MARTIN GUNNARSSON

Formal Verification of WirelessHART

Verifying old and finding new attacks

Presentation

- Short overview of WirelessHART
- Previous security analysis of WirelessHART
- Tamarin introduction
- Modeling WirelessHART
- Modeling results & Novel Attack

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Presentation & Paper Outline

- Short overview of WirelessHART
- Previous security analysis of WirelessHART
- Tamarin introduction
- Modeling WirelessHART
- Modeling results & Novel Attack

Contributions:

- Summary of all published WirelessHART attacks.
- Formal verification of Tamarin including previous attacks.
- Discovered a novel re-keying attack.

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WirelessHART - background

- Wireless HART.
- HART is a legacy (wired) protocol for industrial automation.
- Intended for communication between sensors and actuators.
- Controller sends *commands* to the device.
- Wired protocol – no security considerations or mechanisms.

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WirelessHART

- Intended for communication between sensors and actuators.
- Battery powered wireless device has 30-60% reduced installation costs.
- Uses 7-layer OSI-model with “legacy HART” as *application layer*.
- 2.4GHz IEEE 802.15.4 mesh network as Physical layer.
- At lest 50 million devices installed 2022.
- Supported by major ICS vendors.

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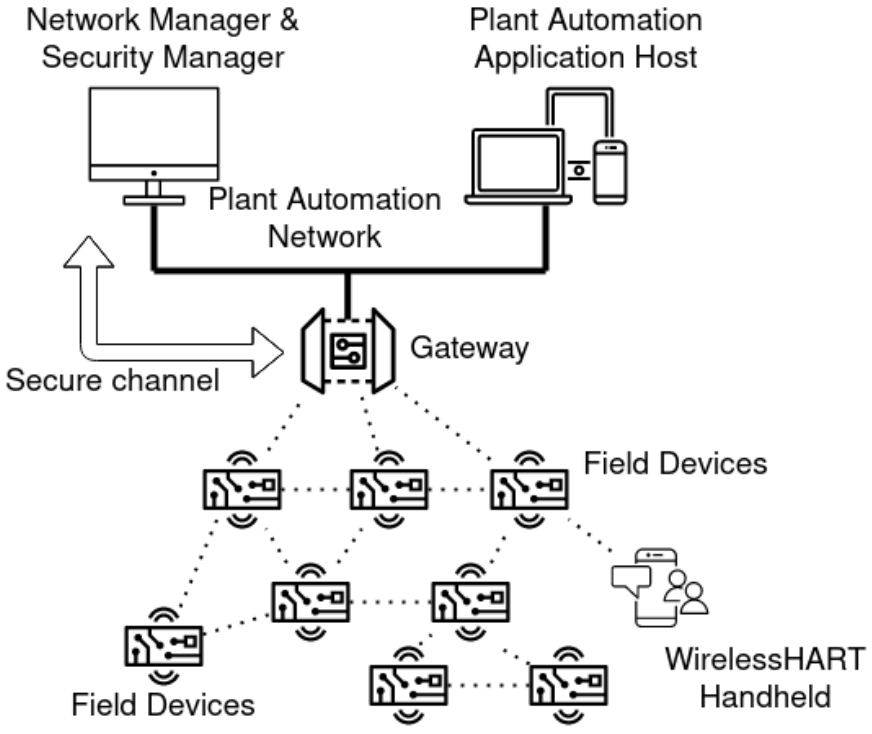
Roles in WirelessHART

- *Field Devices*
- *Gateway*

- *Security & Network Manager*



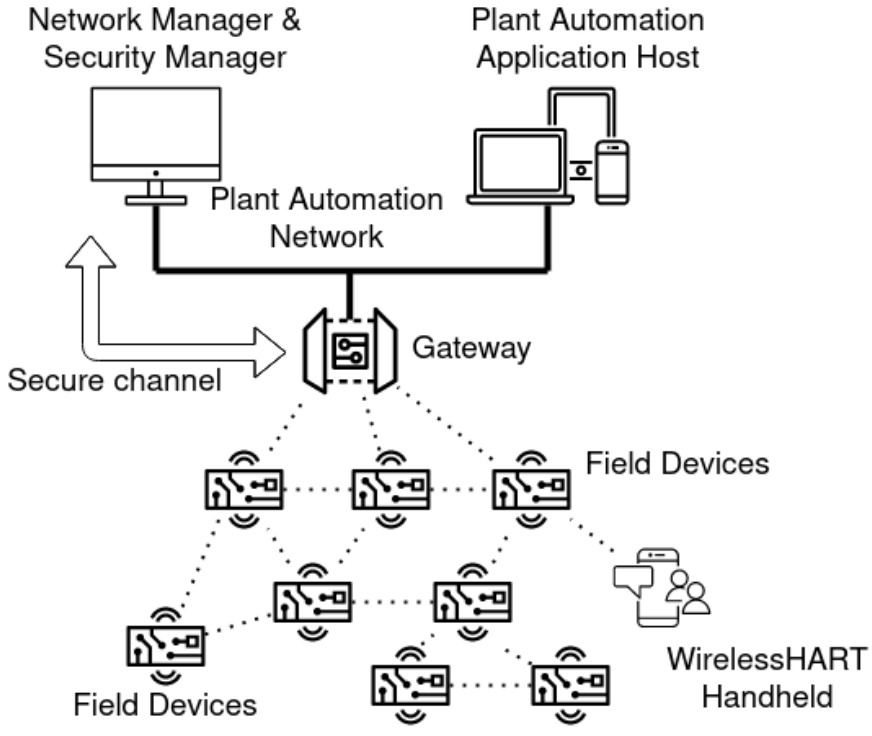
Roles in WirelessHART

- *Field Devices*
- *Gateway*

  - WirelessHART terminate at the *Gateway*

- *Security & Network Manager*

  - Manage the network



WirelessHART security

- Communication can be *unicast* or *broadcast* group communication.
- Messages are end-to-end encrypted and hop-by-hop authenticated.
- Only symmetric cryptography is used.
- AES-128-CCM AEAD.

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WirelessHART security

- Devices are provided with a symmetric Join_key before they join the network.
- Network_Key – Used for hop-by-hop authentication.
- Session Keys – Used for end-to-end encryption of messages.

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WirelessHART sub-protocols

- End-to-End security protocol – Used to communicate data and configurations to Field Devices through *sessions*.
- Join Sequence – Used to authenticate joining Field Device and provide keys and network information.
- Network Key Change Operation – Used to change the keys of Field Devices.

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Previous Security Analysis

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Attackers

- WirelessHART assume two types of attackers, an *Insider Attacker* and an *Outsider Attacker*.
- An *Outsider Attacker* knows nothing.
- An *Insider Attacker* know secrets of the network.
- The previous notion of *Insider Attacker* was too weak.

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Attackers

	Outsider Attacker	Insider Attacker (old)	Insider Attacker (new)
Join_Key	Unknown	Unknown	Known (Unique)
Network_Key	Unknown	Known	Known
BC Session Key	Unknown	Unknown	Known
Session Key	Unknown	Unknown	Known (Unique)
Well-Known-Key	Known	Known	Known

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Related Work

- Several attacks have been published:
  - Jamming attacks, message corruption attacks, disconnect Sybil-attacks, pre-join exhaustion attacks, command injection attacks
- A formal verification of WirelessHART in 2021, only covered the end-to-end security protocol.

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Jamming Attacks

- Blocking the Physical or MAC layer.
- Smart jamming that predict frequencies and slots to selectively jam one device.
- Several attacks published [1],[2]

[1] Raza, Shahid, et al. "Security considerations for the WirelessHART protocol." 2009 IEEE Conference on Emerging Technologies & Factory Automation. IEEE, 2009.

[2] Cheng, Xia, et al. "Launching smart selective jamming attacks in wirelesshart networks." IEEE INFOCOM 2021-IEEE Conference on Computer Communications. IEEE, 2021.

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Disconnect Sybil Attack

- Impersonating another device, telling neighbors the ‘device’ will leave the network.
- Lack of authentication on the Data Layer.

[3] Bayou, Lyes, et al. "Security issue of WirelessHART based SCADA systems." International Conference on Risks and Security of Internet and Systems. Springer, Cham, 2015.

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Command Injection Attack

- An *Insider Attacker* impersonate the Gateway and send ‘commands’ to a Field Device.
- Several variants exists. Direct Command Injection, Bounced Command Injection, and On-the-fly Command Injection.
- Lack of source-authentication due to compromised symmetric keys.

[4] Bayou, Lyes, et al. "Security analysis of WirelessHART communication scheme." International Symposium on Foundations and Practice of Security. Springer, Cham, 2016.

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Previously Published Attacks

Attack	STRIDE CLASSIFICATION	Attacker
Jamming Attack	DoS	Outsider
Disconnect Sybil Attack	Impersonation	Outsider
Pre-Join Exhaustion	DoS	Outsider
Direct Command Injection	Impersonation	Insider
Bounced Command Injection	Impersonation	Insider
Con-the-fly Command Injection	Tampering	Insider

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Security Analysis With Tamarin

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Protocol analysis with Tamarin

- Model the protocol using a protocol modeling language.
- Analyze protocols within a security-model.
- State the security properties as *lemmas*, to be proven.
- Automated reasoning gives proofs that lemmas *hold* or a *counterexample*.
- Intended as a *supplement* to traditional methods.

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Tamarin prover

- Protocols are represented using *rules* and work as a state-machine.
- An execution of a protocol is called a *Trace*.
- *Traces* are used to evaluate if a stated security lemma *holds*, or to provide a *counterexample*.
- Protocols are analyzed within the Dolev-Yao model.
  - The adversary *is* the network.

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Diffie-Hellman in Tamarin

```
rule r1:
  [Fr(~i_sk)]
   -->
  [!Initiator($I, ~i_sk), Out(‘g’^~i_sk]
```

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Diffie-Hellman in Tamarin

```
rule r1:
  [Fr(~i_sk)]
   -->
  [!Initiator($I, ~i_sk), Out('g'^~i_sk]

rule r2:
    let:
    session_key = i_pk^~r_sk
    [In(i_pk), Fr(~r_sk)]
    --[ Resp_S(session_key) ]->
    [!Responder($R,~r_sk, session_key), Out('g'^~r_sk)]
```

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Diffie-Hellman in Tamarin

```
rule r1:
  [Fr(~i_sk)]
   -->
  [!Initiator($I, ~i_sk), Out('g'^~i_sk]

rule r2:
    let:
    session_key = i_pk^~r_sk
    [In(i_pk), Fr(~r_sk)]
    --[ Resp_S(session_key) ]->
    [!Responder($R,~r_sk, session_key), Out('g'^~r_sk)]

rule r3:
    [In(r_pk), !Initiator($I, ~i_sk)]
    --[ Init_S(r_pk^~i_sk) ]->
    [!Initiator_1($I, ~i_sk, r_pk^~i_sk)]
```

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Diffie-Hellman in Tamarin

```
lemma session_key_secrecy:
    “All Ses_K #i #j.
    Resp_S(Ses_K) @ #i
    & Init_S(Ses_K) @ #j &
    #j < #i &
    not(Ex #k. K(Ses_K) @ #k)”
```

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Diffie-Hellman in Tamarin

```
lemma session_key_secrecy:
    “All Ses_K #i #j.
    Resp_S(Ses_K) @ #i
    & Init_S(Ses_K) @ #j &
    #j < #i &
    not(Ex #k. K(Ses_K) @ #k)”
```

```
lemma session_key_secrecy:
    “All Ses_K1 Ses_K2 #i #j.
    Resp_S(Ses_K1) @ #i &
    Init_S(Ses_K2) @ #j &
    #j < #i &
    not(Ex #k1 #k2. K(Ses_K1) @ #k1 | K(Ses_K2) @ #k2 )”
```

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Modeling and Verifying WirelessHART

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Formal verification of WirelessHART

- We have modeled all sub-protocols of WirelessHART relevant to security.
- Replay-protection was not modeled.

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Formal verification of WirelessHART

- We have modeled all sub-protocols of WirelessHART relevant to security.
- Replay-protection was not modeled.

- Split our model into four parts:
  - End-to-End Security Protocol
  - Join Sequence
  - Network key Change Operation
  - DLPDU advertisements

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Formal verification of WirelessHART

- Split our model into four parts:
  - End-to-End Security Protocol
  - Join Sequence
  - Network key Change Operation
  - DLPDU advertisements

<u>Properties tested:</u>

- Secrecy
- Authentication
- Integrity

All properties were tested against an Insider Attacker.

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End-to-End Security Protocol

- Sessions are used to communicate data and configurations to devices.
- Can be used in unicast or broadcast mode.
- Provides confidentiality, integrity protection, replay protection.
- A system wide Network_key is intended to protect the network from an *Outsider Attacker*.

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```
rule Gateway_send_command_UC:
        let
        NL_msg_s = ~command
        NL_header_s = <~NL_nonce_s, 'Command_pkt', 'NL_Ctrl', 'Sec_Ctrl'>
        NL_key_s = ~D_GW_UC

        DL_payload_s = aead_enc(NL_key_s, ~NL_nonce_s, NL_header_s, NL_msg_s)

        DL_key_s = ~NetworkKey
        DL_header_s = <~DL_nonce_s, $device_id, $Gateway_ID>
        DL_mac_s = mac( < DL_header_s, DL_payload_s>, DL_key_s)
        encrypted_message = <DL_header_s, NL_header_s, DL_payload_s, DL_mac_s>

        in
        [!Gateway_1($Gateway_ID, $NetworkID, ~NetworkKey, ~D_GW_BC, ~D_GW_UC),
         !Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC,
~D_NM_BC, ~D_GW_UC, ~D_NM_UC),
         Fr(~DL_nonce_s), Fr(~NL_nonce_s), Fr(~command)]
        --[SendCommand_UC($Gateway_ID, $device_id, ~command)]->
        [Out(encrypted_message) ]
```

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```
rule Device_receive_command_UC:
        let
        /* Incoming Message */
        DL_header_r = <DL_nonce_r, receiver, source>
        NL_header_r = <NL_nonce_r, a, b, c>
        incoming_message = < DL_header_r, NL_header_r, DL_payload_r, DL_MAC_r>
         NL_key_r = ~D_GW_UC
        decrypted_command = aead_dec(NL_key_r, NL_nonce_r, NL_header_r,
DL_payload_r)
        in
        [In(incoming_message),
         !Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC,
~D_NM_BC, ~D_GW_UC, ~D_NM_UC)
        ]
       --[
           Eq( verify_mac(DL_MAC_r, <DL_header_r, DL_payload_r>, ~NetworkKey),
true),
           Eq( aead_verify(NL_key_r, NL_nonce_r, NL_header_r, DL_payload_r), true),
           ReceivedCommand_UC(source, receiver, decrypted_command),
           Authentic(source, receiver, decrypted_command, ~NetworkKey)
        ]->
        []
```

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End-to-End Protocol

- We have modeled end-to-end protocol over unicast and broadcast sessions.
- Rules for sending and receiving messages.

	Unicast	Broadcast
Command Secrecy	Hold	Does not hold
Command Authentication	Hold	Does not Hold

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Lemmas

```
/* A Field Device D will believe a message coming from
Gateway GW over unicast to be authentic, or D's keys has been
revealed. */
lemma message_authentication_UC:
"All GW D cmd #i. ReceivedCommand_UC(GW, D, cmd) @i
==> (Ex #j. SendCommand_UC(GW, D, cmd) @j & j<i) | (Ex #k.
Reveal(D) @ #k) | (Ex c #m. Reveal(c) @ #m & not c = D)"

/* A 'command' cmd sent over unicast to a Field Device D that
is known by ADV implies D has been compromised. */
lemma command_secrecy_UC:
      "All GW D cmd #i #j.
       SendCommand_UC(GW, D, cmd) @ #i &
       K(cmd) @ #j
       ==>
         Ex #k. Reveal(D) @ #k"
```

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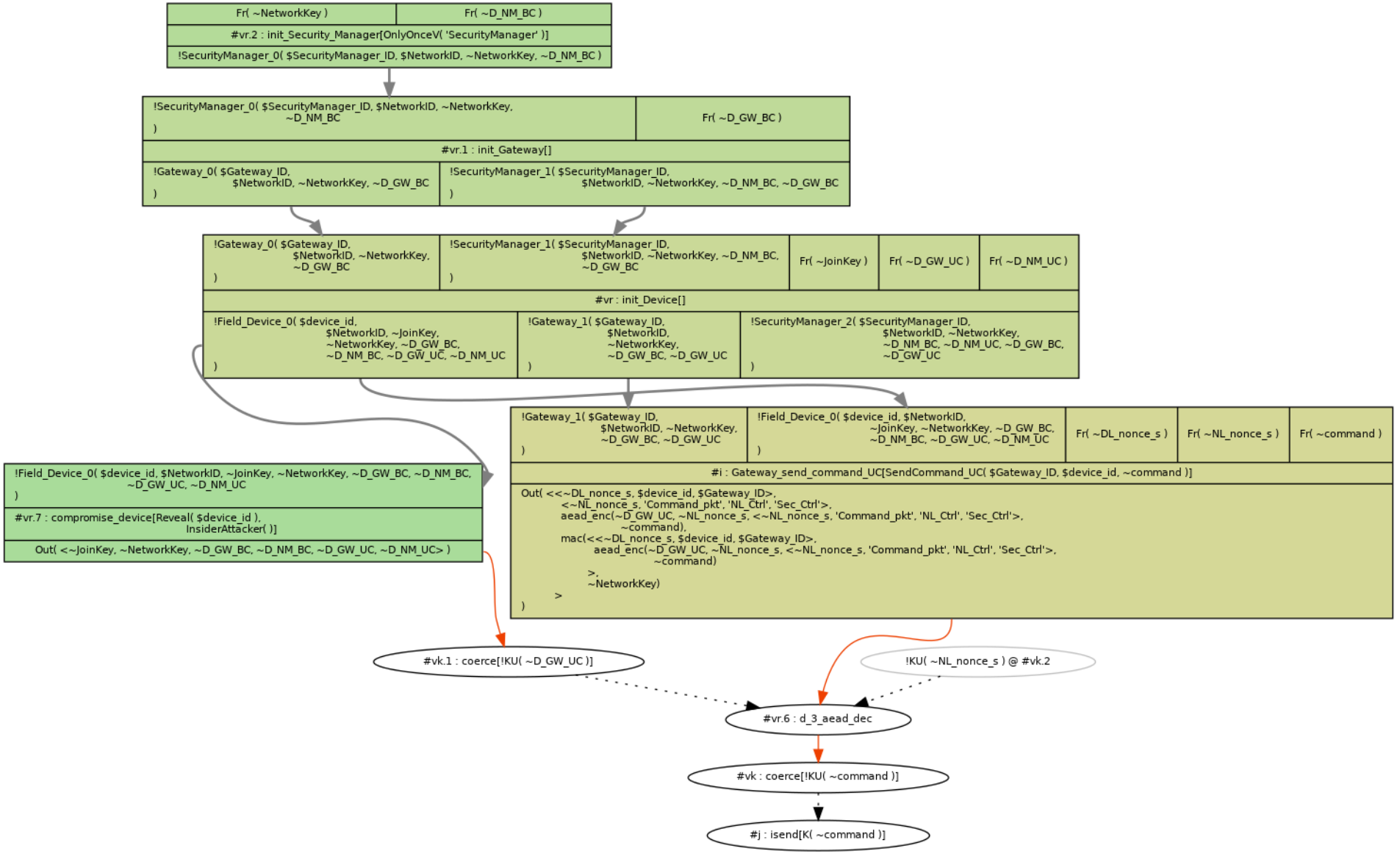
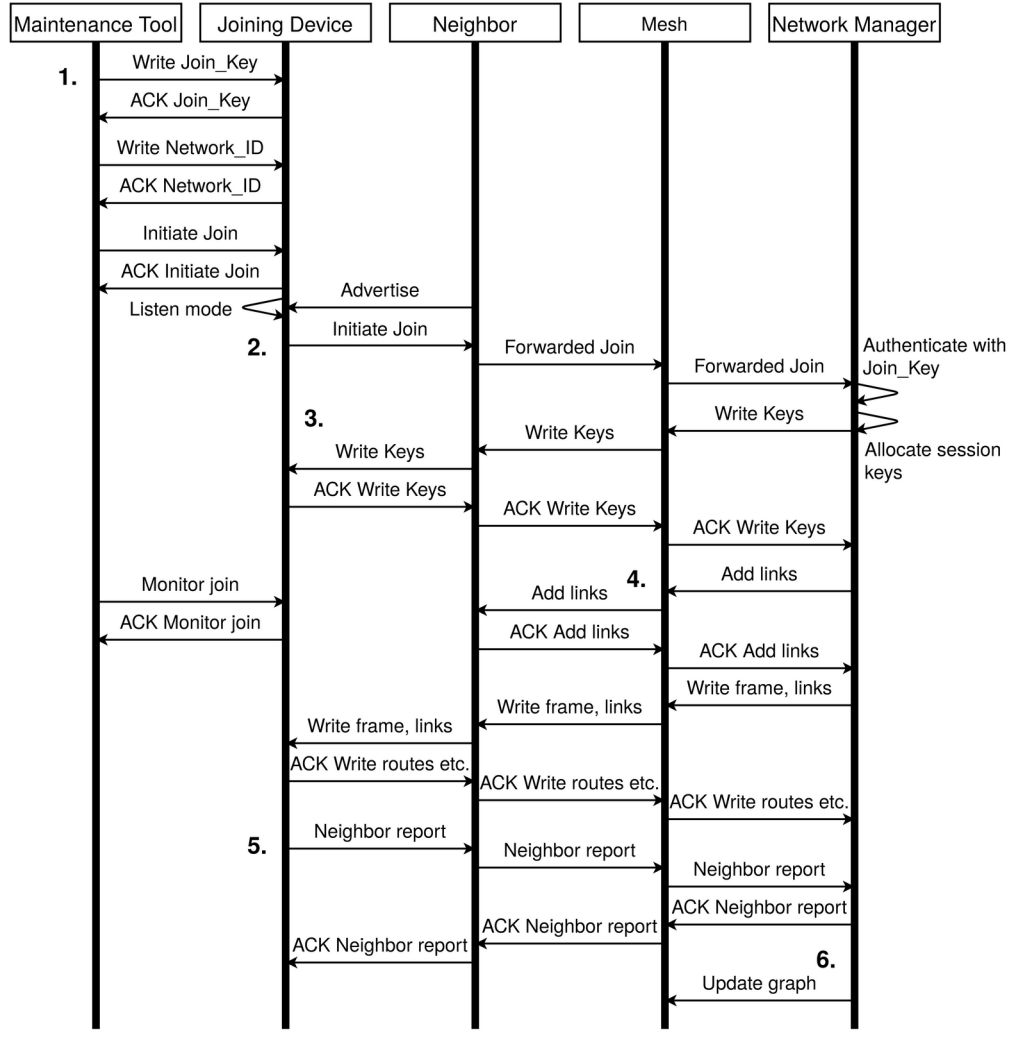

Fr(~NetworkKey)
Fr(~D_NM_BC)
#vr.2 : init_Security_Manager[OnlyOnceV('SecurityManager')]
!SecurityManager_0($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC)
!SecurityManager_0($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC)
Fr(~D_GW_BC)
#vr.1 : init_Gateway[]
!Gateway_0($Gateway_ID, $NetworkID, ~NetworkKey, ~D_GW_BC)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC)
!Gateway_0($Gateway_ID, $NetworkID, ~NetworkKey, ~D_GW_BC)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC)
Fr(~JoinKey)
Fr(~D_GW_UC)
Fr(~D_NM_UC)
#vr : init_Device[]
!Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC, ~D_NM_BC, ~D_GW_UC, ~D_NM_UC)
!Gateway_1($Gateway_ID, $NetworkID, ~NetworkKey, ~D_GW_BC, ~D_GW_UC)
!SecurityManager_2($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_NM_UC, ~D_GW_BC, ~D_GW_UC)
!Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC, ~D_NM_BC, ~D_GW_UC, ~D_NM_UC)
#vr.7 : compromise_device[Reveal($device_id), InsiderAttacker( )]
Out(<~JoinKey, ~NetworkKey, ~D_GW_BC, ~D_NM_BC, ~D_GW_UC, ~D_NM_UC>)
!Gateway_1($Gateway_ID, $NetworkID, ~NetworkKey, ~D_GW_BC, ~D_GW_UC)
!Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC, ~D_NM_BC, ~D_GW_UC, ~D_NM_UC)
Fr(~DL_nonce_s)
Fr(~NL_nonce_s)
Fr(~command)
#i : Gateway_send_command_UC[SendCommand_UC($Gateway_ID, $device_id, ~command)]
Out(<<~DL_nonce_s, $device_id, $Gateway_ID>, <~NL_nonce_s, 'Command_pkt', 'NL_Ctrl', 'Sec_Ctrl'>, aead_enc(~D_GW_UC, ~NL_nonce_s, <~NL_nonce_s, 'Command_pkt', 'NL_Ctrl', 'Sec_Ctrl'>, ~command), mac(<<~DL_nonce_s, $device_id, $Gateway_ID>, aead_enc(~D_GW_UC, ~NL_nonce_s, <~NL_nonce_s, 'Command_pkt', 'NL_Ctrl', 'Sec_Ctrl'>, ~command) >, ~NetworkKey) >)
#vk.1 : coerce[!KU(~D_GW_UC)]
!KU(~NL_nonce_s) @ #vk.2
#vr.6 : d_3_aead_dec
#vk : coerce[!KU(~command)]
#j : isend[K(~command)]

Join Sequence

- Authenticate a device to the network.
- Provision of keys.
- Provision of network specific information.



Join procedure

- We have modeled Join procedure, excluding steps for network configuration.
- Rules for sending and receiving “join requests”, and “write keys” messages.
- Join_key *can* be unique.

	Unique Join_Key
Provisioned Key Secrecy	Hold
Provisioned Key Authentication	Hold

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Lemmas

```
/* For all protocol executions, a key K received at #m
implies that it was sent at #l and that #l happened before #m
*/
lemma key_agreement:
        all-traces
        "All a k #m.
           KeysReceived(a, k) @ #m
          ==>
           (Ex #l. KeysSent(a, k) @ #l) |
           (Ex #j. InsiderAttacker() @ #j)
        "
```

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Lemmas

```
/* For all protocol executions, a key K received at #m
implies that it was sent at #l and that #l happened before #m
*/
lemma key_secrecy:
        all-traces
        "All a k #m #n.
           KeysReceived(a, k) @ #m &
           K(k) @ #n
          ==>
           (Ex #l. KeysSent(a, k) @ #l) &
           (Ex #m. InsiderAttacker() @ #m)
        "
```

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Previously Published Attacks

Attack	STRIDE	Attacker	Verified?
Jamming Attack	DoS	Outsider	-
Disconnect Sybil Attack	Impersonation	Outsider	Yes
Pre-Join Exhaustion	DoS	Outsider	Yes
Direct Command Injection	Impersonation	Insider	Yes
Bounced Command Injection	Impersonation	Insider	Yes
Con-the-fly Command Injection	Tampering	Insider	Yes

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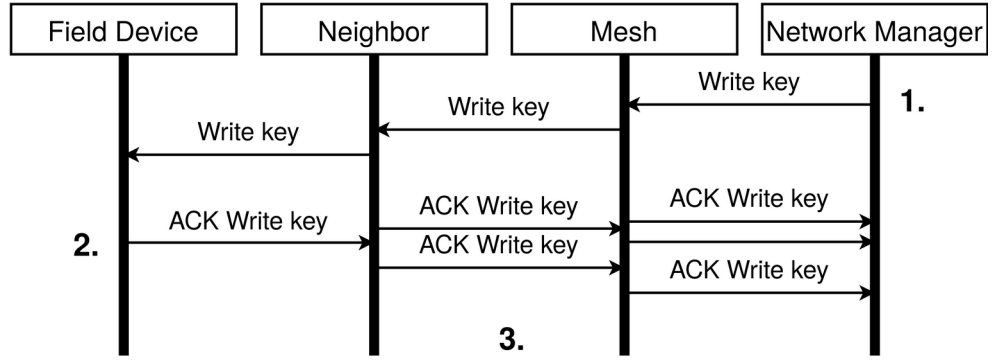
Network Key Change Operation

- New keys are sent to a *Field Device* over a unicast or broadcast session.
- The receiving device(es) will switch to the new key.



Modeling Network key change

- We have modeled Network key change over unicast and broadcast sessions.
- Rules for sending and receiving messages.
- We found a novel attack!

	Unicast	Broadcast
New Key Secrecy	Hold	Does not hold
New Key Authentication	Hold	Does not Hold

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Lemmas

```
/* A Device D will believe a message, sent over broadcast, to be
authentic, or any device's key has been revealed */
lemma key_authentication_BC:
"All SM D k #i. NewKeyReceived_BC(SM,D,k) @i
==> (Ex #j. SendKey_BC(SM,D,k) @j & j<i) | (Ex #k. InsiderAttacker() @ #k)
"

/* A key k sent to device D, over broadcast, that is known by ADV implies
D has been compromised. */
lemma key_secrecy_BC:
      "All SM D k #i #j.
       SendKey_BC(SM, D, k) @ #i &
       K(k) @ #j
       ==>
         Ex #k. InsiderAttacker() @ #k
       "
```

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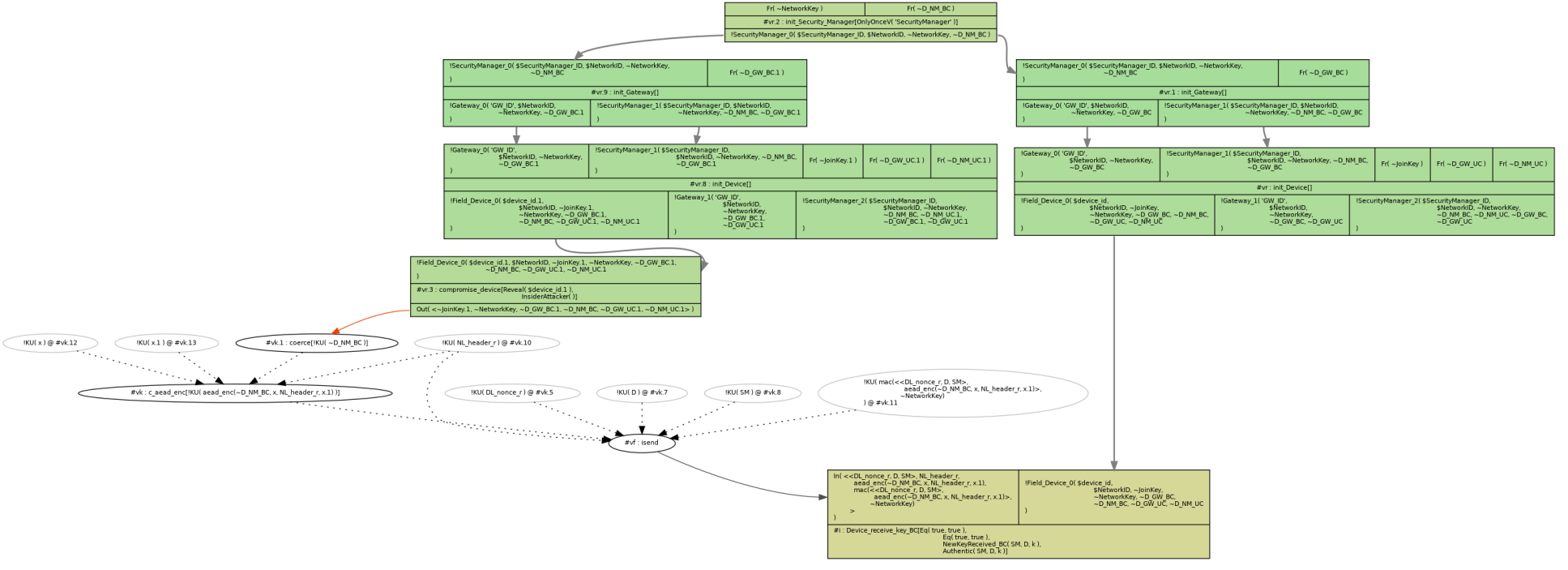
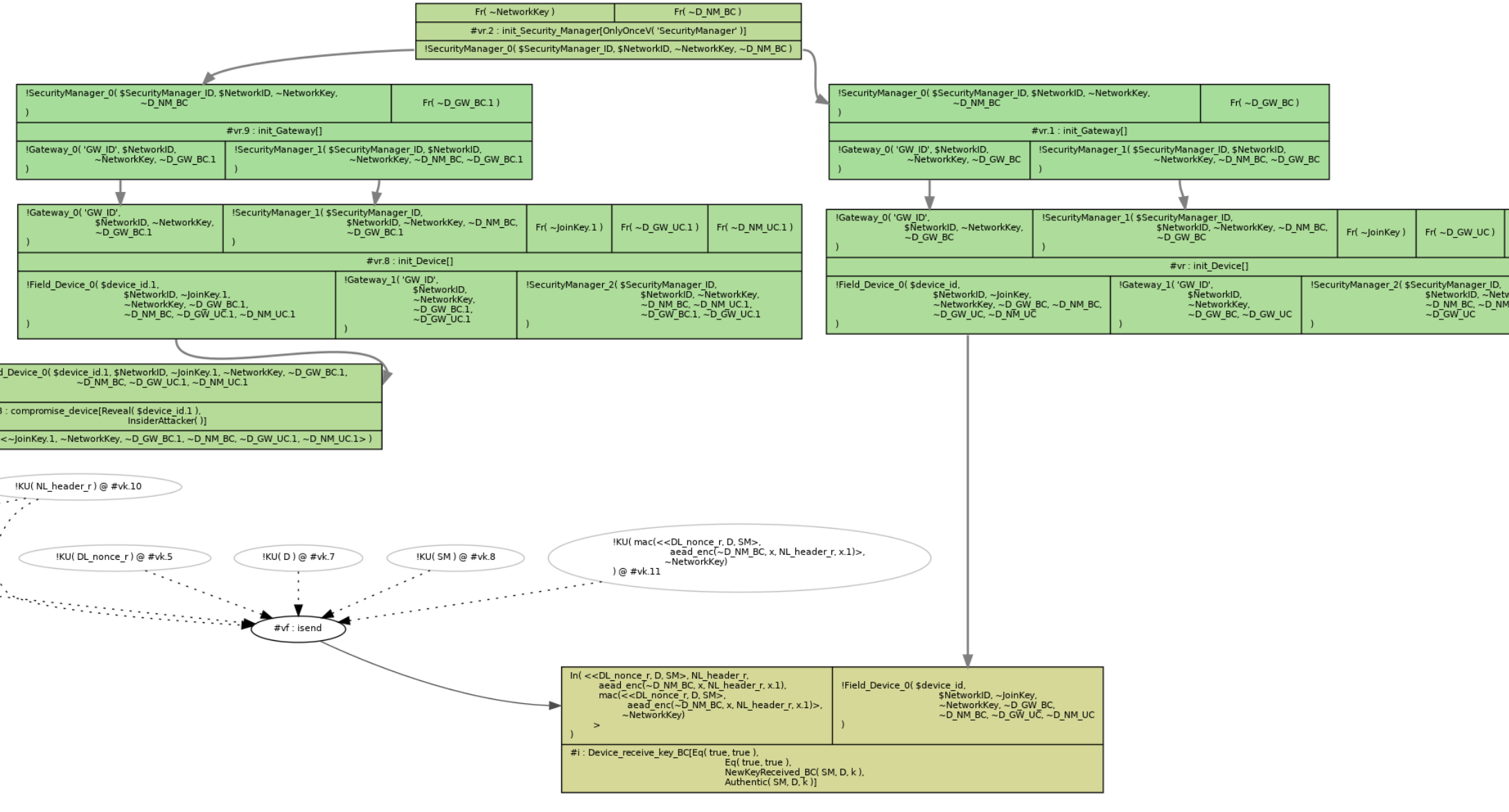
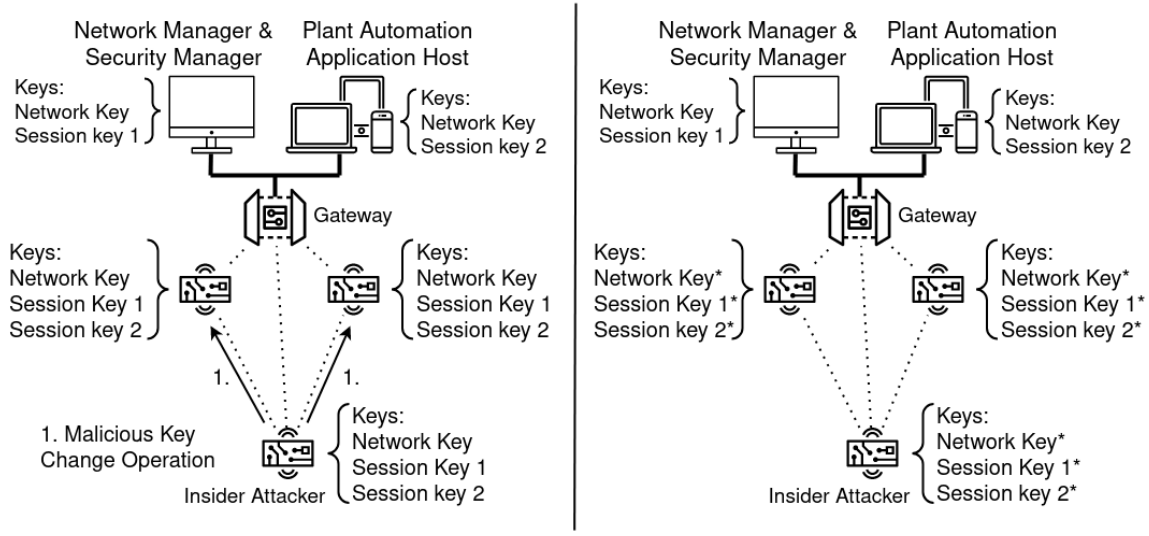
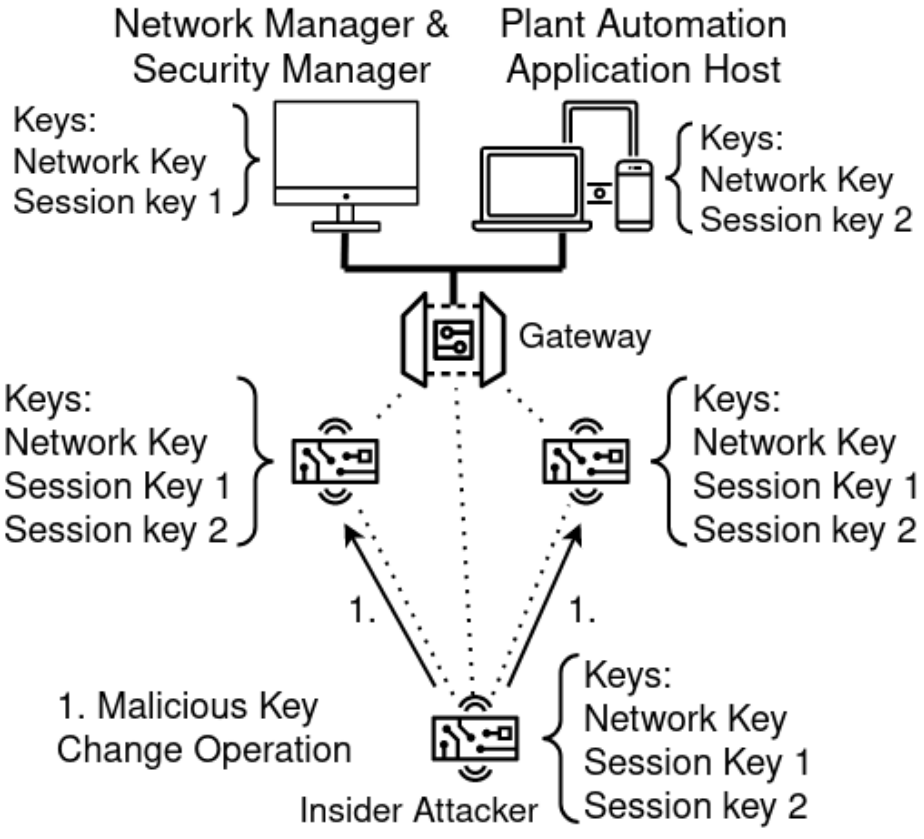

Fr(~NetworkKey)
Fr(~D_NM_BC)
#vr.2 : init_Security_Manager[OnlyOnceVl ‘SecurityManager’)]
!SecurityManager_0($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC)
!SecurityManager_0($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC)
Fr(~D_GW_BC.1)
#vr.9 : init_Gateway[]
!Gateway_0(‘GW_ID’, $NetworkID, ~NetworkKey, ~D_GW_BC.1)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC.1)
!SecurityManager_0($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC)
Fr(~D_GW_BC)
#vr.1 : init_Gateway[]
!Gateway_0(‘GW_ID’, $NetworkID, ~NetworkKey, ~D_GW_BC)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC)
!Gateway_0(‘GW_ID’, $NetworkID, ~NetworkKey, ~D_GW_BC.1)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC.1)
Fr(~JoinKey.1)
Fr(~D_GW_UC.1)
Fr(~D_NM_UC.1)
#vr.8 : init_Device[]
!Field_Device_0($device_id.1, $NetworkID, ~JoinKey.1, ~NetworkKey, ~D_GW_BC.1, ~D_NM_BC, ~D_GW_UC.1, ~D_NM_UC.1)
!Gateway_1(‘GW_ID’, $NetworkID, ~NetworkKey, ~D_GW_BC.1, ~D_GW_UC.1)
!SecurityManager_2($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_NM_UC.1, ~D_GW_BC.1, ~D_GW_UC.1)
!Gateway_0(‘GW_ID’, $NetworkID, ~NetworkKey, ~D_GW_BC)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC)
Fr(~JoinKey)
Fr(~D_GW_UC)
Fr(~D_NM_UC)
#vr : init_Device[]
!Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC, ~D_NM_BC, ~D_GW_UC, ~D_NM_UC)
!Gateway_1(‘GW_ID’, $NetworkID, ~NetworkKey, ~D_GW_BC, ~D_GW_UC)
!SecurityManager_2($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_NM_UC, ~D_GW_BC, ~D_GW_UC)
!Field_Device_0($device_id.1, $NetworkID, ~JoinKey.1, ~NetworkKey, ~D_GW_BC.1, ~D_NM_BC, ~D_GW_UC.1, ~D_NM_UC.1)
#vr.3 : compromise_device[Reveal($device_id.1), InsiderAttacker( )]
Out(<~JoinKey.1, ~NetworkKey, ~D_GW_BC.1, ~D_NM_BC, ~D_GW_UC.1, ~D_NM_UC.1>)
!KU(x) @ #vk.12
!KU(x.1) @ #vk.13
#vk.1 : coerce[!KU(~D_NM_BC)]
!KU(NL_header_r) @ #vk.10
#vk : c_aead_enc[!KU(aead_enc(~D_NM_BC, x, NL_header_r, x.1))]
!KU(DL_nonce_r) @ #vk.5
!KU(D) @ #vk.7
!KU(SM) @ #vk.8
!KU(mac(<<DL_nonce_r, D, SM>, aead_enc(~D_NM_BC, x, NL_header_r, x.1)>, ~NetworkKey)) @ #vk.11
#vf : isend
In(<<DL_nonce_r, D, SM>, NL_header_r, aead_enc(~D_NM_BC, x, NL_header_r, x.1), mac(<<DL_nonce_r, D, SM>, aead_enc(~D_NM_BC, x, NL_header_r, x.1)>, ~NetworkKey) >)
!Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC, ~D_NM_BC, ~D_GW_UC, ~D_NM_UC)
#i : Device_receive_key_BC[Eq(true, true), Eq(true, true), NewKeyReceived_BC(SM, D, k), Authentic(SM, D, k)]

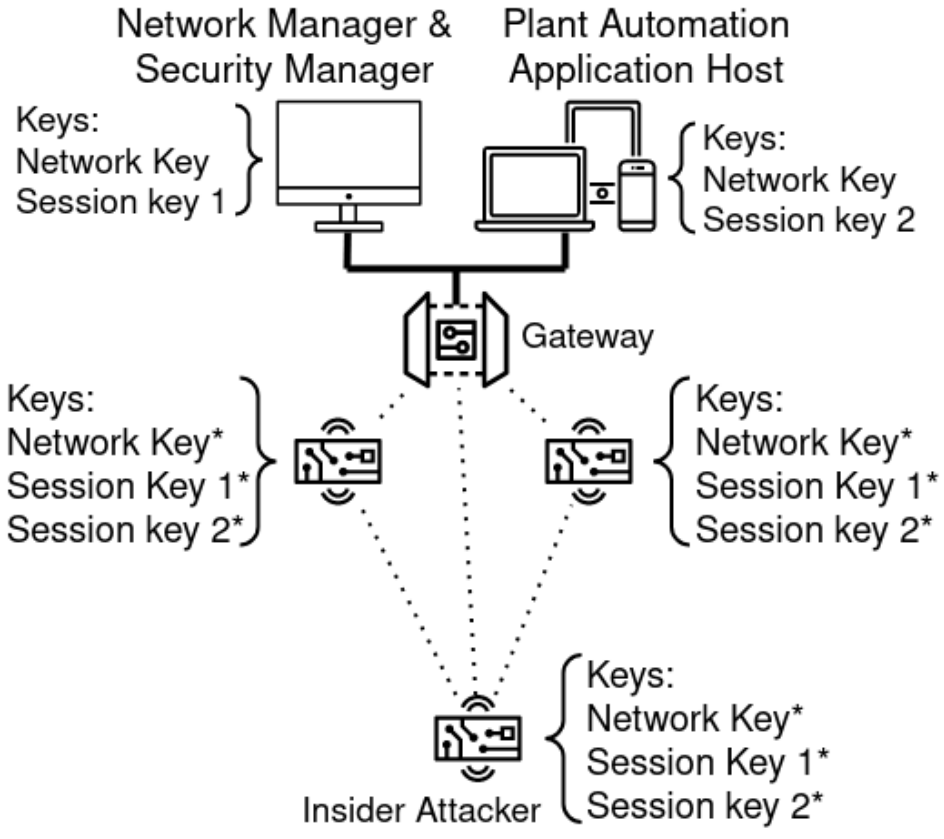

Fr(~NetworkKey)
Fr(~D_NM_BC)
#vr.2 : init_Security_Manager[OnlyOnceV('SecurityManager')]
!SecurityManager_0($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC)
!SecurityManager_0($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC)
Fr(~D_GW_BC.1)
#vr.9 : init_Gateway[]
!Gateway_0('GW_ID', $NetworkID, ~NetworkKey, ~D_GW_BC.1)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC.1)
!SecurityManager_0($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC)
Fr(~D_GW_BC)
#vr.1 : init_Gateway[]
!Gateway_0('GW_ID', $NetworkID, ~NetworkKey, ~D_GW_BC)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC)
!Gateway_0('GW_ID', $NetworkID, ~NetworkKey, ~D_GW_BC.1)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC.1)
Fr(~JoinKey.1)
Fr(~D_GW_UC.1)
Fr(~D_NM_UC.1)
#vr.8 : init_Device[]
!Field_Device_0($device_id.1, $NetworkID, ~JoinKey.1, ~NetworkKey, ~D_GW_BC.1, ~D_NM_BC, ~D_GW_UC.1, ~D_NM_UC.1)
!Gateway_1('GW_ID', $NetworkID, ~NetworkKey, ~D_GW_BC.1, ~D_GW_UC.1)
!SecurityManager_2($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_NM_UC.1, ~D_GW_BC.1, ~D_GW_UC.1)
!Gateway_0('GW_ID', $NetworkID, ~NetworkKey, ~D_GW_BC)
!SecurityManager_1($SecurityManager_ID, $NetworkID, ~NetworkKey, ~D_NM_BC, ~D_GW_BC)
Fr(~JoinKey)
Fr(~D_GW_UC)
#vr : init_Device[]
!Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC, ~D_NM_BC, ~D_GW_UC, ~D_NM_UC)
!Gateway_1('GW_ID', $NetworkID, ~NetworkKey, ~D_GW_BC, ~D_GW_UC)
!KU(NL_header_r) @ #vk.10
!KU(DL_nonce_r) @ #vk.5
!KU(D) @ #vk.7
!KU(SM) @ #vk.8
!KU(mac(<<DL_nonce_r, D, SM>, aead_enc(~D_NM_BC, x, NL_header_r, x.1)>, ~NetworkKey)) @ #vk.11
#vf : isend
In(<<DL_nonce_r, D, SM>, NL_header_r, aead_enc(~D_NM_BC, x, NL_header_r, x.1), mac(<<DL_nonce_r, D, SM>, aead_enc(~D_NM_BC, x, NL_header_r, x.1)>, ~NetworkKey) >)
!Field_Device_0($device_id, $NetworkID, ~JoinKey, ~NetworkKey, ~D_GW_BC, ~D_NM_BC, ~D_GW_UC, ~D_NM_UC)
#i : Device_receive_key_BC[Eq(true, true), Eq(true, true), NewKeyReceived_BC(SM, D, k), Authentic(SM, D, k)]

Malicious re-keying attack

- An *Insider Attacker* can spoof Network Key Change Messages.
- An attacker can then change the keys of uncompromised devices.
- Changing keys will isolate devices from the *Gateway* and *Security Manager*.




Network Manager &
Security Manager
Plant Automation
Application Host
Keys:
Network Key
Session key 1
Keys:
Network Key
Session key 2
Gateway
Keys:
Network Key
Session Key 1
Session key 2
Keys:
Network Key
Session Key 1
Session key 2
1.
1.
1. Malicious Key
Change Operation
Insider Attacker
Keys:
Network Key
Session Key 1
Session key 2


Network Manager &
Security Manager
Plant Automation
Application Host
Keys:
Network Key
Session key 1
Keys:
Network Key
Session key 2
Gateway
Keys:
Network Key*
Session Key 1*
Session key 2*
Keys:
Network Key*
Session Key 1*
Session key 2*
Insider Attacker
Keys:
Network Key*
Session Key 1*
Session key 2*

Re-keying attack impact

- The Network Manager and Plant Automation Host will not be able to contact victims.
- Changing the Network_Key cause devices with the new key to drop all legitimate messages.
- Compromise of one device can lead to DoS of the entire network.
- Devices have to be manually recovered.

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Conclusion

- WirelessHART security suffer from a inherent vulnerabilities.
- A more rigorous process when developing protocols is needed.
- Yet another attack against WirelessHART.
- Formal verification is a valuable tool when designing and evaluating protocols.
- A re-design of the protocol, with new considerations, is probably necessary.

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SE

THANK YOU!

Questions?

RI.SE

THANK YOU!

Questions?