Security in Embedded Systems

The Wireless Sensor Network case

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Agenda

1. Introduction
2. Security
3. Embedded Systems Security
4. Security in WSN
   - Cryptography
5. Our Works
   - TAKS
   - Intrusion Detection
6. Securing IEEE 802.15.4e

Agenda

Who am i

- **Walter Tiberti**
- MoS in Computer and System Engineering
- PhD student @ University of L'Aquila (supervisor: L. Pomante)
- Github/Gitlab: `wtiberti`
  - Embedded Systems
  - Low-level software (e.g. firmware, drivers, OSes etc.)
  - Reverse-Engineering, Malware Analysis, Penetration Testing
  - Cryptography, Intrusion Detection and Countermeasures
  - Digital Electronics Design and Implementation

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L'Aquila (Italy)

Spanish Fort, Fontana Luminosa

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Basilica di Collemaggio, P. del Duomo

L'Aquila: University

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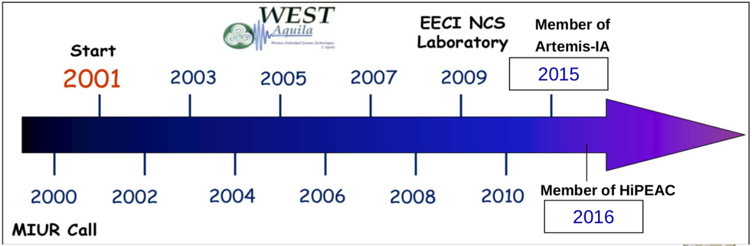
L'Aquila: view from Monteluco di Roio

DEWS

- **Center of Excellence DEWS**
  - **D**esign methodologies for
    Embedded controllers
    Wireless interconnect and
    System-on-chip

CENTER OF EXCELLENCE

http://dews.univaq.it



Embedded Systems Workgroup: Core members

- Coordinator: **Luigi Pomante**
- Senior Researchers:
  - **Tania Di Mascio** (Human-Machine interf., coordination)
  - **Marco Santic** (WSN, Localization)
- PhD Researchers:
  - **Giacomo Valente** (Digital Design, Monitoability)
  - **Paolo di Gianmatteo** (Machine Learning)
- PhD Students:
  - **Vittoriano Muttillo** (HW/SW Co-design)
  - **Walter Tiberti**
  - **Gabriella D'Andrea** (Reconf. Platforms)
  - **Federica Caruso** (Human-Machine interfac.)

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Un-security

- No system is **secure**

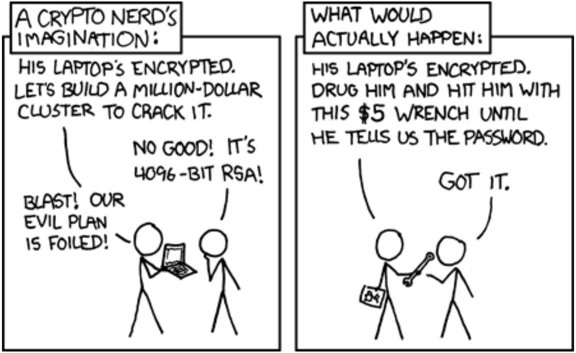

Figure: xkcd.com

Un-security

- No system is **secure**

Un-security: assumptions to make

- Basic assumption: no system is **secure**
- Basic assumption: attackers have **infinite** resources (e.g. money, time, tries etc.)

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Un-security: assumptions to make

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- Basic assumption: attackers have **infinite** resources (e.g. money, time, tries etc.)
- Basic assumption: compilers can fail, hardware can fail (e.g. SPECTRE, MELTDOWN, ROWHAMMER)
- Basic assemption: **People** can fail too!
- While we are talking, *vulnerabilities* are exploited, found, reported etc.

Date	D	A	V	Title	Type	Platform	Author
2019-04-17	⬇		✓	Oracle Java Runtime Environment - Heap Corruption During TTF font Rendering in GlyphIterator::setCurrGlyphID	DoS	Multiple	Google Security Research
2019-04-17	⬇		✓	Oracle Java Runtime Environment - Heap Corruption During TTF font Rendering in sc_FindExtrema4	DoS	Multiple	Google Security Research
2019-04-17	⬇	▣	✗	DHCP Server 2.5.2 - Denial of Service (PoC)	DoS	Windows	Victor Mondragón
2019-04-17	⬇		✗	ASUS HG100 - Denial of Service	DoS	Hardware	YinT Wang
2019-04-17	⬇	▣	✗	MailCarrier 2.51 - POP3 'RETR' SEH Buffer Overflow	Remote	Windows	Dino Covotsos
2019-04-16	⬇		✓	Microsoft Windows 10 1809 - LUAFV PostLuafvPostReadWrite SECTION_OBJECT_POINTERS Race Condition Privilege Escalation	Local	Windows	Google Security Research

Example: ExploitDB website

`https://www.exploit-db.com/`

Cryptography?

- Cryptography **not necessarily** means Security
  - A system using cryptography can be still vulnerable to other (often subtle) attack vectors
  - Once the keys are known, cryptography is useful no more
  - While cryptographic schemes, on paper, are super-secure, **very** often their implementation isn't so.
    - Examples: PODDLE, CRIME, Heartbleed
    - `https://www.acunetix.com/blog/articles/tls-vulnerabilities-attacks-final-part/`
  - Nonces generated by weak PRNG can be learned and replicated
  - Each cryptographic scheme has its issues (e.g. small exponents, backdoor curves)
- **Rule Thumb:** *"Don't roll your own cryptography"*

How to approach security?

- *The attack is the best defence & The defence is the best attack*
- Assess your system by *attacking it* (**Penetration Testing**)

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Learning Platforms

- OverTheWire: `http://overthewire.org/wargames/`
- HackTheBox: `https://www.hackthebox.eu/`
- ExploitEducation: `https://exploit.education/`

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Security in Embedded Systems

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  - Simpler protocols

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  - Simpler HW designs
  - Lighter SW: simpler or no OS, applications deal directly with the HW (and malicious code can access HW easilly)

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  - Simpler protocols
  - Simpler HW designs
  - Lighter SW: simpler or no OS, applications deal directly with the HW (and malicious code can access HW easilly)
  - Light or no **memory management** (e.g. no virtual memory, no access controls etc.): memory access is often unrestricted

Embedded Systems: Security failures (1)

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- Philips Hue lightbulbs
- `https://youtu.be/Ed1OjAuRARU`

Embedded System Security: Future

- **More powerful**?

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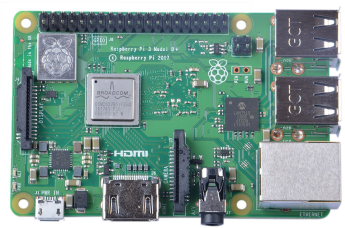
Example: Raspberry PI



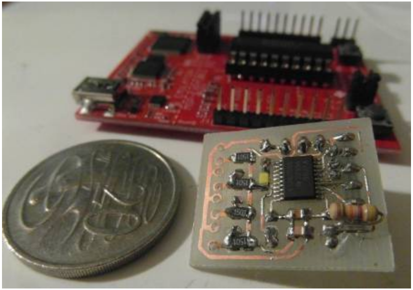
- Quad-core ARM CPU, GBs of RAM
- BT, 802.11, HDMI, Ethernet
- Can run normal OS

Embedded System Security: Future

- **More powerful**? Embedded Systems will start performing like modern bigger platforms, with all the common security issues
- **Smaller**?

Embedded System Security: Future

- **More powerful**? Embedded Systems will start performing like modern bigger platforms, with all the common security issues
- **Smaller**? Less memory, less performance, smaller CPU/MCU, harder to implement security-related functionalities

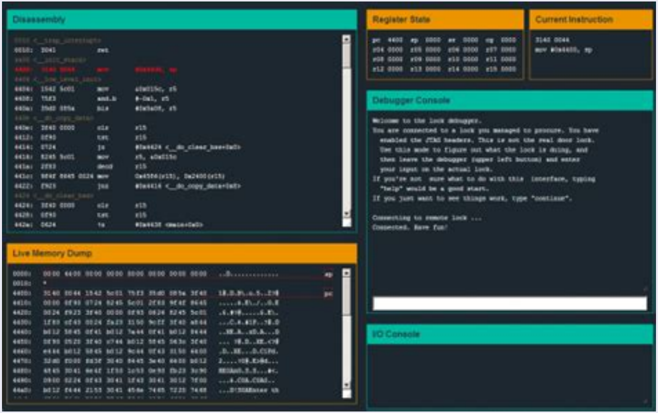


- MSP430-based board (16 bit)
- 10 KB or RAM, 48 KB of Flash storage

Learning Platforms

MSP430 security

Microcorruption: `https://microcorruption.com`



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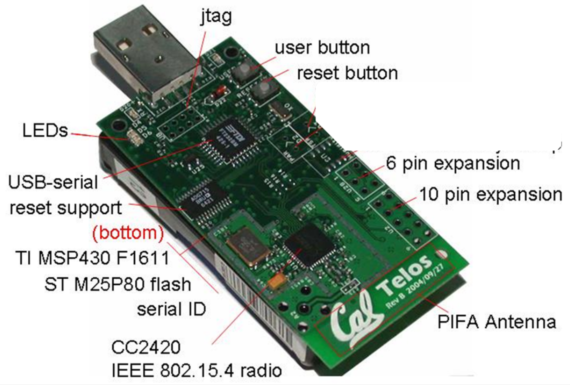
Wireless Sensor Networks

- Wireless Sensor Network (WSN)
- Quick recap
  1. **Small**, **energy-constrained** (battery-powered) nodes (called *motes*)
  2. Motes are equipped with a **radio transceiver** for wireless interconnection
  3. A set of **sensors** are embedded in the mote (directly or by means of *sensorboards*
  4. Small storage, small performance, small costs
  5. Flexible platforms: motes can be densely distributed and/or organized to cover big areas

IEEE 802.15.4

- Nowadays, the term WSN is becoming more *vague*
- In this presentation, we will discuss about **IEEE 802.15.4**-based WSN



Security Overview

In general, in WSNs:

- Mote hardware side: often no security (i.e. attackers can **access the IO pins** with no effort.
- Some mote MCU have **hardware primitives** for symmetric/public-key cryptography (e.g. the TI CC3825)
- The radio channels used are (mostly) in the**unlicensed ISM 2.4GHz bands** (i.e. everybody can listen and transmit over the channel)
- The SoA OS for WSN (TinyOS, ContikiOS, RIOT) have only few security features. External software can provide other features with limitations (e.g. TinyECC)
- iIt is easy to perform different **jamming attacks** (from constant jamming to dynamic self-adapting jamming)
- Some of the 2.4GHz channels of IEEE 802.15.4 **collides**

WSN: Using Symmetric Ciphers?

- Using *Symmetric Cryptography schemes* (e.g. block ciphers such as AES or stream ciphers e.g. Salsa/Chacha20) are generally fast and lightweight, but they requires the secret key to be **available** (e.g. preprogrammed) before any transmission
- $\rightarrow$ *Key Distribution Problem*

WSN: Using Public-Key Cryptography? (1)

- Using *Public-Key Cryptography schemes* solves the key distribution problem (e.g. Diffie-Helman) but is expensive in terms of performance and storage.

WSN: Using Public-Key Cryptography? (2)

Example: RSA

With a maximum of ~ 100 bytes available as MAC payload and using a SoA key size e.g. 2048 bit = 256 bytes, every transmission which requires a key exchange has to be *splitted*.

Example: ECC

Even though ECC keys require less space (e.g. 192bits) the computation involved (e.g. Point Addition/Multiplication) are possible but they can be very expensive.

From the IEEE 802.15.4 standard

- Section 9 "Security"
- AES 128bit CCM as (authenticated) symmetric encryption
- Not enough information to implement a complete solution:
  - 128bit AES is not super-secure
  - CCM mode (CTR+HMAC) have **problems** is the nonces are not carefully "choosen"
  - **No mechanism for key distribution or storage**

Key storage?

Consider the following C source code

```c
#include <stdint.h>
#define KEYLENGTH 128

uint8_t supersecretkey[KEYLENGTH/8] = {
  0x11, 0x22, 0x33, 0x44, 0x55, 0x66, 0x77, 0x88,
  0x11, 0x22, 0x33, 0x44, 0x55, 0x66, 0x77, 0x88
};

int main()
{
        // .. application code ...
        while(1);

        return 0;
}
```

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Compiling into IHEX format for mote programming:

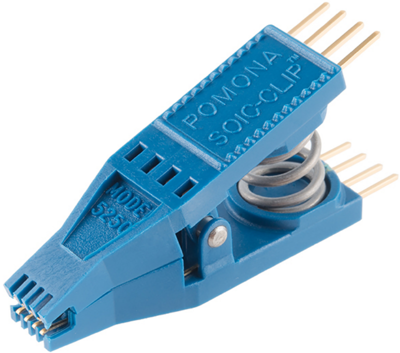
```
:10010000214601360121470136007EFE09D2190140
:100110002146017E17C20001FF5F16002148011928
:10012000194E79234623965778239EDA3F01B2CAA7
:100130003F0156702B5E712B722B732146013421C7
:00000001FF
```

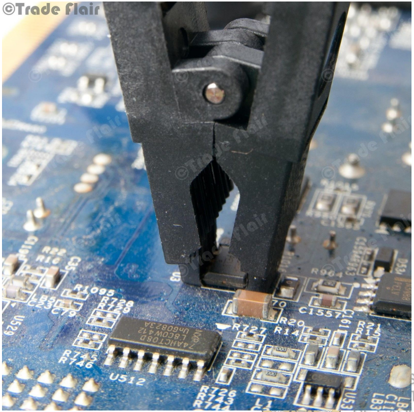
Start code | Byte count | Address | Record type | Data | Checksum

```
:10400000554220135D0085A8245101131400039FF
:104010003F4010000F93082492421011120012F837B
:104020009F4F50400011F8233F4000000F9307249A
:10403000924210112001 1F83CF431011F923044134
:104040002453FF3F32D0F000FD3F30404E4000137C
:1040500011223344556677881122334455667788 98
:10FFE0004A404A404A404A404A404A404A404A40C1
:10FFF0004A404A404A404A404A404A404A400040FB
:040000030000400 0B9
```

Key storage...failure

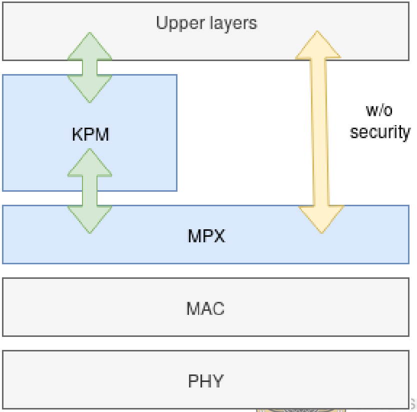
Dumping data from Flash/EEPROM chips:





IEEE 802.15.9 standard

- IEEE 802.15.9
- Recent standard, it addresses the *Key Transport* mechanisms
- Overview:
  - Additional layer on top of MAC (**MPX**)
  - Fragmentation and Multiplexing
  - Additional (vertical) layer for Key management (**KMP**)



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TAKS

- Ad-hoc cryptographic cryptography techniques
- *Topology Authenticated-key Scheme* (**TAKS**)
- **Hybrid Cryptogrphy**: TAKS use both public-key and symmetric cryptography features
- **Lightweight**: designed to run on top of WSN platforms

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TAKS

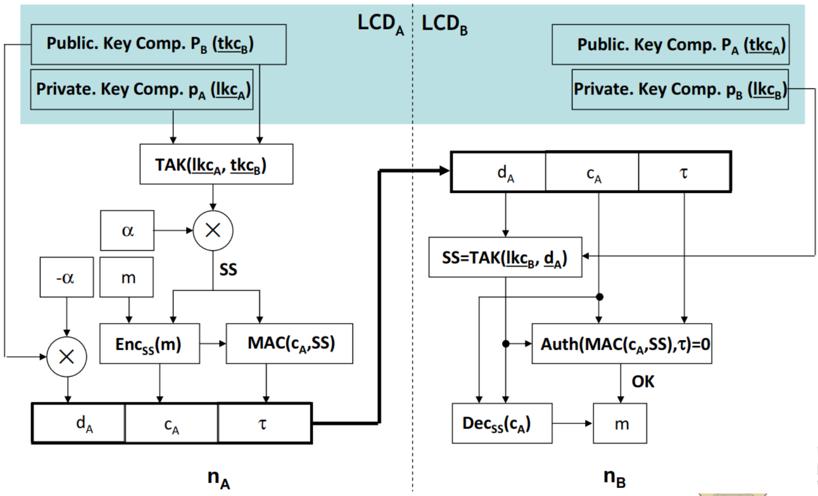
Features:

- **Objective**: creating a *shared secret* with public-key like mechanisms to be used as symmetric key for encrypting/decrypting and to generate a *signature* for authentication.
- **How?** Vector algebra over finite fields (usually $GF(2^n)$)
- Two mode of operation: **Point-to-Point** (star topologies) and **Cluster-wise** (for cluster-wise topologies)

TAKS: idea

- A WSN topology is planned (Planned Network Topology - **PNT**)
- A set of *Key components* is generated offline for each node in the PNT (Local Configuration Data - **LCD**)
    - a node-local, private component (Local Key Component, **LKC**) is pre-programmed in the mote
    - a set of public components (Transmit Key Component - **TKC**)
    - a set of restricted components (Topology Vector - **TV**) known only to the motes enabled to communicate with target node

TAKS: block diagram



TAKS: block diagram

- The **TAK()** function combines the nonce and two components into the *shared secret SS*
- Multiple definitions of **TAK()** are possible. An example is[1]:

$$TAK_{i \to j} = \alpha * LKC \times TV_{i \to j} = KRI \times TKC_{i \to j}$$

$$= \alpha * \left\| \begin{matrix} \hat{i} & \hat{j} & \hat{k} \\ lkc_1 & lkc_2 & lkc_3 \\ tv_1 & tv_2 & tv_3 \end{matrix} \right\| = \left\| \begin{matrix} \hat{i} & \hat{j} & \hat{k} \\ kri_1 & kri_2 & kri_3 \\ tkc_1 & tkc_2 & tkc_3 \end{matrix} \right\|$$

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[1] In this case, LKC, TV and TKC are 3-dimensional vectors over $GF(2^n)$

TAKS: Sending..

- Alice wants to transmit to Bob a message
- Alice has LKC_a and Bob's TKC_b. She uses the $TAK()$ function to combine the two key components
- Alice generate a **nonce** (α) and multiplies it with the result of the component combination to obtain a **shared secret** SS
- She uses SS **as symmetric key** to encrypt the data and to **generate a message authentication code** from the cipher text
- Alice creates also the **key reconstruction information** d_a
- Finally, Alice sends $ciphertext|d_a|MAC$ to Bob

TAKS: ..Receiving

- Bob receives $ciphertext|d_a|MAC$ from Alice
- Due the construction of $TAK()$, $TAK = LKC_a \cdot TKC_b = -LKC_b \cdot TKC_a$, Bob uses $d_a \cdot LKC_b = (-\alpha \cdot TKC_a) \cdot LKC_b = SS$ to derive the SS
- Bob checks the MAC and, if valid, decrypts the message with SS

Practical Example

Demo

ECTAKS: Prologue

- Elliptic Curve Cryptography (**ECC**)
- Old concept, but recently re-discovered
- Public-Key scheme (ECIES, ECDSA, ECDH, ECQV)
- Curve, Point, PointAdd, PointMul, ECDLP
- PubKey = Point, PrivKey = Scalar
- Standard Curves

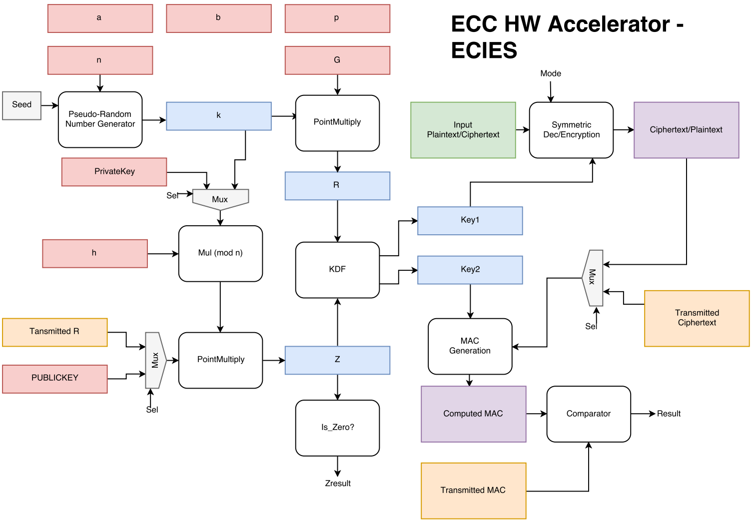
ECTAKS

- **Work-in-Progress**
- Elliptic Curve-based TAKS (**ECTAKS-ECIES**, **ECTAKS-ECDSA**)
- Idea: add TAKS mechanism to EC Points: **TAKS Key Components = Points**
- TAK function combines points into a **private** (scalar) key, which can be used to generate the ECC Public Key
- Target platforms: *TinyOS, Contiki-OS, RIOT-OS*

ECHARP-WSN

- **Work-in-Progress**
- **ECC HW Accelerator** on Reconfigurable Platform for WSN motes
- Idea: *Faster processing* $\rightarrow$ *Less Time* $\rightarrow$ *Less Energy*
- We are developing a ECC HW Accelerator to be embedded and controlled by WSN motes and activated **on-demand** (default: *power off*)
- Full **RTL** design to improve area occupation, performances and energy impact
- **Flexible**: no assumption is taken, e.g. any curve can be used and changed at runtime
- **Very good** initial results (PointAdd, PointDouble, PointMul)

Example: block diagram for ECIES



WSN: Detect anomalies and attacks

- **Intrusion Detection Systems for WSN**
- *Scenario*: an *attacker* targets the WSN and tries to change the behavior of motes remotely in order to manipulate the data exchanged or to leak information (e.g. cryptographic keys)

WIDS

- *WSN Intrusion Detection System* (**WIDS**)
- Design of a WSN IDS based on *Weak Process Models*(**WPM**
- Attacks are modeled into WPM represented as a graph in which the nodes are the **states** in which the mote could be at any time and the edges are the possible **transitions** from and to states
- WIDS tries to perform a state **estimation** based on events (**observables**)

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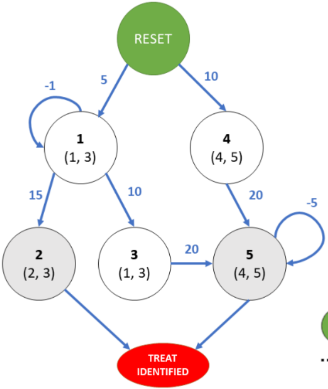
WIDS example

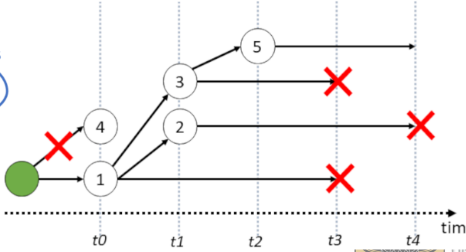


Observables:

t0 -> 1
t1 -> 3
t2 -> 4
t3 -> 2
t4 -> 5

State traces: (only last state is shown)

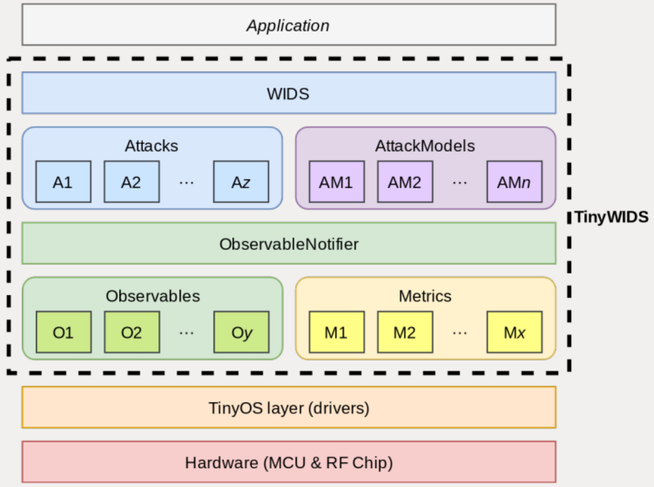
t0 -> {1}
t1 -> {1,2,3}
t2 -> {1,2,3,5,4}
t3 -> {2,5,4}
t4 -> {5}



WIDS implementation: *TinyWIDS*

- Implementation of WIDS on top of TinyOS
- Acquisition of data from the hardware and lower software-layer of the motes in the form of **Metrics**
- Metrics are checked against thresholds. If the checks fails, **observables** are created
- Observables are collected at runtime and the WPM attack models are updated
- If any attack model has an estimated state considered dangerous, a notification is sent

TinyWIDS architecture



WIDS: Countermeasures to attacks

- **Work-in-Progress**
- Question: *When an attack is detected, what can we do?*
- We are studing different techniques to both **contain the attacks** and **retrieving information** of it upon detection

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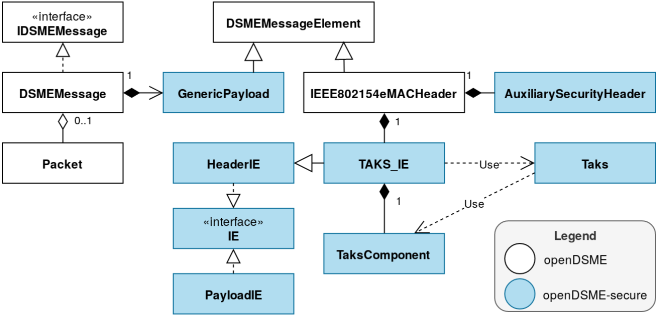
TAKS in IEEE 802.15.4e

- Done here at CISTER!
- TAKS has been adapted and implemented in the Omnet++ based DSME MAC Behavior of the IEEE 802.15.4e (**OpenDSME**)
- OpenDSME has been enhanced by adding support to:
  - IEEE 802.15.4-2015 MAC layer Information Elements (**IE**)
  - Specific TAKS IE (Header IE)
  - Generic packet content (GenericPayload)
- The code is on Github: `https://github.com/wtiberti/openDSME/tree/Security`

TAKS in IEEE 802.15.4e

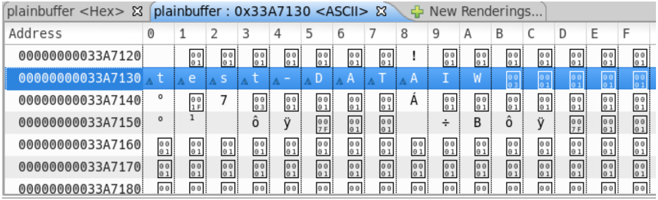


TAKS in IEEE 802.15.4e

Before:

[4] (BytesChunk) : BytesChunk, length = 10 B, bytes = {9, 54, 69, 143, 142, 209, 145, 7, 15, 150}
- mutable = false (bool)
- complete = true (bool)
- correct = true (bool)
- properlyRepresented = true (bool)
- chunkLength = 80 (inet::b)
- bits[3] (string)
- bytes[1] (string)
  - [0] 09 36 45 8F 8E D1 91 07 0F 96

After:



References

TAKS / WIDS / TinyWIDS:

- https://ieeexplore.ieee.org/document/5345623
- https://ieeexplore.ieee.org/document/6583643
- https://ieeexplore.ieee.org/document/6775056
- https://ieeexplore.ieee.org/document/5703728
- https://ieeexplore.ieee.org/document/4660137
- https://dl.acm.org/citation.cfm?doid=3178291.3178293

Thank you!