Formal Analysis of Attested TLS Protocols

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Thanks to my travel sponsors!

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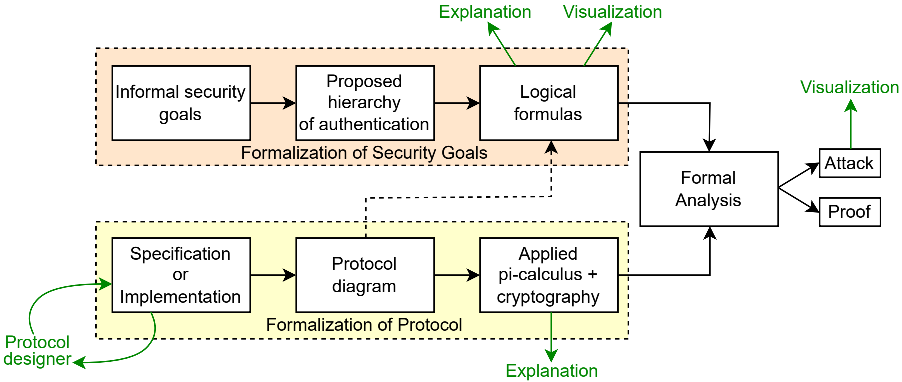
Outline

Approach



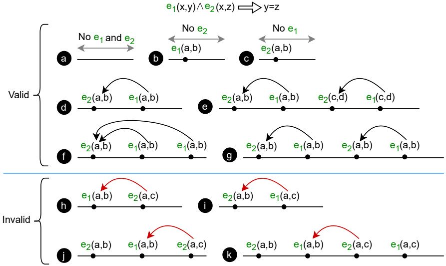
Explanation
Visualization
Informal security goals
Proposed hierarchy of authentication
Logical formulas
Formalization of Security Goals
Visualization
Formal Analysis
Attack
Proof
Specification or Implementation
Protocol diagram
Applied pi-calculus + cryptography
Formalization of Protocol
Protocol designer
Explanation

Correlation Property

- Explanation: If the client and server agree on the first parameter, then they also agree on the second parameter.

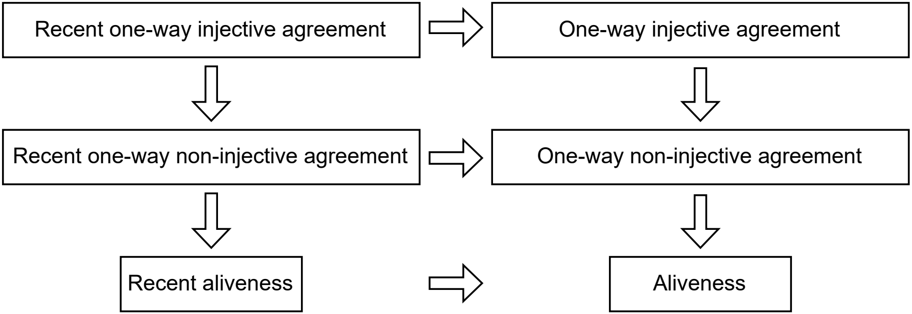
$$
\begin{aligned}
&\forall\, x, y, z. \\
&action(e_1(x, y)) \wedge \\
&action(e_2(x, z)) \rightarrow \\
&y = z
\end{aligned}
\tag{1}
$$

- Visualization



General Hierarchy of One-way Authentication

Level	Property	Agreement		
		Server's identity	Protocol parameters	One-to-one correspondence
1	Aliveness	✓	×	×
2	One-way non-injective agreement	✓	✓	×
3	One-way injective agreement	✓	✓	✓



Comparison with Lowe's Hierarchy

Definition

Weak agreement: We say that a protocol guarantees to an initiator A weak agreement with another agent B if, whenever A (acting as initiator) completes a run of the protocol, apparently with responder B, then B has previously been running the protocol, apparently with A.

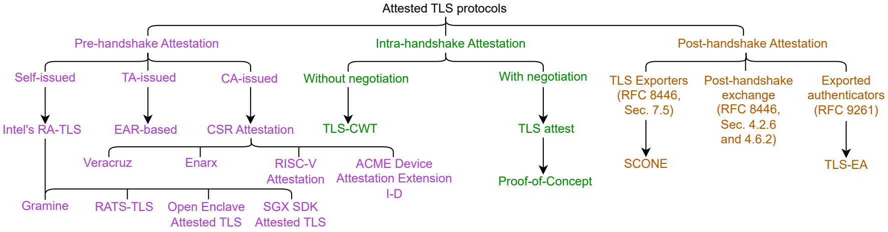
Discussion: What does the RG think?

1. Weak agreement is stronger than a one-way agreement as it requires the responder to agree on the initiator's identity
2. No placement of actions e_1 and e_2 that can satisfy Formula 2, with e_1 still representing an action for a client role and e_2 still representing an action for a server role.

$$\forall\ id_s, id_c.\ action(e_1(id_s, id_c)) \rightarrow action(e_2(id_s, id_c)) \tag{2}$$

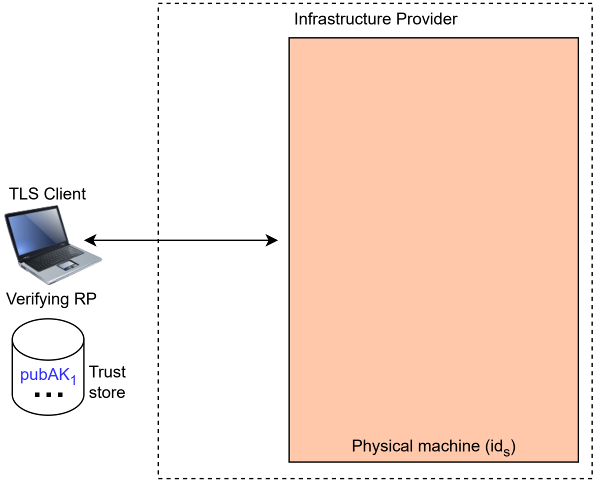
Outline

Scope



- Confidential Computing
- TLS Server as RATS Attester
- Pre- and intra-handshake attestation
- Post-handshake attestation will have the same goals (it is WiP)

System Model (TLS Server as RATS Attester)



- AK = Attestation Key

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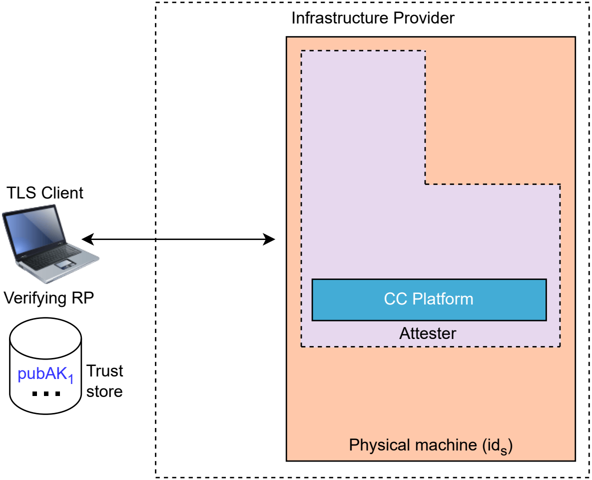

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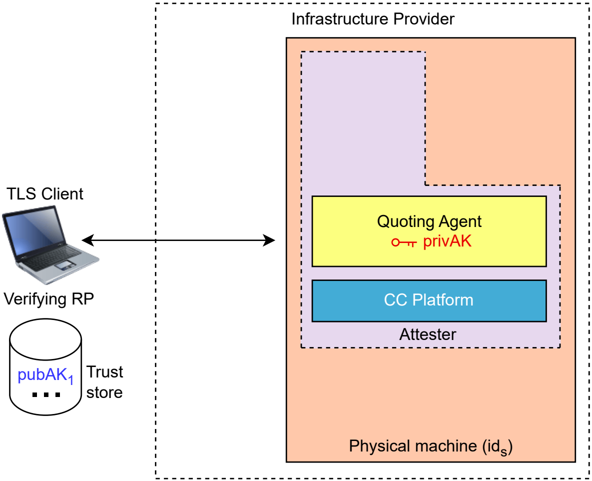

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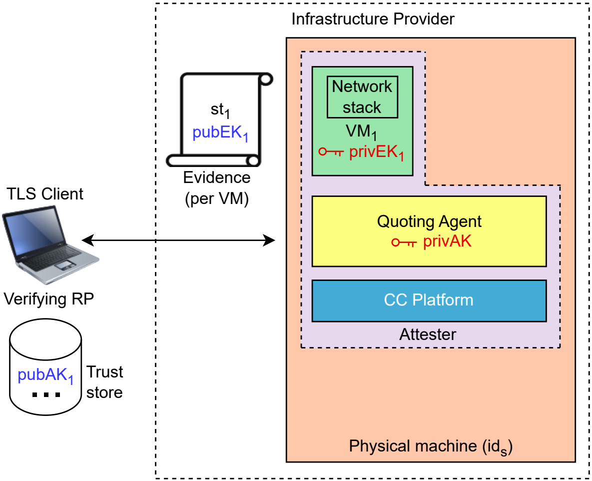
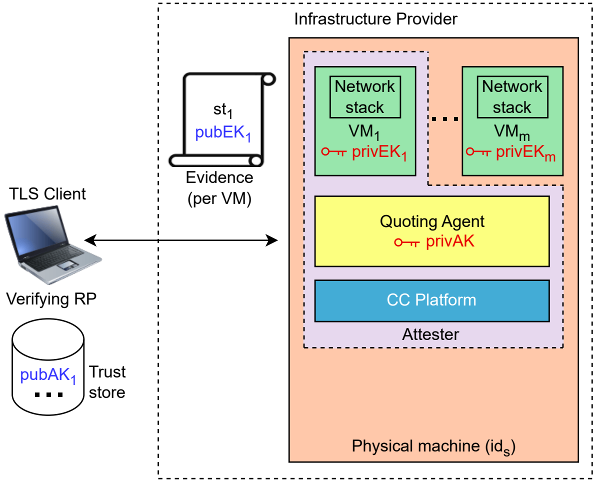
System Model (TLS Server as RATS Attester)



- AK = Attestation Key
- EK = Ephemeral Key

System Model (TLS Server as RATS Attester)



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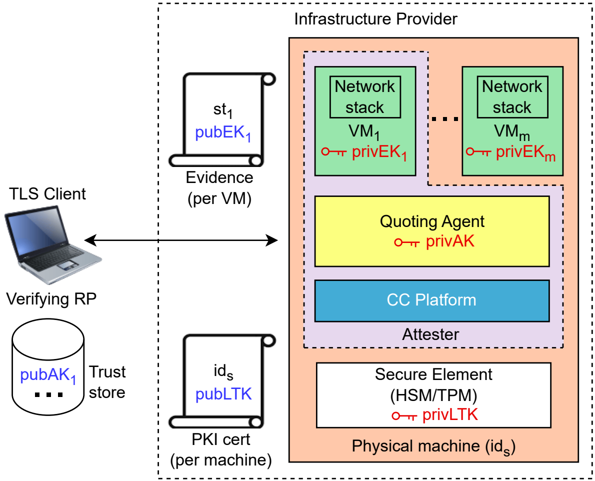
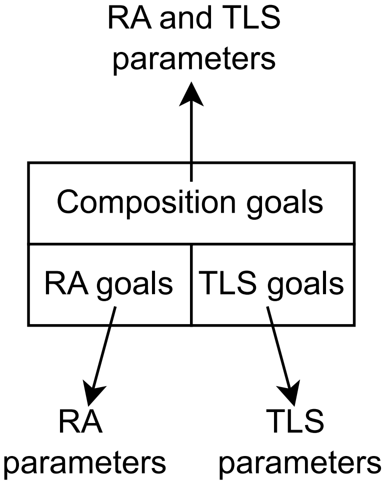


- AK = Attestation Key
- EK = Ephemeral Key
- LTK = Long-Term Key

General Approach for Security Goals



Informal Security Goals

- Remote Attestation
  - G-RA1: Integrity of Evidence
  - G-RA2: Freshness of Evidence
    - Binding Evidence to a specific RA interaction
    - Recentness of Evidence generation
  - G-RA3: Establishment of connection with privAK known to adversary
  - G-RA4: Establishment of connection with privEK known to adversary

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- Standard TLS properties
  - G-TLS1: Establishment of connection with `client_write_key` known to adversary
  - G-TLS2: Server authentication

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- Composition goals
  - G-C1: Evidence is generated by the same server that is authenticated
    - Binding Evidence to a specific TLS connection: $g^{xy}, htsc, atsc$
  - G-C2: Agreement of all Remote Attestation and TLS parameters

Threat Model

- Standard TLS threat model (weak DH, weak hash etc.)
- Long-term Key (privLTK) may be leaked
- Ephemeral Key (privEK) may be leaked
- Attestation Key (privAK) may be leaked (e.g., via Foreshadow[1])

[1] Van Bulck, Minkin, Weisse, Genkin, Kasikci, Piessens, Silberstein, Wenisch, Yarom, and Strackx, "Foreshadow: Extracting the Keys to the Intel SGX Kingdom with Transient Out-of-Order Execution", 2018.

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- Long-term Key (privLTK) may be leaked
- Ephemeral Key (privEK) may be leaked
- Attestation Key (privAK) may be leaked (e.g., via Foreshadow[1])
- Assumptions (complementary to protocol design)
  - No weaknesses in the generation of Claims
  - Verifying RP provisioned with Reference Values
  - Verifying RP provisioned with pubAK
  - Verifying RP provisioned with pubCA
  - TOCTOU attacks out of the scope

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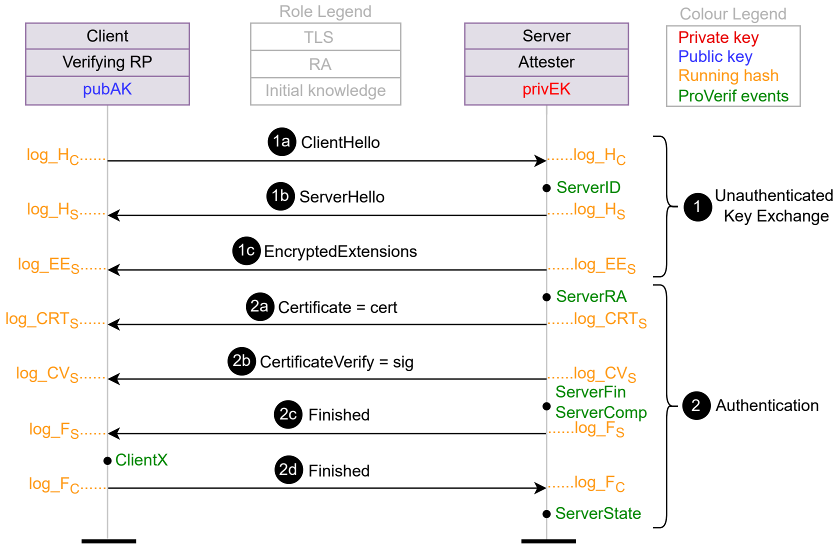
Security Goals and Properties

Security goal	Security property
G-RA1 holds unless `LAK` or `WH`	One-way non-injective agreement
G-RA2 holds unless `LAK` or `WH`	Recent one-way injective agreement
G-RA3 holds unless `LAK`	One-way non-injective agreement
G-RA4 holds unless `LAK`, `LEK`, `WDH` or `WH`	One-way non-injective agreement
G-TLS1 holds unless `LAK`, `LEK`, `WDH`, `WH` or `WE`	One-way non-injective agreement
G-TLS2 holds unless `LAK`, `LEK`, `WDH`, `WH` or `WE`	Recent one-way non-injective agreement
G-C1a should hold	Correlation property
G-C1b should hold	Correlation property
G-C1c should hold	Correlation property
G-C2 holds unless `LAK`, `LEK`, `WDH`, `WH` or `WE`	Recent one-way injective agreement

Events for Formalization of Security Goals



Abstract Security Properties (without assumptions) in ProVerif

Security goal	e_1	e_2	General Arguments
G-RA1	`ClientRA`	`ServerRA`	`RAparams`
G-RA2	`ClientRA`	`ServerRA`	`RAparams,na`
G-RA3	`ClientFin & attacker`	-	`pubAK`
G-RA4	`ClientFin & attacker`	-	`pubEK`
G-TLS1	`ClientFin & attacker`	-	`kc`
G-TLS2a	`ClientID & ServerID`	-	`ID,gxy`
G-TLS2b	`ClientFin`	`ServerFin`	`TLSparams`
G-C1a	`ClientState & ServerState`	-	`ev,gxy`
G-C1b	`ClientState & ServerState`	-	`ev,kch`
G-C1c	`ClientState & ServerState`	-	`ev,kc`
G-C2	`ClientComp`	`ServerComp`	`RAparams,TLSparams`

Results for Pre- and Intra-handshake Attestation

- Pre-handshake attestation: Interoperable RA-TLS (IRA-TLS)
- Intra-handshake attestation: draft-fossati-tls-attestation (TLS-a)

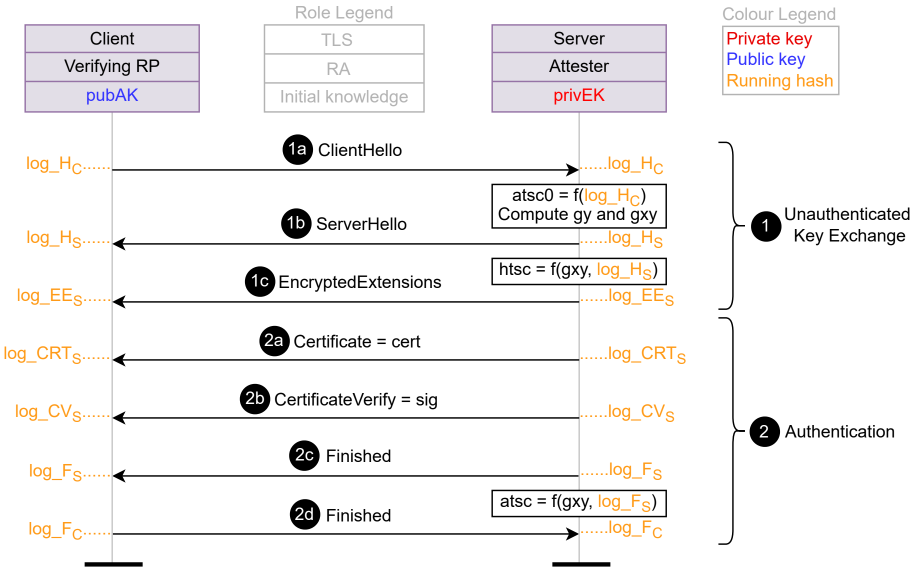
Security goal	IRA-TLS	TLS-a
G-RA1: Integrity of Evidence	✓	✓
G-RA2: Freshness of Evidence	×	✓
G-RA3: Protection of Attestation Keys	✓	✓
G-RA4: Protection of Ephemeral Keys	✓	✓
G-TLS1: Protection of Client's Write Key	✓	✓
G-TLS2.1: Server Authentication	×	×
G-TLS2.2: Server Authentication	×	×
G-C1a: Binding Evidence to `gxy`	×	×
G-C1b: Binding Evidence to `htsc`	×	×
G-C1c: Binding Evidence to `atsc`	×	×
G-C2: Agreement of all parameters	×	×

Results for Proposed Solutions in Intra-handshake Attestation

- Sol.1: Modify CertificateVerify message
- Sol.2: Two CertificateVerify messages
- Sol.3: New signature algorithm
- Sol.4: New Attestation message
- Sol.5: Modify CertificateVerify message + define new exporter

Security goal	Sol.1	Sol.2	Sol.3	Sol.4	Sol.5
G-RA1: Integrity of Evidence	✓	✓	✓	✓	✓
G-RA2: Freshness of Evidence	✓	✓	✓	✓	✓
G-RA3: Protection of Attestation Keys	✓	✓	✓	✓	✓
G-RA4: Protection of Ephemeral Keys	✓	✓	✓	✓	✓
G-TLS1: Protection of Client's Write Key	✓	✓	✓	✓	✓
G-TLS2.1: Server Authentication	✓	✓	✓	✓	✓
G-TLS2.2: Server Authentication	✓	✓	✓	✓	✓
G-C1a: Binding Evidence to `gxy`	×	×	×	×	✓
G-C1b: Binding Evidence to `htsc`	×	×	×	×	✓
G-C1c: Binding Evidence to `atsc`	×	×	×	×	×
G-C2: Agreement of all parameters	✓	✓	✓	✓	✓

Strong Binding vs. Relay of Evidence (Abstracted)



Summary

- Protocol-designer-in-the-loop approach with explanations and visualizations
- Identified subtle problems in Lowe's hierarchy and proposed general hierarchy of one-way authentication
- To my knowledge, SEAT WG is the first WG with formal analysis explicitly mentioned in the charter.
- Key insights
  - Need infrastructure identity to prevent diversion attacks
  - Cryptographic binding of RA and TLS is critical to prevent relay attacks
  - Pre- and intra-handshake attestation are not suitable choices for standardization.
  - One of the most challenging protocols of the IETF: formal analysis is critical to the success of WG.
- Requesting feedback on shared pre-prints
- WiP: post-handshake attestation, i.e., draft-fossati-seat-expat
- WiP: draft-ietf-tls-extended-key-update: formal analysis work is blocked. The authors are not following good practices.

ACK

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- Arto Niemi (Huawei)
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- Ned Smith (Intel)
- Carsten Weinhold (Barkhausen Institut)
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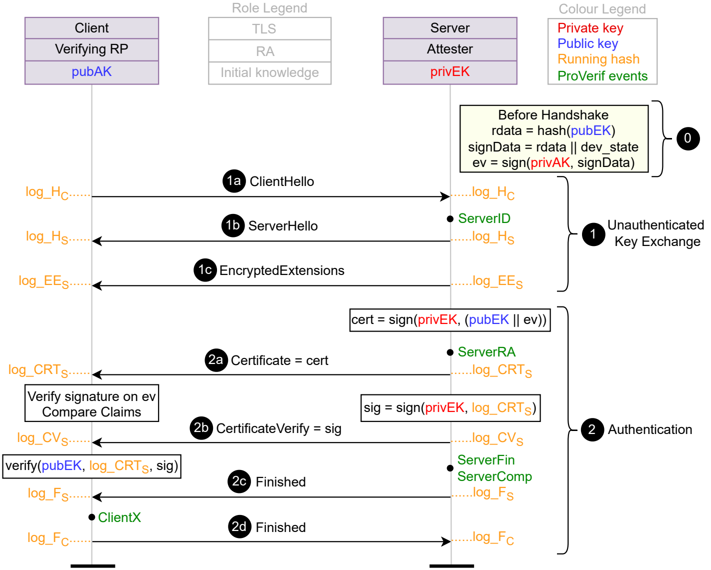
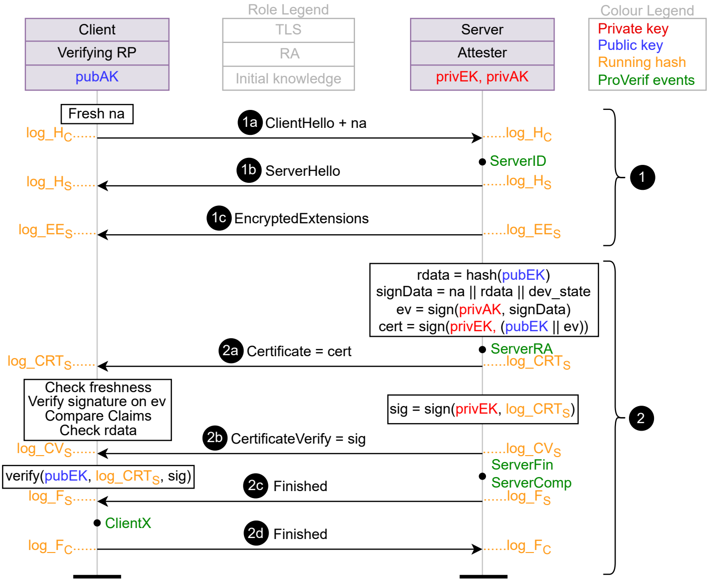
Outline

IRA-TLS


Role Legend
TLS
RA
Initial knowledge
Client
Verifying RP
pubAK
Server
Attester
privEK
Colour Legend
Private key
Public key
Running hash
ProVerif events
Before Handshake
rdata = hash(pubEK)
signData = rdata || dev_state
ev = sign(privAK, signData)
0
1a ClientHello
log_HC
1b ServerHello
ServerID
log_HS
1c EncryptedExtensions
log_EES
1 Unauthenticated Key Exchange
cert = sign(privEK, (pubEK || ev))
2a Certificate = cert
ServerRA
log_CRTS
Verify signature on ev
Compare Claims
sig = sign(privEK, log_CRTS)
2b CertificateVerify = sig
log_CVS
verify(pubEK, log_CRTS, sig)
ServerFin
ServerComp
2c Finished
log_FS
ClientX
2d Finished
log_FC
2 Authentication

TLS-a


Role Legend
TLS
RA
Initial knowledge
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Private key
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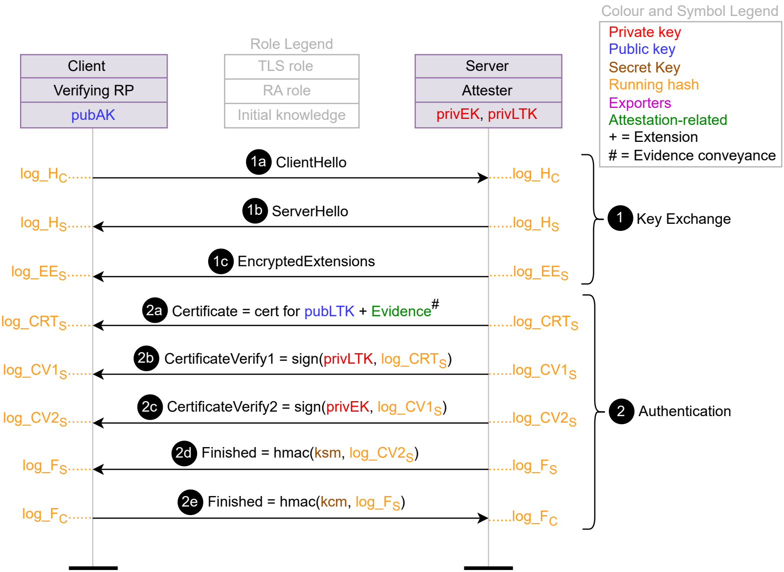
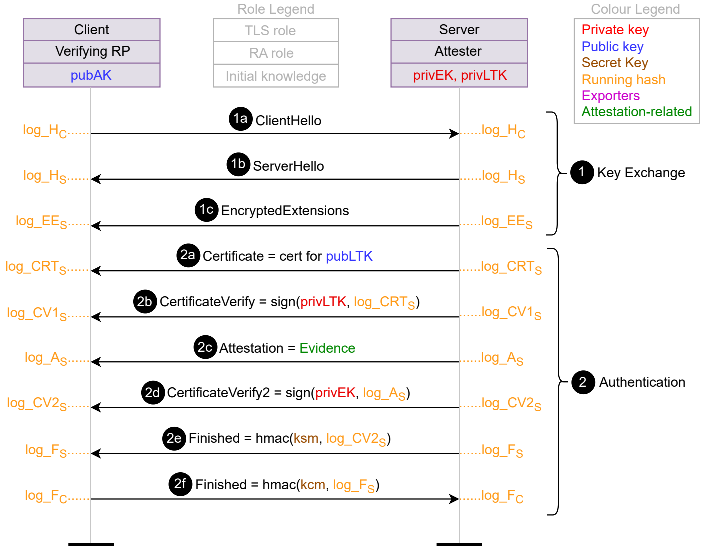
ProVerif events
Client
Verifying RP
pubAK
Server
Attester
privEK, privAK
Fresh na
1a ClientHello + na
log_H$_C$......
......log_H$_C$
ServerID
1b ServerHello
log_H$_S$......
......log_H$_S$
1c EncryptedExtensions
log_EE$_S$......
......log_EE$_S$
1
rdata = hash(pubEK)
signData = na || rdata || dev_state
ev = sign(privAK, signData)
cert = sign(privEK, (pubEK || ev))
2a Certificate = cert
ServerRA
log_CRT$_S$......
......log_CRT$_S$
Check freshness
Verify signature on ev
Compare Claims
Check rdata
sig = sign(privEK, log_CRT$_S$)
2b CertificateVerify = sig
log_CV$_S$......
......log_CV$_S$
ServerFin
ServerComp
verify(pubEK, log_CRT$_S$, sig)
2c Finished
log_F$_S$......
......log_F$_S$
ClientX
2d Finished
log_F$_C$......
......log_F$_C$
2

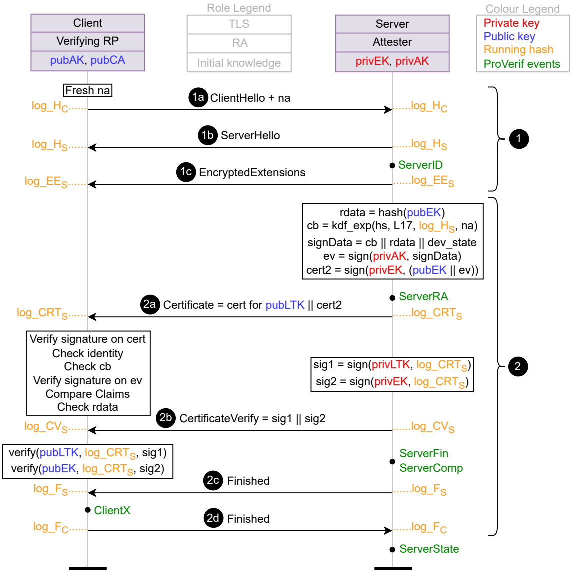
Sol. 2: Two CertificateVerify Messages



Sol. 4: New Attestation Message



Sol. 5: Cryptographic Binding



Sol. 5 (cont.): Cryptographic Binding