

Timed Analysis of Security Protocols

R. Corin*, S. Etalle, P.H. Hartel and A. Mader
University of Twente, The Netherlands

Abstract

We propose a method for engineering security protocols that are aware of timing aspects. We study a simplified version of the well-known Needham Schroeder protocol and the complete Yahalom protocol, where timing information allows the study of different attack scenarios. We model check the protocols using UPPAAL. Further, a taxonomy is obtained by studying and categorising protocols from the well known Clark Jacob library and the Security Protocol Open Repository (SPORE) library. Finally, we present some new challenges and threats that arise when considering time in the analysis, by providing a novel protocol that uses time challenges and exposing a timing attack over an implementation of an existing security protocol.

Keywords: timed automata, security protocols, model checking.

1 Introduction

The communication via a shared medium, like the Internet, is inherently insecure: anyone has access to en route messages and can potentially eavesdrop or even manipulate the ongoing communication. Security protocols are distributed programs specifically designed to achieve secure communication over such media, typically exchanging messages built constructed using cryptographic operations (e.g. message encryption).

Security protocols are difficult to design correctly, hence their analysis is critical. A particularly successful model to analyze security protocols is the Dolev Yao model [16], in which the attacker is assumed to have complete control over the network. Also, the model assumes ideal cryptography, where cryptographic operations are assumed to be perfect. The Dolev Yao model is attractive because it can be easily formalized using languages and tools based on formal methods. Moreover, the model has an appropriate level of abstraction, as many attacks are independent of the underlying details of the cryptographic operations and are based only on combinations of message exchanges plus knowledge gathered by the attacker during the execution.

Typically, Dolev Yao methods for formal verification of security protocols (among the proposals [27, 14, 10]) do not take *time* into account, and this choice simplifies the analysis. However, security protocols, like distributed programs in general, are sensitive to the passage of time. Recently, consideration of time in the analysis of security protocols has received some attention (see Related Work below), but this attention has been focused mostly on timestamps.

In this paper¹ we develop an analysis model for security protocols that explicitly takes into account *time* flowing during the execution of a protocol. In general, in the design and implementation of a security protocol two aspects of timing must be considered at some stage:

1. Time can influence the flow of messages. For instance, when a message does not arrive in a timely fashion (i.e. *timeouts*), retransmissions or other actions have to be considered.
2. Time information can be included within protocol messages (e.g. timestamps).

*Contact author's email is ricardo.corin@utwente.nl.

¹An earlier version appeared in [11].

Consider first (1) above. In general, the influence of time on the flow of messages is not usually considered by current state of the art methods for analysing protocols. However, we believe it to be crucial because (i) Even if the abstract protocol does not decide what action to take at a particular moment of the execution (e.g. in the case of timeouts), the actual implementation will eventually have to consider these issues anyway; (ii) The efficiency and security of the implementation depends critically on these specific decisions; and (iii) The timing of message flows in a protocol can be exploited by an attacker.

Now consider item (2) above. There, we believe that making judicious use of timing information in a protocol has received attention but mostly in the limited setting of using time stamps as opposed to nonces. However, time information can be used to influence message flows as well, as we illustrate in Section 6.

Contributions Our study covers several issues in the study of time in security protocols.

- Firstly, in Section 2 we study which kinds of timing issues, like timeouts and retransmissions, may arise in the study of security protocols. We then proceed in Section 3 to present a method for the design and analysis of security protocols that consider these timing issues. The method is based on modelling security protocols using timed automata [3]. In support of the method we use UPPAAL [4] as a tool to simulate, debug and verify security protocols against classical safety goals like secrecy and authentication, *in a real time scenario*, using reachability properties. As examples, we analyse a simplified version of the Needham Schroeder protocol [26] and the full Yahalom protocol [9] in Section 4.
- Secondly, in Section 5, we categorize all the protocols from the Clark and Jacob library and the SPORE library into different (more abstract) patterns of message flows with timeouts. We then analyse each abstract pattern, independently of the actual protocols, and establish their timing efficiency and security.
- Finally, in Section 6 we illustrate some novel opportunities and difficulties that appear when considering time in the design and analysis of security protocols:
 - In Section 6.1 we give an example protocol that accomplishes authentication by exploiting the *timeliness* of messages. The protocol uses time in a conceptually new way, by employing *time challenges* as a replacement for nonces.
 - As a second example of a novel difficulty in Section 6.2, we describe how timing attacks [17] can be applied to security protocols, by describing an attack over Abadi’s private authentication protocol [2]. Although these protocols can be modelled as timed automata, thus permitting general verification, we leave the detailed verification as future work since for this we need a model checker that is also *probabilistic* (like [13] or [24]): our nondeterministic intruder of UPPAAL is too powerful, since it can always guess correctly times and values even if the probability of guessing is negligible.

2 Timeouts and Retransmissions

To illustrate how time influences the analysis of security protocols (even when it does not explicitly use timing information), consider the following protocol written in the usual notation.

1. $A \rightarrow B$: M_{AB}
2. $B \rightarrow A$: M_{BA}

Here, first A sends message M_{AB} to B , and later B sends message M_{BA} to A . This high-level view does not consider timing. To consider time, we first need to assume that both A and B have

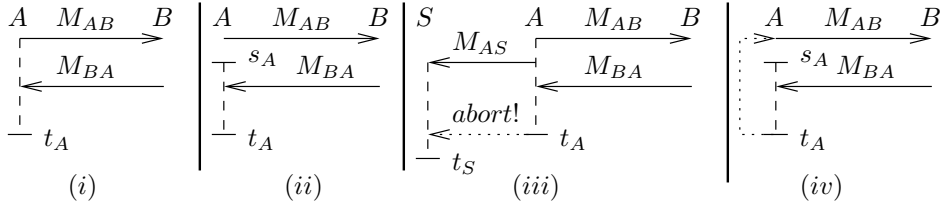


Figure 1: *Left*: Timeouts (i) typical (ii) windowed; *Right*: timeout actions (iii) chained abort and (iv) retransmission

timers. In this paper, we do not require timers between parties to be synchronised (see below for a discussion). The next step consists in distinguishing the different operations that occur, with their respective times. In Step 1, it takes some time to create M_{AB} . The other operation that takes time is the actual sending of the message, ie. the time it takes M_{AB} to travel from A to B . This transmission time is unbounded, since the message may be lost or intercepted, and therefore A may need to *timeout*: After A sends M_{AB} , she starts a timer that will timeout if M_{BA} (Step 2 of the above protocol) is not received after some waiting, say t_A (Figure 1 (i)). Clearly, t_A should be greater than the time of creating M_{BA} , plus the average time of sending both M_{AB} and M_{BA} . In general, A does not need to start waiting for a response immediately after sending a message; for instance, A could hibernate (or start doing another task) for some time s_A before beginning to expect the response M_{BA} . This results in a *windowed* timeout (Figure 1 (ii)). Typically, the values for s_A and t_A depend on implementation details. However, an implementation independent quantitative analysis could already give an early indication of what attacks can be mounted for some values that are no longer possible for others (eg. a smaller t_A and a larger s_A).

Another issue that is not considered either in previous approaches is that the *action* to be taken when a timeout occurs is sensitive. Typically, the implicit assumption is that the protocol should abort, as it is the case in Figure 1 (i). This means that the protocol party that reaches the timeout deduces that a fault has happened. However, aborting may not consist only of stopping execution altogether. For example, if we consider protocols with several parties, we may wish that when a party timeouts it also communicates its decision to abort to other, still active parties. For instance, consider the following protocol:

1. $A \rightarrow B$: M_{AB} A starts timer expecting M_{BA}
2. $A \rightarrow S$: M_{AS} S starts session timer
3. $B \rightarrow A$: M_{BA}

Here, if A times out on Step 2, she could communicate the abort decision to S , as shown in in Figure 1 (iii).

Aborting execution is not the only feasible action to perform after a timeout [25], and in principle protocols could successfully execute when messages *do not* arrive at certain moments. Even if we do assume that a fault occurred, aborting may not be the best choice: sometimes, message retransmission is a better, more efficient and also more realistic option, as depicted in Figure 1 (iv). In this case, a question which arises is whether to retransmit the original message (M_{AB} for Figure 1 (iv)), or to recompute some parts before resending the message. Here, the tradeoff is, as usual, between efficiency versus security.

Time information can also be included in the contents of M_{AB} and M_{BA} . A typical value to include is a timestamp, to prevent replay attacks. However, this requires *secure* clock synchronisation of A and B , which is expensive (see Mills [29] for a security protocol to achieve this). In fact, this is the reason for which Bellare et al. recommend to switch to nonces in the Kerberos protocol [7]. Recently, the analysis of security protocols using timestamps has received consider-

able attention from the research community (see Related Work in Section 7). Therefore, in this paper we do not pursue this direction.

3 A Method for Analysing Security Protocols

We use timed automata [3] to model protocol participants, and this has several advantages. Firstly, our method requires the designer to provide a precise and relatively detailed protocol specification, which helps to disambiguate the protocol behaviour. Secondly, timing values like timeouts need to be set at each state, while retransmissions can be specified as transitions to other protocol states.

Once modelled as timed automata, the protocol can be fed to the real time model checker UPPAAL, which allows the protocol to be simulated and verified. The simulation provides the designer with a good insight of the inner workings of protocol, and already at this stage specific timing values like timeouts can be tuned. Then the designer can proceed with verification of specific properties. As usual in model checking, the verification of the protocol with UPPAAL is automatic.

The resulting timed automata model is an informative and precise description of the security protocol, and thus, it provides a practical way to strengthen implementations while keeping efficiency in mind.

As a third and final step we propose to transfer timing information back to the high level protocol description. This serves to highlight the role of time in the implementation, but also (as we will demonstrate in Section 6.1), to make timing an integral aspect of the protocol design.

3.1 Timed Automata and UPPAAL

In this paper, the timed automata of Alur and Dill are used for modelling [3]. In general, timed automata models have an infinite state space. The region automaton construction, however, shows that this infinite state space can be mapped to an automaton with a finite number of equivalence classes (regions or zones) as states [3]. Finite-state model checking techniques can then be applied to the reduced, finite region automaton. A number of model checkers for timed automata is available, for instance, Kronos [31] and UPPAAL [4].

Parallel composition of automata is one of the main sources for expressiveness. This operation allows to decompose complex behaviour, thus supporting transparent modelling. When composing automata in parallel, we need also to provide some form of communication. For the timed automata we use in this paper, communication comes in form of hand-shake synchronisation. Two parallel automata can share a synchronisation channel, i.e. both have a transition labelled with a complementing channel name, e.g. *synchronise!* in the example of Figure 2. These transitions may only be taken together, at the same moment. In Figure 2 we see an example for a transition, labelled by a guard that has to be true when the transition is taken, a synchronisation channel, and a variable update.

Data transmission is typically modelled by a synchronisation, where global variables are updated. These global variables contain the data that are transmitted.

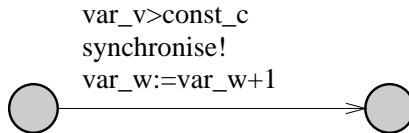


Figure 2: Example transition with guard, synchronisation and update

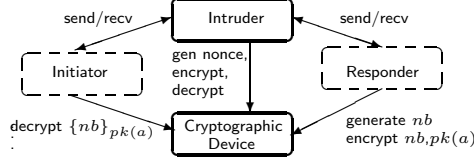


Figure 4: Structure of our UPPAAL Model

Timed automata extend “classical” automata by the use of real-valued clock variables. All clock variables increase with the same speed. For timed automata we make a difference between a state and a location: a state is a location where all clocks have a fixed value. In this sense a location symbolically represents an infinite set of states, for all the different clock valuations. In Figure 3 an elementary fragment of timed automata is shown. When the transition from location I to location II takes place, the clock *clock* is reset to 0. Location II may only be left at time D, where D is a constant. The invariant $clock \leq D$ at location II enforces that the transition to III has to be taken at time D.

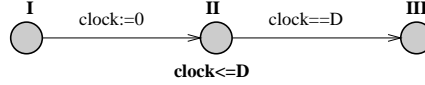


Figure 3: Basic timed automaton fragment with a clock and a constant D

Typically, the initial location of an automaton is denoted by a double circle. We also make use of committed locations, which have the property that they have to be left immediately. In most cases committed locations are used to model a sequence of actions with atomic execution.

The properties verified by the model checker of UPPAAL are reachability properties, like “there is a state where property p holds reachable from the initial state”, or the dual “in all reachable states property p holds”. The latter is falsified if the model checker finds a state that does not satisfy p . In this case a *diagnostic trace* from the initial state to the state that does not satisfy p is produced by the model checker; it serves as counterexample.

We use this mechanism to find attacks. If we can characterize for example the fact that some secret is not secret any more as a propositional property, and the model checker finds a state where this property holds, the diagnostic trace describes a sequence of actions that leads to this state, which gives precisely the attack.

Note that in this context verification comes very much in the guise of debugging. Finding an attack requires an adequate problem model. Not finding an attack increases the confidence in the modelled protocol, but does not exclude that attacks could be found in other models for the same protocol.

3.2 Overview of the UPPAAL Model

Let us now describe the general form of our model, in some detail. We model the protocol participants (initiator, responder, etc) and the intruder as timed automata. Additionally, we model cryptography as another automaton, the *cryptographic device*, which acts as an impartial party that regulates the access to data. In Figure 4 we illustrate a setting consisting of one initiator and one responder. Here, boxes in bold represent our general intruder and the cryptographic device,

while dashed boxes represent the actual initiator and responder. These participants use the cryptographic device to perform operations, but communicate through the intruder (thus the intruder is identified with the network itself, obtaining a Dolev Yao like intruder [16]). Our modelling is *modular*, and allows us to “plug in” different participants (eg., in the analysis of the Yahalom we add a *server*), while the bold boxes, ie. the intruder and the cryptographic device, are the core model.

While modelling security protocols as timed automata in UPPAAL, we will focus on modelling the times required by the principals to encrypt and decrypt values (and generate nonces), but not on the actual time that takes the sending (transmission times are assumed to be unknown). Therefore, for our results to be useful, we assume that computing times (e.g. cryptographic operations) are not negligible w.r.t. communication times, and thus choices for timeout values depend both on communication and computing times.

3.3 Modelling Cryptography

The automaton for a cryptographic device is presented in Figure 5. This cryptographic device performs nonce generation and public key cryptography. Later we also use a device for symmetric cryptography, which can be obtained from the one in Figure 5 in a straightforward manner. In fact, our method allows different cryptographic devices to be plugged in as needed (eg. to add hashing). Basically, the device model is a shared table containing pairs of plaintexts and keys. The first service of the cryptographic device is to provide fresh nonces to the protocol participants (and also the intruder). The process of nonce generation is started via synchronization on the *gen_nonce* channel. To model the new nonce creation, the local variable *gen_nonce* is incremented with the constant *seed* plus the value of **param1** that includes the ID of the requesting participant (this ensures that initial generated nonces differ from each other). The number of possible nonces is bounded by ensuring that *gen_nonce* is always smaller than a fixed constant *MAX*. After synchronization, a global **result** variable is updated with a generated nonce, and the device finishes by synchronizing on the *finish_nonce* channel.

Encryption and decryption are modelled by two local arrays to the cryptographic device, namely **plain** and **key**. When a party wants to encrypt some value *d* with key *k*, it synchronises with the device via the channel *start_encrypt*. If the device has still room in its tables, it stores *d* in the **plain** array and *k* in the **key** array. As a result, it sets in the global variable **result** the *index* in which *d* and *k* reside in the arrays. This index is the “ciphertext”. Upon decryption, the ciphertext is provided to the cryptographic device, which then checks that the provided key is correct: Since we model public-key encryption, the private key of a public key *k* is simply modelled as a function *f* s.t. $f(k) > MAX$, so that private keys do not clash with generated nonces and hence are never known by the attacker simply by guessing. In this simple case we simply let $f(k) = 10k$, which since only one nonce is needed by the participants in the example protocol of Section 4.1, gives enough room for the attacker to generate nonces.

State constructions Now that we have the cryptographic device, an honest principal can use different state constructions to perform cryptographic operations. In Figure 6 we show the different kinds of state constructions used in our models, which designers should use as building blocks for the representation of protocol participants.

In the upper left of Figure 6 we see the building block for nonce generation. Here, a protocol participant first resets the clock **t**, assigns its identity to variable **param** (used by cryptographic device to provide different nonces to different participants) and then fires via the *gen_nonce* channel. Then the participant enters a state in which it waits until the time of nonce generation happens (**time_gen_nonce**), synchronises via the *finish_nonce* channel and obtains the return value via variable **result**. Encryption and decryption are analogous, and only differ in that they use two parameters **param1** and **param2** (for plaintext and key in the former, and ciphertext and key in the latter).

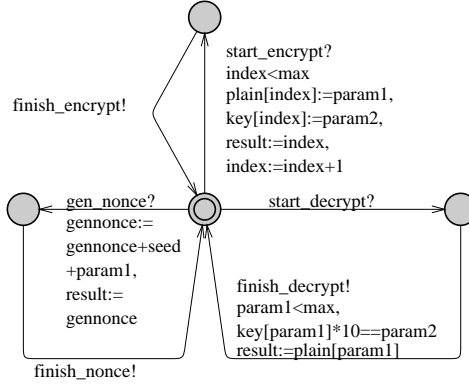


Figure 5: Timed automaton for a Cryptographic Device

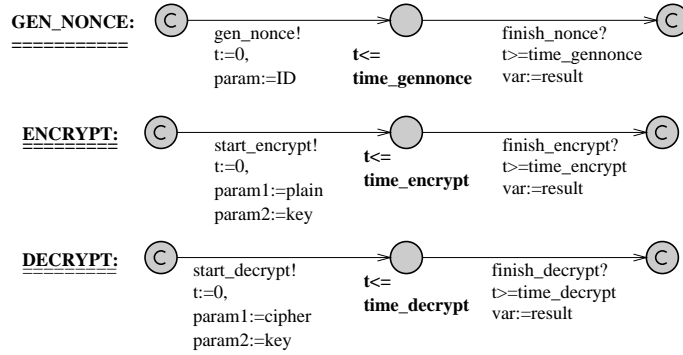


Figure 6: State constructions: nonce generation (above), encryption (middle) and decryption (bottom)

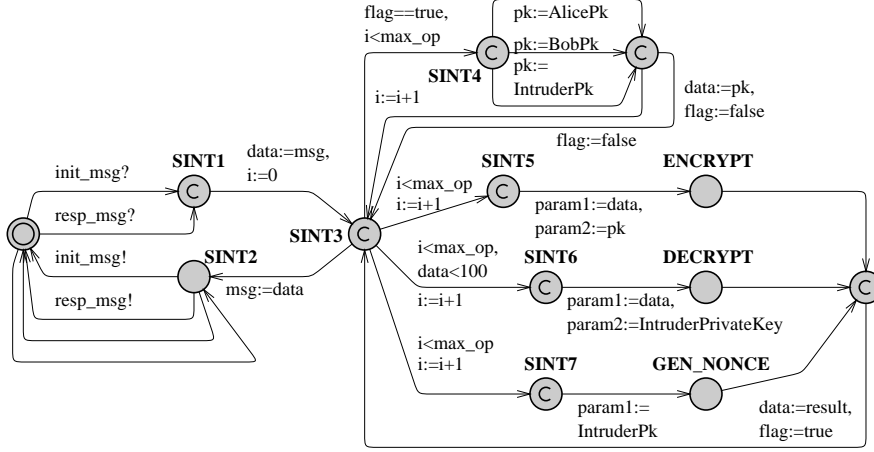


Figure 7: Schema for the timed automaton for the Intruder

3.4 Modelling the Adversary

The intruder, presented in Figure 7, works basically as a Dolev Yao intruder [16]. The intruder models the network itself, by acting as an intermediary of communication between the initiator and responder. This is modelled by letting the intruder synchronise on both channels *init_msg* and *resp_msg*. Upon synchronising by receiving a message, the intruder moves to state (SINT1), where it saves the message *msg* in its local variable *data* and resets an index variable *i* which bounds the total number of actions allowed to do before continuing execution. Then, the intruder moves to state (SINT3), where it makes a nondeterministic choice for an action. More precisely, it can decide to:

- Choose an identity in its local variable *pk* (State SINT4)
- Encrypt a value (State SINT5)
- Decrypt a value (State SINT6)
- Generate a nonce (State SINT7)
- Save variable *data* as message *msg*.

The intruder can then continue to perform these actions, choose to send a message or simply block a message and continue the execution. Moreover, the intruder can also delay arbitrarily a message, by waiting in state (SINT2).

Note that the intruder is independent of the actual protocol under study, and hence it is generic to analyze protocols using public key encryption (although this intruder is not able to concatenate messages; we extend it in the next section).

4 Analysing Protocols

We first consider a simple protocol to illustrate our technique. Later, we move on to analyse the more complex Yahalom protocol.

4.1 An Example Protocol

In this section we study and model in UPPAAL a simplified version of the Needham Schroeder protocol, thoroughly studied in the literature (see eg. [26]). Differently from the Needham Schroeder protocol whose goal is to achieve mutual authentication, our simpler protocol aims at authenticat-

ing the initiator A to a responder B only (we do not lose generality here, this is just a simplification to improve presentation). The protocol is as follows:

1. $A \rightarrow B$: A
2. $B \rightarrow A$: $\{N_B\}_{K_A}$
3. $A \rightarrow B$: $\{N_B\}_{K_B}$

In the first message, the initiator A sends a message containing its identity to the responder B . When B receives this message, it generates a nonce N_B , encrypts it with the public key K_A of A and sends it back to A . Upon receipt, A decrypts this message with her private key, obtains the nonce N_B , reencrypts it with the public key K_B of B and sends it back to B .

We can now move on to describe the actual initiator, responder and intruder. Both the initiator and responder have local constants `time_out`, which represent their timeout values. Also, the initiator, responder and intruder have local constants `time_gennonce`, `time_encrypt` and `time_decrypt` that represent the time required to generate a nonce, encrypt a value or decrypt a value, respectively for *each* principal.

The automata for the initiator and responder of our simple protocol presented above are given in Figure 8 (the dashed transitions of the responder correspond to retransmissions, discussed in Section 4.1.2). The initiator A starts her execution when activated via channel *start* (State SI0). The actual identity of the initiator role is set via the global variable `init_id` (this and other role variables are chosen by the `Init` automaton, described below). The initiator saves `init_id` as the first message (see protocol message 1). Then, the initiator starts her protocol execution, by firing via the channel *init_msg*. After this, the initiator starts a clock t and waits for a response, or until t reaches `time_out` (State SI2). If the timeout occurs, the protocol is aborted (a retransmission at this point would be equivalent to restart the protocol). If a response is received before the timeout via the *init_msg* channel, A tries to decrypt the received message `msg`. This takes time `time_decrypt` for the initiator. After the decryption, the initiator reencrypts the obtained nonce (stored in `result`) and finally sends the last message via the *init_msg* channel, setting to `true` its local boolean variable `finish`.

The responder automaton B works similarly to the initiator. After receiving the start signal, B waits for the message containing the claimed identity of A (State SR1). When received, B saves the first message in the local variable `claimed_id`. After this, B generates a nonce by contacting the cryptographic device. When ready (State SR3), B encrypts the nonce with the value received in Message 1 (we identify identities with public keys). After finishing the encryption (State SR4), the message is sent and B starts to wait for a response (State SR5). If an answer comes before the timeout, B decrypts the message and checks that the challenge is indeed the one B sent. If so, the local boolean variable `finish` is set to `true`.

4.1.1 Verification

We wish to verify that our simple protocol indeed accomplishes authentication of A to B . To this end, we will model check one session of the protocol containing one initiator, one responder and one intruder. We use a special *Init* automaton that instantiates the initiator and responder with identities (like A , B and I), and then starts the execution run by broadcasting via the *start* channel. The *init* automaton is given in Figure 9.

The property we check, *AUT*, is shown in Table 1. *AUT* states that if we reach a state in which the responder has finished executing but the claimed id (corresponding to the first message of protocol) does *not* coincide with the actual identity of the initiator, the protocol is flawed. Indeed, a state in which the initiator can “lie” and still force the responder to finish means that authentication is violated. This is one of the possible forms of authentication failure. It is outside the scope of this paper to illustrate different authentication flaws (see Lowe [27] and Cremers et al. [12] for more on authentication notions).

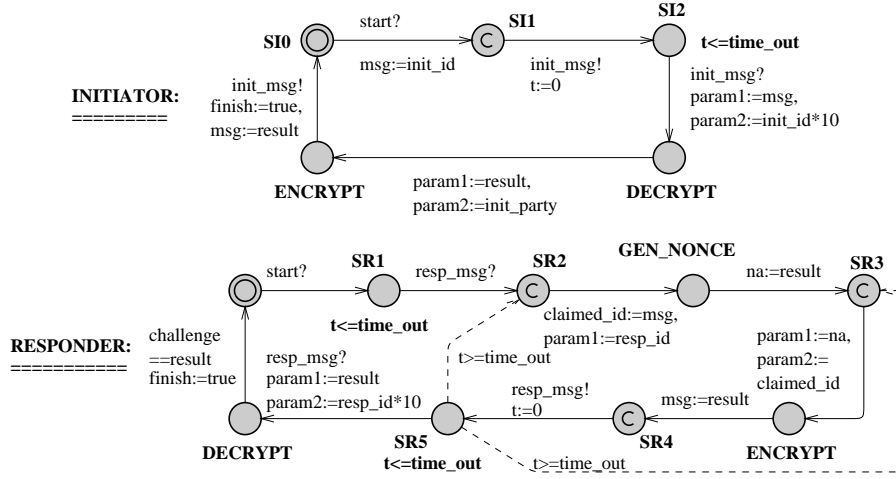


Figure 8: Schemas of timed automata for the Initiator (top) and the Responder (bottom)

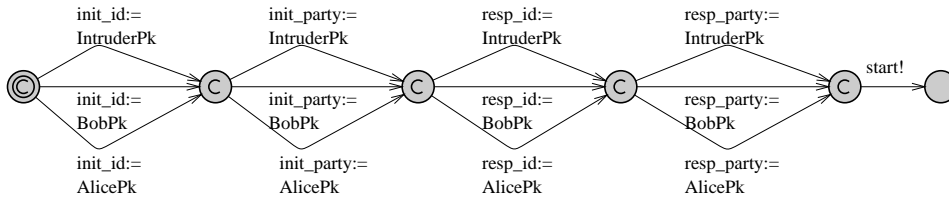


Figure 9: Timed automaton for the Init automaton

AUT	=	$E \langle \rangle \text{Responder.finish and}$ $\text{Responder.claimed_id!} = \text{resp_party}$
AUT_y	=	$E \langle \rangle \text{Initiator.finish and}$ $\text{Initiator.ticks} < (\text{Responder.time_encrypt}$ $+ \text{Responder.time_gennonce} + \text{Server.time_encrypt} * 2$ $+ \text{Server.time_decrypt}) - 1$

Table 1: UPPAAL properties

$\alpha.1$	$A \rightarrow I$	$:A$	1. $I(B) \rightarrow B$	$: B$
$\beta.1$	$I(A) \rightarrow B$	$:A$	2. $B \rightarrow I(B)$	$: \{N_B\}_{K_B}$
$\beta.2$	$B \rightarrow I(A)$	$: \{N_B\}_{K_A}$	3. $I(B) \rightarrow B$	$: \{N_B\}_{K_B}$
$\alpha.2$	$I \rightarrow A$	$: \{N_B\}_{K_A}$		
$\alpha.3$	$A \rightarrow I$	$: \{N_B\}_{K_I}$		
$\beta.3$	$I(A) \rightarrow B$	$: \{N_B\}_{K_B}$		

Table 2: A man-in-the-middle attack (left) and a replay attack (right)

If we use a long timeout for B , i.e.

$$B.\text{time_out} \geq \text{Intruder.time_decrypt} + \text{Intruder.time_encrypt} + A.\text{time_encrypt} + A.\text{time_decrypt}$$

here UPPAAL finds a man-in-the-middle attack, presented on the left hand side of Table 2. This attack is similar to Lowe’s attack [26], in which an attacker fools B into thinking he is communicating with A , while in reality A only talks to I . Of course, we could patch the protocol as Lowe did. But, in the context of time, it is interesting to model-check the protocol with a *tighter* timeout, ie. $B.\text{time_out} < \text{Intruder.time_decrypt} + \text{Intruder.time_encrypt} + A.\text{time_encrypt} + A.\text{time_decrypt}$. When this constraint is verified, the man-in-the-middle attack vanishes. Of course, we cannot pretend that B knows the intruder’s times of encryption and decryption. Nevertheless, B can set $B.\text{time_out} = A.\text{time_encrypt} + A.\text{time_decrypt}$, leaving *no* space for any interruption.

A second attack which is independent of timeouts (even if we set $B.\text{time_out} = 0!$) was also found by UPPAAL; this time, the vulnerability is much simpler. We report it on the right hand side of Table 2. This attack corresponds to a “reflection” replay attack [30]. This attack occurs when the intruder simply replies B ’s message. The attacker fools B into thinking its communicating with himself, while it is not true in reality. Interestingly, suppose we change message 3 of the protocol to 3’. $A \rightarrow B : \{N_B + 1\}_{K_B}$. Now, the above replay attack is prevented, since message 2 is not valid as message 3 anymore. Of course, a patch à la Lowe for *both* also prevents both problems:

1. $A \rightarrow B : A$
2. $B \rightarrow A : \{B, N_B\}_{K_A}$
3. $A \rightarrow B : \{N_B\}_{K_B}$

Having find confirmation that our framework is capable of finding *untimed* attacks (and thus confirming known attacks), we proceed to provide a good baseline to study extended security protocols with timing issues, like timeouts and retransmissions.

4.1.2 Retransmissions

Consider again the automaton for the responder, given in Figure 8. In state SR4, the responder sends the challenge $\{N_B\}_{K_A}$, and waits for a response in state SR5. If the response does not arrive before the timeout, the responder simply aborts. Now we consider possible retransmissions that allow the protocol to recover and continue its execution. With timed automata, retransmissions are easy to model by adding transition arrows from state SR5 to previous states of the automaton (the dashed lines in Figure 8); These transitions are guarded, allowing to perform the action only when the timeout is reached (ie., $t \geq \text{time_out}$). A further refinement not explored here would be to add counters so that the number of retransmissions can be limited before aborting.

We consider two potential target states for the timeout of the Responder in SR5, namely states SR3 and SR2. Choosing the former corresponds to retransmitting the exact same message that was sent before, $\{N_B\}_{K_A}$. On the other hand, linking the retransmission arrow to SR2 corresponds to recomputing the whole message, by creating a new nonce N'_B and sending $\{N'_B\}_{K_A}$.

We implemented both strategies in our UPPAAL model. As can be expected, retransmitting the exact message *once* has the effect of *duplicating* the timeout for B , and thus the man-in-the-middle attack becomes possible even for tight timeout values. On the other hand, recomputing the whole message preserves the security of the protocol, at a higher computational cost. This evidences that indeed these design decisions are important for both security and efficiency, and a careful analysis can help to choose the best timeouts and retransmissions for a practical implementation.

4.2 A Real Protocol

Having illustrated our approach with a simple example we now study a more realistic protocol, the Yahalom protocol [9]. This protocol aims at authentication of A and B as well as key distribution of A and B using a shared server S with whom both A and B share secret keys K_{AS} and K_{BS} .

Our choice is based on the fact that Yahalom is a complex and strong protocol, with no known attacks over it (However, a modification proposed by Abadi et al. [8] has a known type-flaw attack). Our aim is to study the protocol in more detail (and thus closer to an implementation) with timing information. The protocol is as follows:

1. $A \rightarrow B$: A, N_A
2. $B \rightarrow S$: $B, \{N_B, A, N_A\}_{K_{BS}}$
3. $S \rightarrow A$: $\{B, K_{AB}, N_A, N_B\}_{K_{AS}}, \{A, K_{AB}, N_B\}_{K_{BS}}$
4. $A \rightarrow B$: $\{A, K_{AB}, N_B\}_{K_{BS}}, \{N_B\}_{K_{AB}}$

Here we use symmetric encryption, and key K_{XY} is shared between X and Y .

To model concatenation in an efficient way, we gathered several message components into a 16 bit field, thus keeping the state space as small as possible. In our case, we assume that nonces have 4 bits, principal id's 2 bits and keys 4 bits. To access these values, we use bit-wise **and** with appropriate masks, and (left,right) bit shifts. Our intruder has also the capability to do the shifts and mask, and we also removed the “public key” choice from the intruder of Figure 7. We have modelled the protocol in UPPAAL (the initiator, responder, server and intruder are shown in Figures 10 and 11).

As we did with the previous protocol, first we check whether authentication of A to B could be falsified, using property *AUT* from Table 1. This property is not satisfied, confirming that Yahalom is secure. Now we move to study time sensitive issues.

There are two places in which timeouts and retransmissions can occur in this protocol. The first one is in Message 1: After A sends her message, she starts a timer waiting for message 3. Now, suppose that a timeout occurs, and A wants to retransmit her message. We can be confident that resending the same nonce N_A will *not* affect security, since in any case it was already sent in the clear in the first time. However, an interesting timing issue arises here. An answer that is received *too early* by A could be suspicious, because some time must pass while B talks to S . If A knows B 's and S 's encryption and decryption times, A could even deliberately “hibernate” (eg. to save energy) until the response is likely to arrive (this models a windowed timeout, see Figure 1 (ii)). We model checked this property by measuring the time after A sends her message, and a response arrive (we count **ticks**, the dashed loop transition of the initiator in Figure 10). The specified property is *AUT_y*, shown in Table 1. This property is not satisfied, confirming that there is no way that the initiator can receive a valid answer *before* the time required by the responder and server to process A 's request. In an implementation, it is reasonable for A to set a timeout like above, since it is realistic to assume that A can know the responder and server's times of encryption and decryption.

The second timeout is set by B after sending his message at step 2. If a timeout occurs, the retransmission decision is more delicate: It is not clear whether B should resend the original message, should recompute N_B or whether B should abort, since clearly N_A cannot be recomputed. Intuitively, N_B could be reused. We modelled in UPPAAL the retransmission of the exact message

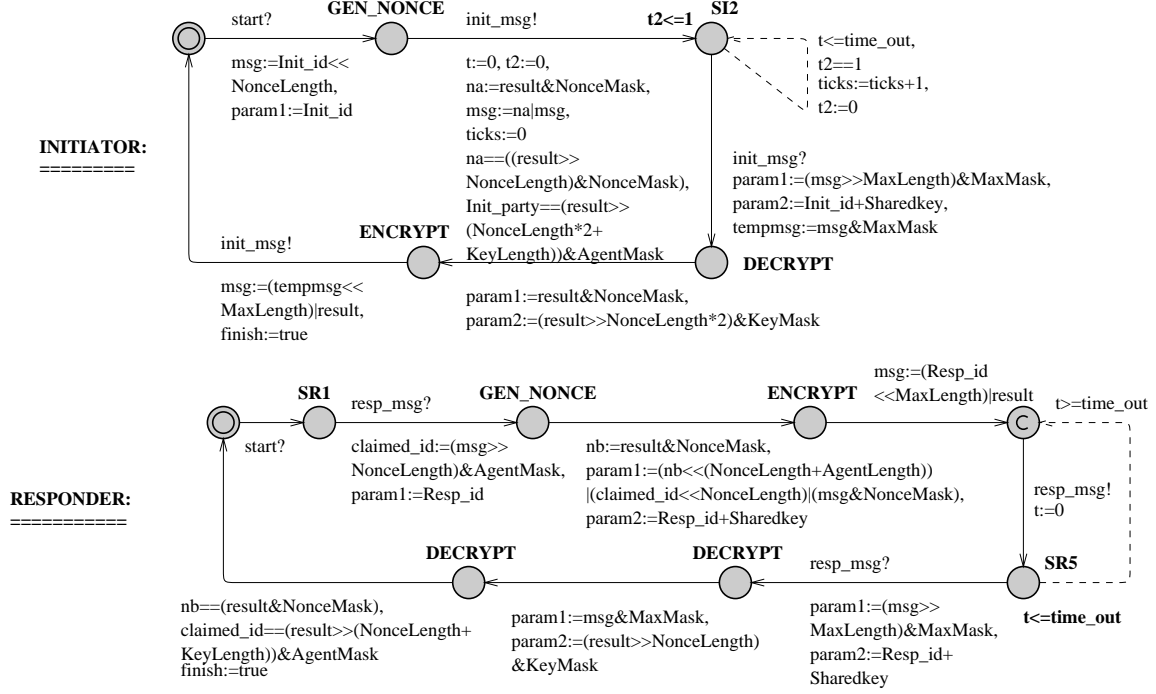


Figure 10: Timed automata schemas for the Yahalom Initiator (top) and responder (bottom)

(as the dashed transition of the responder in Figure 10). When we model check again property AUT_y , we obtain that it is still unreachable, confirming that in that case an efficient retransmission of the same message 2 by B is secure.

However, by observing the messages flow, we know that if B timeouts then it is very likely that A has also reached its timeout and aborted (see Figure 1 (iv)). This mainly happens because since A is unsure whether B is alive or not, and thus A 's timeout needs to be tight. If A knew that B is alive and waiting for an answer from S , then A could *extend* its timeout. We then sketch a more efficient implementation in Figure 12, in which at Message 2 B also sends a special *subm* message notifying A of the submission to S . Then A can extend its timeout with more confidence (the second dashed line in Figure 12). In the case *subm* is never received by A , she can send an *abort* message to B . Of course, in this simple model the attacker can also send this messages, thus performing denial of service attacks; in any case, our attacker is powerful enough to stop communication altogether.

In summary, for the Yahalom protocol we obtain that retransmitting for the responder is secure, and also that the initiator can be implemented to efficiently “hibernate” a safe amount of time before receiving a response.

5 Taxonomy of Message Flows in Security Protocols

The flow of messages of many protocols follow a small set of specific patterns. By exploring the well known Clark Jacob library [9] of authentication protocols and the Security Protocols Open Repository (SPORE) [1], we were able to categorize the protocols in four categories, as shown in Figure 13. To each pattern, we add the corresponding timeouts, and analyze their impacts on security and efficiency. For the original references of the protocols, the interested reader may consult the Clark Jacob library [9] and the SPORE library [1].

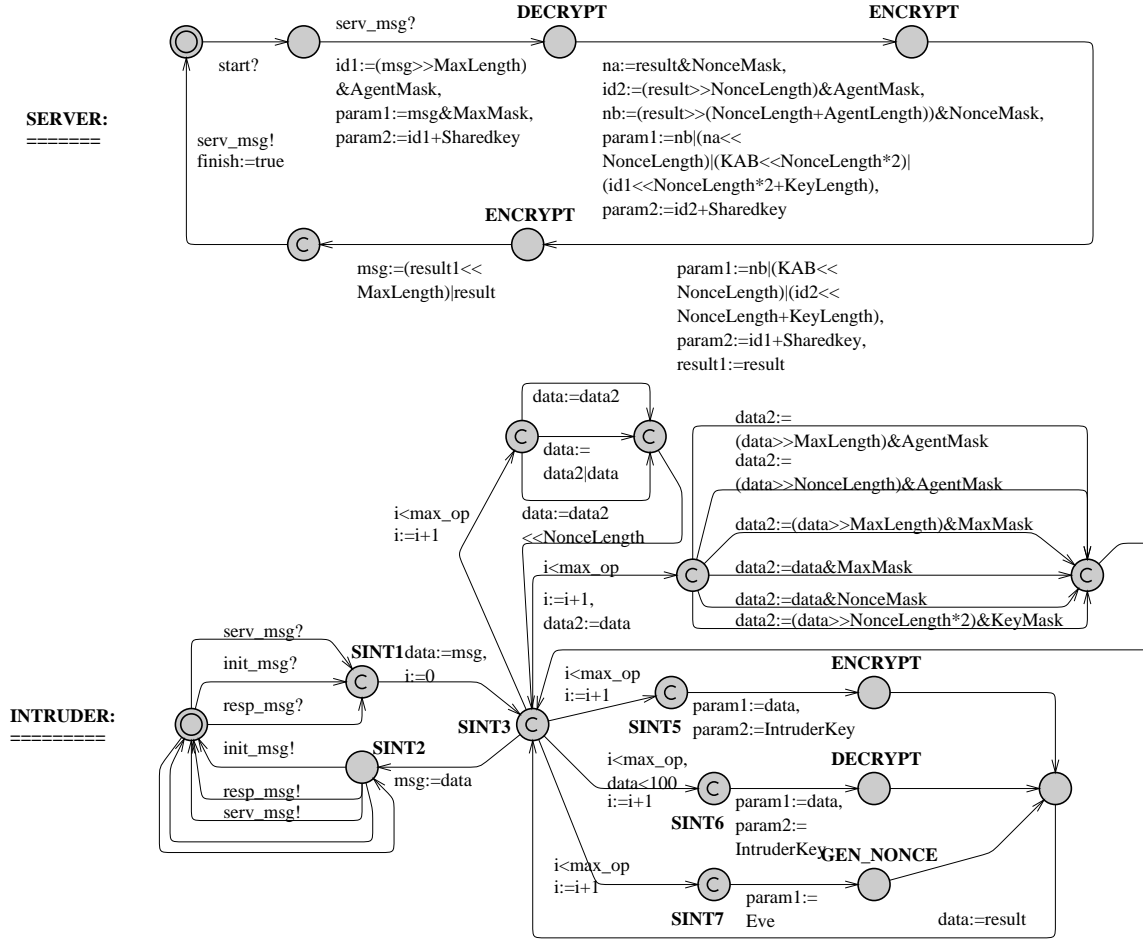


Figure 11: Timed automata schemas for the Server (top) and Intruder (bottom)

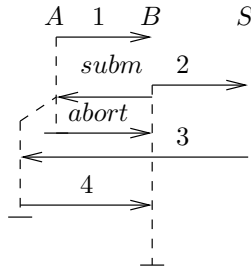


Figure 12: An more detailed implementation of Yahalom

Not shown in this categorization are non-interactive protocols which do not wait for messages and thus do not require timeouts. In this category fall the Wide Mouthed Frog protocol, the CCITT X.509 simple pass protocol and the CAM protocol for mobile IP.

First, we discuss the simplest pattern in Figure 13 (i). This is a three-message exchange with two participants. This pattern is the simplest and also the most secure one from timing point of view, since timeouts can be set tight, due to the ping-pong nature of the exchanges. To this pattern correspond both the example protocol of Section 4.1 and the one in Section 6.1, and also the protocols CCITT.509 three pass, the Shamir Rivest and Adleman Three-Pass protocol, the ISO XXX Key Three-Pass (and their repeated protocols), the SmartRight view-only protocol (from SPORE) and the Diffie-Hellman key exchange protocol. With a fourth message from B to A in the same fashion we find the Andrew Secure RPC protocol. Adding a third participant S , but still doing ping-pong exchanges, we can add the Needham Schroeder symmetric key protocol and the Denning Sacco protocol.

Secondly, we identify three-party protocols, in which a server S also takes part in the communication (Figure 13 (ii)) but ping-pong exchanges are not anymore used. This pattern is potentially unsafe and inefficient for A , since she has to wait until a long timeout as elapsed after the first message before receiving an answer from S . This is due to the fact that three messages have to be exchanged after A 's initial message. By consulting again the Clark and Jacob library and the SPORE repository, we see that the Otway Rees protocol, the Gong mutual authentication protocol, the Woo-Lam mutual authentication protocol, the Carlsen protocol, and finally the Kehne Schoenwalder Langendorfer (KSL) protocol all fall in this category. Adding ping-pong exchanges before and after the exchanges of Figure 13 (ii) we find the Needham Schroeder Public key protocol. Adding a ping-pong exchange before Figure 13 (ii), and removing the last exchange gives us the SPLICE/AS protocol.

Thirdly, we see a pattern to which only the Kao Chow protocol belongs in Figure 13 (iii). This pattern is however better than (ii), since shorter and fewer timeouts are used: A needs to wait for the timeout corresponding to only two messages (instead of three as in (ii)), and B has to wait for only one timeout (comparing to two timeouts in (ii)).

Finally, in Figure 13 (iv) we see the last pattern. This pattern is worse than (iii) since B needs to wait longer (for two messages instead of one in (iii)). However, it is unclear whether it is better than (ii), which uses two timeouts of one message each: the actual efficiency and security depends on the actual timeout values used in each case. This category is inhabited by the Yahalom and Neuman Stubblebine protocols.

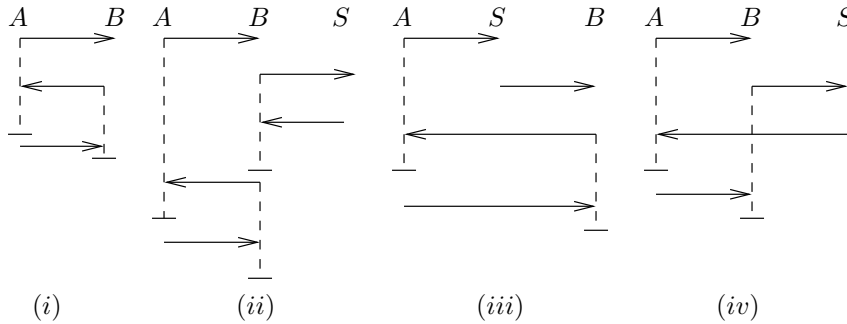


Figure 13: Typical message flows for authentication protocols

This taxonomy shows how authentication protocols can be categorized into a handful of patterns. The efficiency and security that an implementation of a protocol will have depends on which pattern the protocol follows, and thus it is useful to consider the patterns in isolation from the actual protocols. In this paper we do not pursue this further, although as future work it would be interesting to further analyze these abstract timing patterns induced from security protocols.

6 Beyond Model Checking: Novel Issues Considering Time

So far our method has been used for analysis purposes, ie. to model, classify and debug security protocols as a source of hints for the improvement of the protocol implementations. We now explore some ideas to improve the protocols themselves, and also present the threat of a more subtle attack, based only on timing.

6.1 Using Time as Information: Timed Challenges

Sometimes it can be useful to include other timed information than timestamps, *even* if the clocks are not synchronised. Consider the following protocol, obtained by omitting the encryption of the last message of the (patched) protocol of Section 4.1:

1. $A \rightarrow B$: A
2. $B \rightarrow A$: $\{B, N_B\}_{K_A}$
3. $A \rightarrow B$: N_B

Even though N_B is now sent in the clear, this protocol still achieves authentication of A to B , although now the nonce obviously cannot be regarded as a shared secret. Still, the intruder can prevent a successful run of the protocol (eg. by intercepting message 3), hence the protocol is as strong as it was before in this respect.

Imagine now a situation in which there is a link from A to B in which data can be sent very fast, but at a high cost per bit sent. For example, think that the high cost of sending information comes from the fact that we have devices with a very limited amount of energy, like wireless sensor networks for instance. Alternatively, in some networks, operators charge according to quality of service, and many networks have asymmetric links (eg. Cable modem and ADSL).

Assume therefore that, sending N_B in message 3 is expensive and not desirable. We propose a solution based exclusively on using *time* as information. Let δ_{AB} be the average time it takes for a message to be sent from A to B , and analogously δ_{BA} . Then consider the “timed” variant of the above protocol, demonstrating how timing information is brought back to the (abstract) protocol level (ie. Step 3 of Section 3):

1. $A \rightarrow B$: A
2. $B \rightarrow A$: $\{B, t_B\}_{K_A}$
3. $A \rightarrow B$: “ack” at time $t_B - \delta_{AB} - \delta_{BA}$

In Message 2, instead of a nonce, B generates some random time value $t_B > \delta_{AB} + \delta_{BA}$, concatenates it with B ’s identity and encrypts the message with A ’s public key. Then, B starts a timer t and sends the message. Upon reception, A extracts t_B , *waits* time $t_B - \delta_{AB} - \delta_{BA}$, and replies the single bit message “ack”. When B receives this message, the timer is stopped and B checks that t is *sufficiently* close to t_B ; if so, A is authenticated to B . Of course, the amount of noise in the time measurements influences what we mean by “*sufficiently* close” above. Also, to be realistic, the length in bits of t_B should be small enough, otherwise B would be waiting too long (on average); this would give an intruder the chance to guess t_B , and answer the “ack” at the appropriate time. Moreover, if encryption $\{\cdot\}$ is deterministic, an attacker can record $\{B, t_B\}_{K_A}$ and the answers t_B in a table. As soon as A chooses t_B again (and this is likely since t_B is small) and sends out $\{B, t_B\}_{K_A}$, the attacker can notice the repeated message in its table since encryption is deterministic, and hence the attacker can intercept the message (so it never arrives to B) and still authenticate to A , since the attacker knows precisely when to send t_B . Probabilistic encryption solves this issue, although even then the attacker can simply guess t_B and violate authentication

with non-negligible probability. However, we can strengthen the protocol as follows:

1. $A \rightarrow B$: A
2. $B \rightarrow A$: $\{B, t_{B_1}, \dots, t_{B_n}\}_{K_A}$
3. $A \rightarrow B$: “ack” at time $t_{B_1} - \delta_{AB} - \delta_{BA}$
- \vdots
- $n + 3$. $A \rightarrow B$: “ack” at time $t_{B_n} - \delta_{AB} - \delta_{BA}$

For example, if t_{B_i} is of length 4 bits, for $i \in [1..n]$, then the total answer is n bits, in comparison with an answer of $4n$ bits required in the nonce protocol.

Of course, sending several short messages can be worse than sending one long message, in which case our protocol would not be so useful. In general, the value of n must be chosen as small as possible, depending on the desired security and network latency. A fast network allows us to reduce n and at the same time increment the length of t_{B_i} , for $i \in [1..n]$.

Intuitively, the sent times of the “ack”’s represent information, and the above protocols exploit that. To the best of our knowledge, this is a novel usage of time in security protocols.

Application This protocol can be used to authenticate a whole chain of network packets, as follows. Suppose A has a large sequence of n packets which must be streamed to B over a network. For instance, these packets can represent an audio stream in the Internet. We want to authenticate the audio stream, but we do not wish to spend lots of resources on doing this. Let $t_{B_i} \in \{\delta_{AB} + \delta_{BA}, \delta_{AB} + \delta_{BA} + C\}$ for some constant C and p_i denote packet i , for $1 \leq i \leq n$. Then the protocol becomes:

1. $A \rightarrow B$: A, n
2. $B \rightarrow A$: $\{B, t_{B_1}, \dots, t_{B_n}\}_{K_A}$
3. $A \rightarrow B$: p_1 at time $t_{B_1} - \delta_{AB} - \delta_{BA}$
- \vdots
- $n + 3$. $A \rightarrow B$: p_n at time $t_{B_n} - \delta_{AB} - \delta_{BA}$

When t_{B_i} is $\delta_{AB} + \delta_{BA}$, it is the delay introduced by A is zero, ie. p_i is sent right away. However, when t_{B_i} is $\delta_{AB} + \delta_{BA} + C$, the delay is C . To be as efficient as possible, C should be chosen to be the minimum amount of time that allows B to distinguish the delay modulated by A .

In this protocol, only one bit is authenticated per packet. However, the larger the n is, the more confidence we can obtain of A ’s authentication.

Discussion In this protocol, we are in reality exploiting a well-known feature of channel coding: a so-called *timing covert channel*. In such a channel, the transmitting party modulates packets so that information can be passed even if its not allowed by the environment. Our usage differs in three ways:

- Firstly, we use a mixed approach, in which some information is sent in the standard channel, and other is sent in the timing channel.
- A second difference is more fundamental than the previous one. Our usage of the timing channel is purposely public, and there is no environment trying to stop the unauthorized information flow. Timing is used only because of its practical advantages, namely low-bandwidth.
- Finally, in our protocol both communicating parties do not initially trust on the other’s identity, in principle: Indeed, ours is an *authentication* protocol.

6.2 Timing Leaks in an Implementation of the Private Authentication Protocol

We now present a threat against an implementation of security protocols with branching: the so called timing attack. We illustrate this by showing an attack over a careless implementation of Abadi's Private Authentication (PAP) protocol [2] (The *second* protocol). It is worthwhile to mention that the protocol has been proved correct by Abadi and Fournet [21], in a setting without time. We assume that each principal X has a set of communication parties S_X , listing the principals with whom X can communicate. The aim of the protocol is to allow a principal A to communicate *privately* with another principal B . Here “privately” means that no third party should be able to infer the identities of the parties taking part in the communication (i.e. A and B) (PAP Goal 1). Moreover, if A wants to communicate with B but $A \notin S_B$, the protocol should also conceal B 's identity (and presence) to A (PAP Goal 2). A run of the protocol in which A wants to communicate with B proceeds as follows:

1. A generates a nonce N_A . Then, A prepares a message $M = \{\text{"hello"}, N_A, K_A\}_{K_B}$, and broadcasts $(\text{"hello"}, M)$.
2. When a principal C receives message $(\text{"hello"}, M)$, it performs the following three steps:
 - (a) C tries to decrypt M with its own private key. If the decryption fails, (which implies that $C \neq B$), then C creates a “decoy” message $\{N\}_K$ (creating a random K , and keeping K^{-1} secret), broadcasts $(\text{"ack"}, \{N\}_K)$ and finish its execution. If decryption succeeds, then $C = B$ (and so from now on we will refer to C as B). B then continues to the next step.
 - (b) B checks that $A \in S_B$. If this fails, i.e. $A \notin S_B$, then B creates a “decoy” message $\{N\}_K$, broadcasts $(\text{"ack"}, \{N\}_K)$ and finishes execution. Otherwise B continues to the next step.
 - (c) Finally, B generates a fresh nonce N_B , and broadcasts the message $(\text{"ack"}, \{\text{"ack"}, N_A, N_B, K_B\}_{K_A})$.

It is interesting to see the use of “decoy” messages, to prevent attacks in which an intruder I prepares a message $M = \{\text{"hello"}, N_C, K_A\}_{K_B}$, impersonating principal A . If decoy messages were not present, then I would send $(\text{"hello"}, M)$, and deduce whether $A \in S_B$ by noticing a response from B . However, using decoys only helps to confuse an attacker doing traffic analysis, and breaks down when considering a “timed” intruder, as we will show in the next section.

An Attack Over an Implementation of the Private Authentication protocol

We show an attack in which I can find whether $A \in S_B$. The attack is illustrated in Figure 14, where I is trying to attack A , B and C , which since I does not know their identities are called X , Y and Z . First, suppose that $I \notin S_B$ (the attack for the case in which $I \in S_B$ is analogous). First I needs to know how long, on average, it takes to B to compute each step of the protocol as described above. To discover this I could prepare various messages:

1. Firstly, I sends a message $(\text{"hello"}, \{N\}_K)$, where K is not the public key of any other participant. This would generate a number of decoy responses from the other participants, which I can time (Step 1 in Figure 14, for times x , y and z).
2. Secondly, I sends a message $(\text{"hello"}, \{\text{"hello"}, N_I, K_I\}_{K_B})$. Again, this generates decoy responses from the other parties which I can time (Step 2 in the figure). However, if B is present, then *one* response will have longer time (ie. we get times x , z and y' with y' longer than y), reflecting the successful decryption and check that $I \notin S_B$ performed by B (Recall we assume that $I \notin S_B$). Up to this point, I has information that allows him to

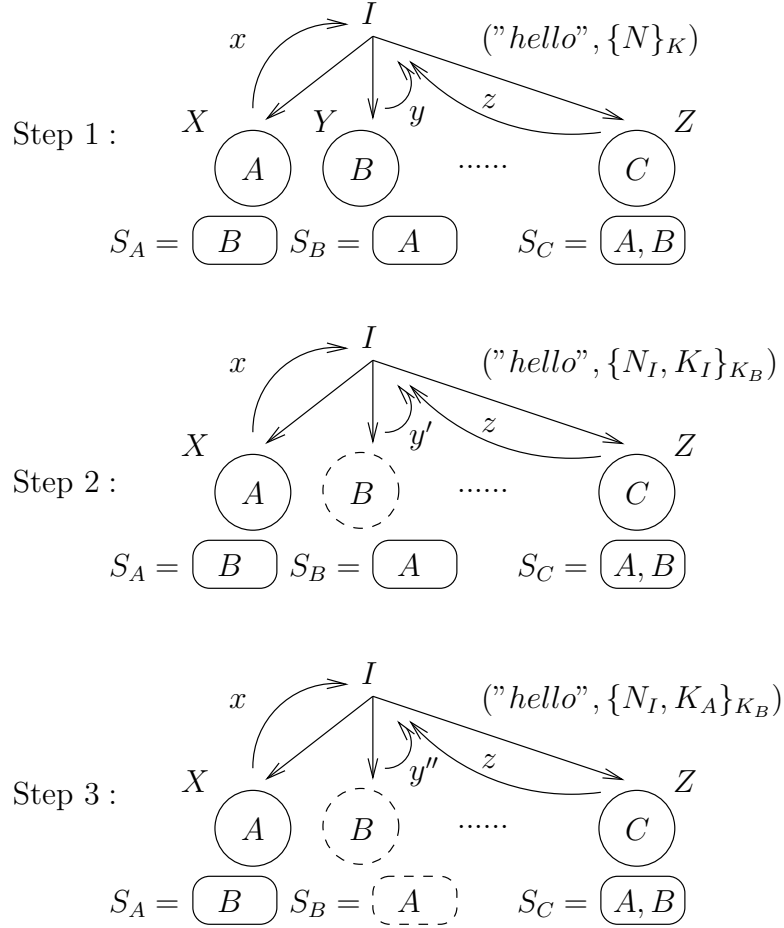


Figure 14: The attack over the PAP protocol, where X , Y and Z are unknown identities by the intruder I . A , B and C are real identities, with corresponding S_A , S_B and S_C sets; x , y , y' , y'' and z are timing values (Dashed circles indicate the intruder's knowledge of inner values)

infer B 's presence (hence the dashed circle in the figure); Thus, this attack already violates goal 2 of Abadi's requirements [2]: B should protect its presence if a party X is willing to communicate with B but $X \notin S_B$ (Step 2).

3. Finally, if B is present, then I sends message $(\text{"hello"}, \{\text{"hello"}, N_I, K_A\}_{K_B})$. This would generate again the same decoy responses, except one that takes longer (Step 3 in the figure, for x, z and y'' with y'' longer than y'). If this response takes the same time as the above item, then I can deduce that $A \notin S_B$. Otherwise, if the response takes longer (reflecting the nonce generation N_B and encryption performed by B) then I can deduce that $A \in S_B$.

If $I \in S_B$, then the second step above returns the *longest* time, and the third message would take either *less* time or equal.

After recording this information, I has three time values t_0, t_1 and t_2 . t_0 corresponds to the time in which B is not present; t_1 corresponds to the time in which B is present but its communicating party $X \notin S_B$. Finally, t_2 corresponds to the case in which B is present and its communicating party $X \in S_B$. With these values at hand, now an attacker can check if $A \in S_B$ for an arbitrary A .

Timing in networks is often accurate but if the accuracy is too low, the intruder can repeat the timings (i), (ii) and (iii) and perform statistical analysis to increase the probability of the inferences to be correct [23]. We propose this as future work, when we have a probabilistic, timed model checker at disposal.

7 Related Work

Many approaches focus on the study of protocols that use timestamps [15, 18, 27, 6, 22]. Recent work of Delzanno et.al. [15] presents an automatic procedure to verify protocols that use timestamps, like the Wide Mouthed Frog protocol. In their work, differently from ours, a global clock is assumed, and timeouts and retransmissions are not discussed. Evans and Schneider [18] present a framework for timed analysis. Differently from our (UPPAAL) model checking, it is based on a semi-decision procedure with discrete time. In that work, the usage of retransmissions is hinted at as future work, but not (yet) addressed. Lowe [27] also analyses protocols with timing information; his work shares with us the model checking approach, although Lowe's approach is based on a discrete time model. A global clock is also assumed, and timeouts nor retransmissions are addressed. Closer to ours is the work of Gorrieri et al. [22], in which a real-time process algebra is presented for the analysis of time-dependent properties. They focus on compositionality results, and no model checking is presented. Gorrieri et al. also show how timeouts can be modelled, although retransmissions are not discussed.

Regarding our timing attack upon Abadi's protocol, Focardi et al [20] develop formal models for Felten and Schneider's *web privacy* timing attack [19]; their modelling activity shares with our work the idea of using timed automata for analysis, although our attack illustrates a timing attack over a "pure" security protocol.

8 Conclusions

Security protocol analysis is a mature field of research that has produced numerous results and valuable tools for the correct engineering of security protocols. Despite a large body of literature on the subject, most analysis methods do not take time into consideration (with the exception of a few papers, considering mainly the use of timestamps). We argue that this is not realistic as all distributed protocols need to implement timeouts (possibly followed by retransmissions).

In this paper we address some of the issues that need to be considered when including time-related parameters in the engineering process of a security protocol.

Our first contribution is a method for the design and analysis of security protocols that consider timing issues. We model security protocols using timed automata, and use UPPAAL to simulate, debug and verify security protocols in a real time setting. To this end, we employ a general Dolev Yao style intruder (naturally encoded in UPPAAL), and we remark that modelling the intruder as a timed automata implicitly extends its power to take into account the time sensitivity. Our method allows us to specify security protocols in detail, with timeouts and retransmissions. This increases the confidence in the analysis, since the modelled protocols are closer to their implementations than the classical analysis (e.g. CASPER [27] or the constraint-based methods of [28, 10]).

Secondly, by analyzing the protocols in the Clark and Jacob library and the SPORE library, we see that most protocols schemas (w.r.t. timeouts) fit into a small number of common patterns. We analyse the efficiency and security of each of the patterns. Still, as possible future work we would like to perform a full UPPAAL analysis of each of these literature protocols (just as we do for Yahalom in Section 4.2).

Other novel and more real-life protocols which are sensitive to timing issues (e.g. besides timeouts, use for instance puzzles) may benefit from our analysis, e.g. the Host-Identity-Protocol (HIP), initially analysed by Aura et al. [5].

Our third contribution is an illustration of the implicit information carried by timing. The mere act of sending a message at a specific moment in time, and not another, carries information. We propose a novel security protocol that exploits this fact to achieve authentication. The protocol replaces the standard nonces with timed challenges, which must be replied at specific moments in time to be successful. Although it is a preliminary idea, it exposes clearly the fact that security protocols can use and take advantage of time.

Finally we address threats specifically involving timing should also be considered; specifically, timing attacks. We illustrate these attacks in the context of security protocols, where branching allows an intruder to deduce information that is intended to be kept secret. Specifically, we mount an attack over an imperfect implementation of Abadi's private authentication protocol [2]. Solutions to avoid timing attacks in the implementations are usually expensive (e.g. noise injection or branch equalization), and it is not our purpose to investigate them. Here we merely lift the known problem of timing attacks, typically mounted against the cryptosystem to obtain secrets keys, to security protocols in general where the information leakage can be, in principle, anything.

One possible direction of future work is to consider a timed and probabilistic model checker (in the lines of [13] or [24]), that would allow us to study the protocols of Section 6. Moreover, a probabilistic setting would allow us to model, more realistically, the network latency. This, in turn, would provide us with a finer method to tune sensitive timing values. Another possible direction for future research would be to implement a compiler from a meta notation (similar to the standard notation, plus timing information) supporting symbolic terms, to UPPAAL automata. Ultimately, these directions of future work would contribute to a method of secure systems engineering.

Acknowledgements Gabriele Lenzini, Conrado Daws, Jeroen Doumen, Jerry den Hartog, Ari Saptawijaya and the anonymous reviewers of FMSE2004 provided useful comments.

References

- [1] Security Protocols Open Repository (SPORE). At <http://www.lsv.ens-cachan.fr/spore/>, INRIA, March 2005.
- [2] M. Abadi. Private authentication. In R. Dingleline and P. F. Syverson, editors, *2nd. Int. Workshop on Privacy Enhancing Technologies (PET)*, volume LNCS 2482, pages 27–40, San Francisco, California, Apr 2002. Springer-Verlag, Berlin. <http://www.springerlink.com/link.asp?id=t4wpgvurht109g11>.

- [3] R. Alur and D.L. Dill. A theory of timed automata. *Theoretical Computer Science*, (138):183–335, 1994.
- [4] T. Amnell, G. Behrmann, J. Bengtsson, P. R. D’Argenio, A. David, A. Fehnker, T. Hune, B. Jeannet, K. G. Larsen, M. O. Möller, P. Pettersson, C. Weise, and W. Yi. UPPAAL - Now, Next, and Future. In F. Cassez, C. Jard, B. Rozoy, and M. D. Ryand, editors, *4th Summer School on Modeling and Verification of Parallel Processes (MOVEP)*, volume LNCS 2067, pages 99–124, Nantes, France, Jun 2000. Springer-Verlag, Berlin. <http://www.springerlink.com/link.asp?id=8km1eyyvfqfm740f>.
- [5] T. Aura, A. Nagarajan, and A. Gurtov. Analysis of the hip base exchange protocol. In *ACISP*, pages 481–493, 2005.
- [6] G. Bella and L. C. Paulson. Kerberos version IV: Inductive analysis of the secrecy goals. In J.-J. Quisquater, editor, *Proc. 5th European Symposium on Research in Computer Security*, volume LNCS 1485, pages 361–375, Louvain-la-Neuve, Belgium, 1998. Springer-Verlag.
- [7] S. M. Bellovin and M. Merritt. Limitations of the kerberos authentication system. *SIGCOMM Comput. Commun. Rev.*, 20(5):119–132, 1990.
- [8] M. Burrows, M. Abadi, and R. Needham. A logic of authentication. *ACM Transactions on Computer Systems*, 8(1):18–36, 1990.
- [9] J. Clark and J. Jacob. A survey of authentication protocol literature: Version 1.0. <http://www.cs.york.ac.uk/jac/papers/drareview.ps.gz>, 1997.
- [10] R. Corin and S. Etalle. An improved constraint-based system for the verification of security protocols. In M. V. Hermenegildo and G. Puebla, editors, *9th Int. Static Analysis Symp. (SAS)*, volume LNCS 2477, pages 326–341, Madrid, Spain, Sep 2002. Springer-Verlag, Berlin.
- [11] R. Corin, S. Etalle, P. H. Hartel, and A. Mader. Timed model checking of security protocols. In V. Atluri, M. Backes, D. Basin, and M. Waidner, editors, *2nd ACM Workshop on Formal Methods in Security Engineering: From Specifications to Code (FMSE)*, pages 23–32, Fairfax, Virginia, Oct 2004. ACM Press, New York.
- [12] C.J.F. Cremers, S. Mauw, and E.P. de Vink. Defining authentication in a trace model. In T. Dimitrakos and F. Martinelli, editors, *Fast 2003*, Proceedings of the first international Workshop on Formal Aspects in Security and Trust, pages 131–145, Pisa, September. IIT-CNR technical report.
- [13] P. R. D’Argenio, H. Hermanns, J.-P. Katoen, and J. Klaren. MODEST: A modelling language for stochastic timed systems. In L. de Alfaro and S. Gilmore, editors, *Joint Int. Workshop on Process Algebra and Probabilistic Methods, Performance Modeling and Verification (PAPM-PROBMIV)*, volume LNCS 2165, pages 87–104, Aachen, Germany, Sep 2001. Springer-Verlag, Berlin. <http://www.springerlink.com/link.asp?id=ka9lrbfnj7g6a9dd>.
- [14] G. Delzanno and S. Etalle. Proof theory, transformations, and logic programming for debugging security protocols. In A. Pettorossi, editor, *11th Int. Logic Based Program Synthesis and Transformation (LOPSTR)*, volume LNCS 2372, pages 76–90, Paphos, Greece, Nov 2001. Springer-Verlag, Berlin. <http://www.cs.utwente.nl/~etalle/papers/de02lopstr.pdf>.
- [15] G. Delzanno and P. Ganty. Automatic verification of time sensitive cryptographic protocols. In K. Jensen and A. Podelski, editors, *Tools and Algorithms for the Construction and Analysis of Systems: 10th International Conference, TACAS 2004, Held as Part of the Joint European Conferences on Theory and Practice of Software, ETAPS 2004*, pages 342 – 356, Barcelona, Spain, March 2004. Springer-Verlag, Berlin.

- [16] D. Dolev and A. C. Yao. On the security of public key protocols. *IEEE Transactions on Information Theory*, 29(2):198–208, 1983.
- [17] E. English and S. Hamilton. Network security under siege: the timing attack. *IEEE Computer*, 29(3):95–97, Mar 1996. <http://www.computer.org/computer/co1996/r3095abs.htm>.
- [18] N. Evans and S. Schneider. Analysing time dependent security properties in CSP using PVS. In F. Cuppens, Y. Deswarte, D. Gollmann, and M. Waidner, editors, *ESORICS*, volume LNCS 1895, pages 222–237. Springer, 2000.
- [19] E. W. Felten and M. A. Schneider. Timing attacks on web privacy. In *7th ACM conference on Computer and communications security*, pages 25–32, Athens, Greece, 2000. ACM Press, New York. <http://doi.acm.org/10.1145/352600.352606>.
- [20] R. Focardi, R. Gorrieri, R. Lanotte, A. Maggiolo-Schettini, F. Martinelli, S. Tini, and E. Tronci. Formal models of timing attacks on web privacy. In M. Lenisa and M. Miculan, editors, *Electronic Notes in Theoretical Computer Science*, volume 62. Elsevier, 2002.
- [21] C. Fournet and M. Abadi. Hiding names: Private authentication in the applied pi calculus. In *Symp. on Software Security*, volume LNCS 2609, pages 317–338, Tokyo, Japan, Jan 2003. Springer-Verlag, Berlin. <http://www.springerlink.com/link.asp?id=2a24gfmwamq7metw>.
- [22] R. Gorrieri, E. Locatelli, and F. Martinelli. A simple language for real-time cryptographic protocol analysis. In P. Degano, editor, *12th European Symposium on Programming, ESOP 2003*, volume LNCS 2618, pages 114–128. Springer-Verlag, Berlin, 2003.
- [23] P. C. Kocher. Timing attacks on implementations of Diffie-Hellman, RSA, DSS and other systems. In N. Koblitz, editor, *16th Advances in Cryptology (CRYPTO)*, volume LNCS 1109, pages 104–113, Santa Barbara, California, Aug 1996. Springer-Verlag, Berlin. <http://www.cryptography.com/resources/whitepapers/TimingAttacks.pdf>.
- [24] M. Kwiatkowska, G. Norman, and D. Parker. Probabilistic symbolic model checking with PRISM: A hybrid approach. In J.-P. Katoen and P. Stevens, editors, *Proc. 8th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS'02)*, volume LNCS 2280, pages 52–66. Springer-Verlag, Berlin, 2002.
- [25] L. Lamport. Using time instead of timeout for fault-tolerant distributed systems. *ACM Transactions on Programming Languages and Systems*, 6(2):254–280, April 1984.
- [26] G. Lowe. An attack on the Needham-Schroeder public-key authentication protocol. *Information Processing Letters*, 56(3):131–133, November 1995.
- [27] G. Lowe. Casper: A compiler for the analysis of security protocols. In *Proc. 10th IEEE Computer Security Foundations Workshop (CSFW '97)*, pages 18–30. IEEE, 1997.
- [28] J. Millen and V. Shmatikov. Constraint solving for bounded-process cryptographic protocol analysis. In *Proc. 2001 ACM Conference on Computer and Communication Security*, pages 166 – 175. ACM press, 2001.
- [29] D. Mills. Cryptographic authentication for real-time network protocols. *AMS DIMACS Series in Discrete Mathematics and Theoretical Computer Science*, 45:135–144, 1999.
- [30] P. Syverson. A taxonomy of replay attacks. In *Proceedings of the 7th IEEE Computer Security Foundations Workshop*, pages 131–136, 1994.
- [31] S. Yovine. KRONOS: a verification tool for real-time systems. *International Journal on Software Tools for Technology Transfer*, 1(1/2):123–133, 1997.