Bridging Dolev-Yao Adversaries and Control Systems with Time-Sensitive Channels

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Formal verification tools (one side of our work)

Commonly employed for automatic protocol analysis

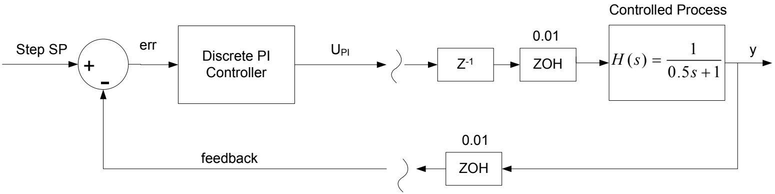
Outstanding results in showing protocol insecurity (for protocols assumed to be secure), e.g., Needham-Schroeder KE (Lowe'95)

Advantages compared to manual analysis:

- easy to use with limited security/cryptography expertise
- less prone to errors
- can deal with larger and complex systems

Control systems (the other side of our work)

Control systems regulate the behaviour of other systems (called plants) usually by means of a feed-back loop



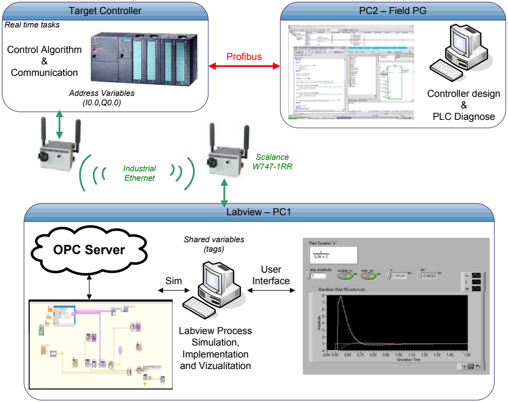
Discrete time systems, expressed as recurrent equations, are commonly used as abstractions for both controllers and plants

$$DTS(\mathbb{X}, \mathbb{U}, \mathbb{Y}, \mathcal{F}, \mathcal{G}) : \begin{cases} x(t+1) = \mathcal{F}(x(t), u(t)) \\ y(t) = \mathcal{G}(x(t), u(t)) \end{cases}$$

Relevance by practical scenario (previous work)

No doubts that control systems are increasingly exposed to cyber-attacks

One relevant target: WiFi (used in industrial networks if laying cables is difficult, e.g., moving objects: cranes, carousels)



SCALANCE (Siemens routers) Security Features

WPA2 WiFi Security and HTTPS Web Security (SSL/TLS)

Includes state-of-the-art cryptography: RSA, ECC, AES, etc.

Attack surfaces

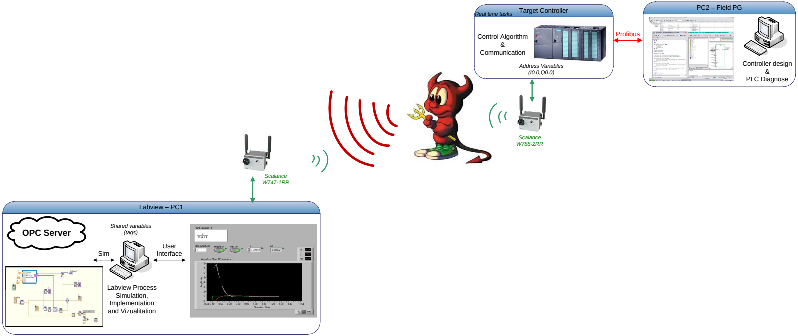
Two main targets:

- communication channel - allows manipulation of commands and responses from the control system and controlled process (WPA2)
- configuration interface - allows full control over the access points and clients (SSL/TLS)

State-of-the art, but is the system secure?

Attacking wireless communication

The easiest attack: cut down communication



Need a wireless signal jammer ?

No jammer needed - just use the 802.11 standard

Deauthentication packets force the STA to disassociate from AP

”Deauthentication shall not be refused by either party”
- IEEE 802.11 (2007)

A print-screen from the 802.11 standard

The complete set of IEEE 802.11 architectural services are as follows:

a) Authentication
b) Association
c) Deauthentication
d) Disassociation

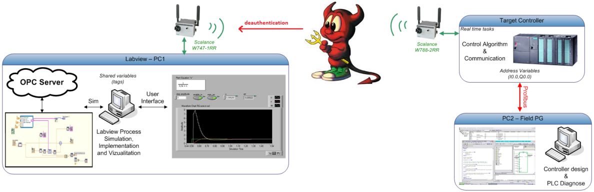
. . .

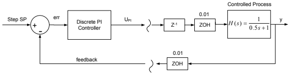
Clone AP MAC address then use *Aircrack-ng* to generate the deauthentication packets

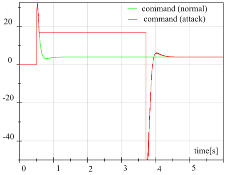
```
sudo aireplay-ng -0 0 -a 00:0E:8C:BF:25:78 -c 00:0E:8C:BC:2D:60 mon0
```

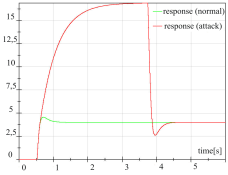
Effect

Last command preserved by the controller and process response increases rapidly (abnormal behavior)





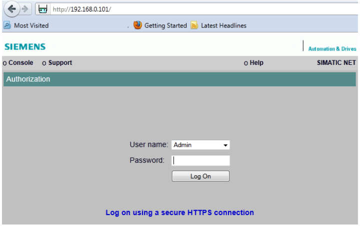




Important: the attack used mere standard specifications to manipulate time-sensitive goals (introduce delays) and subvert the output

Attacking the configuration interface

Protection by SSL/TLS - bullet proof?



Step 1: find how authentication works

No obfuscation of the JavaScript Code

$\Rightarrow$ authentication protocol obvious

Weak password-based protocol

1. $C \rightarrow AP$: *request*
2. $AP \rightarrow C$: N_{AP}
3. $C \rightarrow AP$: $C, MD5(C, pw_C, N_{AP}), N_{AP}$

No nonce from the client side – dictionary attacks

Fortunately runs under SSL/TLS if HTTPS is used

Remark 1: HTTP still works while HTTPS is locked

Inject a wrong SSL/TLS packet
$\Rightarrow$ HTTPS locks but HTTP still works

(same could be done by flooding with HTTPS requests)

Bug or feature?

Security implication: users can be tempted to log on HTTP

Step 2: determine user to login over HTTP
User enters password over HTTP $\Rightarrow$ intercept response

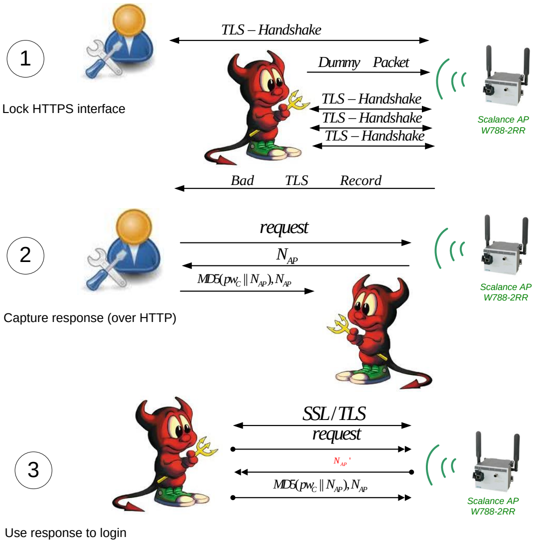
Remark 2: bug in the authentication protocol

Previous responses can be reused under HTTPS

Step 3: Send the response over HTTPS

1. $Adv(C) \rightarrow AP$: *request*
2. $AP \rightarrow Adv(C)$: N_{AP}
3. $Adv(C) \rightarrow AP$: $C, MD5(C, pw_C, N'_{AP}), N'_{AP}$

Attack summary



Problems and potential solutions

Attacks due to:

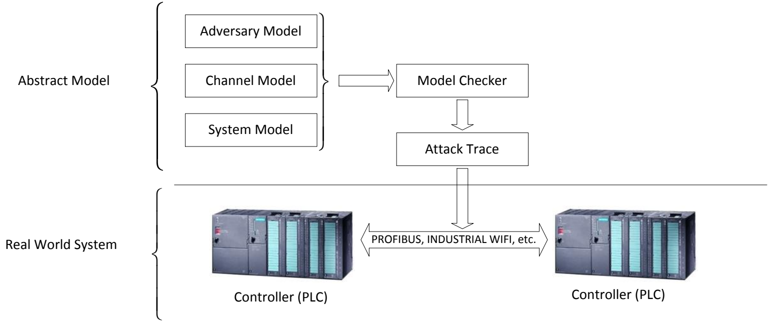
- obscure specifications in standards: de-authentication
- strange engineering decision: HTTP works when HTTPS locked
- erroneous implementation: reuses responses

The attacks can be circumvented if the system is formally analyzed before releasing it in the real world

Challenges and goals

Main challenge: bind formal verification tools (work with transition systems and symbolic terms) with control systems expressed as discrete time systems (defined by recurrent equations on real numbers)

Goals: find attack traces and (future work) test them on real-world industrial networks (e.g., penetration testing)



The ASLan language

Supported by the tools of AVANTSSAR and SPaCIoS projects

Used to define protocol actions via transitions

1. $A \rightarrow B : A$
2. $B \rightarrow A : N_B$
3. $A \rightarrow B : N_A, H(k_{AB}, N_A, N_B, A)$
4. $B \rightarrow A : H(k_{AB}, N_A)$

```
state_A(A,ID,1,B,Kab,H,
        Dummy_Na,Dummy_Nb)
.iknows(Nb)
=[exists Na]⇒
state_A(A,ID,2,B,Kab,H,Na,Nb)
.iknows(pair(Na,apply(H, pair(Kab,
        pair(Na, pair(Nb, A))))))
```

`iknows`: communication mediated by intruder

`exists`: generates fresh values

`state`: set of ground terms

`transition`: removes terms on LHS, adds terms on RHS (iknows is persistent)

Time-sensitive properties

Having principals A_{i_0} and A_{i_1} of a protocol specification, we can formally define:

- uniqueness, messages accepted only once, i.e.,

$$\mathrm{recv}_{i_b}(m, i_{\neg b}, t_1) \wedge \mathrm{recv}_{i_b}(m, i_{\neg b}, t_2) \Rightarrow t_1 = t_2, \forall b \in \{0, 1\}$$

- ordering, order of messages at sender is the same as at receiver, i.e.,

$$\mathrm{recv}_{i_b}(m_1, i_{\neg b}, t_1) \wedge \mathrm{recv}_{i_b}(m_2, i_{\neg b}, t_2) \wedge t_1 < t_2$$

$$\Rightarrow \mathrm{sndtime}_{i_{\neg b}}(m_1) < \mathrm{sndtime}_{i_{\neg b}}(m_2), \forall b \in \{0, 1\}$$

- δ-bounded lifespan, messages not accepted no later than some delay δ, i.e.,

$$\mathrm{recv}_{i_b}(m, i_{\neg b}, t) \Rightarrow t \leq \mathrm{sndtime}_{i_{\neg b}}(m) + \delta, \forall b \in \{0, 1\}$$

Next step?

We can reason about protocol properties and time-related goals but control-systems are still out of reach ... symbolic terms vs. real valued functions

Δ-grain abstractions

Used to make the state-space model approachable with our symbolic verification tools

Definition

$DTS^\natural(\mathbb{X}^\natural, \mathbb{U}^\natural, \mathbb{Y}^\natural, \mathcal{F}^\natural, \mathcal{G}^\natural)$ is a Δ-grain abstraction of $DTS(\mathbb{X}, \mathbb{U}, \mathbb{Y}, \mathcal{F}, \mathcal{G})$ under relations $\mathcal{R}_x$, $\mathcal{R}_u$, $\mathcal{R}_y$ if

(i) $\forall x \in \mathbb{X}, y \in \mathbb{Y}, u \in \mathbb{U}$ there exist $x^\natural \in \mathbb{X}^\natural, y^\natural \in \mathbb{Y}^\natural, u^\natural \in \mathbb{U}^\natural$ with $(x, x^\natural) \in \mathcal{R}_x$, $(y, y^\natural) \in \mathcal{R}_y$ and $(u, u^\natural) \in \mathcal{R}_u$,

(ii) $\forall x_0 \in \mathbb{X}, u_0 \in \mathbb{U}$, $x_0^\natural \in \mathbb{X}^\natural$, $u_0^\natural \in \mathbb{U}^\natural$ with $(x_0, x_0^\natural) \in \mathcal{R}_x$, $(u_0, u_0^\natural) \in \mathcal{R}_u$ there exists $0 < k \leq \Delta$ such that $(x(k), x^\natural(1)) \in \mathcal{R}_x$ and $(y(k), y^\natural(1)) \in \mathcal{R}_y$ if the input is constant for k steps, i.e., $u(i) = u_0, i \in [0, k-1]$, and

(iii) for any $k' < k$, $(x(k'), x^\natural(0)) \in \mathcal{R}_x$ and $(y(k'), y^\natural(0)) \in \mathcal{R}_y$ (all intermediary states and outputs have the same abstraction).

Completeness results

Two relevant proofs for the the correctness of the approach:

- Proposition 2, realizability of the abstract trajectory, shows that for any trajectory of the abstract system there exists a trajectory of the real system
- Proposition 3, couplability of abstractions, shows that for any two coupleable abstractions (controller-plant ensembles) there exists a trajectory of the coupled real system

Adversary goals

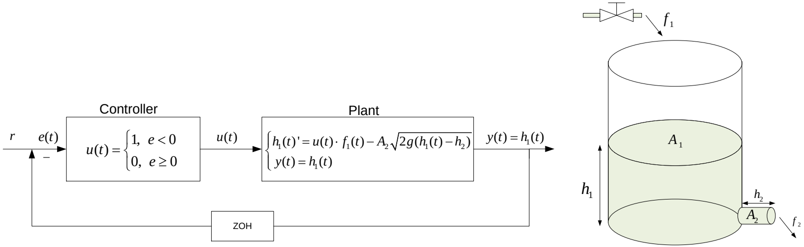
Definition (λ-step subversion)

Let the execution $\rho^\natural = (\sigma^0, \mathrm{X}^0, \mathrm{U}^0) \xrightarrow{r^1, s^1} (\sigma^1, \mathrm{X}^1, \mathrm{U}^1) \ldots \xrightarrow{r^t, s^t} (\sigma^t, \mathrm{X}^t, \mathrm{U}^t)$ $\rho^\natural = \sigma^0 \xrightarrow{r^1, s^1} \sigma^1 \ldots \xrightarrow{r^t, s^t} \sigma^t$ and let $\mathcal{G}_{adv} = \{\mathrm{X}^0_{adv}, \mathrm{X}^1_{adv}, ..., \mathrm{X}^\lambda_{adv}\}$ (defined over λ transitions). The adversary can perform a λ-step subversion w.r.t. $\mathcal{G}_{adv}$ over the control system if the states in the goal of the adversary hold during all of the last λ steps of the execution, i.e., $\forall i \in [0, \lambda) : X^{t-i} = X^{\lambda - i}_{adv}$.

Note: adversary actions are standard Dolev-Yao capabilities, i.e., he can intercept, modify and send messages at will, he can perform crypto-operation only if he has the corresponding keys (cryptography is perfect)

Example: a flow-control system

Scenario: simple *on/off* controller that regulates the water level inside the tank



Adversary's goal: subvert the water-level at will by using Dolev-Yao abilities (includes tampering with time-sensitive goals freshness, ordering and lifespan)

Δ-grain abstraction of the flow-control system

Associate states to symbolic operators that change at steps where controller and intruder behaviour requires changes

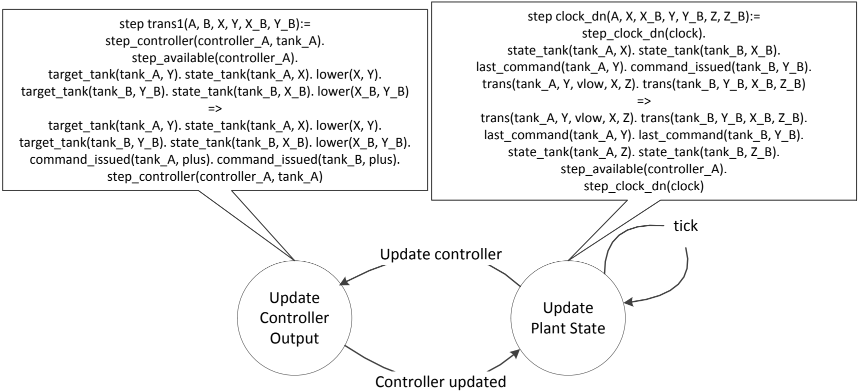
Abstraction sets	Relations between abstract and real values
$\mathbb{U}^\natural = \{off, on\}$	$\forall x \in [0,5) : (x, vlow^-) \in \mathcal{R}_x, \forall x \in [5,10) : (x, vlow^+) \in \mathcal{R}_x$
$\mathbb{X}^\natural = \mathbb{Y}^\natural = \{vlow^-,$	$\forall x \in [10,15) : (x, low^-) \in \mathcal{R}_x, \forall x \in [15,20) : (x, low^+) \in \mathcal{R}_x$
$vlow^+, low^-, low^+,$	$\forall x \in [20,25) : (x, med^-) \in \mathcal{R}_x, \forall x \in [25,30) : (x, med^+) \in \mathcal{R}_x$
$med^-, med^+, high^-,$	$\forall x \in [30,35) : (x, high^-) \in \mathcal{R}_x, \forall x \in [35,40) : (x, high^+) \in \mathcal{R}_x$
$high^+, vhigh^-, vhigh^+\}$	$\forall x \in [40,45) : (x, vhigh^+) \in \mathcal{R}_x, \forall x \in [45,50) : (x, vhigh^+) \in \mathcal{R}_x$
	$(0, off) \in \mathcal{R}_u, (1, on) \in \mathcal{R}_u$

Table : Abstraction sets and relations with the real system

Define state evolution based on precedence operators, e.g.,
$\mathcal{G}_{\mathcal{P}}^\natural(off, y^\natural(n-1)) = prec(y^\natural(n-1))$ and
$\mathcal{G}_{\mathcal{P}}^\natural(on, y^\natural(n-1)) = succ(y^\natural(n-1))$

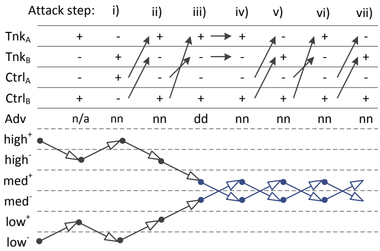
Defining the system

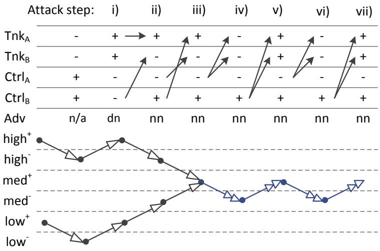
Now the control system can be described in the formal language (ASLan) via state-transitions



Attack traces reported by the CL-Atse model-checker

Adversary’s abilities are successfully used subvert the water-level at will: *delays* (step i), *redirection* (step ii), *replay* (steps iii) to vii)





Conclusions

Assuring time-related security goals (freshness, timeliness, life-span) in the presence of Dolev-Yao adversaries is critical for control systems

Δ-grain abstractions provide a workable model to tackle control systems properties in the framework of protocol analysis (via formal verification tools)

Experimental results: practical scenarios are within reach

Future work: more complex practical scenarios/protocols

SPaCIoS Secure Provision and Consumption in the Internet of Services, Project no. 257876, FP7-ICT-2009-5, 1.4: Trustworthy ICT 01.10.2010 - 31.01.2013