\mathcal{T}_{ID}} \leftarrow$ Corrupt(vtag)
$out_{\mathcal{T}_{ID}} \leftarrow \mathcal{T}_{ID}(S^{\mathcal{T}_{ID}}, m_{final})$
if $out_{\mathcal{T}_{ID}} =$ real **then**
    return 0
else
    return 1
end if

What remains is to assess the odds of $\mathcal{A}_{prv}$ discerning between real/simulated oracles.

Firstly, for the case in which the adversary interacts with the real system/oracles, it follows from correctness that probability p_{real} of $out_{\mathcal{T}_{ID}}$ is overwhelming, meaning $Pr[Exp^{prv-0}_{\mathcal{A}_{prv}} = 1] = 1 - p_{real}$ is negligible. Secondly we consider the case with the blinder. From the assumption (there is reader authentication) $\mathcal{B}$ generates the last message such that $out_{\mathcal{T}_{ID}} = \perp$ with non-negligible probability $p_\perp$. Thus $Pr[Exp^{prv-1}_{\mathcal{A}_{prv}} = 1] = p_\perp$ is non-negligible. It follows that $Adv^{prv}_{\mathcal{A}_{prv}} = |1 - p_{real} - p_\perp|$ is non-negligible, thus a contradiction.

The contradiction means that the assumption was incorrect and $\mathcal{A}^{\mathcal{B}}_{sec}$ has non-negligible odds to win the security game.

Step 5. This adversary yields $Pr[Exp^{\mathcal{R}-aut}_{\mathcal{A}^{\mathcal{B}}_{sec}} = 1]$ non-negligible meaning that reader authentication is disproved. This means that the assumption at step 1 is false which means Theorem 1 is correct: there is no RFID system in Vaudenay's model that achieves both reader authentication and narrow-forward privacy under tempo-

rary state disclosure.

Below is shown how the narrow-forward adversary interacts with the tag to thwart reader authentication. This is an attack on security.

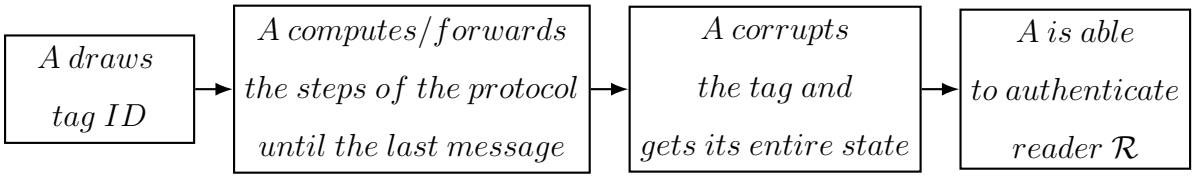


Figure 3.1: Temporary state disclosure attack

3.3 Corruption without temporary state disclosure

Another result from [10] is presented in this chapter. The result obtained above shows there are more assumptions to evaluate than previously considered in the context of tag corruption. A natural direction to follow up on is what level of privacy can be achieved if temporary state disclosure is not a factor. Thus, we study the case in which corruption discloses *just the permanent state*, leaving global and local temporary variables secret.

The previous result is built upon the fact that $\mathcal{A}_{prv}$ can learn the temporary state of a tag during the Ident Protocol. This permits $\mathcal{A}_{prv}$ to verify the last message of the protocol with the tag and due to reader authentication can distinguish between real oracles and a blinded environment. However if the corruption yields only the persistent state, the previous result might not hold.

Theorem 2: *There is no RFID system in Vaudenay's model that achieves both reader authentication and narrow-strong privacy under permanent state disclosure.*

The result of Theorem 2 is deducted in the following:

Step 1. There is assumed that there is a scheme that achieves both reader authentication and narrow-strong privacy. This will lead to a contradiction.

Step 2. Narrow-strong privacy means an adversary $\mathcal{A}_{prv}$ and a blinded adversary $\mathcal{A}_{prv}^{\mathcal{B}}$ with no discernible advantage between them.

$\mathcal{A}_{prv}^{\mathcal{B}}$ simulates the Launch, SendReader and SendTag oracles. The blinded adversary is used for an attacker for reader authentication, $\mathcal{A}_{sec}^{\mathcal{B}}$.

Step 3. The construction of $\mathcal{A}_{sec}^{\mathcal{B}}$ is shown in Algorithm 3 and the win condition for $\mathcal{A}_{sec}^{\mathcal{B}}$ is established (Eq. 2 to be non-negligible).

Algorithm 3 Adversary $\mathcal{A}_{sec}^{\mathcal{B}}$ against reader authentication

1: CreateTag(ID)
2: $vtag \leftarrow$ DrawTag(ID)
3: $S_0^{\mathcal{T}_{ID}} \leftarrow Corrupt(vtag)$
4: $\pi \leftarrow$ Launch() ▷ simulated by $\mathcal{B}$
5: $m_1 \leftarrow SendReader(-, \pi)$ ▷ simulated by $\mathcal{B}$
6: i $\leftarrow 1$
7: **while** $i < stepsOfProtocol$ **do**
8: $\quad m_{2i} \leftarrow SendTag(m_{2i-1}, vtag)$ ▷ simulated by $\mathcal{B}$
9: $\quad m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$ ▷ simulated by $\mathcal{B}$
10: $\quad i \leftarrow i + 1$
11: **end while**
12: $out_{\mathcal{T}_{ID}} \leftarrow SendTag(m_{final}, vtag)$ ▷ computed by $\mathcal{T}_{ID}$

$\mathcal{A}_{sec}$ succeeds if $\mathcal{T}_{ID}$ accepts m_{final} and returns $out_{\mathcal{T}_{ID}} = real$. It means that $\mathcal{T}_{ID}$ accepts $\mathcal{B}$ as reader $\mathcal{R}$. Formally to break reader authentication:

$Pr[Exp_{\mathcal{A}_{sec}^{B}}^{\mathcal{R}-aut} = 1] = Pr[Ident[\mathcal{T}_{ID} : S_0^{\mathcal{T}_{ID}}; \mathcal{A}_{sec}^{\mathcal{B}} : -; * : pk_R] \rightarrow [\mathcal{T}_{ID} : real; \mathcal{A}_{sec}^{\mathcal{B}} : .]]$

(Equation 2) ($S_0^{\mathcal{T}_{ID}}$ denotes the initial tag state) needs to be non-negligible.

Step 4. A proof that $\mathcal{A}_{sec}^{\mathcal{B}}$ has non-negligible odds to win the security game i.e. Eq. 2 is non-negligible. This is a proof by contradiction as well. Equation 2 being negligible means a non-negligible probability that $out_{\mathcal{T}_{ID}} = \perp$. Let p_t be that probability. The consequence is that $\mathcal{A}_{prv}$ has a non-negligible advantage in distinguishing the real oracles from the simulated ones, contradicting privacy.

The construction of $\mathcal{A}_{prv}$ is shown in Algorithm 4.

Notation is:

$S_0^{\mathcal{T}_{ID}}$ denotes the initial (0) state S of tag $\mathcal{T}_{ID}$;

q_t denotes the (expected) number of SendTag queries specified by the Ident protocol;

$\mathcal{T}_{ID}(state, message)$ denotes the computation done by $\mathcal{T}_{ID}$ when given message on specified state.

$\mathcal{A}_{prv}$ is a narrow-strong adversary because during the experiment there were no Result(π) calls and after Corrupt(vtag) was called the adversary continued to use the tag.

Algorithm 4 $\mathcal{A}_{prv}$ against narrow-strong privacy

1: CreateTag(ID)
2: $vtag \leftarrow$ DrawTag(ID)
3: $S_0^{\mathcal{T}_{ID}} \leftarrow Corrupt(vtag)$
4: $\pi \leftarrow$ Launch()
5: $m_1 \leftarrow SendReader(-, \pi)$
6: $t \in \{1, ..., q_t\}$
7: i $\leftarrow 1$
8: **while** $i < t$ **do**
9: $\quad (S_{i+1}^{\mathcal{T}_{ID}}, m_{2i}) \leftarrow \mathcal{T}_{ID}(S_i^{\mathcal{T}_{ID}}, m_{2i-1})$
10: $\quad m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$
11: $\quad i \leftarrow i + 1$
12: **end while**
13: $out_{\mathcal{T}_{ID}} \leftarrow \mathcal{T}_{ID}(S_t^{\mathcal{T}_{ID}}, m_{final})$
14: **if** $out_{\mathcal{T}_{ID}} =$ real **then**
15: $\quad$ **return** 0
16: **else**
17: $\quad$ **return** 1
18: **end if**

In this context the Corrupt(vtag) call (line 3) yields only the persistent state $S_0^{\mathcal{T}_{ID}}$ of $\mathcal{T}_{ID}$. $\mathcal{A}_{prv}$ guesses t (step 6) and simulates the tag in the Ident protocol until the reader returns m_{final}. $\mathcal{A}_{prv}$ performs the computation for $\mathcal{T}_{ID}$ with the last message m and return 0 for the case it interacted with the real oracles or 1 otherwise.

Next we study what advantage $Adv_{\mathcal{A}_{prv}}^{prv}$ adversary $\mathcal{A}_{prv}$ has when p_t is assumed non-negligible. For the case of the real oracles, it follows from correctness that $out_{\mathcal{T}_{ID}} = real$ with overwhelming probability p_{real}. This means that $Pr[Exp_{\mathcal{A}_{prv}}^{prv-0} = 1] = 1 - p_{real}$ is negligible. Secondly we consider the case with the blinder. From the assumption $\mathcal{B}$ generates the last message such that $out_{\mathcal{T}_{ID}} = \perp$ with non-negligible probability p_t. Furthermore $\mathcal{A}_{prv}$ guesses number of tag messages t with probability $1/q_t$. Thus $Pr[Exp_{\mathcal{A}_{prv}}^{prv-1} = 1] \geq p_t/q_t$. The advantage becomes $Adv_{\mathcal{A}_{prv}}^{prv} \geq |1 - p_{real} - p_t/q_t|$. Due to correctness p_{real} is overwhelming, the assumption gives p_t non-negligible and q_t is polynomially bounded. It results in a non-negligible advantage which contradicts narrow-strong privacy.

The contradiction means that the assumption was incorrect and $\mathcal{A}_{sec}^{\mathcal{B}}$ has non-negligible odds to win the security game.

Step 5. This adversary yields $Pr[Exp_{\mathcal{A}_{sec}^{B}}^{\mathcal{R}-aut} = 1]$ non-negligible meaning that reader authentication is disproved. This means that the assumption at step 1 is false which means Theorem 2 is correct.

Below is shown how the narrow-strong adversary interacts with the tag to thwart reader authentication. This is an attack on security.

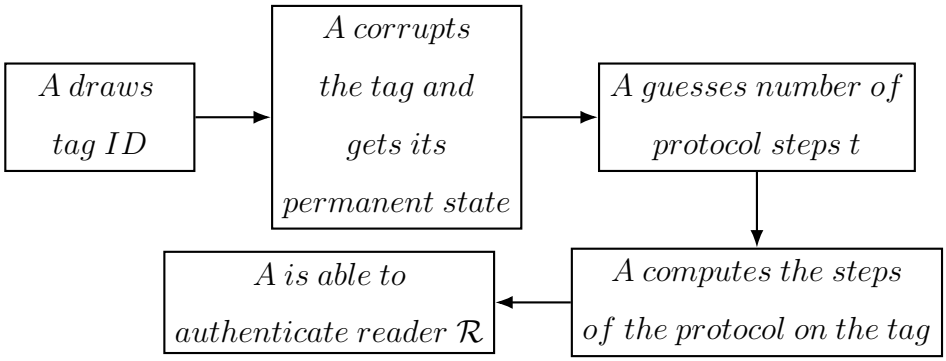


Figure 3.2: Permanent state disclosure attack

3.4 The impossibility results for resettable tags

It is known that standard security notions do no longer work when the adversary can reset the internal state of the tags. Reset attacks have been motivated in particular by the use of smart cards since in specific cases they go to their initial state when disconnected from power. Subsequently they compute with the same randomness they already used before. Reset attacks are always possible when the adversary controls the environment.

In a similar fashion as before, the reset capabilities are studied for the case of total state reset (permanent and temporary memory) and for the case in which the reset affects only the persistent state.

To cover the case of reset attacks, a new oracle is introduced: Reset(vtag) to Vaudenay's model. This oracle allows the adversary to reset the state of the vtag to its original values and its randomness as well. It is assumed that it can be computed in polynomial time. As for the Corrupt(vtag) oracle the Reset(vtag) is also not carried out by the blinder $\mathcal{B}$ but merely observed by it.

Theorem 3: *Against an adversary that is allowed to call the Reset oracle no privacy can*

be achieved in Vaudenay's model.

To demonstrate the theorem an experiment is constructed to show that a narrow-weak adversary $\mathcal{A}_{prv}$ can distinguish with a non-negligible advantage between an interaction with the real oracles or through a blinder $\mathcal{B}$. This is shown in algorithm 5.

Algorithm 5 $\mathcal{A}_{prv}$ against narrow-weak privacy

1: CreateTag(ID_0)
2: CreateTag(ID_1)
3: $vtag_0 \leftarrow$ DrawTag($ID_k, Pr(k) = 1/2, k \in \{0, 1\}$)
4: $m_1 \leftarrow SendReader(-, \pi)$
5: i $\leftarrow 1$
6: **while** $i < stepsOfProtocol$ **do**
7: $\quad m_{2i} \leftarrow SendTag(m_{2i-1}, vtag_0)$
8: $\quad m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$
9: $\quad i \leftarrow i + 1$
10: **end while**
11: $Reset(vtag_0)$
12: $Free(vtag_0)$
13: $vtag_1 \leftarrow$ DrawTag($ID_k, Pr(k) = 1/2, k \in \{0, 1\}$)
14: i $\leftarrow 1$
15: **while** $i < stepsOfTag$ **do**
16: $\quad m_{2i} \leftarrow SendTag(m_{2i-1}, vtag_1)$
17: $\quad i \leftarrow i + 1$
18: **end while**
19: **if** $\tau_0 = \tau_1$ **then**
20: $\quad out \leftarrow 1$
21: **else**
22: $\quad out \leftarrow 0$
23: **end if**
24: $return(\Gamma[vtag_0] = \Gamma[vtag_1] \wedge out) \vee (\Gamma[vtag_0] \neq \Gamma[vtag_1] \wedge \neg out)$

The adversary is narrow-weak because the algorithm uses no Corrupt() oracle (thus a weak adversary) and calls no Result() oracle (thus a narrow adversary).

$\mathcal{A}_{prv}$ eavesdrops a complete execution of the protocol between $vtag_0$ and $\mathcal{R}$(lines 6-10). Let τ_0 be the transcript of the protocol, including the messages sent both by the

reader and the tag.

To simulate $\mathcal{R}$ adversary $\mathcal{A}_{prv}$ uses the messages of τ_0 to simulate a new interaction with a newly drawn tag, $vtag_1$, obtaining τ_1. If the same tag was drawn both times then $\mathcal{A}_{prv}$ expects the transcripts to match. A blinder would not know the result of DrawTag() (line 13) and would have the guess which tag was selected.

Next, the $Adv^{prv}_{\mathcal{A}_{prv}}$ is studied to determine privacy. For the case in which the attack uses the real oracles the reset of the tag always yields the same transcript a second time. The messages of the reader are the same by design of the attack and those of the tag also match because of the reset. Thus $\mathcal{A}_{prv}$ succeeds with probability $1 - \epsilon(l)$ where ϵ is a negligible function and l is the security parameter.

Formally:

$Pr[Exp^{prv-0}_{\mathcal{A}_{prv}} = 1] = Pr[(\Gamma[vtag_0] = \Gamma[vtag_1]) \wedge out] + Pr[(\Gamma[vtag_0] \neq \Gamma[vtag_1]) \wedge \neg out] = \frac{1}{2} * 1 + \frac{1}{2} * (1 - \epsilon(l)) = 1 - \epsilon(l)/2$.

For the case of the blinder, $\mathcal{B}$ can only guess the tag selected by the second DrawTag call. Thus output out can only be $\frac{1}{2}$. The probability becomes:

$Pr[Exp^{prv-1}_{\mathcal{A}_{prv}} = 1] = Pr[(\Gamma[vtag_0] = \Gamma[vtag_1]) \wedge out] + Pr[(\Gamma[vtag_0] \neq \Gamma[vtag_1]) \wedge \neg out] = \frac{1}{2} * \frac{1}{2} + \frac{1}{2} * \frac{1}{2} = \frac{1}{2}$.

The difference between the two cases leads to a non-negligible probability and therefore the privacy definition is contradicted, proving theorem 3: against an adversary that is allowed to call the Reset oracle no privacy can be achieved in Vaudenay's model.

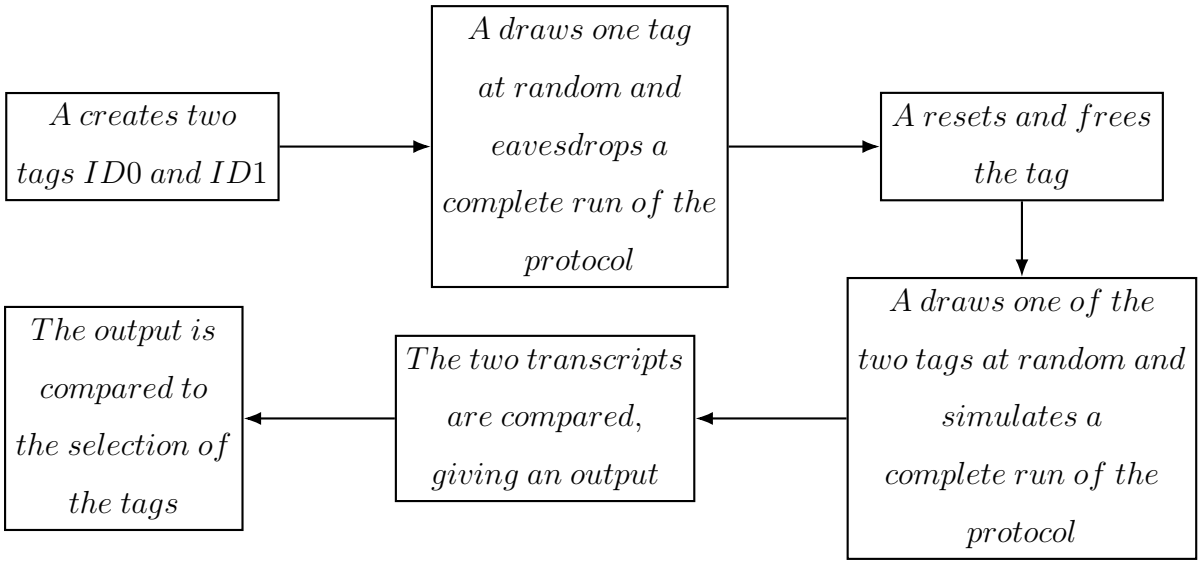


Figure 3.3: Resettable state experiment

This experiment highlights how the Reset() oracle makes it possible to link tags.

If a tag is reset then its default values and randomness will yield the same output, making it possible to link it to a particular tag. Even a narrow-weak adversary can use this to break privacy.

The following scheme shows how privacy is attacked for resettable tags:

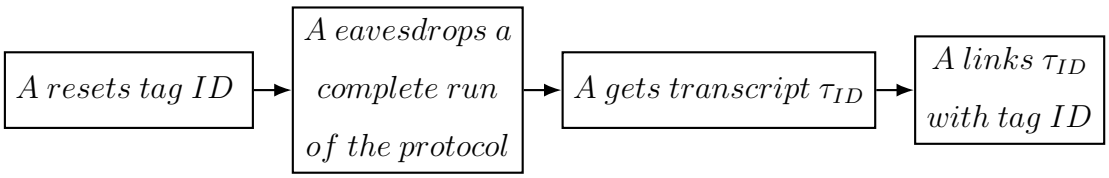


Figure 3.4: Resettable tag privacy attack

3.5 The impossibility results for stateless tags

This section covers the results for stateless tags, meaning tags that cannot update their persistent state. The less restrictive definition of this is that the adversary can reset only the permanent state thus making the tags use the same state multiple times. This property will lead to the impossibility of destructive privacy in Vaudenay's model using such tags.

In a stateless RFID scheme the Free(vtag) oracle erases any temporary information stored on the tag. Thus the scheme will make use of tags that have the same persistent state throughout the protocol and the temporary memory is used only when communicating with a reader, when the tag is powered by it.

Algorithm 6 presents how an adversary would interact with a scheme using stateless tags with temporary memory.

Algorithm 6 $\mathcal{A}_{prv}$ against narrow-forward privacy with stateless tags

CreateTag(ID)
$vtag \leftarrow$ DrawTag(ID)
Free(vtag) ▷ deletes the temporary state
$vtag \leftarrow$ DrawTag(ID)
$t \in \{1, ..., q_t\}$
$m_1 \leftarrow SendReader(-, \pi)$
i $\leftarrow 1$
while $i < t$ **do**
    $m_{2i} \leftarrow SendTag(m_{2i-1}, vtag)$
    $m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$
    $i \leftarrow i + 1$
end while
$S \leftarrow$ Corrupt(vtag)
if $temporary\ state\ of\ S = empty$ **then**
    return 1
end if

However [10] leaves us with the following lemma:

Lemma 2: The temporary state of tags is always empty in any stateless narrow-forward RFID scheme.

This is justified through contradiction, let it be assumed the temporary state is non-empty. The outcome is that a tag would use temporary variables if it would communicate with the real oracles. If the protocol would be blinded then all SendTag() calls are simulated, meaning no temporary variables. An adversary would be able to distinguish between the two cases after a Corrupt() oracle query, shown in algorithm 6. This is possible by guessing for the former case with non-negligible probability a protocol round where the tag uses temporary variables. This contradicts narrow-forward privacy, meaning Lemma 2 holds.

Lemma 2 formally means: $(S^{\mathcal{T}_{ID}}, \cdot) \leftarrow \mathcal{T}^i_{ID}(S^{\mathcal{T}_{ID}}, \cdot)$. Thus the scheme will work with a fixed persistent state and an empty temporary state.

Theorem 4: *There is no stateless RFID scheme that achieves destructive privacy.*

Destructive privacy implies forward privacy so both must be true for a scheme at the same time. For our stateless scheme it is proved in the following that is not the

case. The proof is by contradiction so we start with the presumption of privacy and arrive at a conclusion that is false.

A destructive privacy scheme implies the existence of a blinder $\mathcal{B}$ such that an adversary can not distinguish between the real oracles and their simulation. Using this blinder, $\mathcal{B}_D$, a narrow-forward adversary $\mathcal{A}_{prv}^{\mathcal{B}_D}$ can be constructed. This adversary will be able to thwart forward privacy, hence the contradiction.

The scheme makes use of stateless tags, meaning the persistent memory remains the same. Let $\mathcal{T}^i$ be the computation done by a tag at the i-th SendTag() query.

$\mathcal{A}_{prv}$ is defined in algorithm 7.

The idea is for the adversary $\mathcal{A}_{prv}$ to forward the messages between the tag and the reader up to a set round $j_{\mathcal{R}}$. After that $\mathcal{A}_{prv}$ corrupts $\mathcal{T}$ and gets its state. Even though the adversary is destructive, they can compute the remaining tag steps of the protocol using the obtained state and the protocol algorithm. $\mathcal{A}_{prv}$ also picks a state at random, with the same distribution as creating a new tag. Then it picks randomly from the two states and continues the protocol until the end. When the randomly selected state is the one obtained by the Corrupt() oracle, due to correctness the Result() query will yield 1 and for the other case the reader will reject it.

Algorithm 7 shows that there is an adversary that can distinguish if a tag has changed its state.

The definition for privacy states that there is a blinder $\mathcal{B}_D$ such that $Adv_{\mathcal{A}_{prv}}^{prv} = |Pr[Exp_{\mathcal{A}_{prv}}^{prv-0} = 1] - Pr[Exp_{\mathcal{A}_{prv}}^{prv-1} = 1]| = \epsilon(l)$ for a negligible function ϵ. If such a $\mathcal{B}_D$ exists then it can simulate the tag and the reader for the first $j_{\mathcal{R}}$ rounds and after can simulate the reader until the protocol terminates. Two discrete phases can be observed. Thus $\mathcal{B}_D$ can answer Result() queries as well as the reader and by extension can distinguish if the messages have the same origin.

Algorithm 7 $\mathcal{A}_{prv}$ against destructive privacy

CreateTag(ID_0)
CreateTag(ID_1)
$vtag_0 \leftarrow$ DrawTag($ID_k, Pr(k) = 1/2, k \in \{0, 1\}$)
$\pi \leftarrow$ Launch()
$m_1 \leftarrow SendReader(-, \pi)$
$j_{\mathcal{R}} \in \{1, \ldots, q_{\mathcal{R}}\}$
i $\leftarrow 1$
while $i < j_{\mathcal{R}}$ **do**
    $m_{2i} \leftarrow SendTag(m_{2i-1}, vtag_0)$
    $m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$
    $i \leftarrow i + 1$
end while
$\mathcal{S}^{\mathcal{T}_{ID}} \leftarrow Corrupt(vtag)$
$b \in \{0, 1\}$
if $b = 1$ **then**
    $m_{2j_{\mathcal{R}}} \leftarrow \mathcal{T}^{j_{\mathcal{R}}}(\mathcal{S}^{\mathcal{T}_{ID}}, m_{2j_{\mathcal{R}}-1})$
else
    pick a state with the same distribution as CreateTag()
    $\mathcal{S}^{\mathcal{T}_{ID}} \leftarrow \mathcal{S}$
    $m_{2j_{\mathcal{R}}} \leftarrow \mathcal{T}^{j_{\mathcal{R}}}(\mathcal{S}^{\mathcal{T}_{ID}}, m_{2j_{\mathcal{R}}-1})$
end if
$m_{2j_{\mathcal{R}}+1} \leftarrow SendReader(m_{2j_{\mathcal{R}}}, \pi)$
i $\leftarrow j_{\mathcal{R}} + 1$
while $i < q_{\mathcal{R}}$ **do**
    $m_{2i} \leftarrow \mathcal{T}^{i}(\mathcal{S}^{\mathcal{T}_{ID}}, m_{2i-1})$
    $m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$
    $i \leftarrow i + 1$
end while
$return(Result(\pi) \wedge b) \vee (\neg Result(\pi) \wedge \neg b)$

Next, it is shown how a narrow-forward adversary can use $\mathcal{B}_D$ to distinguish between the blinder $\mathcal{B}$ and the real oracles. This disproves narrow-forward privacy and in turn destructive privacy. $\mathcal{A}_{prv}$ uses the capabilities of $\mathcal{B}_D$ by feeding it information

similarly to algorithm 7. This is described in the following, algorithm 8.

Algorithm 8 $\mathcal{A}_{prv}^{\mathcal{B}_D}$ against narrow-forward privacy

1: CreateTag(ID_0) ▷ shown to $\mathcal{B}_D \rightarrow 1$
2: CreateTag(ID_1) ▷ shown to $\mathcal{B}_D \rightarrow 2$
3: $vtag_0 \leftarrow$ DrawTag($ID_k, Pr(k) = 1/2, k \in \{0,1\}$) ▷ shown to $\mathcal{B}_D \rightarrow 3$
4: $\pi \leftarrow$ Launch() ▷ simulated by $\mathcal{B}_D \rightarrow 4$
5: $m_1 \leftarrow SendReader(-, \pi)$ ▷ simulated by $\mathcal{B}_D \rightarrow 5$
6: $j_{\mathcal{R}} \in \{1, \ldots, q_{\mathcal{R}}\}$
7: i $\leftarrow 1$
8: **while** $i < j_{\mathcal{R}}$ **do**
9: $\quad m_{2i} \leftarrow SendTag(m_{2i-1}, vtag_0)$ ▷ simulated by $\mathcal{B}_D \rightarrow 9$
10: $\quad m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$ ▷ simulated by $\mathcal{B}_D \rightarrow 10$
11: $\quad i \leftarrow i + 1$
12: **end while**
13: $m_{2j_{\mathcal{R}}} \leftarrow SendTag(m_{2j_{\mathcal{R}}-1}, vtag_0)$ ▷ computed by $vtag_0$ *with real oracle or blinder*
14: $Free(vtag_0)$
15: $vtag_1 \leftarrow$ DrawTag($ID_k, Pr(k) = 1/2, k \in \{0,1\}$)
16: $\mathcal{S}^{\mathcal{T}_{ID}} \leftarrow Corrupt(vtag_1)$ ▷ shown to $\mathcal{B}_D \rightarrow 13$
17: $m_{2j_{\mathcal{R}}+1} \leftarrow SendReader(m_{2j_{\mathcal{R}}}, \pi)$ ▷ simulated by $\mathcal{B}_D \rightarrow 22$
18: $i \leftarrow j_{\mathcal{R}} + 1$
19: **while** $i < q_{\mathcal{R}}$ **do**
20: $\quad m_{2i} \leftarrow \mathcal{T}^i(\mathcal{S}^{\mathcal{T}_{ID}}, m_{2i-1})$ ▷ computed by $\mathcal{A}_{prv}^{\mathcal{B}_D}$
21: $\quad m_{2i+1} \leftarrow SendReader(m_{2i}, \pi)$ ▷ simulated by $\mathcal{B}_D \rightarrow 26$
22: $\quad i \leftarrow i + 1$
23: **end while**
24: $b \leftarrow Result(\pi)$ ▷ simulated by $\mathcal{B}_D \rightarrow 29$
25: $return(\Gamma[vtag_0] = \Gamma[vtag_1] \wedge b) \vee (\Gamma[vtag_0] \neq \Gamma[vtag_1] \wedge \neg b)$

The adversary makes $\mathcal{B}_D$ to compute the first $j_{\mathcal{R}}$ rounds of the protocol (8-12). After, $\mathcal{A}_{prv}^{\mathcal{B}_D}$ queries the SendTag() oracle with message $m_{2j_{\mathcal{R}}-1}$ given by $\mathcal{B}_D$. This is the tag side of the protocol for step $j_{\mathcal{R}}$. Next the adversary frees $vtag_0$ and draws a new tag: $vtag_1$. Steps 13-15 are not shown to $\mathcal{B}_D$. Next $\mathcal{A}_{prv}^{\mathcal{B}_D}$ obtains the state of the new tag $vtag_1$ by corrupting it. This is shown to $\mathcal{B}_D$. $\mathcal{A}_{prv}^{\mathcal{B}_D}$ sends $\mathcal{B}_D$ the message $m_{2j_{\mathcal{R}}}$ (line 13). This message has been computed either with the real oracles or via blinder $\mathcal{B}$. $\mathcal{B}_D$

expects this message to be the product of the Corrupt() oracle (line 12, algorithm 7).

Until now the algorithm has computed $j_{\mathcal{R}}$ steps with a tag and 2 options discerned themselves, to continue with the original tag or choose another. The selected tag will be subjected to the evaluation done by $\mathcal{B}_D$.

After the protocol enters phase 2 of $\mathcal{B}_D$, it plays the reader side until the end. By hypothesis $\mathcal{B}_D$ can distinguish if the messages received in the second phase match the behaviour of the tag from the first phase, in which case Result() will output 1 or not, and Result() will output 0.

What remains is to calculate the advantage $Adv^{prv}_{\mathcal{A}^{\mathcal{B}_D}_{prv}}$ if $\mathcal{B}_D$ exists.

Firstly the case in which the adversary interacts with the real oracles, i.e. uses the real SendTag() oracle (line 13 of algorithm 8). If $\Gamma(vtag_0) = \Gamma(vtag_1)$ then by the capabilities of $\mathcal{B}_D$ the Result query returns 1 with overwhelming probability, which leads to $\mathcal{A}^{\mathcal{B}_D}_{prv}$ returning 1 by the same probability. Even though $\mathcal{B}_D$ receives the state $\mathcal{S}^{\mathcal{T}_{ID}}$ after the first phase by the property of Lemma 2, the state is the same as in the beginning of the protocol. If $\Gamma(vtag_0) \neq \Gamma(vtag_1)$ then the messages in the first phase were computed to the state of one vtag and the rest were computed to the state of a vtag identifying another tag. This is not what $\mathcal{B}_D$ expects (Corrupt() gives the state of another tag) and it could wrongly output 1. Let p be the probability of $\mathcal{B}_D$ outputting 0 after $j_{\mathcal{R}}$ messages computed with a random state and the rest computed by an arbitrary state $\mathcal{S}^{\mathcal{T}_{ID}}$. Thus $Pr[Exp^{prv-0}_{\mathcal{A}^{\mathcal{B}_D}_{prv}} = 1] = \frac{1}{2} * (1 - \epsilon(l)) + \frac{1}{2} * p \leq \frac{(1+p)}{2}$.

Next, we study the case where $\mathcal{A}_{prv}$ interacts with a blinder $\mathcal{B}$. For the both cases: $\Gamma(vtag_0) = \Gamma(vtag_1)$ and $\Gamma(vtag_0) \neq \Gamma(vtag_1)$ the output of the SendTag() query computed by $\mathcal{B}_D$ is by way of a random state that is with overwhelming probability different from $vtag_0$ or $vtag_1$. Thus in both cases $j_{\mathcal{R}}$ messages are computed with a random state different than $\mathcal{S}^{\mathcal{T}_{ID}}$ and the rest computed by an arbitrary state $\mathcal{S}^{\mathcal{T}_{ID}}$. Therefore $Pr[Exp^{prv-1}_{\mathcal{A}^{\mathcal{B}_D}_{prv}} = 1] = \frac{1}{2} * (1 - p) + \frac{1}{2} * p = \frac{(1-p)}{2} + \frac{p}{2} = \frac{1}{2}$. What follows is that $Adv^{prv}_{\mathcal{A}^{\mathcal{B}_D}_{prv}} \leq |\frac{(1+p)}{2} - \frac{1}{2}| = \frac{p}{2}$. Given the way in which probability p is defined and the fact that $\mathcal{B}_D$ is able to distinguish if a state changed through a protocol instance then p is non-negligible and so is $Adv^{prv}_{\mathcal{A}^{\mathcal{B}_D}_{prv}}$, concluding the proof.

Scheme 3.5 presents the interaction between $\mathcal{A}^{\mathcal{B}_D}_{prv}$ and the blinder $\mathcal{B}_D$.

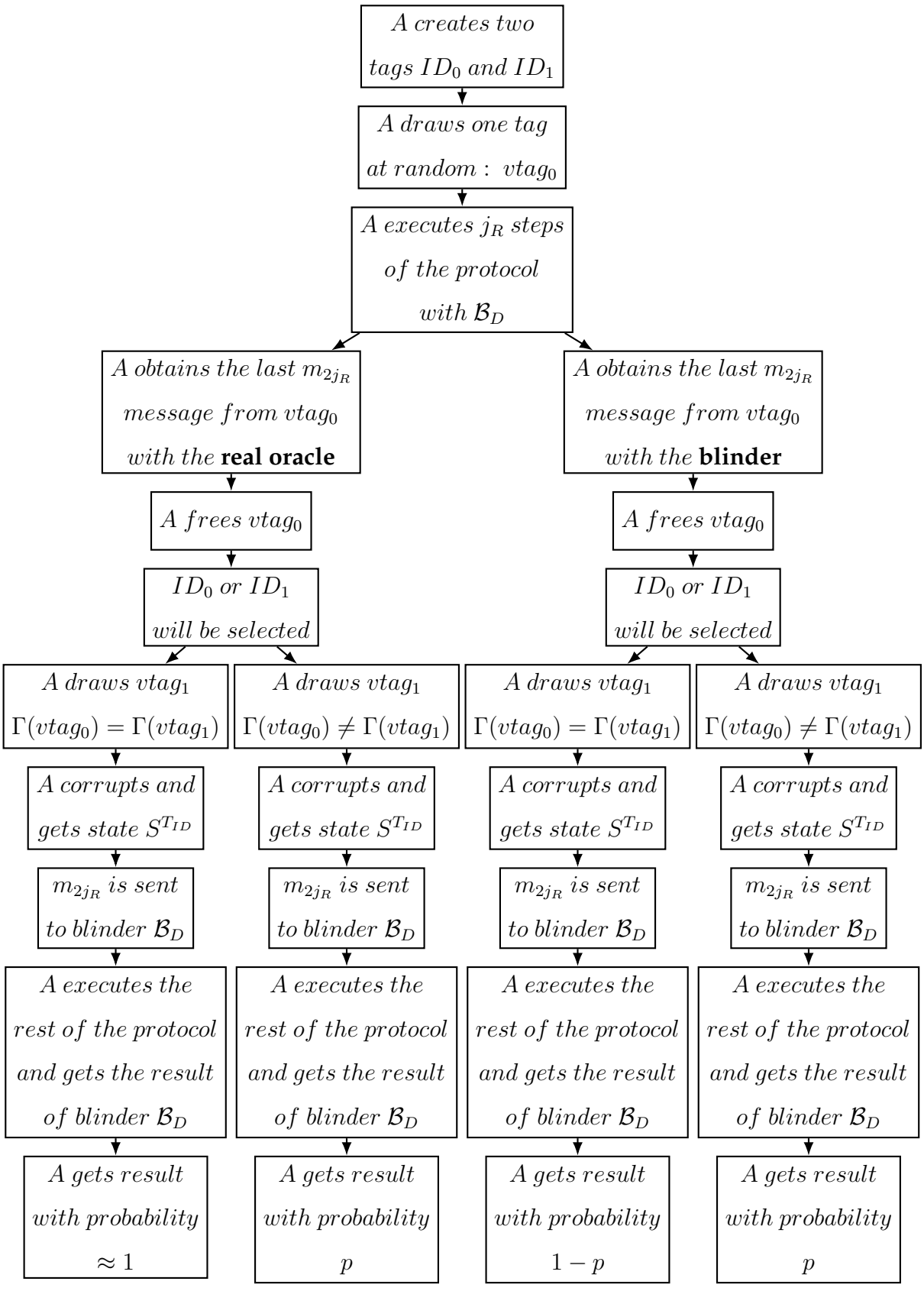


Figure 3.5: Stateless tags experiment

An adversary can feed the blinder against destructive privacy $\mathcal{B}_D$ in such a way that the results of the experiment with stateless tags are produced by different distri-

butions. These probabilities point to a difference between real and random states, thus making possible to draw non-trivial relations between tags. This is a breach of privacy and it is shown in figure 3.6.

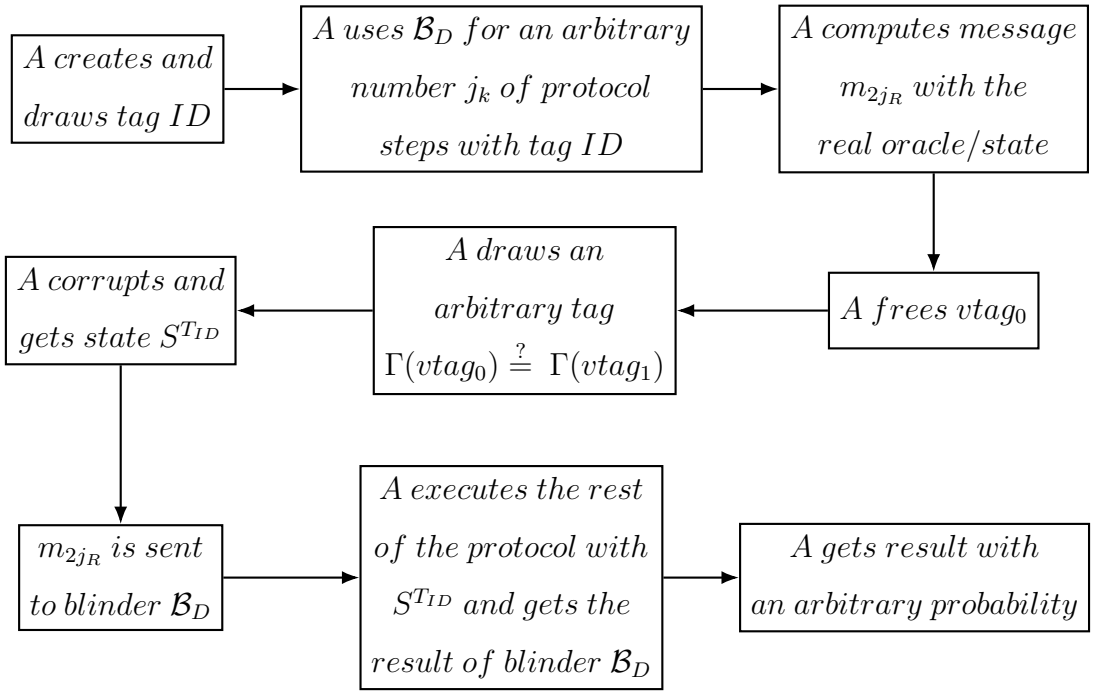


Figure 3.6: Stateless tag privacy attack

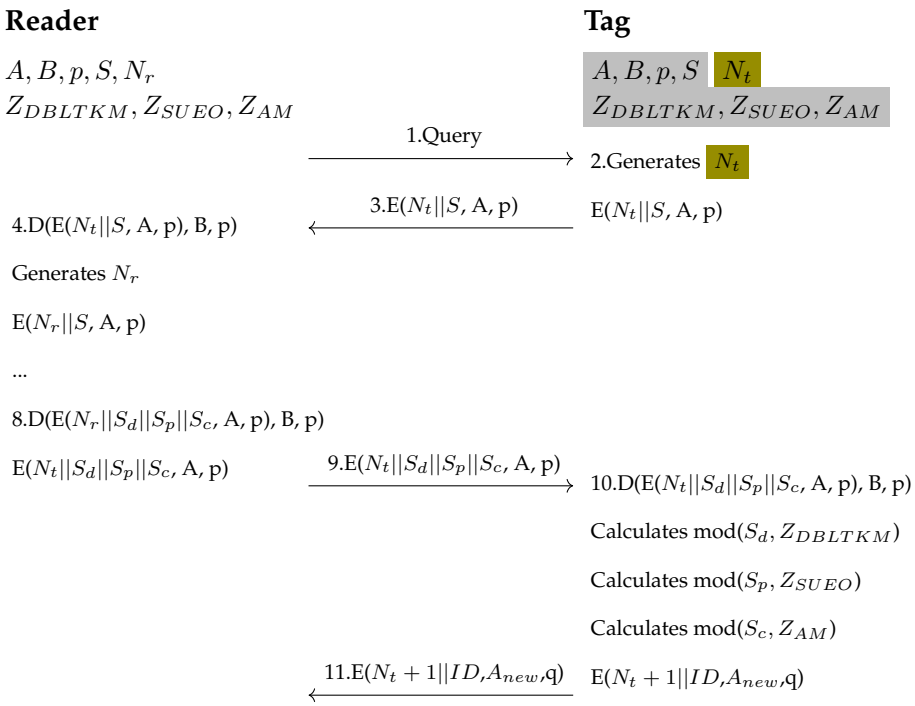
Chapter 4

Case study

4.1 A tag's memory usage

For the authentication proposed in [1], the tag stores in its permanent memory the values: $A, B, p, S, Z_{DBLTKM}, Z_{SUEO}, Z_{AM}$. The global temporary memory will hold the value N_t used to authenticate the reader. It is generated at step 2 and held until step 10.

The tag-reader side protocol: Tag memory usage



4.2 Temporary state disclosure attack

As it was presented in section 3.2, a narrow-forward adversary can interact with a scheme the following way, given the assumption that the Corrupt() oracle yields the persistent and the temporary memory is true:

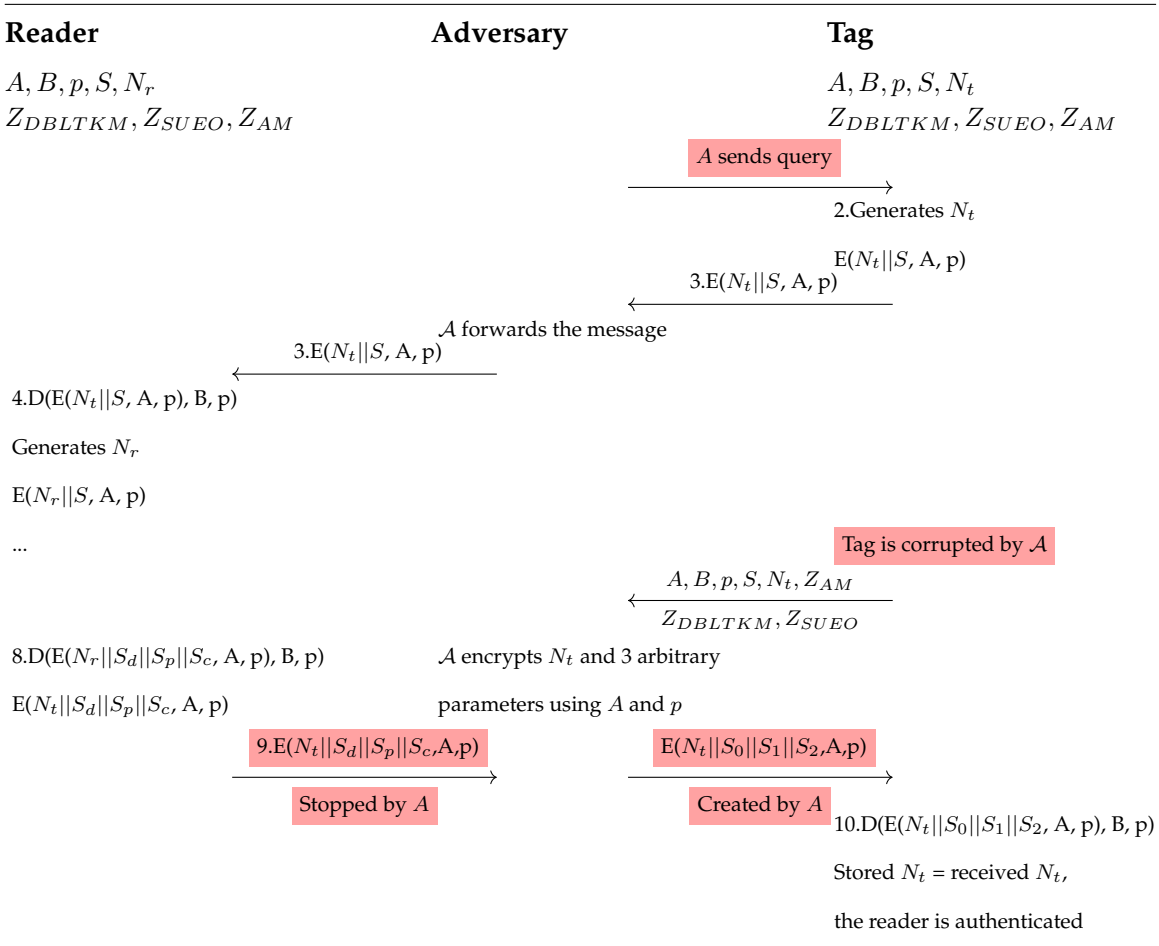
1. Adversary waits for a legitimate tag to respond to a reader query (step 3 of the protocol): E($N_t||S$, A, p). This can be achieved by also sending a query to the tag, compelling it to compute a nonce and send E($N_t||S$, A, p).

2. Before the tag receives the message from the reader with an encrypted nonce N_t the adversary corrupts the tag, obtaining its internal state. By doing that the adversary now knows $A, B, p, S, Z_{DBLTKM}, Z_{SUEO}, Z_{AM}$ and the nonce N_t.

3. Adversary impersonates the reader and sends an encrypted message. This message will seem legitimate to the tag because it would contain the nonce N_t and be encrypted by A and p.

4. The tag receives the message, decrypts it, receives the nonce and authenticates the illegitimate reader.

The tag-reader side protocol: Temporary state disclosure attack



This attack is the equivalent of the one presented in Figure 3.2, adapted for the block-order-modulus protocol.

This is how an adversary bypasses reader authentication, applied to a practical protocol. Making a tag accept an illegitimate reader leads to the tag to disclose sensitive information. This data can be linked to the tag, breaching privacy. However for this case, privacy is already broken by the ability of the adversary to corrupt the tag, thus obtaining the ID of the tag. The attack emphasizes that if a protocol achieves reader authentication then that scheme cannot also achieve anything higher than weak privacy because of the Corrupt() oracle.

4.3 Permanent state disclosure attack

In the following is presented how an narrow-strong adversary can interact with the scheme. It is assumed that corruption of the tags yields only the persistent state. This mirrors the results in section 3.3.

The interaction consists of:

1. The adversary corrupts the tag before it generates the temporary variables, obtaining the persistent state: A, B, p, S, Z_{DBLTKM}, Z_{SUEO}, Z_{AM}.

2. The adversary takes a guess at the number of protocol steps to be computed.

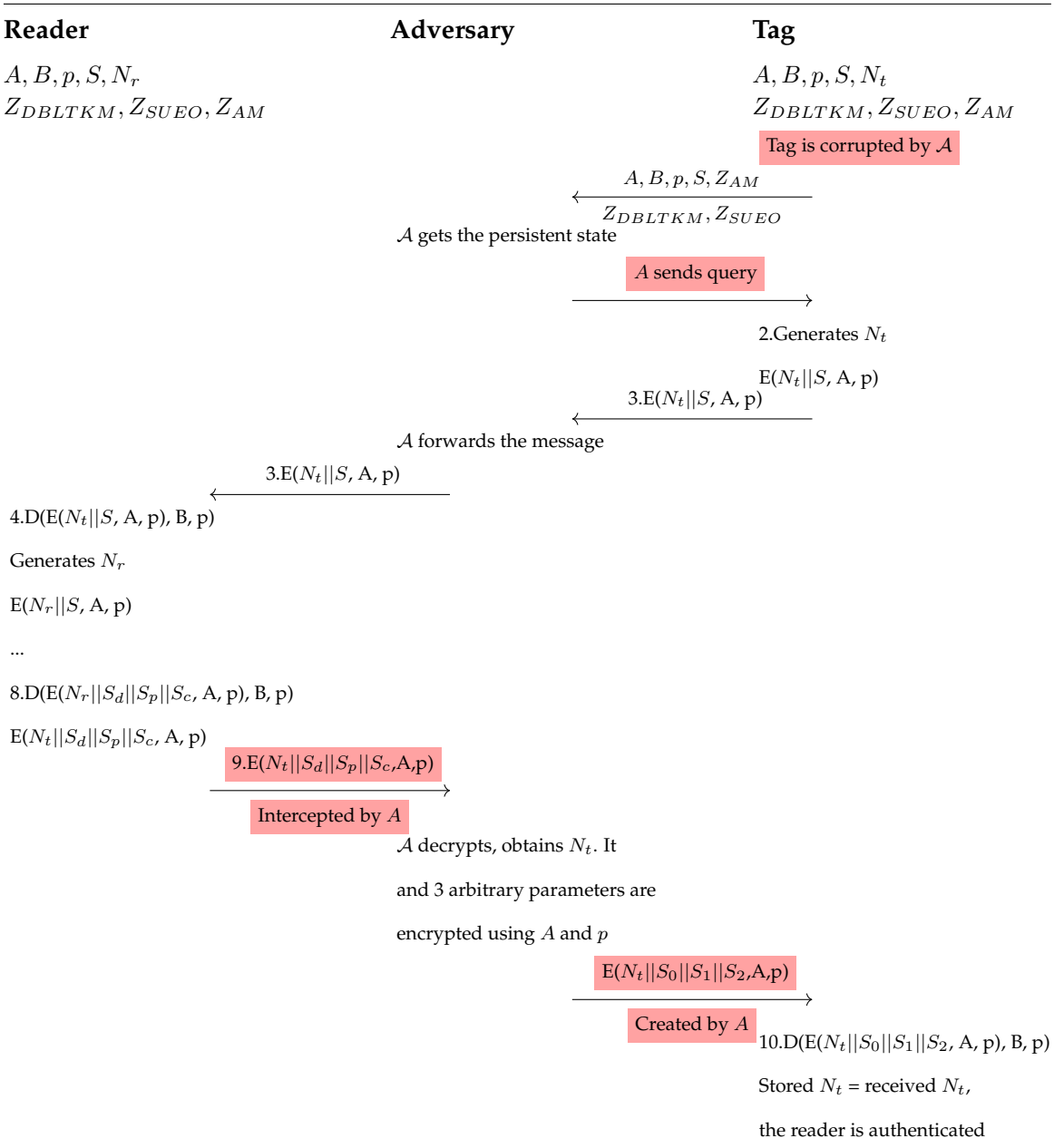
3. Adversary sends a query, prompting the tag to start an instance of the protocol.

4. Using the variables obtained from the Corrupt() oracle the adversary intercepts the response from the reader, is able to decrypt the message and get nonce N_t.

5. The adversary impersonates the reader by encrypting the nonce and 3 arbitrary variables. The tag will receive the nonce, compare it to its own and authenticate the illegitimate reader.

This attack is the equivalent of the one presented in Figure 3.3, adapted for the block-order-modulus protocol.

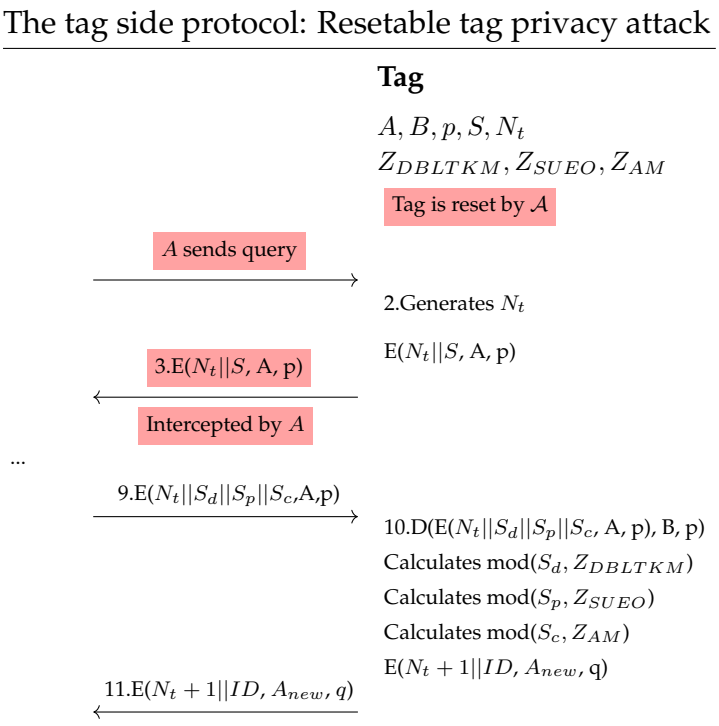
The tag-reader side protocol: Permanent state disclosure attack



The same conclusions drawn in the previous section are viable for this scheme as well. Due to the assumption of permanent state disclosure the previous attack had to be adapted such that the nonce used for authentication is obtained differently.

4.4 Resettable tag privacy attack

In the case of resettable tags the adversary can revert them to their default values, meaning predictable behaviour of sent messages. These messages can be linked to particular tags, breaking privacy.



For resettable tags, the adversary eavesdrops on the output generated by the tag and links it to it. The Figure 3.4 presents how the adversary interacts in this context. For the block-order-modulus protocol the output generated at step 11 cannot be added to the transcript because it depends on the variables S_d, S_p, S_c and it can vary for the same tag. Thus the transcript is formed by the encrypted message at step 3.

4.5 Stateless tag privacy attack

From the methods used to construct the block-order-modulus protocol it is clear that the state of tags changes over time. However in order to combat the potential loss of privacy due to state disclosure by Corrupt() a stateless scheme might be considered. The steps of the protocol will remaining largely the same, only the computations that change the state of the tag are removed. The protocol still achieves mutual authentication between its three components and the server obtains the identity of the tag by the end of its completion. The nonce N_t is no longer randomly generated.

Section 3.5 presents a blinder/simulator that can simulate the tag and the reader in a first phase and the reader in a second phase and is able to distinguish if a tag has changed its state. This blinder was noted by $\mathcal{B}_D$ and is used to attack a stateless tag protocol.

In the following is presented how an adversary interacts with such a scheme:

1. The adversary chooses a tag and uses the blinder $\mathcal{B}_D$ for the tag and the reader until step 10.

2. The decryption performed at step 10 is done with the real tag with its state.

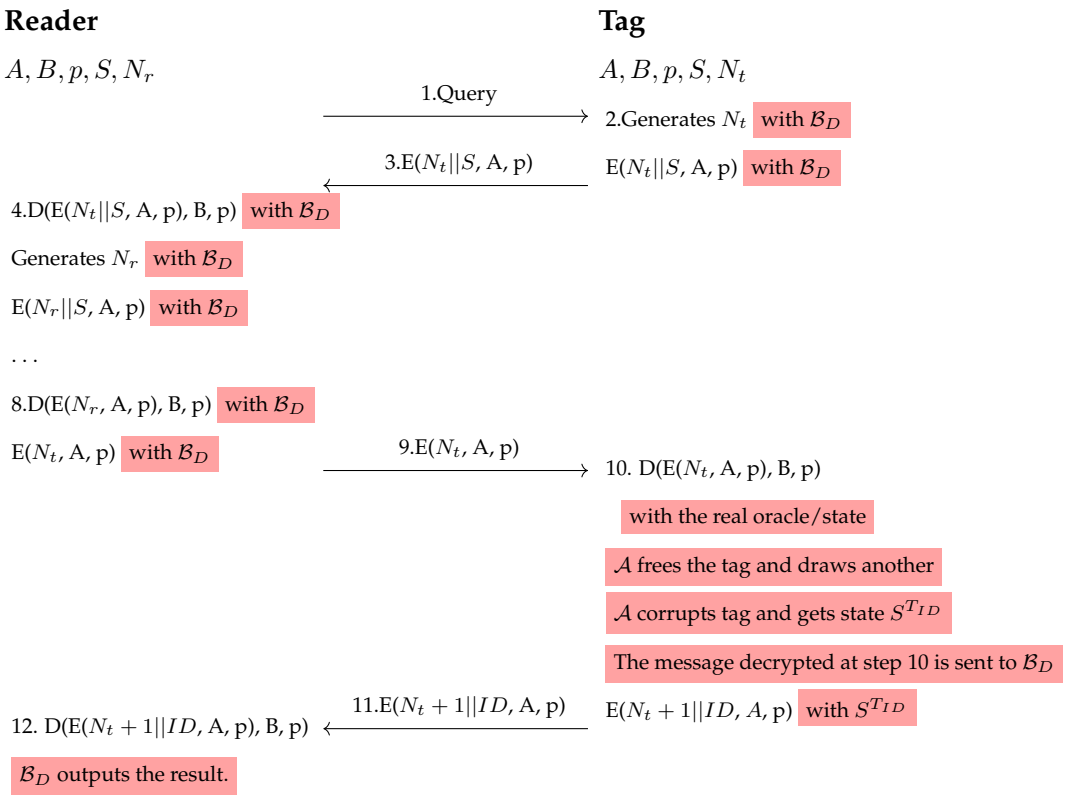
3. The tag used until now is freed. The adversary draws another tag, corrupts it and gets its state $S^{T_{ID}}$.

4. The message obtained at step 10 is sent to the blinder $\mathcal{B}_D$ in order for it to continue the protocol (and change the distribution by which the result is formed).

5. Adversary uses the state of the new tag to encrypt $N_t + 1||ID$.

6. The blinder $\mathcal{B}_D$ which simulates the reader outputs if it was able to decrypt the message.

The tag side protocol: Stateless tag privacy attack



Normally when the blinder outputs the result it indicates if the tag is authenticated. However for the block-order-modulus protocol the tag is authenticated at step 4. In this particular case $\mathcal{B}_D$ outputs if it is able to decrypt the message sent at step 11.

The adversary studies the distribution by which the end result is produced and can infer from it if it was the same tag used for the first and second phases of the blinder $\mathcal{B}_D$. This means that the adversary can link relations between tags and so, breach privacy.

4.6 Scheme security

Protocol	Claimed
Mutual authentication	Yes
Location tracking	**Yes**
DoS	**Yes**
Impersonation attack	**Yes**
Man-in-the-middle attack	**Yes**
Replay attack	Yes
De-synchronization	Yes
Forward secrecy	Yes

Table 4.1: The security properties claimed by [1]

However many of the security claims do not hold in the context of tag corruption. An important note is that an adversary can corrupt a tag during the execution of the protocol, being it earlier or later in its computation.

In the case of **mutual authentication**, an adversary can use the Corrupt() oracle to obtain secret S. By calling the CreateTag() oracle and using value S illegitimate tags can be authenticated by a reader. Thus tag authentication is bypassed. Attacks on reader authentication are presented in sections 4.2 and 4.3. These ways of thwarting authentication is also the base for **impersonation attacks**.

In the case of **location tracking** an adversary can corrupt a tag and infer relations or straight out obtain secret value S, meaning they can link it with a particular location. Strong adversaries can corrupt the tags and release them back. By sending a query (step 1 of the protocol) and breaking reader authentication the adversary can further track the tag in case it was moved.

A **DoS attack** consists in sending large amounts of data to a system in order to cause it to malfunction. The original protocol stops its execution as soon as a party fails to authenticate another, in an effort to prevent such an attack. However if the adversary has access to sensitive data from tags then a DoS attack is more plausible than initially thought.

The adversary can also use the sensitive information from a tag to implement a **man-in-the-middle attack**, for example the interaction described in section 4.2 and 4.3.

4.7 Use of BAN logic and assumptions

Burrows, Abadi and Needham developed a logic that can be used for analysing authentication protocols. The BAN logic makes it possible to formalise cryptographic protocols into structures usable in proofs. The basis of the logic is the belief of one party in the truth of a formula.

It should be noted that BAN logic has limitations. It is used for reasoning for cryptographic protocols however an analysis using this logic does not necessarily mean that no attacks are possible. BAN logic yields good proofs of correctness based on a set of assumptions.

Notations	Meaning
$P \mid\equiv X$	P believes X
$P \triangleleft X$	P receives X
$P \mid\sim X$	P sends X
$P \Rightarrow X$	P has jurisdiction over X
$\#(X)$	X is fresh
$\{X\}_k$	X is encrypted by the secret key k
$P \overset{k}{\leftrightarrow} Q$	P and Q have a shared secret k

Table 4.2: BAN logic notations

Some BAN logic rules are formed, one of them being R1 (Message-meaning rule):

$$\frac{P \mid\equiv Q \overset{k}{\leftrightarrow} P, P \triangleleft \{X\}_k}{P \mid\equiv Q \triangleleft X}$$

This rule states: if P believes that Q and P have a shared secret (a key for this rule) and P receives encrypted X by secret key k, then P can believe Q has sent X. This rule is based on good reasoning, that the key k is only usable for sending information between P and Q and is known only by P and Q.

However taking into consideration tag corruption and the possibility of a strong adversary that can obtain the state of a tag and then release it back into the environment makes the second part of R1 false. A rule that does not cover such an adversary means a BAN logic demonstration that cannot correctly verify security properties.

Tag corruption affects two of the assumptions for the BAN logic demonstration for the protocol [1]:

$$A3 : R \mid\equiv T \Rightarrow \{N_t||S\} \; and \; A12 : T \mid\equiv R \Rightarrow \{N_t||S_d||S_p||S_c\}$$

For assumption A3, a reader cannot trust a tag while a strong adversary can bypass tag authentication. In section 3.2 it is shown that a scheme cannot achieve narrow-forward privacy and reader authentication. This means that narrow-forward adversary can make a tag authenticate a false reader and so assumption A12 cannot also be used. If the state disclosure covers only the persistent state then the same is true but for a narrow-strong adversary.

4.8 Achievable classes of privacy

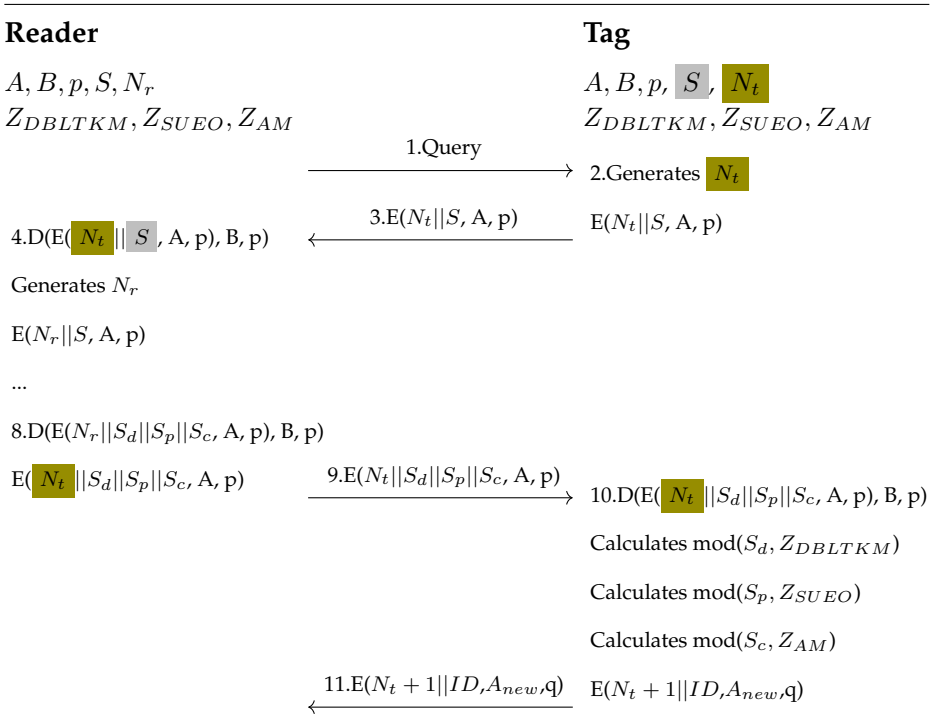
Clearly access to the Corrupt() oracle has major consequences on RFID schemes. Following the impossibility results from section 3, depending on the tags used, these classes of privacy can be achieved:

Class of tag	achievable privacy
With temporary state disclosure	weak & narrow-weak privacy
Without temporary state disclosure	destructive & narrow-destructive privacy
Resettable	no privacy
Stateless	narrow-destructive & forward privacy

Table 4.3: The security properties achievable for various tags

These results lead to an extended discussion about security for a given RFID scheme. The [1] scheme achieves (mutual) authentication between tags and reader and between reader and server. For the former, the reader authenticates the tag by receiving the secret value S and querying it into its internal database to check its legitimacy. Reader authentication is achieved by decrypting the message at step 9 and receiving back value N_t. Only the reader should be able to decrypt E($N_t||S$, A, p) (step 3) and obtain N_t and be able to send it back, thus proving authenticity.

The tag-reader side protocol: mutual authentication



For tag-reader mutual authentication, recall:

Theorem 1: *There is no RFID system in Vaudenay's model that achieves both reader authentication and narrow-forward privacy under temporary state disclosure.*

This means that for the scheme presented the achievable privacy is weak or narrow-weak for the case in which the adversary has no access to the Result() oracle. This result is based on the presumption that temporary state disclosure includes the temporary memory of the tag and additionally the persistent state.

For the case of disclosure of only the permanent state of the tag the impossibility results of theorem 2 state:

Theorem 2: *There is no RFID system in Vaudenay's model that achieves both reader authentication and narrow-strong privacy under permanent state disclosure.*

Thus under the presumption that the Corrupt() oracle yields only the permanent state, the scheme can achieve at most destructive or narrow-destructive privacy.

Resettable tags and the ability of the adversary to change the state to its initial values lead to the impossibility of narrow-weak privacy. Thus the use of such tags does not guarantee even the weakest class of privacy.

Stateless tags do not change their internal memory and the use of them can yield at best narrow-destructive or forward privacy.

Conclusions

Closing remarks

RFID schemes have vast applications that come each with various desired properties, being for example security in the sense of resistance to impersonation attacks or privacy in the sense of linking tags and location tracking. If the application requires privacy there needs to be payed special attention to information leaks and how an adversary with the ability to corrupt tags can thwart this property.

The tags are deeply restrained devices and these constraints often define the achievable privacy. These challenges define the difficulties in developing protocols resistant to attacks.

RFID schemes have the role first and foremost to successfully identify a tag, thus security assumed a central role, however in the present environment focused on gathering data, privacy also occupies a key position.

Future directions and research

The Corrupt() oracle has vast implications to the security and privacy of RFID schemes. We showed the results that are achievable for tags when the adversary can obtain the full state or just the persistent state and the properties achievable for resettable and stateless tags. A reasonable direction for RFID schemes is what can be realised when tamper-proof tags are used, i.e. PUFs. A PUF is a tag that irreversibly changes its response if there are attempts to physically access it. Using this [13] has achieved a higher level of privacy then it was previously achievable.

Bibliography

[1] Yan Wang, Ruiqi Liu, Tong Gao, Feng Shu, Xuemei Lei, Yongpeng Wu, Guan Gui, Jiangzhou Wang, "A Novel RFID Authentication Protocol Based on A Block-Order-Modulus Variable Matrix Encryption Algorithm", https://doi.org/10.48550/arXiv.2312.10593

[2] Vaudenay, S. (2007). "On Privacy Models for RFID". In: Kurosawa, K. (eds) Advances in Cryptology - ASIACRYPT 2007. ASIACRYPT 2007. Lecture Notes in Computer Science, vol 4833. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-76900-2_5

[3] F. L. Țiplea, "Lessons to be learned for a good design of private RFID schemes," IEEE Transactions on Dependable and Secure Computing, vol. 19, no. 4, pp. 2384-2395, 2022.

[4] Shoup, Victor. "Sequences of games: a tool for taming complexity in security proofs." cryptology eprint archive (2004).

[5] Bocchetti, Salvatore. "Security and privacy in rfid protocols." July (2006) - Citeseer.

[6] Domdouzis, Konstantinos, Bimal Kumar, and Chimay Anumba. "Radio-Frequency Identification (RFID) applications: A brief introduction." Advanced Engineering Informatics 21.4 (2007): 350-355.

[7] Feldhofer, M., Rechberger, C. (2006). "A Case Against Currently Used Hash Functions in RFID Protocols". In: Meersman, R., Tari, Z., Herrero, P. (eds) On the Move to Meaningful Internet Systems 2006: OTM 2006 Workshops. OTM 2006. Lecture Notes in Computer Science, vol 4277. Springer, Berlin, Heidelberg. https://doi.org/10.1007/11915034_61

[8] Robshaw, M.J.B. (2006). "Searching for Compact Algorithms: cgen". In: Nguyen, P.Q. (eds) Progress in Cryptology - VIETCRYPT 2006. VIETCRYPT 2006. Lecture

Notes in Computer Science, vol 4341. Springer, Berlin, Heidelberg. https://doi.org/10.1007/11958239_3

[9] Feldhofer, M., Dominikus, S., Wolkerstorfer, J. (2004). "Strong Authentication for RFID Systems Using the AES Algorithm". In: Joye, M., Quisquater, JJ. (eds) Cryptographic Hardware and Embedded Systems - CHES 2004. CHES 2004. Lecture Notes in Computer Science, vol 3156. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-28632-5_26

[10] Armknecht, F., Sadeghi, AR., Scafuro, A., Visconti, I., Wachsmann, C. (2010). "Impossibility Results for RFID Privacy Notions". In: Gavrilova, M.L., Tan, C.J.K., Moreno, E.D. (eds) Transactions on Computational Science XI. Lecture Notes in Computer Science, vol 6480. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-17697-5_3

[11] Radu-Ioan Paise and Serge Vaudenay. 2008. Mutual authentication in RFID: security and privacy. In Proceedings of the 2008 ACM symposium on Information, computer and communications security (ASIACCS '08). Association for Computing Machinery, New York, NY, USA, 292-299. https://doi.org/10.1145/1368310.1368352

[12] Wessels, Jan, and C. F. Bv. "Application of BAN-logic." CMG FINANCE BV 19 (2001) - ipa.win.tue.nl : 1-23.

[13] Hristea, C., Ţiplea, F.L. (2023). "Destructive Privacy and Mutual Authentication in Vaudenay's RFID Model". In: Balas, V.E., Jain, L.C., Balas, M.M., Baleanu, D. (eds) Soft Computing Applications. SOFA 2020. Advances in Intelligent Systems and Computing, vol 1438. Springer, Cham. https://doi.org/10.1007/978-3-031-23636-5_51