Analyzing and Securing SOME/IP Automotive Services with Formal and Practical Methods

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ABSTRACT

Automotive Ethernet is increasingly used in modern vehicles and complements or replaces legacy bus systems such as CAN. Ethernet also enables service-oriented communication with the Scalable service-Oriented MiddlewarE over IP (SOME/IP) middleware. In this paper, we present a formal and practical security analysis of SOME/IP, the identified Man-in-the-Middle (MITM) attacks, and propose two security extensions. The attacks are possible even if SOME/IP is used in combination with link layer security mechanisms. The attacker can impersonate a service offering server and a service consuming client. The two most common communication methods, request/response and publish/subscribe, are both vulnerable. In most communication scenarios, we are able to route all messages over the attacker. Our security extensions for authentication and authorization of service provisioning and usage protect against these attacks. We formally analyze the security and evaluate the overhead with practical implementations.

CCS CONCEPTS

• **Security and privacy** → **Security protocols**; *Embedded systems security*; • **Applied computing** → *Transportation*.

KEYWORDS

Automotive Security, SOME/IP, Man-in-the-Middle Attack

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1 INTRODUCTION

A major technology shift is currently taking place in vehicles, e.g., to implement new infotainment functionalities or advanced driver assistance systems, which are also required for autonomous driving. These functionalities require high and flexible communication bandwidths and are more and more realized using Automotive Ethernet (e.g., BroadR-Reach) and IP-based communication. In contrast to the Controller Area Network (CAN) bus, which provides only static communication, the use of Ethernet and IP enables dynamic and service-oriented communication with efficient bandwidth use. The Scalable service-Oriented MiddlewarE over IP (SOME/IP) can be used as an automotive middleware solution supporting remote procedure calls, event notifications, and the underlying serialization/wire format. SOME/IP has been developed to address automotive requirements (e.g., integration in AUTomotive Open System ARchitecture (AUTOSAR) or fast response times) and supports devices of different sizes and operating systems. Electronic Control Units (ECUs) use SOME/IP to announce offered services (as a server) or make use of a service (as a client). Since the SOME/IP specification does not consider any security mechanisms, it is often used in combination with link layer security mechanisms such as MACsec or AUTOSAR Secure Onboard Communication (SecOC).

This paper has two main contributions. First, we introduce MITM attacks on SOME/IP which are even possible when link layer security mechanisms are deployed. If an attacker has compromised a single ECU of the Electrical / Electronic (E/E) system of the vehicle (either by physical access or remotely like in the Jeep hack [23]), the attacker can impersonate both, a SOME/IP server and a client to direct the communication through the attacker. For this, we present a formal analysis with the Tamarin prover¹, which we used to identify the MITM attacks, and a practical evaluation with the open-source reference SOME/IP implementation vsomeip [7] and the automotive development and testing tool CANoe [11]. Second, we propose two SOME/IP protocol extensions for securing SOME/IP service discovery and all subsequent SOME/IP communication. Our solutions enable authentication and authorization of the provision and use of SOME/IP services. Our first approach initially uses certificates and digital signatures for establishing symmetric keys used to secure the subsequent SOME/IP communication. The second approach uses only efficient symmetric cryptography but

¹<https://tamarin-prover.github.io/>

requires an additional authorization server (AS) in the E/E architecture. Both approaches restrict service provisioning and usage, thus, limiting the damage an attacker can cause by compromising an ECU. We formally analyze the security of both approaches with the Tamarin prover and evaluate the introduced additional overhead with our practical implementation.

The paper is structured as follows: In Section 2, we discuss related work. An overview of SOME/IP is given in Section 3. Section 4 introduces our formal security analysis approach which we used to identify the MITM attacks described in Section 5. Implementation and evaluation of the attacks are described in Section 6. In Section 7, we describe our two security extensions for SOME/IP, their formal analysis, and the practical evaluation. Finally, we conclude the paper in Section 8.

2 RELATED WORK

Complex MITM attacks were not relevant for in-vehicle networks using classical automotive bus systems such as the CAN since routing is necessary in a bus system. Thus, previous work on in-vehicle attacks focused on replay or injection attacks on CAN and other bus systems. Koscher et al. presented attacks enabling brake and acceleration control via CAN in [17]. How to send messages directly or indirectly to in-vehicle networks via OBD-II, CD, WiFi, Bluetooth, or cellular has been investigated in [9]. Miller and Valasek showed in [22] how to control the steering, braking, acceleration, and the display of a car via the CAN network. They also presented an attack to remotely control a car in [23].

To secure the communication in automotive E/E architectures, several approaches have been proposed. SecOC [1] is standardized by AUTOSAR for securing CAN communication with symmetric cryptography. The security of SecOC has been formally analyzed in [19]. With increasing computing power and higher bandwidth also asymmetric cryptography can be used. For example, TLS is part of AUTOSAR (both classic and adaptive platform) and has been discussed in the literature, e.g., in [31]. IPsec is also supported by the adaptive platform. TLS 1.3 has also been formally analyzed using Tamarin [10], as well as ProVerif [5]. Tamarin has been also used to analyze V2X revocation protocols [29] and an electric vehicle charging protocol [20].

Securing SOME/IP was discussed in [18]. They propose a central entity for the key material distribution using (D)TLS during the event group subscription. The service offer and find offer are not protected. SOME/IP itself is extended with a TESLA protocol allowing broadcast communication. Using TESLA with a delayed authentication (cf. [25]) for broadcast messages has the drawback that the SOME/IP process flow needs to be changed (for caching messages until the verification messages arrive) and that the introduced latency is not suitable for time-critical data.

To detect attacks on SOME/IP, Herold et al. present an Intrusion Detection System (IDS) for SOME/IP based on Complex Event Processing (CEP) in [12]. The IDS can detect attacks from the following groups: malformed packages, protocol violations, and timing problems. This approach has the same problems as other IDS approaches, namely false-positive and false-negative results.

Iorio et al. propose a security framework to protect SOME/IP communications [15]. Initially, individual handshakes between each

client requesting a service and the service offering server using certificates and asymmetric cryptography are executed for establishing a shared symmetric key. This key is used for securing subsequent messages. The main drawbacks are similar to TLS, i.e., the introduced overhead for asymmetric cryptography and that broadcast messages, for service offer messages, are not possible anymore. Instead, "find service" messages are sent to perform an individual key exchange.

Securing service-oriented communication is also discussed in other areas. For example, to secure the Robot Operating System (ROS) the fork Secure ROS [27] enables secure communication among ROS nodes by setting up an IPsec connection and restricting service providers and requesters by predefining allowed IP addresses. However, this approach contradicts the idea of a dynamic network and service discovery.

3 SOME/IP

The Scalable service-Oriented MiddlewarE over IP (SOME/IP) [3] is a middleware specification designed for transmission and serialization of control signals, especially in automotive use cases. SOME/IP resides on top of an (automotive) TCP/IP or UDP/IP stack and provides an abstract service-oriented interface for applications (cf. Figure 1). Thus, an application does not need to handle IP addresses and ports but services instead. The main goal of SOME/IP is the realization of flexible and bandwidth-efficient communication.

Figure 1: SOME/IP Architecture

SOME/IP can be roughly divided into three parts: Service Discovery (SD), Remote Procedure Call (RPC), and access to process data. SD enables server ECUs to publish services and client ECUs to subscribe to services in the vehicle network which are identified by a *Service ID* and, if required, additional options such as the *endpoint option* (i.e., IP-address, transport protocol (UDP/TCP), and port number). Multiple instances of a service (with the same Service ID) are possible in a network and are uniquely identified by different *Instance IDs*. The offered services can be accessed using RPC and it is possible to get notifications about events. Process data can be accessed by applications using set and get.

SOME/IP-SD is used to locate service instances, detect if service instances are running, and implements a publish/subscribe handling [2]. For offering a service instance, a server sends a multicast service offer message `OfferService(Service ID, Instance ID)` with optional options such as the above-mentioned endpoint options. The server can stop offering a service instance by sending a `StopOffer(Service ID, Instance ID)` message. If clients

do not receive suitable service offer messages with the required Service ID, they can actively send a `FindService(Service ID, Instance ID)` message which can be answered by servers offering the requested service. The Instance ID can be either set to a specific value or `0xFFFF`, if all service instances shall be found. The publish/subscribe mechanism can be used in cases in which a client requires a set of signals from a server but does not want to request that information manually each time it is required. A client subscribes to an event group with a `SubscribeEventgroup(Service ID, Instance ID)` confirmed with `SubscribeEventgroupACK(Service ID, Instance ID)` by the server. A client unsubscribes with a `StopSubscribeEventgroup(Service ID, Instance ID)` message. While a subscription is active, the server regularly sends event messages to the client. Additionally, SOME/IP provides a load balancing option for service instances. A server can set a priority and a weight in its service offer. A client shall select the service with the highest priority. In case there are multiple service instances with the same priority, the service instance shall be chosen randomly based on the weights of the service instances.

For RPC, SOME/IP provides several communication patterns. The most common pattern is the request/response pattern, where the client sends a request message, which is answered by the server. Requests without response are called fire&forget. Notification events are sent regularly from a server to a client if the client has subscribed to a service using SOME/IP-SD. In certain cases, the server sends the client a notification event, e.g., an updated value or an event that occurred. SOME/IP is used for transporting the event data and SOME/IP-SD is used for publishing and subscribing.

Both, the SOME/IP Protocol Specification [3] and the SOME/IP-SD Protocol Specification [2] do not really consider security aspects (cf. Section 2). Since SOME/IP does not provide any security mechanisms, attacks are obviously possible. For this reason, vehicles lately introduce network security protocols like Media Access Control Security (MACsec) [13, 14] or AUTOSAR's SecOC [1]. Thus, ECUs accept only authentic messages from other ECUs, e.g., attackers with physical access cannot inject messages to the network.

SOME/IP is typically used in Automotive Ethernet networks which replace parts of classical vehicle network technology for example CAN bus, MOST or FlexRay. Using Ethernet, the network topology also changes from a bus to a star system with several switches. According to [26], the first generation of Automotive Ethernet networks using SOME/IP consist of few switches and a low two-digit number of Ethernet-ECUs where each ECU offers a few tens of services.

4 FORMAL SECURITY ANALYSIS APPROACH

In this section, we outline our formal security analysis approach used to evaluate SOME/IP and our proposed security extensions.

4.1 Symbolic Model

We analyze the security of SOME/IP and our proposed extensions in the symbolic model, also called Dolev-Yao model. In this model, cryptographic primitives are assumed to be perfectly secure, i.e., the attacker cannot break their security properties. For example, encrypted messages can only be decrypted when in possession of the corresponding decryption key. Thus, security analysis in

this model focuses on the composition of these primitives. This simplification makes the model more suitable for automation and there are powerful tools available supporting the verification of security properties within this model. Despite this simplification, analyses in the symbolic model are very powerful and enable the identification of most practical attacks on protocols (cf. Section 2).

Since SOME/IP does not provide any security mechanisms, we restrict the capabilities of the attacker in the analysis of SOME/IP by assuming the use of an underlying authentication protocol, such as SecOC or MACsec. However, we allow the attacker to compromise ECUs. As the multitude of attacks such as the Jeep hack [23], the Mercedes-Benz hack [30], attacks on BMW [8], the hack of Volkswagen infotainment systems [16] and the attacks on Tesla Model S [24] show, compromised ECUs are a real and serious threat. For the analysis of our proposed security extensions, we assume the powerful Dolev-Yao attacker with full control over the network, which can also compromise ECUs.

4.2 Security Properties in the Symbolic Model

The focus of our analysis is authentication, which is required to prevent unauthorized manipulation of the SOME/IP communication, especially MITM attacks. We use the authentication properties defined by Lowe [21]. They form a hierarchy, starting with the relatively weak *aliveness* property and going up to the much stronger notion of *injective agreement*.

Applied to a message authentication protocol, *aliveness* requires that whenever a message is received and accepted by a protocol entity, the entity it assumes to be the sender has previously sent a message. However, that message is not required to be identical to the received message. As the name implies, this property only verifies that the supposed sender was *alive*, that it was previously running the same protocol with the corresponding role.

We use the *injective agreement* property in the verification of our proposed security extensions (cf. Section 7.3). In essence, the property requires that whenever a message is received and accepted, exactly the same message has been previously sent to the recipient by the claimed sender. Moreover, the message can only be accepted once by the recipient, therefore, message replay by the attacker is not possible. Thus, providing injective agreement is an effective countermeasure against MITM attacks. While *injective agreement* is a very strong authentication property, it does not consider broadcast communication patterns. Lauser et al. [19] proposed *One-time group agreement* as an adaptation of this property to analyze protocols that allow broadcast communication in a shared-key setting, such as SecOC which they analyze in their paper. The property requires that whenever a message is received and accepted, it has been previously sent by a legitimate sender and is only accepted once by each recipient. Therefore, the property is slightly weaker than *injective agreement*, as it does not verify that the message was intended for the recipient. Moreover, it does not distinguish between individual senders, and thus, does not provide suitable guarantees if the attacker model considers compromised protocol entities.

In addition, we require *syntactic secrecy* for the secrets used within our proposed extensions. It requires that there exists no valid trace of the model, in which the secret is learned by the attacker. *Forward secrecy* additionally requires that the secret remains

unknown to the attacker, even if the long-term credentials of the involved parties are leaked after the protocol run.

4.3 Tamarin Prover

The Tamarin prover [4, 28] is a well-established tool for formal analysis in the symbolic model. It can automatically generate proofs or counterexamples for security properties based on a model of the protocol, considering an unbounded number of protocol entities and sessions. Protocol models are specified as rules for a multiset rewriting system. The state of the system is represented by facts that are manipulated through these rules. Hereby, facts in the premise of a rule are consumed and replaced by the facts in the conclusion. Moreover, rules can be labeled with action facts for referencing in security lemmas and their applicability can require input verification by adding restrictions. Security properties are specified using a subset of first-order logic over action facts and time points. However, due to the undecidability of the underlying problem, Tamarin may not terminate and manual intervention or optimization, such as intermediate security lemmas, may be required.

5 SOME/IP ANALYSIS AND ATTACKS

We use Tamarin to formally analyze the security of SOME/IP which is used with some link layer security mechanism. The complete Tamarin model is given in Appendix A.1.

We assume that ECUs communicate via group authenticated channels with replay protection and focus on the authentication of service discovery messages. As expected, we can prove strong authentication properties given that no legitimate ECU has been compromised, especially *One-time group agreement*. In this case, the attacker cannot inject valid OfferService messages. However, in the presence of a stronger attacker that may compromise an ECU, authentication of messages is no longer ensured, even considering the relatively weak *aliveness* property, which would be implied by all other authentication properties we consider (cf. Section 4.2):

Definition 5.1 (Aliveness w.r.t. OfferService). For an honest server S and an honest client C , we require that whenever C accepts an OfferService message m as coming from S , S has previously been active.

In Tamarin’s syntax, the lemma looks as follows, where $E_C_ReceiveOfferService$ is the event that client received an OfferService message, supposedly from server. $E_S_Created$ describes the event that server has been created by a rule and, thus, has been active. The nonce parameter is used by other lemmas to distinguish between individual OfferService messages. The last two lines require that server and client have not been corrupted.

```
lemma AlivenessOfferService :
  " All server client nonce #i.
    E_C_ReceiveOfferService(client, server, nonce) @i
    ==> (Ex #j. E_S_Created(server) @j)
          | (Ex id #r. E_Corrupted(id) @r
              & Honest(id) @i) "
```

The property fails because the attacker can easily forge messages from an arbitrary Service ID. There is no mechanism in SOME/IP that binds the Service ID within an OfferService message to its sender. The same holds for the Client ID that is part of service

requests. The attacker can use any Client ID when sending a request from a compromised ECU. Combining these two weaknesses, the attacker can conduct a MITM attack which requires minimal a priori knowledge of the system. In the following, we describe these practical MITM attacks we derived from our formal analysis.

5.1 Copycat Attack on the Service Offer

The general idea of the copycat attack is waiting for a regular server S to send a broadcast service offer and then immediately send a service offer but with the endpoint option of the attacker A .

Figure 2 illustrates the attack with an example. First, the regular S sends the service offer message OfferService(0x1234, 0x5678) with Service ID 0x1234 and Instance ID 0x5678 and endpoint option Endpoint(10.0.0.2:30509). As soon as A receives this message, she sends the same service offer but with her own endpoint option Endpoint 10.0.0.4:30510. A client C would (usually) receive both service offers, since the attacker is not capable to influence lower-layer communication. C may choose A as the service provider to send his requests to. A can now forward these requests to the original server S as well as the responses from S back to C . In this MITM position, A can perform further attacks, e.g., manipulating message contents or (selectively) dropping messages.

Figure 2: Copycat Attack on the Service Offer

In the Tamarin model, the presence of this attack can be shown by verifying that whenever a client receives a response from a server which contains some random data that was newly generated by the server and, thus, unknown by the attacker before the send event, the response was sent by the server to the correct client endpoint. For this lemma, Tamarin produces an attack trace that corresponds to the described attack.

In practice, the copycat attack has several problems (from the point of view of the attacker). First, a client may have already established a connection with the server and will not change to another server. Second, even if this is not the case, there is no guarantee that the client will choose the attacker as the service provider. Since the service offer of the original server is always sent before the attacker’s service offer, the client may never choose the attacker as a service provider. This approach is also in conflict with the SOME/IP specification, which demands that SOME/IP service instances are unique. Thus, this might enable the detection of the attack with an Intrusion Detection System (IDS). However, as our

implementation and evaluation have shown (cf. Section 6), a regular server simply ignores such messages.

Alternatively, the attacker could use a different Instance ID. A client, who accepts other service instances, could possibly choose the attacker as before. However, there is still no guarantee that the client chooses the attacker as service instance. In addition, the attacker needs to know valid Instance IDs the client accepts (if the client does not accept all Instance IDs).

In case the load balancing options are used (cf. Section 3), the attacker may also send a service offer with the highest priority and weight option. If other instances with the same priority and weight are present, the attacker still has a chance to be chosen randomly.

5.2 De-association Attack on the Service Offer

To address the aforementioned issues, we extend the copycat attack by making the clients *C* believe that the service of the regular server *S* is no longer available. For this, *A* additionally de-associates *C* from *S* by sending a unicast StopOffer message with the regular server's endpoint option.

Figure 3 shows an exemplary attack. *S* sends OfferService(0x1234, 0x5678) with Endpoint(10.0.0.2:30509). Then, *A* immediately sends StopOffer(0x1234, 0x5678) for Endpoint(10.0.0.2:30509) of *S* as unicast to *C* with interest in the service. As in the copycat attack, *A* also immediately sends her own service offer to get in the MITM position.

Figure 3: De-association Attack on the Service Offer

Tamarin generates this attack, if the lemma mentioned in the previous section is further restricted to cases where the server was known by the client a priori.

The StopOffer messages are sent to the clients as unicast, since if *S* would receive this, it would stop providing the service, assuming another server would take over. This would prevent *A* from getting into the MITM position. The OfferService message of the attacker can be sent as broadcast since *S* just ignores this message.

The de-association attack has the drawback that *A* needs to know the clients which are interested in the service. Otherwise, she could not send unicast StopOffer messages to them. Thus, the attacker needs to identify these clients. Since *A* can only eavesdrop on broadcast communication, she can either listen to broadcast FindService() messages of clients or other broadcast messages

which identify clients and their IP addresses. Alternatively, *A* can simply send the StopOffer message to the entire IP range of the network (excluding the regular server).

5.3 Attack on Publish/Subscribe

Based on the request/response attack discovered with Tamarin, we developed an attack on publish/subscribe as shown in Figure 4. The regular server sends OfferService(0x1234, 0x5678) with Endpoint(10.0.0.2:30509). Then, *C* and *S* subscribe to the service with SubscribeEventgroup(0x1234, 0x5678) and their respective endpoint option, i.e., Endpoint(10.0.0.3:3333) for *C* and Endpoint(10.0.0.4:4444) for the attacker. *S* acknowledges this by sending SubscribeEventgroupACK(0x1234, 0x5678).

Figure 4: Attack on Publish/Subscribe

A also performs – as fast as possible – one of the presented attack on the service offer, making *C* believe that the attacker offers the desired service. *C* sends SubscribeEventgroup(0x1234, 0x5678) with Endpoint(10.0.0.4:3334) to subscribe to *A*. *A* sends StopSubscribeEventgroup(0x1234, 0x5678) with *C*'s endpoint option Endpoint(10.0.0.3:3333) to *S* for unsubscribing *C* and stopping *S* to send event messages to *C*. *A* sends the Acknowledgment SubscribeEventgroupACK(0x1234, 0x5678) to *C*.

C can now perform MITM attacks. When *S* sends event messages Event(0x1234, 0x5678) for his service, these messages are sent to the attacker and not to *C*. *A* can then decide what to do with these messages, e.g., alter them before forwarding them to the client or drop them.

6 ATTACK EVALUATION

In this section, we briefly describe our implementation of the attacks with *vsomeip* and *CANoe* as well as the evaluation.

6.1 Attack Implementation

Our first implementation consists of a client, a server offering a service, and the MITM attacker which are each implemented on an ARM1176JZF-S board running Linux Debian (Kernel 4.19) and *vsomeip* [7] 3.1.16.1. The three boards are connected via a switch and communicate via UDP (or TCP with similar results). We used the examples shipped with *vsomeip* as test cases for request/response and publish/subscribe communication. For request/response, the server offers a service for around 10 seconds and regularly sends *OfferService* messages (at the latest every 2.5 seconds). After 10 seconds, the server sends a *StopOffer* message and waits for around 10 seconds before it starts over. The client requests data around every second while the service is offered. Note that there are small variations when messages are sent depending on the load of the system and network. The publish/subscribe example starts the same way. Instead of a request, the client sends a subscribe message as soon as the service is available which is acknowledged by the server. The server then sends events every second to the subscribed client. The attacker is implemented with Scapy [6].

In our second implementation, *SOME/IP* client and server are implemented on a PC running *CANoe* 9.0.137 [11] with the *SOME/IP* library in combination with the VN5610 Automotive Ethernet interface. PC and VN5610 are connected via a switch. The attacker is implemented in a Linux VM on the PC. The *SOME/IP* communication is implemented in the same way as in the *vsomeip* implementation.

6.2 Evaluation of Service Offer Attacks

The copycat and de-association attack on the service offer (cf. Section 5.1 and 5.2) have the goal to route messages via the attacker. For our evaluation, we run the request/response example for 1000s and evaluate the number of response messages, which are sent directly from server to client and the messages sent via the attacker.

Table 1 shows the results of our evaluation with *vsomeip* and *CANoe*. For both, we compare the three cases: no attack, copycat attack, and de-association attack. The column "Direct" shows the number of response messages sent directly from the regular server to the client, i.e., for these messages, our attack was not successful. The column *MITM* shows the number of response messages sent via the MITM attacker, i.e., the attack was successful and these messages are redirected to our MITM attacker.

Table 1: Evaluation of Copycat and De-association Attack

	<i>vsomeip</i>		<i>CANoe</i>	
	Direct	MITM	Direct	MITM
No Attack	458	0	498	0
Copycat	471	0	0	497
De-association	2	473	0	499

When implementing our attacks in *vsomeip* we had the following result: Without attack, in total 458 response messages were sent, i.e., during the 10 second sending period 9 to 10 messages have

been sent. As expected, all of these messages are sent directly from the regular server to the client.

In the case of the copycat attack, in total 471 messages were sent and all of them were sent directly. The implementation only accepts new services for the same Service ID with a different IP if the time to life (TTL) of the original service is expired. Thus, the attack was not successful at all. In our example application, this occurs only after a *StopOffer* message has been sent.

In contrast to the copycat attack, the de-association attack works very well. Only two of the 475 total response messages were sent directly from the server to the client. All other 473 messages were sent via the attacker. The reason for the two missed messages is the non-deterministic timing, i.e., the server's response was sent before the attacker could send a *StopOffer* message.

In comparison to *vsomeip*, we observed different results for our attacks on the *SOME/IP* implementation using *CANoe*. Both, the copycat and the de-association attack are successful in the request/response scenario. All messages are redirected via our MITM attacker. The results indicate the implementation favors the last *ServiceOffer* contrary to *vsomeip*. Since this implementation is closed source, we cannot verify this observation.

6.3 Evaluation of Publish/Subscribe Attack

Attacks on publish/subscribe can be either combined with copycat or de-association attack. Table 2 shows these two cases and the case without attack for our implementations in *vsomeip* and *CANoe*.

When implementing our attacks in *vsomeip* we had the following results. Without attack, the server sends 556 event notifications during the evaluation period of 1000 seconds directly to the client. In total, the server generates event messages for 556 events. For all of the 556 events, the server generates respective event messages and sends them to the attacker. However, the server also generates 380 event messages for some of these events and sends these event messages directly to the client. Thus, the client receives some events twice. The reason is in a different implementation compared to the request/response handling. Clients subscribe to all suitable services as soon as they receive a *ServiceOffer*. Since the server regularly sends *OfferService* messages, the client subscribes each time again and the server sends some events to the client since the attacker is not fast enough to send a *StopSubscribeEventgroup* message in time.

Table 2: Evaluation of the Attack on Publish / Subscribe

	<i>vsomeip</i>		<i>CANoe</i>	
	Direct	MITM	Direct	MITM
No Attack	556	0	500	0
Copycat	380	556	(499)	499
De-association	0 (385)	(0) 422	(500)	500

The attack in combination with the de-association attack does not work with the reference implementation of *vsomeip*, due to some implementation error. Clients ignore the first *OfferService* after a *StopOffer* message. We indicate this behavior with (0) in the table. To address this issue, we are sending two *OfferService* messages after a *StopOffer*, and the MITM attack works. The server

sends 422 event messages to the attacker, who forwards them to the client. In addition, the server sends 385 event messages directly to the client, which are rejected since the client has already received the StopOffer message for this server. The total number of received event messages at the client is lower than in the first two cases (422 compared to 556) since all attack steps (subscription handshake between attacker and server, subscription handshake between attacker and client, StopSubscribeEventgroup, a StopOffer, and two OfferService messages) require some time before the attacker is in the MITM position.

Using the CANoe implementation of SOME/IP, both attacks are effective in the publish/subscribe case. Contrary to vsomeip, the CANoe implementation server does not stop sending to a client even if the attacker sends a StopSubscribeEventgroup. However, the client ignores these messages after the StopOffer message.

7 SECURITY EXTENSIONS

The presented attacks on SOME/IP-SD at application layer are possible even when security mechanisms are deployed at lower layers. An attacker, who has compromised a single ECU (not necessarily a service offering server) can authenticate as a legitimate member of the network and perform the MITM attacks.

In Section 2, we already discussed related work for securing SOME/IP with an IDS [12], TLS [18], TESLA [18], and digital signatures with asymmetric cryptography [15]. Approaches such as TLS and digital signatures with asymmetric cryptography can achieve a high level of security while meeting general automotive requirements (e.g., zero false positives, low latency). Both approaches can prevent an outsider from performing MITM attacks. However, in our attacker model we also consider an insider attacker who can authenticate and execute MITM attacks. Also, TLS and the approach proposed in [15] cannot be used for SD broadcast communication.

In the next sections, we propose two security extensions for SOME/IP. To prevent or at least mitigate MITM attacks on SOME/IP-SD of an insider, we propose to restrict keys to the services which the ECU is allowed to offer and/or to use. Thus, an attacker who has compromised an ECU and the keys can only offer and use services that are allowed, mitigating the impact of the attacker.

Secure SOME/IP service discovery and session establishment using restricted certificates and digital signatures (SESO-RC) secures SOME/IP-SD broadcast messages and all subsequent SOME/IP communication. Similar to [15], our approach uses initially digital signatures with asymmetric cryptography for establishing symmetric keys for securing the subsequent communication. Certificates contain information about authorized services to limit the possible impact of an ECU compromise. In contrast to [15], our approach still enables SD broadcast communication and thus, does not change the specified SOME/IP protocol flow.

Secure SOME/IP service discovery and session establishment using an authorization server (SESO-AS) uses only efficient symmetric cryptography but requires an additional authorization server (AS) in the E/E architecture. The AS also stores additional information about the authorized services of an ECU. We assume that the AS is especially protected against compromise, e.g., by means of a hardware security module and mechanisms like secure boot.

7.1 SESO-RC

Each ECU is equipped with a private secret key sk_{ECU} and corresponding certificate $Cert_{ECU}$ (including the public key pk_{ECU}). Certificates are issued by a trusted certification authority (CA) and all ECUs store the CA public key for verifying the validity of certificates of other ECUs. A certificate contains additional information about the services the ECU is allowed to offer, stop, request, or subscribe to. For the sake of simplicity, we assume all (trusted) certificates are preconfigured on all ECUs and the hash of a certificate is used as a unique identifier ID_{ECU} of an ECU. Alternatively, the entire certificate could be sent within SOME/IP messages and ECUs store only a trusted root CA certificate for verifying received certificates. The preconfigured certificates could, for example, be deployed during production and updated via firmware updates. How this can be done securely is out of scope for our paper.

The service offer is signed with the private key of the sender and includes an ephemeral-static² Diffie-Hellman (DH) key exchange to establish a symmetric session key. The session key is subsequently used to protect the integrity of the following SOME/IP messages by appending a Message Authentication Code (MAC). In addition, a timestamp ensures the freshness of messages if ECUs are loosely time-synchronized. Otherwise, a counter could be used.

Figure 5 illustrates SESO-RC for a request/response communication. The server S stores a certificate $Cert_S$ containing the public key pk_S and a list of services the server is allowed to offer and stop. It also stores the corresponding private key sk_S and the public keys of all clients. A client stores a certificate $Cert_C$ containing the public key pk_C and a list of services the client is allowed to request. It also stores the corresponding private key sk_C and the certificates of all servers (including the respective public keys).

The server broadcasts a service offer message OS including the usual payload such as service ID, instance ID (denoted with ...), identifier ID_S , a freshness value f_1 , and a DH public key pk_{SDH-S} (used by all clients later in the generation of the shared symmetric keys). This message is signed with the private key sk_S of the server. A client, which wants to request a service, first verifies whether the signature is valid and f_1 is current. If the verification passes, the client generates an ephemeral DH key pair and includes the public part pk_{EDH-C} , a freshness value f_2 dependent on f_1 , and ID_C in the service request message Req , signed with the private key sk_C of the client. Client and server can now both calculate the shared symmetric key k_{SC} with their private DH key and the received public key. Other clients also use pk_{SDH-S} of the server but generate their own ephemeral DH key pair so that each connection uses an individual symmetric key. Finally, the server sends the response message Res including the requested service data, ID_S and a freshness value f_3 . Since client and server now possess the shared symmetric key k_{SC} , this and further message are secured with a MAC.

Figure 6 illustrates SESO-RC for Publish/Subscribe. Since the server later broadcasts events to all clients C_i (where i is used for numbering of the clients) which are subscribed to the service, a group key is required. The first two steps for the service offer OS and Subscribe Eventgroup SE messages are similar as for the request/response. All clients C_i have established individual symmetric

²only static for one service offer as all clients use the same server DH public key

Figure 5: SESO-RC with Request/Response

keys k_{SC_i} . The server generates a group key k_{group} which is individually encrypted for each client with k_{SC_i} and distributed in the Subscribe Eventgroup Acknowledgment message SEA . To prevent replay attacks, the encryption contains a freshness value. A MAC is calculated using k_{SC_i} and appended to ensure integrity. Note that we use k_{SC_i} for both encryption and MAC only for the sake of simplicity. Since one should use distinct keys for each purpose, K_{SC_i} should be used only as a basis for deriving distinct keys.

Figure 6: SESO-RC with Publish/Subscribe

7.2 SESO-AS

Each ECU is assigned with a unique identifier ID_{ECU} and symmetric key k_{ECU} . Again, we assume that these values are preconfigured and stored on the ECU as well as at the AS. For each ECU, the AS also stores additional information about the services the ECU is allowed to offer, stop, request, or subscribe to. Similar to SESO-RC, some mechanism to ensure freshness is deployed. Thus, either all ECUs and AS are loosely time-synchronized or a counter is used.

Figure 7 illustrates SESO-AS for the Offer Service. A server sends a service offer OS , including the usual payload such (denoted with $\dots$), ID_S , a freshness value f_0 , the encrypted session key k_{se} and a MAC to the AS. The AS verifies MAC, f_0 , and whether the server is allowed to offer this service. If the verification passes, the AS derives shared symmetric keys k_{SC_i} from k_{se} for the server and clients C_i which are authorized to use (request or subscribe) this service. These keys are individually encrypted for each C_i using k_{C_i} . Then the AS broadcasts the service offer message OS with the usual payload and a new freshness value f_1 . The AS appends individual containers E_i for each legitimate client C_i to the message. For example, E_1

contains ID_{C_1} , the encrypted symmetric key $Enc_{k_{C_1}}(k_{SC_1})$ and a MAC $MAC_{k_{C_1}}(OS, E_1)$. Client C_1 verifies the MAC, decrypts k_{SC_1} , and uses k_{SC_1} to secure subsequent messages with a MAC.

Figure 7: Offer Service with SESO-AS

7.3 Security Analysis and Verification

We use the Tamarin prover to verify the key exchange during SOME/IP-SD of our proposed protection mechanisms. The corresponding Tamarin models are given in Appendix A.2 and A.3. In contrast to our analysis of SOME/IP, we do not assume underlying security protocols but allow the attacker full control over the network. We abstract the freshness values f_n with random nonces.

7.3.1 SESO-RC. For SESO-RC we verify strong authentication of session keys as well as forward-secrecy of session keys with the following two security properties (cf. Section 4.2):

Definition 7.1 (Injective-agreement on session keys). For an honest server S and honest client C it holds that whenever S establishes a session, apparently with C , then C has previously established a session, apparently with S , and C and S agree on all parameters of the session, especially the session key. Moreover, each session established by S corresponds to a unique session established by C .

Injective agreement not only implies aliveness (cf. Section 5), but also protection against replay and MITM attacks, given that no ECU is authorized to offer and consume a service at the same time.

Definition 7.2 (Forward-secrecy of session keys). For an honest server S and honest client C and a session key k that either of the two parties believes to be a session key shared with the other party, the attacker cannot learn k even if she compromises private keys of S or C later.

7.3.2 SESO-AS. For the formal verification of SESO-AS we assume that access control is done by the authorization server AS, that is, AS will only allow key exchanges for a specific service between authorized servers/clients. Therefore, we do not represent this within our model. We require *injective agreement* on the shared keys between a client and a server k_{SC_n} as well as *secrecy* of the session key k_{se} and k_{SC_n} . In contrast to SESO-RC, SESO-AS does not provide *perfect forward-secrecy* of session keys as encrypted session keys are transmitted. Both properties can be verified in Tamarin.

Definition 7.3 (Injective agreement on shared keys). For an honest server S , honest client C , and honest authorization server AS, it holds that whenever C receives an OfferService message, apparently from S , then S has sent an OfferService message before and

the shared symmetric key k_{SC} received by C has been correctly derived from the session key k_{se} . Moreover, each received event by C corresponds to a unique send event by S .

Definition 7.4 (Secrecy of shared keys). For an honest server S , honest authorization server AS , and every session key k_{se} generated by S , the attacker cannot learn k_{se} .

In addition, for an honest server S , honest client C , and honest authorization server AS , it holds that whenever C receives an OfferService message with a shared symmetric key k_{SC} , apparently shared with S , the attacker cannot learn k_{SC} .

7.4 Performance Evaluation

In this section, we describe the implementation and evaluation of the performance overhead of SESO-RC and SESO-AS and compare them with "Secure SOME/IP" [15]. We excluded [18] from the comparison since service discovery is not protected in this approach. First, we discuss the communication overhead introduced by the increased message size. Then, we analyze the computational overhead by implementing all approaches and measuring the additional latency. Finally, we summarize the performance evaluation of all three approaches.

7.4.1 Message Overhead. SESO-RC adds a freshness value f of 4 bytes to every message. The OfferService() message of the server contains the public key of the elliptic curve Diffie-Hellman (ECDH) key exchange (X25519) with a size of 32 bytes and the SHA-256 hash value of the certificate with a size of 32 bytes. The Ed25519 elliptic-curve signature of the message has a size of 64 bytes. Figure 8 shows the complete message format of the service offer. Request() and SubscribeEventgroup() messages of the client have the same message format. All following messages of client and server add only a 32 bytes HMAC-SHA-512/256 (HMAC with SHA-512 truncated to 256 bits) and the 4 bytes freshness value.

Figure 8: Message Format of Offer Service with SESO-RC

SESO-AS adds a freshness value f of 4 bytes and a set of encrypted keys for each possible client to a OfferService() message. For encryption and authentication, we choose an Authenticated Encryption with Associated Data (AEAD) construction (ChaCha20-Poly1305) for improved performance. An entry of the key set consists of a 1 byte identifier of the client ID_{C_i} , the encrypted key k_{SC_i} for a client of 32 bytes, and the AEAD authentication tag of 16 bytes. This authentication tag includes the SOME/IP OfferService message through associated data. The freshness value is used as input nonce for ChaCha20-Poly1305 to encrypt the key k_{SC_i} . The complete message format is illustrated in Figure 9. All following messages are authenticated with a 32 bytes HMAC-SHA-512/256 and include a 4 bytes freshness value.

Figure 9: Message Format of Offer Service with SESO-AS

The overhead of regular SOME/IP messages is 36 bytes with both solutions, but they differ in the key exchange handshake depending on the number of clients that request a service. Table 3 shows a comparison of the different approaches for different numbers of clients where msg denotes the number of additional messages and bytes the total value of additional bytes over all necessary messages.

Table 3: Overhead of Cryptographic Key Exchange

		Number of Clients				
		1	2	4	8	16
SESO-AS	msg	1	1	1	1	1
	bytes	106	155	253	449	841
SESO-RC	msg	0	0	0	0	0
	bytes	264	396	660	1188	2244
"Secure SOME/IP" [15]	msg	0	2	4	8	16
	bytes	180	360	720	1440	2880

SESO-AS introduces a message overhead of 53 bytes to the service offer sent to the AS and an additional OfferService message with $4 + 49c$ bytes, where c is the number of legitimate clients, which is a broadcast message to every client in the network.

The key exchange of SESO-RC does not introduce additional messages since the service offer message is broadcasted directly to the clients. The service offer and the first request introduce the same overhead of 132 bytes. Every further client requesting the service also adds 132 bytes of overhead.

Secure SOME/IP [15] uses a unicast handshake between every client and the server. To enable a fair comparison, we replaced RSA with Ed25519 EC signatures in their implementation. The client part of the handshake transports 36 bytes of the certificate hash with a freshness value and the server adds 144 bytes since it contains the asymmetrically encrypted and signed group key. Both messages are sent for every additional client.

Comparing the three approaches regarding the number of messages, SESO-RC introduces the least number of additional messages while Secure SOME/IP introduces the most messages since it is not capable of broadcasting service discovery messages. Thus, Secure SOME/IP has the highest overhead in message size as soon as a service is used by more than three clients. The least overhead is introduced by SESO-AS.

7.4.2 CPU overhead. For the evaluation of the CPU overhead introduced by our security extensions, we implemented SESO-RC, SESO-AS, and Secure SOME/IP on two ARMv6 boards (ARM1176JZF-S at

700Mhz) connected via a 100 MBit/s switch. We used libsodium³ as cryptography library.

We evaluate the latency of the cryptographic extensions by counting the additional number of CPU instructions using the `perf_events` of the Linux Kernel. The measurements do not include network transfer time or interpretation of the SOME/IP message. For SESO-RC and Secure SOME/IP we evaluate client and server side and for SESO-AS additionally the AS side. For all three approaches, we perform 1000 measurements for different numbers of clients and calculate the arithmetic mean and the mean absolute deviation (MAD) to determine the error of our measurements. The results are shown in Figure 10.

Figure 10: Additional CPU Instructions for Cryptography

SESO-AS clients and servers have a very low overhead of only 7,032 (MAD: 13.1) and 9,182 (MAD: 225.2) instructions independent of the number of clients. The authorization server requires at most 153,937 (MAD: 3,615.6) instructions when encrypting a broadcast message for 16 clients. As expected SESO-AS outperforms SESO-RC which requires 4,134,880 (MAD: 22,059.0) additional instructions for the server and 4,134,550 (MAD: 21,707.0) for the client. Secure SOME/IP in comparison is faster (2,939,572 instructions, MAD: 15,371.1) compared to SESO-RC on the client side. The signature verification of every client causes a very high CPU usage of the SESO-RC server compared to the Secure SOME/IP, which does not verify the clients. A larger number of clients increase the CPU usage of SESO-RC and Secure SOME/IP equally compared to a very moderate increase of SESO-AS. Due to the unicast communication for the service offers in Secure SOME/IP, a further delay needs to be considered for the handshake. In an already established system, previously exchanged symmetric keys could be used to validate the client request for a new key, which would significantly improve server performance.

7.4.3 Summary. SESO-AS outperforms the other approaches in terms of latency and message overhead. However, it also introduces a single point of failure in terms of security and safety. Moreover, it is much more complex to introduce new devices into the E/E

system since the permission list of the authorization server needs to be updated and keys need to be exchanged in advance.

SESO-RC solves these problems with the use of certificates that can be easily distributed, and the distributed authorization can be easily integrated into the SOME/IP protocol. SESO-AS needs a minor protocol change to send all service discovery messages to the authorization server. Both approaches support broadcast service discovery like SOME/IP which Secure SOME/IP does not support. With sufficient processing power, SESO-RC is the best option, since it avoids a single point of failure, provides forward-secrecy and introduces certificates as a simple way to distribute keys and permissions securely. Hardware-based cryptography accelerators may improve the performance for low-performance devices to allow the use of asymmetric cryptography. However, this introduces additional cost. As an alternative, SESO-AS can be used with ECUs with less computational power. However, the protection of the authorization server is of paramount importance for ensuring the security of the whole network.

All approaches protect against our identified MITM attacks. In addition, SESO-RC and SESO-AS provide the ability to create individual secure channels between client and server as well as secure broadcast channels for subscriptions.

8 CONCLUSION

Our formal analysis of SOME/IP using Tamarin shows three different types of MITM attacks on SOME/IP even when link layer security mechanisms are deployed. The copycat and de-association attack on the service offer enable an attacker to get in a MITM position for request/response communication. The third attack enables a MITM attack on publish/subscribe using one of the first two attacks. Our implementation and evaluation show the effectiveness of our attacks against two real world SOME/IP libraries. For attacking request/response communication using `vsomeip`, the de-association attack is the most effective. Nearly all messages are routed via the MITM attacker. Attacking publish/subscribe in combination with the copycat attack using `vsomeip` enables the redirection of more than $\frac{2}{3}$ of the messages over the attacker. In combination with the slightly adapted de-association attack, all messages the client receives are sent over the attacker. However, in this case some event messages of the server are lost. With CANoe both attacks are successful for request/response and publish/subscribe even though the regular server keeps sending messages to the client in the publish/subscribe case. To protect against these attacks, we present and analyze the security extensions SESO-RC and SESO-AS. Our Tamarin analysis shows the security and our implementation the practical feasibility. SESO-RC is suitable for scenarios where ECUs have sufficient resources for asymmetric cryptography. In contrast to related work, SESO-RC can be still used with broadcast communication for service discovery. In case ECUs have scarce resource constraints, SESO-AS might be a viable solution since it uses only efficient symmetric cryptography but on the cost of introducing the AS as an additional component.

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³<https://github.com/jedisct1/libsodium>

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A APPENDIX

In the following, we provide the Tamarin models we used to analyze SOME/IP as well as our proposed security extensions SESO-RC and SESO-AS. A digital version of the models can be found at <https://code.fbi.h-da.de/seacop/someip-tamarin>. Details on Tamarin’s specification language can be found in [28].

A.1 Tamarin model of SOME/IP

As described in Section 5, our Tamarin model of SOME/IP focuses on the authentication properties of service discovery messages. Thus, to reduce the model’s complexity, it does not implement *Publish/Subscribe* communication. However, the identified weaknesses apply to all communication patterns and, thus, the attack can be extended for *Publish/Subscribe* communication as shown in Section 5.3. In addition, the session ID counters have been abstracted by nonces.

The underlying security protocol is abstracted by a *group-secure* channel. Only legitimate entities can send or receive messages on this channel and messages cannot be replayed. This corresponds to an authenticated and encrypted communication. Note, that in many cases, only authentication will be used. Thus, the adversary could read but not manipulate the communication. However, we only consider the most restrictive case as we are looking for practical attacks instead of security verification. Similarly, the channel models point-to-point and broadcast communication instead of a bus architecture, as this is more suitable for Automotive Ethernet.

The first set of security lemmas considers the case that the adversary has access to the network but has not corrupted any legitimate ECU and thus, is prevented from manipulation of the network. Next, we consider the case where the adversary is allowed to corrupt ECUs. The model allows for corruption of a single ECU only to get more practical and simple attacks. The last two lemmas correspond to the copycat and de-association attacks described in Section 5.1 and 5.2.

```
theory Someip
begin
/*
Public Variables
$ServiceID – identifier of a service
```

```

$InstanceID - identifier of a instance
               offering a service
$Endpoint - IP + TCP/UDP address information
            (S_/C_ prefix for server/client)
$MethodID - method identifier within a service
$ClientID - client identifier within ECU

Variables
  SessionID - enables to differentiate between
              previous requests, abstracted by a nonce

Facts:
  !S_Identity(<$ServiceID, $InstanceID, $
              S_Endpoint>)
    - server identity information
  S_State(<$ServiceID, $InstanceID, $Endpoint>,
         'open')
    - server is currently offering its service
  S_OpenSubscription(<$ServiceID, $InstanceID, $
                    S_Endpoint>, <$ClientID, SessionID>)
    - Open Subscription Request from Client
  S_SubscribedClient(<$ServiceID, $InstanceID, $
                    S_Endpoint>, <$ClientID, SessionID, $
                    C_Endpoint>, $EventgroupID)
    - Connection data of a client subscribed
      to the server
  !C_Identity(<$ClientID, $C_Endpoint>)
    - Client identity information
  C_Available(<$ClientID, $C_Endpoint>,
             <$ServiceID, $InstanceID, $S_Endpoint>)
    - Client has previously received a service
      offer for this service
  C_OpenSubscription(<$ClientID, $C_Endpoint>,
                    <$ServiceID, $InstanceID, $S_Endpoint>,
                    $EventgroupID, SessionID)
    - Client has an open subscription request
      at server
  C_Subscription(<$ClientID, $C_Endpoint>,
                 <$ServiceID, $InstanceID, $S_Endpoint>,
                 $EventgroupID, SessionID)
    - Client has an active subscription at
      server

*/

// **** Service Discovery ****
// ** Server **
rule CreateServer:
let
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[]
--[ OnlyOnce(<'create_server', $ServiceID,
            $InstanceID>),
     OnlyOnce(<'create_server', $S_Endpoint>),
     E_S_Created(server)
]->
[ !S_Identity(server) ]

rule SendOfferService:
let

```

```

  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[ !S_Identity(server), Fr(~nonce) ]
--[ E_S_SendOfferService(server, ~nonce),
     E_Send(<'offer_service', server, ~nonce>)
]->
[ Out_P('broadcast', <'offer_service', server,
        ~nonce>),
  S_State(server, 'open')
]

rule SendStopService:
let
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[ !S_Identity(server),
  S_State(server, 'open'),
  Fr(~nonce)
]
--[ E_S_SendStopOfferService(server, ~nonce),
     E_S_OpenServiceOffer(server),
     E_Send(<'stop_service', server, ~nonce>)
]->
[ Out_P('broadcast', <'stop_service', server,
        ~nonce>) ]

rule ReceiveAndAnswerFindService:
let
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[ !S_Identity(server),
  S_State(server, 'open'),
  In_P($S_Endpoint, <'find_service', $ServiceID>,
        nonce)
]
--[ OnlyOnce(<server, nonce>),
     E_S_OpenServiceOffer(server),
     E_Send(<'offer_service', server>)
]->
[ Out_P('broadcast', <'offer_service', server>),
  S_State(server, 'open') ]

// ** Client **
rule CreateClient:
[]
--[ OnlyOnce(<'create_client', $ClientID>),
     OnlyOnce(<'create_client', $C_Endpoint>)
]->
[ !C_Identity(<$ClientID, $C_Endpoint>) ]

rule SendFindService:
let
  client = <$ClientID, $C_Endpoint>
in
[ !C_Identity(client) ]
--[ E_Send(<'find_service', $ServiceID>) ]->
[ Out_P('broadcast', <'find_service', $ServiceID>)
]

```

```

rule ReceiveOfferService :
let
  client = <$ClientID, $C_Endpoint>
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[ !C_Identity(client), In_P($C_Endpoint,
  <'offer_service', server, nonce1>, nonce2)
]
--[ E_C_ReceiveOfferService(client, server, nonce1),
  OnlyOnce(<client, nonce2>),
  Honest(client), Honest(server)
]->
[ C_Available(client, server) ]

rule ReceiveStopService :
let
  client = <$ClientID, $C_Endpoint>
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[ !C_Identity(client),
  C_Available(client, server),
  In_P($C_Endpoint, <'stop_service', server,
    nonce1>, nonce2)
]
--[ E_C_ReceiveStopOfferService(client, server,
  nonce1),
  OnlyOnce(<client, nonce2>),
  E_C_Available(client, server),
  Honest(client), Honest(server)
]->
[]

// **** Request/Response Communication ****
// ** Server **
rule ReceiveRequest :
let
  client = <$ClientID, SessionID, $C_Endpoint>
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[ !S_Identity(server),
  S_State(server, 'open'),
  In_P($S_Endpoint, <'request', client,
    <$ServiceID, $S_Endpoint>, $MethodID,
    'request_data'>, nonce)
]
--[ OnlyOnce(<server, nonce>),
  E_S_OpenServiceOffer(server)
]->
[ S_OpenRequest(server, client, $MethodID),
  S_State(server, 'open')
]

rule SendResponse :
let
  client = <$ClientID, SessionID, $C_Endpoint>
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in

```

```

[ !S_Identity(server),
  S_State(server, 'open'),
  S_OpenRequest(server, client, $MethodID),
  Fr(~nonce)
]
--[ E_S_SendResponse($ServiceID, $ClientID,
  $C_Endpoint, SessionID, $MethodID,
  <'response_data', ~nonce>),
  E_S_OpenServiceOffer(server),
  E_Send(<'response', <$ServiceID>, client, $
    MethodID, 'response_data'>)
]->
[ Out_P($C_Endpoint, <'response', <$ServiceID>,
  client, $MethodID, <'response_data',
  ~nonce>),
  S_State(server, 'open')
]

rule ReceiveFireAndForget :
let
  client = <$ClientID, SessionID, $C_Endpoint>
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[ !S_Identity(server),
  S_State(server, 'open'),
  In_P($S_Endpoint, <'fire_and_forget', client,
    <$ServiceID, $S_Endpoint>, $MethodID, data>,
    nonce)
]
--[ E_S_ReceiveFireAndForget(server, <$ClientID,
  $C_Endpoint>, SessionID, $MethodID, data),
  OnlyOnce(<server, nonce>),
  E_S_OpenServiceOffer(server),
  Honest(client), Honest(server)
]->
[ S_State(server, 'open')
]

// ** Client **
rule SendRequest :
let
  client = <$ClientID, $C_Endpoint>
  server = <$ServiceID, $InstanceID, $S_Endpoint>
in
[ !C_Identity(client),
  C_Available(client, server),
  Fr(~SessionID)
]
--[ E_C_SendRequest(client, ~SessionID, <$
  ServiceID,
  $S_Endpoint>, $MethodID, 'request_data'),
  E_C_Available(client, server),
  E_Send(<'request', <$ClientID, ~SessionID,
  $C_Endpoint>, <$ServiceID, $S_Endpoint>,
  $MethodID, 'request_data'>)
]->
[ Out_P($S_Endpoint, <'request', <$ClientID,
  ~SessionID, $C_Endpoint>, <$ServiceID,
  $S_Endpoint>, $MethodID, 'request_data'>),

```



```

    C_OpenRequest( client , <$ServiceID , $S_Endpoint>
                  , $MethodID , ~SessionID ) ,
    C_Available( client , server )
]

rule ReceiveResponse :
let
    client = <$ClientID , $C_Endpoint>
    server = <$ServiceID , $InstanceID , $S_Endpoint>
in
[ !C_Identity( client ) ,
  C_OpenRequest( client , <$ServiceID , $S_Endpoint>
                , $MethodID , SessionID ) ,
  In_P( $C_Endpoint , <'response' , <$ServiceID> ,
        <$ClientID , SessionID , $C_Endpoint> ,
        $MethodID , data> , nonce )
]
--[ E_C_ReceiveResponse( $ClientID , $C_Endpoint ,
                        $ServiceID , SessionID , $MethodID , data ) ,
    OnlyOnce( < client , nonce> )
]->
[ ]

rule SendFireAndForget :
let
    client = <$ClientID , $C_Endpoint>
    server = <$ServiceID , $InstanceID , $S_Endpoint>
in
[ !C_Identity( client ) ,
  C_Available( client , server ) ,
  Fr( ~SessionID )
]
--[ E_C_SendFireAndForget( client , server ,
                        ~SessionID , $MethodID , 'request_data' ) ,
    E_C_Available( client , server ) ,
    E_Send( <'fire_and_forget' , <$ClientID ,
                        ~SessionID , $C_Endpoint> ,
                        <$ServiceID , $S_Endpoint> ,
                        $MethodID , 'request_data'> )
]->
[ Out_P( $S_Endpoint , <'fire_and_forget' ,
                    <$ClientID , ~SessionID , $C_Endpoint> ,
                    <$ServiceID , $S_Endpoint> ,
                    $MethodID , 'request_data'> ) ,
  C_Available( client , server )
]

// **** Corruption Rules ****
rule CorruptClient :
let
    client = <$ClientID , $C_Endpoint>
in
[ !C_Identity( client ) ]
--[ E_Corrupted( client ) ,
    OnlyOnce( 'corrupt' )
]->
[ !CorruptedChannel( $C_Endpoint ) ]

rule CorruptServer :
let

```

```

    server = <$ServiceID , $InstanceID , $S_Endpoint>
in
[ !S_Identity( server ) ]
--[ E_Corrupted( server ) ,
    OnlyOnce( 'corrupt' )
]->
[ !CorruptedChannel( $S_Endpoint ) ]

rule CorruptedChannelWrite :
[ In( <$Dst_Endpoint , x , nonce> ) , !CorruptedChannel(
    $Src_Endpoint ) ]
-->
[ In_P( $Dst_Endpoint , x , nonce ) ]

rule CorruptedChannelRead :
[ In_P( $Endpoint , x , nonce ) , !CorruptedChannel(
    Endpoint ) ]
-->
[ Out( <x , nonce> ) ]

// **** Channel Rules ****
rule PrivateChannel :
[ Out_P( $Endpoint , x ) , Fr( ~nonce ) ]
--[ E_Transmit( x ) ]->
[ In_P( $Endpoint , x , ~nonce ) ]
rule PrivateChannelBroadcast :
[ Out_P( 'broadcast' , x ) , Fr( ~nonce ) ]
--[ E_Transmit( x ) ]->
[ In_P( $Endpoint , x , ~nonce ) ]

// **** Restrictions ****
restriction OnlyOnce :
" All x #i #j. OnlyOnce(x) @i & OnlyOnce(x) @j
  ==> #i = #j "

restriction OnlyOneEndpointPerService :
" All ClientID C_Endpoint ServiceID InstanceID
  InstanceID_2 S_Endpoint S_Endpoint_2 nonce1
  nonce2 #i #j .
  E_C_ReceiveOfferService( <ClientID , C_Endpoint> ,
    <ServiceID , InstanceID , S_Endpoint> , nonce1 )
    @i
  & E_C_ReceiveOfferService( <ClientID , C_Endpoint> ,
    <ServiceID , InstanceID_2 , S_Endpoint_2> ,
    nonce2 ) @j
  & i < j
  ==> Ex nonce3 #k. E_C_ReceiveStopOfferService(
    <ClientID , C_Endpoint> , <ServiceID ,
    InstanceID , S_Endpoint> , nonce3 ) @k & k < j
"

restriction BroadcastAddress :
// No identity can have 'broadcast' as its
  endpoint
" All #i .
  OnlyOnce( <'create_client' , 'broadcast'> ) @i
  ==> F
  & All #j .
  OnlyOnce( <'create_server' , 'broadcast'> ) @j
  ==> F
"

```

```

// **** Helper lemmas **
lemma Availability [sources]:
" All client server #i.
  E_C_Available(client, server) @i
  ==> (Ex nonce #j. E_C_ReceiveOfferService(
    client, server, nonce) @j & j < i)
"

lemma OpenServiceOffer [sources]:
" All server #i.
  E_S_OpenServiceOffer(server) @i
  ==> (Ex nonce #j. E_S_SendOfferService(server,
    nonce) @j & j < i)
"

// **** Executability lemmas ****
lemma RequestResponseComm:
exists-trace
" Ex ClientID C_Endpoint ServiceID SessionID
  MethodID data #i.
  E_C_ReceiveResponse(ClientID, C_Endpoint,
    ServiceID, SessionID, MethodID, data) @i
  & not(Ex x #k. E_Corrupted(x) @k)
"

lemma FireAndForgetComm:
exists-trace
" Ex ClientID C_Endpoint ServiceID InstanceID
  S_Endpoint SessionID MethodID data #i #j.
  E_C_SendFireAndForget(<ClientID, C_Endpoint>,
    <ServiceID, InstanceID, S_Endpoint>,
    SessionID, MethodID, data) @i
  & E_S_ReceiveFireAndForget(<ServiceID,
    InstanceID, S_Endpoint>, <ClientID,
    C_Endpoint>, SessionID, MethodID, data) @j
  & not(Ex x #k. E_Corrupted(x) @k)
"

// **** Security lemmas ****
// ** Message authentication without corruption **
lemma AlivenessOfferService_NC:
// If a client accepts a service offer,
// apparently from server S, S has previously
// been active.
" All server client nonce1 #i.
  E_C_ReceiveOfferService(client, server, nonce1
    ) @i
  ==> (Ex #j. E_S_Created(server) @j)
  | (Ex id #k. E_Corrupted(id) @k)
"

lemma AlivenessStopOfferService_NC:
// If a client accepts a stop service offer from
// server S, S has previously been active.
" All server client nonce1 #i.
  E_C_ReceiveStopOfferService(client, server,
    nonce1) @i
  ==> (Ex #j. E_S_Created(server) @j)
  | (Ex id #k. E_Corrupted(id) @k)
"

lemma OneTimeGroupAgreementOfferService_NC:

```

```

// If a client C accepts a service offer from a
// server S, the exact same offer has been
// previously send by S and has not previously
// been accepted by C.
" All server client nonce #i.
  E_C_ReceiveOfferService(client, server, nonce)
    @i
  ==> (Ex #j. E_S_SendOfferService(server, nonce)
    @j
    & j < i
    & not (Ex #i2. E_C_ReceiveOfferService(
      client, server, nonce) @i2 & not(#i2 = #
        i)))
  | (Ex id #r. E_Corrupted(id)@r)
"

lemma OneTimeGroupAgreementFireAndForget_NC:
// If a server S accepts a fire&forget message
// from a client C, the exact same message has
// been previously send by C and has not
// previously been accepted by S.
" All server client session method data #i.
  E_S_ReceiveFireAndForget(server, client,
    session, method, data) @i
  ==> (Ex #j. E_C_SendFireAndForget(client,
    server, session, method, data) @j
    & j < i
    & not (Ex #i2. E_S_ReceiveFireAndForget(
      server, client, session, method, data)
      @i2 & not(#i2 = #i)))
  | (Ex id #r. E_Corrupted(id)@r)
"

// ** Message authentication with corruption **
lemma AlivenessOfferService:
// If a client accepts a service offer,
// apparently from server S, S has previously
// been active.
" All server client nonce #i.
  E_C_ReceiveOfferService(client, server, nonce)
    @i
  ==> (Ex #j. E_S_Created(server) @j)
  | (Ex id #r. E_Corrupted(id) @r & Honest(id) @i)
"

lemma AlivenessStopOfferService:
// If a client accepts a stop service offer from
// server S, S has previously been active.
" All server client nonce1 #i.
  E_C_ReceiveStopOfferService(client, server,
    nonce1) @i
  ==> (Ex #j. E_S_Created(server) @j)
  | (Ex id #r. E_Corrupted(id)@r & Honest(id) @i)
"

lemma OneTimeGroupAgreementOfferService:
// If a client C accepts a service offer from a
// server S, the exact same offer has been
// previously send by S and has not previously
// been accepted by C.
" All server client nonce #i.
  E_C_ReceiveOfferService(client, server, nonce)
    @i

```



```

==> (Ex #j. E_S_SendOfferService(server, nonce)
    @j
    & j < i
    & not (Ex #i2. E_C_ReceiveOfferService(
        client, server, nonce) @i2 & not(#i2 =
        #i)))
    | (Ex id #r. E_Corrupted(id)@r & Honest(id)
        @i)
"
lemma OneTimeGroupAgreementFireAndForget:
// If a server S accepts a fire&forget message
from a client C, the exact same message has
been previously send by C and has not
previously been accepted by S.
" All server client session method data #i.
E_S_ReceiveFireAndForget(server, client,
    session, method, data) @i
==> (Ex #j. E_C_SendFireAndForget(client,
    server, session, method, data) @j
    & j < i
    & not (Ex #i2. E_S_ReceiveFireAndForget(
        server, client, session, method, data) @
        i2 & not(#i2 = #i)))
    | (Ex id #r. E_Corrupted(id)@r & Honest(id)
        @i)
"

// ** Practical attack lemmas **
lemma NoMitM:
// The adversary cannot get in a MitM position,
acting as client towards a server and as
server towards a client, relaying data and
potentially modifying parts of the data
" All ClientID C_Endpoint1 C_Endpoint2 ServiceID
S_Endpoint SessionID
MethodID data1 data2 nonce #i #j #k.
E_C_SendRequest(<ClientID, C_Endpoint1>,
    SessionID,
    <ServiceID, S_Endpoint>, MethodID, '
    request_data') @i
& E_S_SendResponse(ServiceID, ClientID,
    C_Endpoint2, SessionID,
    MethodID, <data1, nonce>) @j
& E_C_ReceiveResponse(ClientID, C_Endpoint1,
    ServiceID, SessionID,
    MethodID, <data2, nonce>) @k
& i < j & j < k
& not (Ex id #r. E_Corrupted(id)@r & Honest(id)
    @i)
==> C_Endpoint1 = C_Endpoint2
"

lemma NoDeassociationAttack:
// The adversary cannot 'hijack' an already
existing client/server association
" All ClientID C_Endpoint ServiceID InstanceID
S_Endpoint nonce S_Endpoint_3 SessionID
MethodID data #i #j #l.
( E_S_SendOfferService(<ServiceID, InstanceID
    , S_Endpoint>, nonce) @i
    & E_C_ReceiveOfferService(<ClientID,
        C_Endpoint>, <ServiceID, InstanceID,
        S_Endpoint>, nonce) @j

```

```

    & i < j
    & not (Ex nonce2 #k.
        E_S_SendStopOfferService(<ServiceID,
            InstanceID, S_Endpoint>, nonce2) @k & k
            < l)
    & E_C_SendRequest(<ClientID, C_Endpoint>,
        SessionID, <ServiceID, S_Endpoint_3>,
        MethodID, data) @l & j < l
    & not (Ex id #m. E_Corrupted(id) @ m & m < j)
    & not (Ex id #r. E_Corrupted(id)@r & Honest(id)
        @i)
)
==>
S_Endpoint = S_Endpoint_3
"
end

```

A.2 Tamarin model of SESO-RC

For our model of SESO-RC (Section 7.1), we focus on the security of the proposed mechanism and, thus, providing a more abstract model than for our SOME/IP evaluation. Freshness values have been abstracted by nonces.

```

theory SESOrc
begin
builtins: diffie-hellman, signing, hashing
functions: inc/1, dec/1 // increase/decrease
    freshness values
equations: dec(inc(x))=x
/*
Public Variables
    $A, $B – identity information, such as Client/
    Service ID, Instance ID and Endpoint
    $id_o – service ID that an identity is allowed
    to offering
    $id_r – service ID that an identity is allowed
    to requests

Facts
    !Ca_priv_key('ca', ~ca_priv) – private key of
    Certificate Authority (CA)
    !Ca_pub_key('ca', ca_pub) – public key of CA
    !Identity($A, ~priv_key, pub_key, cert) – Entity '
    s identity and certificate information
    !Cert_store($A, $B, cert_b) – $A stored
    certificate cert_b for entity $B
    !Dh($server, ~server_dh_priv) – stores the
    static Diffie-Hellman key of $server
    Session($$A, $B, s_key) – $A has an open session
    with $B with session key s_key
*/

// **** Protocol ****
rule Create_ca:
let
    ca_pub = pk(~ca_priv)
in
[ Fr(~ca_priv) ]
--[ OnlyOnce('create_ca') ]-->
[ !Ca_priv_key('ca', ~ca_priv),
  !Ca_pub_key('ca', ca_pub),

```

```

    Out(<'ca', ca_pub>)
]

rule Create_identity:
let
    pub_key = pk(~priv_key)
    cert = <$A, pub_key, $id_o, $id_r,
        sign(<$A, pub_key, $id_o, $id_r>, ~ca_priv)>
in
[ Fr(~priv_key), !Ca_priv_key('ca', ~ca_priv) ]
--[ OnlyOnce(<'create_id', $A>) ]->
[ !Identity($A, ~priv_key, pub_key, cert) ]

rule Distribute_cert:
[ !Identity($A, ~priv_key_a, pub_key_a, cert_a) ]
-->
[ Out(<'cert_exchange', cert_a>) ]

rule Reveal_priv_key:
[ !Identity($A, ~priv_key, pub_key, cert) ]
--[ E_Corrupt_identity($A) ]->
[ Out(~priv_key) ]

rule Store_cert:
let
    cert_b = <$B, pub_key_b, $id_o_b, $id_r_b,
        signature_b>
in
[ !Identity($A, ~priv_key_a, pub_key_a, cert_a),
  !Ca_pub_key('ca', ca_pubkey),
  In(<'cert_exchange', cert_b>) ]
--[ Eq(verify(signature_b, <$B, pub_key_b, $id_o_b,
    $id_r_b>, ca_pubkey), true),
    Neq(cert_a, cert_b),
    E_Cert_stored($A, $B) ]->
[ !Cert_store($A, $B, cert_b) ]

rule Offer_service:
let
    server_dh_pub = 'g' ^ ~server_dh_priv
in
[ Fr(~server_dh_priv),
  Fr(~server_fresh),
  !Identity($server, ~priv_key_server,
    pub_key_server, server_cert) ]
--[ ]->
[ Out(<'offer_service', $server, ~server_fresh,
    server_dh_pub, h(server_cert),
    sign(<'offer_service', $server, ~server_fresh,
    server_dh_pub, h(server_cert)>,
    ~priv_key_server)>),
  !Dh($server, ~server_dh_priv, ~server_fresh) ]

rule Request_service:
let
    client_dh_pub = 'g' ^ ~client_dh_priv

```

```

    server_cert = <$server, server_pub_key,
        $server_id_o, $server_id_r,
        sign_server_cert>
    client_cert = <$client, client_pub_key,
        $client_id_o, $client_id_r,
        sign_client_cert>
    session_key = server_dh_pub ^ ~client_dh_priv
    client_fresh = inc(server_fresh)
in
[ Fr(~client_dh_priv),
  !Cert_store($client, $server, server_cert),
  !Identity($client, ~priv_key_client,
    pub_key_client, client_cert),
  In(<'offer_service', $server, server_fresh,
    server_dh_pub, server_cert_hash,
    signed_offer>) ]
--[ Eq(verify(signed_offer, <'offer_service',
    $server, server_fresh, server_dh_pub,
    server_cert_hash>, server_pub_key), true),
    Eq(h(server_cert), server_cert_hash),
    Eq($server_id_o, $client_id_r),
    E_C_Session_established($client, $server,
    client_fresh, session_key),
    Honest($client), Honest($server),
    Secret(session_key) ]->
[ Session($client, $server,
    server_dh_pub ^ ~client_dh_priv),
  Out(<'request_service', $client, $server,
    client_fresh, client_dh_pub,
    h(client_cert),
    sign(<'request_service', $client, $server,
    client_fresh, client_dh_pub,
    h(client_cert)>, ~priv_key_client)>) ]

rule Response_service_request:
let
    server_cert = <$server, server_pub_key,
        $server_id_o, $server_id_r,
        sign_server_cert>
    client_cert = <$client, client_pub_key,
        $client_id_o, $client_id_r,
        sign_client_cert>
    session_key = client_dh_pub ^ ~server_dh_priv
    client_fresh = inc(~server_fresh)
in
[ In(<'request_service', $client, $server,
    client_fresh, client_dh_pub,
    client_cert_hash, signed_request>),
  !Identity($server, ~priv_key_server,
    pub_key_server, server_cert),
  !Cert_store($server, $client, client_cert),
  !Dh($server, ~server_dh_priv, ~server_fresh) ]
--[ Eq(verify(signed_request, <'request_service',
    $client, $server, client_fresh,
    client_dh_pub, client_cert_hash>,
    client_pub_key), true),
    Eq(h(client_cert), client_cert_hash),
    Eq($server_id_o, $client_id_r),

```

```

    E_S_Session_established($server,$client,
        client_fresh, session_key),
    OnlyOnce(<$server, ~server_fresh,
        client_dh_pub>),
    Honest($client), Honest($server),
    Secret(session_key)
]->
[
    Session($server,$client, client_dh_pub^~
        server_dh_priv)
]

// **** Restrictions ****
restriction Equality:
    "All x y #i. Eq(x,y) @i ==> x = y"

restriction OnlyOnce:
    "All #i #j x. OnlyOnce(x)@#i & OnlyOnce(x)@#j ==
        > #i = #j"

restriction Inequality:
    "All x #i. Neq(x,x) @ #i ==> F"

// **** Executability lemmas ****
lemma Certificates_can_be_exchanged:
exists-trace
// Certificates can be exchanged without any
// corrupted parties
"Ex server client #i.
(
    E_Cert_stored(server, client) @i
    & not(Ex #k. E_Corrupt_identity(server) @k)
    & not(Ex #k. E_Corrupt_identity(client) @k)
)"

lemma Session_can_be_established:
// A session can be established without any
// corrupted parties
exists-trace
"Ex server client session_key session_id #i #j.
(
    E_S_Session_established(server, client,
        session_id, session_key) @i
    & E_C_Session_established(client, server,
        session_id, session_key) @j
    & j < i
    & not(Ex #k. E_Corrupt_identity(server) @k)
    & not(Ex #k. E_Corrupt_identity(client) @k)
)"

// **** Security lemmas ****
lemma Perfect_forward_secrecy:
// The adversary cannot learn a session key of a
// session between a client C and a server S
// without having corrupted either C or S before
// the key exchange.
"All x #i. Secret(x) @i
==>
not (Ex #j. K(x) @j)
| (Ex id #r. E_Corrupt_identity(id) @r
    & Honest(id) @i & r < i)
"

lemma Weak_agreement:

```

```

// If a server S established a session,
// apparently with a client C, C also established
// a session, apparently with S.
"All server client session_id session_key #i.
E_S_Session_established(server, client,
    session_id, session_key) @i
==>
(Ex session_id2 session_key2 #j.
    E_C_Session_established(client, server,
        session_id2, session_key2) @j)
| (Ex id #r. E_Corrupt_identity(id) @r
    & Honest(id) @i)
"

lemma Non_injective_agreement:
// If a server S established a session,
// apparently with a client C, C established a
// session, apparently with S, and they agree on
// all session parameters.
"All server client session_id session_key #i.
E_S_Session_established(server, client,
    session_id, session_key) @i
==>
(Ex #j. E_C_Session_established(client, server,
    session_id, session_key) @j)
| (Ex id #r. E_Corrupt_identity(id) @r
    & Honest(id) @i)
"

lemma Injective_agreement:
// If a server S established a session,
// apparently with a client C, C established a
// session, apparently with S, and they agree on
// all session parameters. Each session of S
// corresponds to a unique session of C.
"All server client session_id session_key #i.
E_S_Session_established(server, client,
    session_id, session_key) @i
==>
(Ex #j. E_C_Session_established(client, server,
    session_id, session_key) @j
    & j < i
    & not (Ex server2 client2 #i2.
        E_S_Session_established(server2,
            client2, session_id, session_key)
            @i2
            & not (#i2 = #i)))
| (Ex id #r. E_Corrupt_identity(id) @r
    & Honest(id) @i)
"
end

```

A.3 Tamarin model of SESO-AS

In our model of SESO-AS, freshness values have been abstracted by nonces. Moreover, the broadcast of service offer messages by the AS is represented by individual messages per client.

```

theory SESOas
begin

```

```

builtins: symmetric-encryption, hashing
functions: mac/2
// Computes a message authentication code as mac(
  data, key)
/*
Public Variables
  $A, $S, $C – Identities. $S represents a
    server, $C a client

Variables
  os – service offer
  f0, f1 – freshness values (abstracted by
    nonces)
  kS, kC – symmetric keys shared between
    Authentication Server (AS) and a server or
    client
  kSe – session key of a server, masterkey to
    derive shared client keys
  kSC – symmetric key shared between a server
    and a client

Facts
  !Identity($A, ~kA) – Identity and
    corresponding key shared with the AS
  !Shk($C, $S, kSC) – kSC is believed a shared
    key between $C and $S by $C
*/

// **** Protokol ****
rule Create_identity:
  [Fr(~kA)]
  -->
  [!Identity($A, ~kA)]

rule Corrupt_identity:
  [!Identity($A, ~kA)]
  --[ Reveal($A) ]->
  [Out(~kA)]

rule OfferServiceSAS:
  let
    os = <$S, ~data, ~f0>
    e0 = <$S, senc(~kSe, kS)>
  in
  [
    !Identity($S, kS),
    Fr(~kSe), Fr(~f0), Fr(~data)
  ]
  --[ E_S_Send($S, os, ~kSe),
    Honest($S),
    Secret1(~kSe)
  ]->
  [Out(<os, e0, mac(<os, e0>, kS)>)]

rule OfferServiceASC:
  let
    os_in = <$S, data, f0>
    e0 = <$S, senc(kSe, kS)>
    os_out = <$S, data, ~f1>
    kSC = h(kSe, $C)
    e1 = <$C, senc(kSC, kC)>
  in

```

```

  [
    !Identity($S, kS),
    !Identity($C, kC),
    Fr(~f1),
    In(<os_in, e0, mac(<os_in, e0>, kS)>)
  ]
  --[ OnlyOnce(<'offer_service_as', f0>),
    OnlyOnce(<'offer_service_as', ~f1>),
    E_AS_Receive($S, os_in, kSe),
    E_AS_Send($S, $C, os_out, kSC)
  ]->
  [ Out(<os_out, e1, mac(<os_out, e1>, kC)>) ]

rule ReceiveOfferService:
  let
    os = <$S, data, f1>
    e1 = <$C, senc(kSC, kC)>
  in
  [
    !Identity($C, kC),
    In(<os, e1, mac(<os, e1>, kC)>)
  ]
  --[ E_C_Receive($C, os, kSC),
    OnlyOnce(<'offer_service_c', f1>),
    Honest($C),
    Honest($S),
    Secret2(kSC),
    NotEq($C, $S)
  ]->
  [!Shk($C, $S, kSC)]

// **** Restrictions ****
restriction OnlyOnce:
  "All x #i #j. OnlyOnce(x) @i & OnlyOnce(x) @j
    ==> #i = #j"

restriction NotEq:
  "All x y #i. NotEq(x, y) @i ==> not(x = y)"

// **** Executability lemmas ****
lemma Key_can_be_exchanged:
  exists-trace
  "Ex server client data f0 f1 key0 key1 #i #j.
    E_S_Send(server, <server, data, f0>, key0) @i
    & E_C_Receive(client, <server, data, f1>, key1)
      @j
    & i < j
    & not(Ex id #r. Reveal(id) @r)
  "

// **** Security lemmas ****
lemma Non_injective_agreement:
  // If a client C receives a message, apparently
  // from a server S, S has previously sent this
  // message to C and both agree on the content.
  "All server client data f1 kSC #i.
    E_C_Receive(client, <server, data, f1>, kSC) @i
    ==> (Ex f0 kSe #j. E_S_Send(server, <server,
      data, f0>, kSe) @j & kSC = h(kSe, client))
      | (Ex #r1. Reveal(server) @r1)
      | (Ex #r2. Reveal(client) @r2)
  "
lemma Injective_agreement:

```

```

// If a client C receives a message, apparently
// from a server S, S has previously sent this
// message to C and both agree on the content.
// In addition, the receive event corresponds to
// a unique send event.
"All server client data f1 kSC #i.
  E_C_Receive(client, <server, data, f1>, kSC) @
  i
  ==> ( (Ex f0 kSe #j. E_S_Send(server, <
    server, data, f0>, kSe) @j
    & j < i
    & kSC = h(kSe, client))
    & not (Ex server2 data2 f2 kSe #k.
      E_C_Receive(client, <server2, data2,
        f2>, kSC) @k
      & kSC = h(kSe, client)
      & not (#k = #i))
    )
  | (Ex #r1. Reveal(server) @r1)
  | (Ex #r2. Reveal(client) @r2)
"

// ** Secrecy **
lemma Secrecy_of_session_key:
// The adversary cannot learn a session key
// generated by a server S without corrupting S.
"All x #i.
  Secret1(x) @i
  ==> not(Ex #j. K(x) @j)
  | (Ex id #r. Reveal(id) @r & Honest(id) @i
    )
"

lemma Secrecy_of_shared_symmetric_key:
// The adversary cannot learn a shared symmetric
// key between a client C and a server S without
// corrupting either C or S.
"All x #i.
  Secret2(x) @i
  ==> not(Ex #j. K(x) @j)
  | (Ex id #r. Reveal(id) @r & Honest(id) @i
    )
"

// ** Perfect Forward Secrecy **
lemma PFS_of_session_key:
// The adversary cannot learn a session key
// generated by a server S which has not
// previously been corrupted.
"All x #i.
  Secret1(x) @i
  ==> not(Ex #j. K(x) @j)
  | (Ex id #r. Reveal(id) @r & Honest(id) @i
    & r < i)
"

lemma PFS_of_shared_symmetric_key:
// The adversary cannot learn a shared symmetric
// key between a client C and a server S without
// either of these parties being corrupted before
// the key exchange occurs.
"All x #i.
  Secret2(x) @i
  ==> not(Ex #j. K(x) @j)
  | (Ex id #r. Reveal(id) @r & Honest(id) @i
    & r < i)

```

```

"
end

```