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Major Infotronics

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OT Security

PEN-testing and security about embedded devices

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Titre / Titel	OT Security labs development
<i>Description</i>	
The goal of this Bachelor thesis is to prepare several security related experiments in an Operational Technology (OT) environment. The environment is simulated, either using a platform named "Winter Resort Simulator Pro" or using Minecraft. In the latter case, the simulated environment still must be defined and developed. The scenarios that will be developed include wired communication by MODBUS, wireless communication using a 862 MHz radio, process control using sensors and PLC's.	
<i>Tasks</i>	
<ul style="list-style-type: none"> • Create an environment and select tools permitting to intercept, modify and reinject MODBUS packets, assuming the intruder has access to the communication infrastructure. Propose solutions to monitor the communication infrastructure and therefor detect and prevent such activity. • Create an environment and select tools permitting to scan a wireless network. Intercept packets and reinject them into the network. Propose solution to harden wireless protocols against such actions. • Create an environment and select tools to intercept sensor data to compromise the function of the controller due to invalid data. Propose approaches permitting hardening the controller software against such action. • Prepare a setup and tools permitting to break into a PLC. Propose solutions hardening PLCs against such action. 	
<i>Deliverables</i>	
<ul style="list-style-type: none"> • A report • A working demonstrator • All source code and tools • A presentation 	

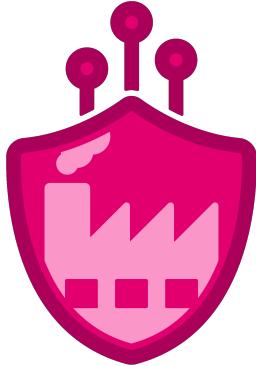
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OT Security



Graduate

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Bachelor's Thesis | 2024 |



Degree programme
Systems Engineering

Field of application
Infotronics

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Objective

Produce attack scenarios that include an unsecure situation, an attack, and a solution to secure against such attack. These scenarios must be usable as the basis for a laboratory experience for students or industrial partner formation.

Methods | Experiences | Results

This thesis is separated into 2 scenarios. The first one, the Man in the Middle attack, consists of intercepting the communication between two devices and modifying the packets. The second scenario is a replay attack on a wireless transmission medium performed with a flipper zero.

The first scenario (Man in the Middle) is implemented on a modbus/TCP communication between a controller and a house security system. An attacker (a Kali Linux laptop) redirects communication to him to modify the sensor value sent to the controller. He can also send fake data. This Thesis also shows what happens if you secure your communication with certificates (modbus/TLS) but do not check the certificates. The attacker can intercept the communication in the same way. This thesis shows that it is important to always check certificates to guarantee the interlocutor.

The second scenario (Replay) is implemented on a 433MHz basic wireless communication. A flipper zero can record the transmission and replay it to trigger the same effect. Securing it is simple with implementation of a rolling code or signature. If the message is unique, an attacker cannot replay it.

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Declaration of honor

I, undersigned, Rémi Heredero, hereby declare that the work submitted is the result of a personal work. I certify that I have not resorted to plagiarism or other forms of fraud. All sources of information used and the author quotes were clearly mentioned.

Place, date: Sion, 29.08.2024

Signature:

A handwritten signature in black ink, appearing to read "Rémi Heredero". It is written in a cursive style with some loops and flourishes.

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Abstract

TODO

Le résumé est une synthèse concise de l'ensemble de votre thèse, résumant les éléments clés sur une seule page, tels que

- Informations générales
- Objectif
- Approche et méthode
- Conclusions

Keywords: *OT, security, man in the middle, modbus, replay, attack, flipper*

1 | Introduction

TODO

L'introduction sert à présenter le sujet de votre mémoire de bachelor et à éveiller la curiosité du lecteur par une vue d'ensemble. Nous expliquons ici pourquoi elle est importante et comment elle est structurée. Vous pouvez considérer l'introduction comme une accroche pour votre mémoire de licence. Vous éveillez l'intérêt et donnez un avant-goût en présentant votre motivation, votre méthode et l'état de la recherche dans votre introduction.

Dès l'introduction, convainquez vos examinateurs que votre mémoire de licence sera passionnant. Si votre professeur commence à lire votre mémoire avec impatience et intérêt, les chances d'obtenir de bonnes notes sont plus élevées. Accordez une attention particulière aux éléments suivants dans votre introduction :

- Introduire le sujet - Qu'est-ce qui caractérise le sujet ?
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L'introduction doit contenir les éléments suivants :

- **Présentation initiale du sujet** - Vous introduisez le sujet par un "appât" passionnant. Vous fournissez des informations initiales sur le sujet et l'objet de la recherche et expliquez l'état actuel de la recherche.
- **Pertinence de la motivation du sujet** - Vous justifiez la pertinence de votre sujet (d'un point de vue scientifique) et le placez dans le contexte de votre domaine. En outre, il est souvent demandé que vous divulguiez votre motivation personnelle.
- **Description du problème et délimitation thématique** - Au moyen d'une question de recherche spécifique (ou d'une hypothèse), vous présentez votre intérêt de recherche explicite. Si nécessaire, expliquez les termes techniques.
- **Objectifs** - Votre introduction doit clairement indiquer l'objectif de votre travail et le résultat que vous espérez obtenir à l'issue de la rédaction de votre mémoire de licence.
- **Méthode** - Vous expliquez l'approche et justifiez le choix de la méthode.
- **Structure du mémoire de bachelor** - Enfin, vous donnez au lecteur un aperçu général de votre mémoire de bachelor en expliquant la structure, en montrant le fil rouge et en expliquant comment la question de recherche est résolue.

2 | Impact on Sustainability

This section explores the impact of this thesis on sustainability, with a specific focus on the United Nations' [Sustainable Development Goals \(SDGs\)](#). By examining the intersection of OT security and sustainability, this section demonstrates how securing industrial and home automation systems contributes to achieving global sustainability targets.

The [SDGs](#) provide a blueprint for achieving a better and more sustainable future. This thesis aligns particularly with the following goals:

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE



Goal 9: Industry, Innovation, and Infrastructure

Industry 4.0 relies heavily on interconnected OT systems. By addressing vulnerabilities and enhancing the security of these systems, this thesis promotes the development of robust and resilient infrastructure. Secure industrial processes foster innovation and sustainable industrialization. This thesis contributes to building infrastructure that supports economic development and human well-being, with a focus on sustainable industrialization and fostering innovation.

11 SUSTAINABLE CITIES AND COMMUNITIES



Goal 11: Sustainable Cities and Communities

Home automation systems are integral to the development of smart cities. This thesis examines security measures for these systems, ensuring they are protected against cyber threats. Secure home automation contributes to the safety, efficiency, and sustainability of urban environments. By protecting the systems that manage energy use, water distribution, and waste management, this research supports the development of cities and human settlements that are inclusive, safe, resilient, and sustainable.

12 RESPONSIBLE CONSUMPTION AND PRODUCTION



Goal 12: Responsible Consumption and Production

Efficient resource management is a key aspect of responsible consumption and production. This thesis enhances the security of systems that monitor and control resource usage, such as smart meters and automated manufacturing processes. By preventing tampering and ensuring accurate data collection, this research helps optimize resource consumption and reduce waste. This aligns with the goal of ensuring sustainable consumption and production patterns.

Conclusion

This bachelor thesis on OT security helps to advance on sustainability goals. By enhancing the security and reliability of industrial and home automation systems, this research supports the UN's Sustainable Development Goals, promoting a more sustainable and secure future. Integrating security into these systems is crucial for sustainable development, highlighting the need for interdisciplinary approaches in addressing global challenges.

3 | Analysis

This section discusses various attacks, communication media and simulation environments that could be used in the laboratory. It aids in selecting the appropriate attack on the right medium and simulation environment, essential for the future laboratory. The requirements of this thesis include the use of Modbus and an attack with the [Flipper Zero](#) device.

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3.1 Attacks

Numerous attacks can occur in the context of OT security and can be classified into different categories. This thesis covers some attack as following, though many others exist.

3.1.1 Sniffing Attack

This attack consists in listening to the communication between two devices [1]. It can be performed on every communication medium with varying levels of difficulty. Wireless communication is particularly vulnerable because anyone can intercept the signals. For example, in Figure 1, Alice sends a message to Bob over the air without encryption, allowing Eve to listen to and read the message.

A sniffing attack can be performed to get secret information or understand a chemical recipe, for example. It can also be used as part of other more complex schemes.

Security Measures

To protect against sniffing attacks, the communication must be encrypted. The encryption must be strong enough to resist the attacker. A simple symmetrical encryption is enough. Particular attention must be paid to the key exchange. Protocols such as Diffie-Hellman with symmetrical encryption are recommended to ensure protection against sniffing attacks.

3.1.2 Spoofing

In network security, spoofing involves impersonating another device. This attack is often used in combination to other attacks, such as creating a fake Wi-Fi hotspot. In the context of [Operational Technology \(OT\)](#) security, spoofing is less relevant and will not be discussed further in this thesis.

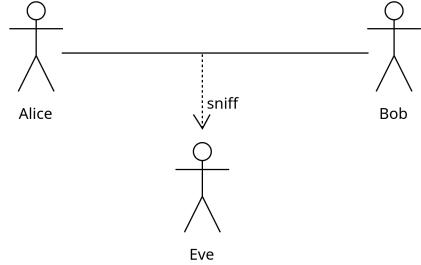


Figure 1: Sniffing attack

3.1.3 Denial of Service

An attack by **DoS** aims to render a service unavailable by overloading a device or network with messages [2]. In **OT** environments, a capable computer can execute a **DoS** attack effectively. To reach this goal, a device sends a large number of messages to surcharge a device or a network. In Figure 2 we can see that Mallory wants to overload Bob with messages. Bob is hence unable to answer to all messages and becomes unavailable. In **Information Technology (IT)** world, it is more often a **Distributed Denial of Service (DDoS)** attack because usually servers are more powerful than a computer, and thus can handle more concurrent messages. The attacker distributes the messages on multiple devices to make the offense more difficult to block. In **OT** world, it is useless to perform a **DDoS** to make a device unavailable since a **DoS** with a capable computer is generally enough. Another perspective is that **OT** world is typically in closed loop networks and thus not accessible from the outside world.

There are two primary types of **DoS** attacks in **OT** systems:

- **DoS on the communication medium:** This type of attack focuses on disrupting the data flow between devices by flooding the network with excessive traffic. This leads to network congestion and delays or blocks legitimate communication.
- **DoS on the controller:** This attack targets the processing capabilities of the controllers, such as **Programmable Logic Controllers (PLCs)**, by sending numerous commands. This overcharge of the **PLC** can lead to system failure rendering it unresponsive.



Did you know that when the Apollo 11 mission landed on the moon, the navigation system was overloaded because of a faulty sensor [3], forcing Neil Armstrong to take manual control of the landing?

This is an example of an unintentional **DoS**.

Security Measures

Several ways exist to protect against **DoS**. At this stage, the best is to avoid doing an action at the reception of a message. Unfortunately, it is not always possible. Another way is to limit the number of messages that can be received in a particular timespan. To achieve that, it is often necessary to use another device to filter the messages. This device can be a firewall for example. However, in the case of a **DDoS**, it is almost impossible to block the attack. The only way is to have a very powerful filtering device. Still, even with such a device, the attack can be successful.

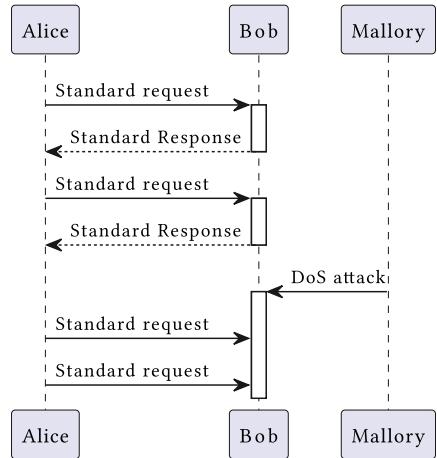


Figure 2: **DoS** attack

3.1.4 Replay

A replay attack involves resending a previously intercepted message as if it were from the original sender [4]. As we can see in Figure 3 Mallory sniffs the message between Alice and Bob. Mallory can then send the message to Bob as if Alice had sent it. This is particularly relevant in OT environment with wireless communication, such as the typical example: replaying a command to open a garage door. The attacker sniffs the command and replays it to open the door.

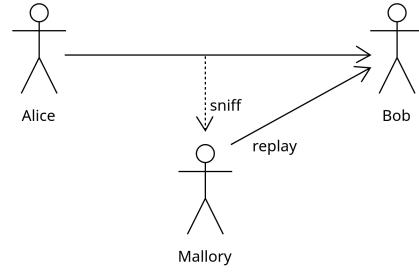


Figure 3: Replay attack

Security Measures

Two main ways exist to protect against replay attacks. It depends on whether the communication is broadcast or bidirectional.

When both devices communicate together in a bidirectional transmission, it is possible to add a timestamp to the message and sign the hash.

When communication is broadcast, the sender device is often not directly connected to other devices. In this case, it is not possible to have a timestamp. Using rolling codes is a good way to secure against replay attacks. The rolling code is a value that changes at each message. Both devices use a pseudo-random number generator. The receiver device can check whether it is a valid subsequent code.

3.1.5 Man in the Middle - Connected

A **MitM** attack occurs when a third party can actively intercept, modify or send packets on a network [5]. Usually, this involves connecting a new device to a star or bus network topology. Once connected to the network, Mallory (Figure 4) can perform a sniffing attack or send a message. The aim is often to intercept an message from Alice, modify it and send it to Bob.

Security Measures

Encryption with a symmetrical key can be used to protect the message from being intercepted, modified or impersonated. The key can be exchanged with the standard **Diffie-Hellman** algorithm.

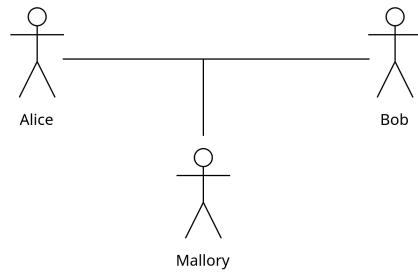


Figure 4: MitM on a connected network

3.1.6 Man in the Middle - Full interception

When Mallory is on the gateway or between Alice and Bob, as in Figure 5, Mallory can intercept all messages and neither Alice nor Bob can be sure that they send and receive messages to the right person. This is the most dangerous attack because Mallory can impersonate Alice and Bob and send a message to the other person. Even with the security measures seen in Section 3.1.5, Mallory was able to impersonate Alice and Bob and create its own key with each other. This is why a **MitM** attack is so dangerous.

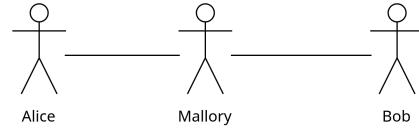


Figure 5: **MitM** intercept everything

Security Measures

When an attacker can intercept all messages exchanged since the beginning of the communication, it is impossible to be completely sure that the messages are from the right person. We need to trust someone before. Certificates are made for this exact purpose. They are signed by a trusted third party and can be used to verify the identity of the person or device with which we are communicating. The most common type certificate is [X.509](#) certificate.

3.2 Communication media

Different communication media are vulnerable to these attacks, highlighting the critical distinction between **IT** and **OT** security. In **OT** security, communication is a highly sensitive aspect, and historically, security measures were minimal or non-existent [6].

3.2.1 Modbus

Modbus is a communication protocol developed by Modicon in 1979 [7]. It involves a Modbus Master requesting data from a Modbus Slave. The client (master) sends a request to read from or write data to a server (slave). Modbus was originally designed for serial communication (called Modbus **RTU**). It has since been adapted for use over **TCP/IP** (called Modbus **TCP**).

Modbus **RTU**

Modbus with **RTU** is a serial, compacted, binary representation of the data. It is transported on the physical layer RS232 or RS485. Modbus **RTU** includes a **Cyclic Redundancy Check (CRC)**—16 bits checksum for error detection.

A frame is composed of:

- Address: 1 byte
- Function code: 1 byte
- Data: 0-252 bytes
- **CRC**: 2 bytes

Each byte of the frame is sent as 11 bits:

- 1 start bit
- 8 data bits
- 1 parity bit
- 1 stop bit

Modbus TCP

Modbus over [TCP](#) is a modern adaptation of Modbus. It is also a binary protocol, but transported over [TCP](#). This adaptation eliminates the need for [CRC](#) due to inherent error detection in [TCP](#). The rest of the frame is composed like Modbus [RTU](#) and the default port for Modbus [TCP](#) is 502.

3.2.2 wM-Bus

[wM-Bus](#) [8, part. 4] is a wireless version of the [Meter-Bus \(M-Bus\)](#) [8] protocol, used primarily in Europe for metering applications. It adheres to the ISO layer model [9] but implements only specific layers :

- Layer 1: Physical layer ([8, part. 2] for wired and [8, part. 4] for wireless)
- Layer 2: Data link layer ([8, part. 2] for wired and [8, part. 4] for wireless)
- Layer 7: Application layer ([8, part. 3])

The wireless specification has several modes of operation, to work on several frequency bands. The most common are:

Mode S

This mode [8, part. 4, p. 16] works on 868 MHz with [2-Level Frequency-Shift Keying \(2FSK\)](#) modulation on a single channel. Meters send data many times a day to a stationary collector. The collector can be used in a power-saving function and is awakened up by the long heading of the frame. This mode has a one-directional (S1) or bidirectional (S2) sub-mode.

Mode T

This mode [8, part. 4, p. 19] works on 868 MHz with [2FSK](#) modulation. The one-directional sub-mode T1 has a single-channel, but the bidirectional sub-mode T2 can use 2 channels. Meters are frequently sending data to a collector. This collector can be mobile.

Mode R2

This mode [8, part. 4, p. 24] works on 868 MHz with [2FSK](#) modulation. This mode is bidirectional and has 10 channels. This mode can use frequency hopping for a duty cycle higher than with other modes.

Mode C

This mode [8, part. 4, p. 27] works on 868 MHz with [2FSK](#) modulation. The one-directional sub-mode C1 has a single channel and the bidirectional sub-mode C2 has 2 channels with 2 different bandwidths. It can be used for stationary or mobile collectors.

Mode N

This mode [8, part. 4, p. 30] works on 169 MHz with [4-Level Gaussian Frequency-Shift Keying \(4GFSK\)](#) modulation. It can be one- or bidirectional and has 13 channels. This mode is used for long-range communication with a stationary collector.

Mode F

This mode [8, part. 4, p. 35] work on 433 MHz with [2FSK](#) modulation. This mode has only a bidirectional sub-mode. It is used for long-range communication with a stationary or mobile collector.

3.3 Simulation environments

As this thesis is part of the preparation of a new laboratory, the simulation environment must extend beyond abstract communication. The objective is to have a real physical controller interfaced with a simulated process. This simulated process remains necessary because a fully physical setup is prohibitively expensive and far less flexible than a simulated one.

3.3.1 Factory I/O

Factory I/O, developed by Real Games, is a realistic simulation software designed to emulate a factory environment. It allows for the creation of custom scenes, providing flexibility for various industrial scenarios. However, the software comes with an expensive licence, which must be considered when selecting the simulation environment. Factory I/O could also be beneficial for the Power & Control specialization. This software can interface with modbus over [TCP](#), but an additional third-party software is required to implement a security layer. While Factory I/O is only available on Windows, it operates effectively on Linux using Wine.



Figure 6: Factory I/O palletizer scene

Scenario idea

In this scenario, a [PLC](#) could control the [palletizer scene](#) (). A wireless sensor could indicate the presence of a truck to be loaded. The wireless replay attack could target this sensor. The [DoS](#) attack could be executed on the same sensor. The [MitM](#) attack could be conducted on the Modbus/[TCP](#) communication between the [PLC](#) and the palletizer, with the objective of gaining control over the clamp.

3.3.2 Home I/O

Home I/O is also developed by Real Games and simulates a House () equipped with extensive home automation features. This software is available at a lower organizational licence cost and could be of interest to ETE students. Home I/O offers a REST API for interfacing with all sensors and actuators. Similar to Factory I/O, it runs well on Linux using Wine.



Figure 7: Home I/O scene

Scenario idea

In this scenario, a [PLC](#) manages the alarm and access systems, including the main door and garage. The garage door can be opened using a wireless remote, which could be the target of a wireless replay attack. An external presence detector on the main door could be used for the [DoS](#) attack. [MitM](#) attacks could be executed on the Modbus/[TCP](#) communication between the PLC and the alarm system, aiming to deactivate the alarm system.

3.3.3 Minecraft

Another suitable approach would be to use the Electrical Age world in Minecraft () which was previously featured in the Telecommunication course. The goal of this lab was to control a factory and energy system to maximize production. Continuing this laboratory could provide valuable opportunities for students to explore and secure communication systems. In Minecraft, security can be implemented using the Open Computers mod or by creating an extension mod for Modbus over [Transport Layer Security \(TLS\)](#), which might be simpler than using Lua with Open Computers.



Figure 8: Minecraft Electrical Age scene

Scenario idea

The scenario involves reusing the [PLC](#) from the previous lab, which controls various operations. A physical [Human-Machine Interface \(HMI\)](#) could be constructed to manage the factory and coal production, similar to the HTML interface used in the previous lab. A wind wireless sensor could be added to the setup. Wireless replay and [DoS](#) attacks could target this sensor. [MitM](#) attacks could be executed on the Modbus/[TCP](#) communication between the [PLC](#) and the factory, with the goal of gaining control over the factory's operations.

3.4 Conclusion

This section presented various attacks that can be performed on [OT](#) systems. The communication media discussed during the preliminary phase of this work were also outlined. Additionally, potential simulation environments for laboratory use were evaluated.

Based on this information, M.Rieder and M. Clausen have decided on the simulation environment. The chosen platform is Home I/O, as it could benefit ETE students.

The planned attacks include a replay attack on a wireless control or sensor, a [DoS](#) attack on an external sensor with valid data (overloading the controller rather than the communication medium) and a [MitM](#) attack on the Modbus/[TCP](#) communication. The [MitM](#) attack will be conducted in two phases. The first phase will involve an unencrypted Modbus/[TCP](#) communication while the second phase will involve encrypted Modbus/[TCP](#) communication with a symmetrical key exchanged by [Diffie-Hellman](#).

Wired communication will be carried out using Modbus, a widely used protocol in [OT](#) systems, which aligns with the brief for this thesis.

For the replay attack on a wireless control or sensor, the idea is to use the [Flipper Zero](#) to record and replay a message. This attack will be performed only on the physical layer. The [Flipper Zero](#) can only execute such an attack on basic wireless protocols, as it cannot perform a replay attack on frequency hopping protocols. The wireless protocol must employ [On-Off Keying \(OOK\)](#), [Amplitude-Shift Keying \(ASK\)](#) (with 270 or 650 kHz Bandwidth) or [2FSK](#) modulation. Consequently, protocols like Zigbee or DigiMesh are not suitable for this attack and were not explored in depth.

[wM-Bus](#) is a single canal [2-Level Gaussian Frequency-Shift Keying \(2-GFSK\)](#) protocol and is well-suited for replay attacks using the [Flipper Zero](#). Given that typical [wM-Bus](#) T-mode application include electricity or water meters, incorporating such meters into the simulation would be relevant with a replay attack targeting these devices.

If the [wM-Bus](#) implementation proves too challenging, a contingency plan involves using a simple [OOK](#) modulation at 433 MHz.

4 | Man in the Middle Scenario

The Man-in-the-Middle (MitM) scenario focuses on intercepting, modifying, and forwarding packets to gain control over a Modbus/TCP installation. This protocol, commonly used in industrial settings, was selected for this thesis because it is widely adopted and fulfils the requirement to demonstrate an attack on it. The MitM attack was chosen due to its prevalence and potential for significant impact. It is a comprehensive attack that encompasses several other techniques, such as sniffing and spoofing through ARP poisoning. This scenario assumes that the attacker has already gained access to the network, enabling them to intercept and manipulate the data packets.

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4.1 Simulation Environment

Home I/O is a smart home simulation platform that allows interaction with a wide range of sensors and actuators, as detailed in Section 3.3.2. For the Man-in-the-Middle attack scenario, the entrance hall within this simulation is particularly relevant. As shown on Figure 9 the entrance hall has two doors with their sensor, one motion sensor and the house alarm.

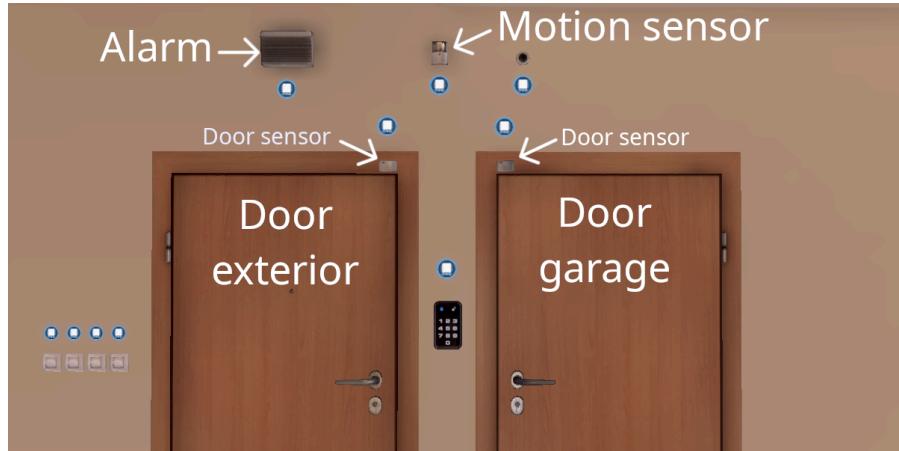


Figure 9: Home I/O scene

Since Home I/O does not natively support Modbus communication, a custom Go software was developed by Michael Clausen to convert Modbus requests into the REST requests required by the simulation. This software simulates a Modbus server for each room. In this thesis, the architecture consists of one computer running the simulation and another acting as the house controller, as shown in Figure 10. The controller, functioning as a Modbus client, is implemented using another Go program that could be deployed on a Wago CC100 PLC in a real-world scenario. For the purposes of this thesis, the controller is intentionally kept simple.

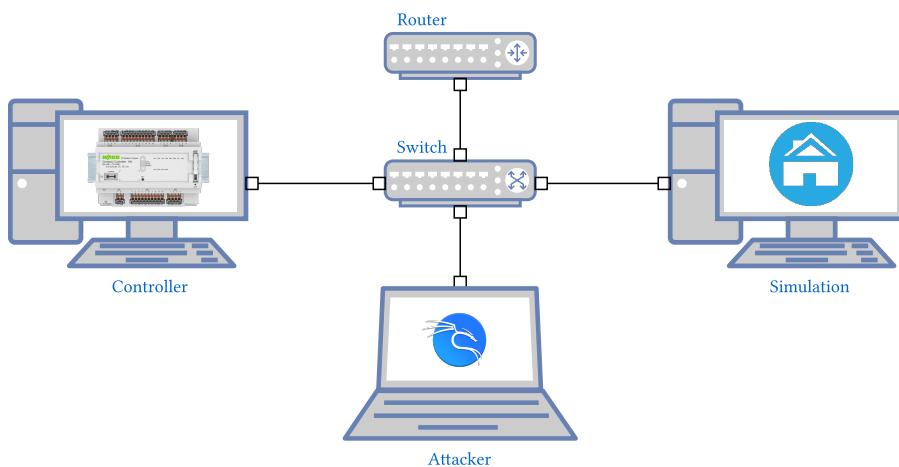


Figure 10: MitM scenario implementation

In this demonstration, the controller sends requests to check the status of both door sensors and the motion sensor. If either door is open or motion is detected, the controller

sends a request to the alarm to activate it. If no activity is detected, the controller sends a request to deactivate the alarm.

The controller, the simulation, and an attacker are all connected to the same network via a switch. This thesis was made under a Kali Linux (Icon 1) laptop, although it is performed on any computer with the appropriate tools.

4.2 Requirements

This scenario centres on a **MitM** attack, where the attacker must position themselves between the communication parties, ensuring that all packets pass through their system. Since Modbus/TCP is an **IP**-based protocol, the attacker can utilize a powerful tool called Ettercap (Icon 2). Ettercap simplifies the execution of an **ARP** poisoning attack.

An **Address Resolution Protocol (ARP)** poisoning attack involves sending fraudulent **ARP** messages across the network, tricking the target into associating the **IP** address of another party with the attackers **Media Access Control (MAC)** address, as illustrated in Figure 11. As a result, the target's packets are sent to the attacker, who can then manipulate these packets before forwarding them (or not) to the intended recipient. This attack occurs at layer 3 of the OSI model [10].

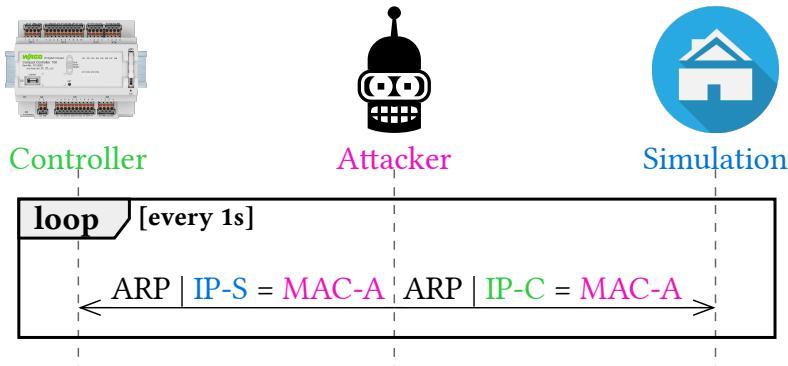


Figure 11: **ARP** poisoning

To use Ettercap, the attacker need to know the **IP** address of the controller and the Home I/O simulation. This information can be obtained by sniffing the network using Ettercap itself or other tools such as **Wireshark**, **nmap**, or **hping3**. Once the **IP** addresses are identified, the attacker can initiate the **ARP** poisoning attack with the following command:

```
ettercap -T -i eth0 -M arp /IP_CONTROLLER// /IP_HOMEIO//
```

Listing 1: Start an ARP poisoning with Ettercap

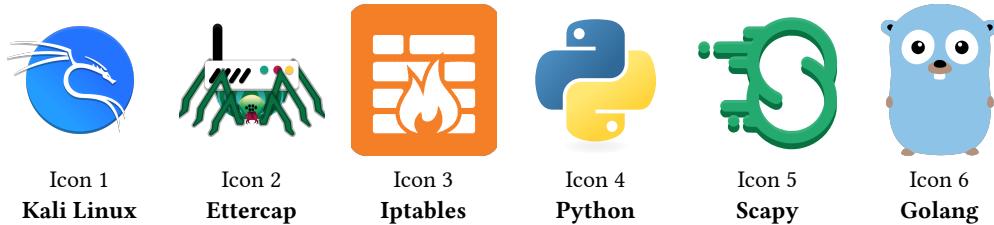
This command, shown in Listing 1 start Ettercap in text mode (**-T**) on the **eth0** network interface (**-i eth0**) and perform an **ARP** poisoning attack (**-M arp**). The **IP** addresses of the controller and the Home I/O simulation are specified by **/IP_CONTROLLER//** and **/IP_HOMEIO//**. An graphical interface is also available but have to be installed as an extra package.

To execute this attack, **iptables** (Icon 3) will be used to redirect the packet to a python (Icon 4) script that modifies them in real-time. This script employs the **scapy** (Icon 5) li-

brary, a powerful tool for crafting or decoding packets from a wide range of protocols. The second part of this attack scenario (see on Section 4.4) will use a go (Icon 6) script.

4.2.1 Tools

Here are all the tools that are used for this scenario :



4.2.2 Closer look on Modbus

As discussed on Section 3.2.1, Modbus is a straightforward protocol that was initially developed for serial communication via [RTU](#) but is now commonly implemented over [TCP/IP](#). This protocol operates in request-response mode, as illustrated in Figure 12. In this setup, the controller sends a request to the Home I/O to retrieve a value or alter an output. The Home I/O then replies with the requested value or an acknowledgment message, after which the controller can issue another request or close the connection.

This request-response mechanism means that the attacker must capture traffic in both directions to modify packets in real-time effectively. The attacker needs to know the nature of the request to determine if the response needs alteration. Without this knowledge, it would be impossible to decide if a response needs to be modified.

In this thesis simulation, the controller is tasked with checking the status of two door sensors and a motion detector, all of which are connected to the same Modbus slave, the **Entrance Hall** (UnitID=5). The alarm system is represented as a coil on the same slave. A summary of these registers can be found in Table 1.

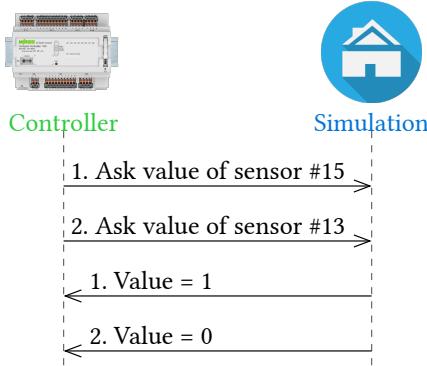


Figure 12: Home IO details

Sensor / Actuator	Unit ID	Fonction	Address
Door exterior	5	Discrete Inputs	13
Door garage	5	Discrete Inputs	14
Motion detector	5	Discrete Inputs	15
Alarm	5	Coils	5

Table 1: Modbus Registers

4.3 Attack on Modbus/TCP

To modify a packet during a Modbus/TCP attack, the first step is to establish a [MitM](#) position. This is achieved using [ARP](#) poisoning as described in Section 4.2. Once the attacker intercepts all the packets, they need to redirect them to a Python (Icon 4) script for real-time modification. This redirection can be accomplished by configuring iptables (Icon 3) to add rules to the attacker's firewall. The idea is to place all the packets into a queue, enabling the Python script to retrieve and analyse them sequentially. Listing 2 demonstrates how to use iptables (Icon 3) to enqueue all packets destined for the **192.168.0.0/16** subnet into queue 1.

```
iptables -I OUTPUT -d 192.168.0.0/16 -j NFQUEUE --queue-num 1
```

Listing 2: Put packets on queue 1 with Iptables

4.3.1 Closer look on TCP

[Transmission Control Protocol \(TCP\)](#) operates at layer 4 of the OSI model [10] and is responsible for establishing a reliable connection between two devices. In this thesis, the primary concern is [TCP](#)'s mechanism for ensuring packet integrity via checksums. The checksum ensures that the packet has not been corrupted during transmission; if the checksum does not match, the packet is discarded. This aspect is crucial for the attacker, who must modify the packet on the fly. If the modified packet has an incorrect checksum, it will be discarded, causing the attack to fail. An acknowledgment (ACK) is sent when the packet is received correctly, as illustrated in Figure 13. Within the [TCP](#) segment, the Modbus packet is encapsulated as shown in Table 2.

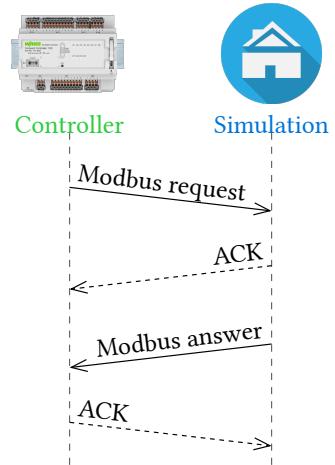


Figure 13: TCP exchange

0	1	2	3	4	5	6	7	8	9	10	...
Transaction ID	Protocol identifier	Length	Unit ID	Func. code	Reference number	Modbus data					

Table 2: Modbus TCP packet structure

4.3.2 Modify packet on the fly

The packet modifications are carried out using a Python (Icon 4) script, leveraging the [scapy](#) (Icon 5) library. Scapy is particularly useful for on-the-fly modification. With Scapy it is straightforward to dissect the different layers of a packet. To extract the [IP](#) layer, one can use the command `scapy_packet = IP(pck.get_payload())`. To check if the packet is [TCP](#) and retrieve its payload, the command `payload = bytes(scapy_packet.payload.payload)` can be used.

This binary payload contains the Modbus message, which can be inspected and altered as needed. If the destination port is 1502, the packet is from the controller heading to the

server. In this case, the attacker should check if the request concerns a door sensor or the motion sensor and then save the transaction ID of this request.

If the source port is 1502, the packet is from the server and is destined for the controller. The attacker should then verify whether the response corresponds to a previously saved transaction ID and, if so, modify the response as necessary.

4.3.3 Summary

The entire process is summarized in Figure 14.

- (1) Initially, under normal conditions, the controller sends a request to the server, the server responds, and the controller triggers the alarm if necessary.
- (2) However, when the attacker initiates an **ARP** poisoning attack, all packets are routed through the attacker.
- (3) This allows the attacker to perform a **MitM** attack and modify the packets in real-time. In this scenario, the controller sends a request to the server, the attacker intercepts and alters the response, and the controller proceeds as if the modified response were legitimate.

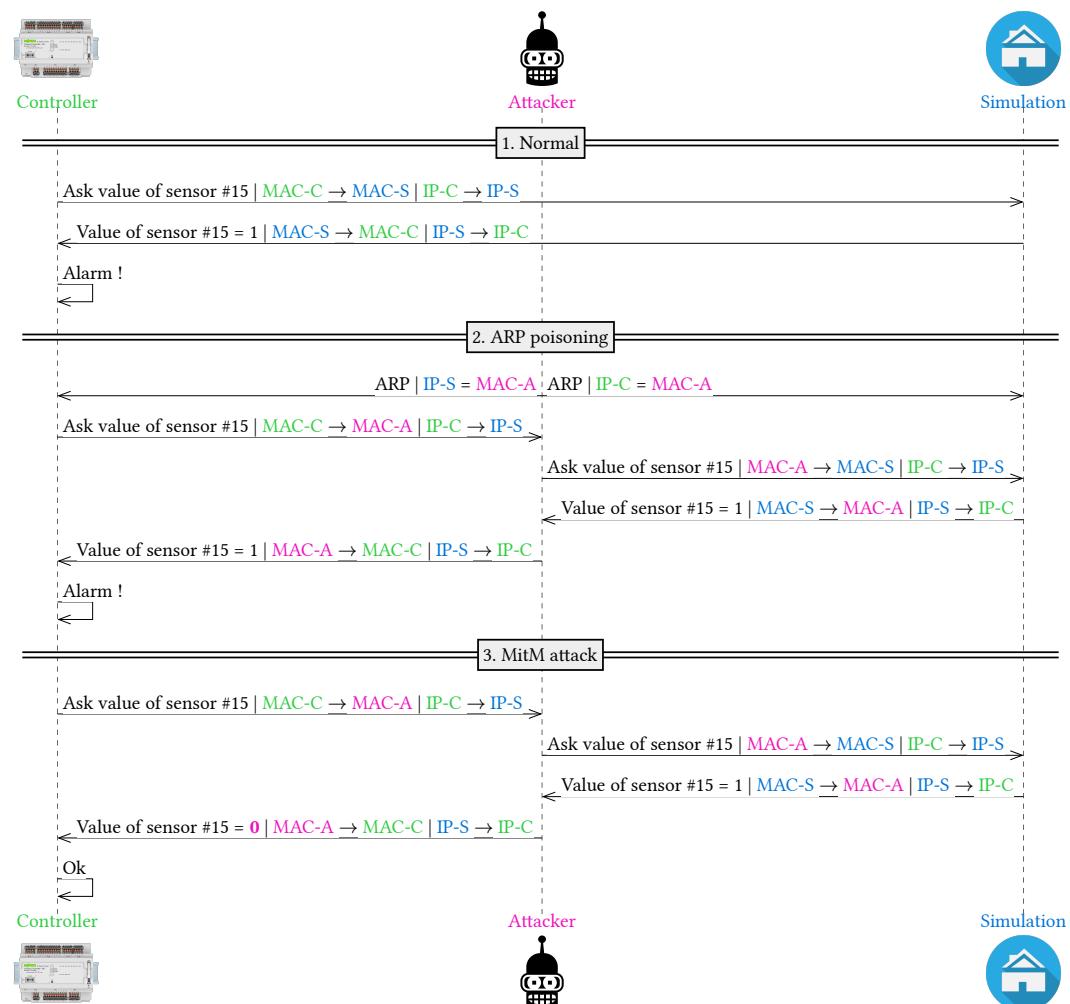


Figure 14: Modbus/TCP attack scenario

4.4 Implement Modbus/TLS

While clear communication can work, it falls short when it comes to security. To safeguard Modbus/TCP communication, it is essential to add an encryption layer. Modbus over TLS is a secure version of Modbus/TCP, encrypting the communication between the controller and the server. With Modbus/TLS in place, the attacker is unable to intercept and modify the packets in real-time, as they are protected by encryption.

4.4.1 Closer look on TLS

Transport Layer Security (TLS) is a cryptographic protocol that operates over TCP, primarily associated with layers 5 and 6 of the OSI model [10]. While it technically spans both these layers, establishing an encrypted session (layer 5) and handling the encryption itself (layer 6). TLS is commonly considered a layer 6 protocol.

TLS provides secure communication between two parties, typically a client and a server. The process begins with a handshake, as illustrated in Figure 15, where the client and server exchange a series of messages to establish a secure connection. This handshake involves the exchange of random numbers, a certificate, and a seed. The Diffie-Hellman key exchange is used to generate a master key, a symmetric key that will be used to encrypt all communications within that session.

During the handshake, the client, and server also exchange X.509 certificates to verify each other's identity. An X.509 certificate contains information about the certificate's owner, such as their name, expiration date, and address for TLS communication. The certificate also includes the owner's public key, which is used to authenticate their identity. X.509 certificates rely on a chain of trust provided by **Certificate Authority (CA)**. A CA is a trusted third party that verifies the identity of the certificate's owner and signs the certificate to validate it. The client and server can verify the validity of each other's certificates by checking the CA's signature. If the signature is valid, the certificate is considered trustworthy, forming the basis of the TLS handshake.

4.5 Attack on Modbus/TLS

This thesis demonstrated how easily Modbus/TCP packets can be intercepted and modified. However, when Modbus/TLS is employed, the packets are encrypted, making it

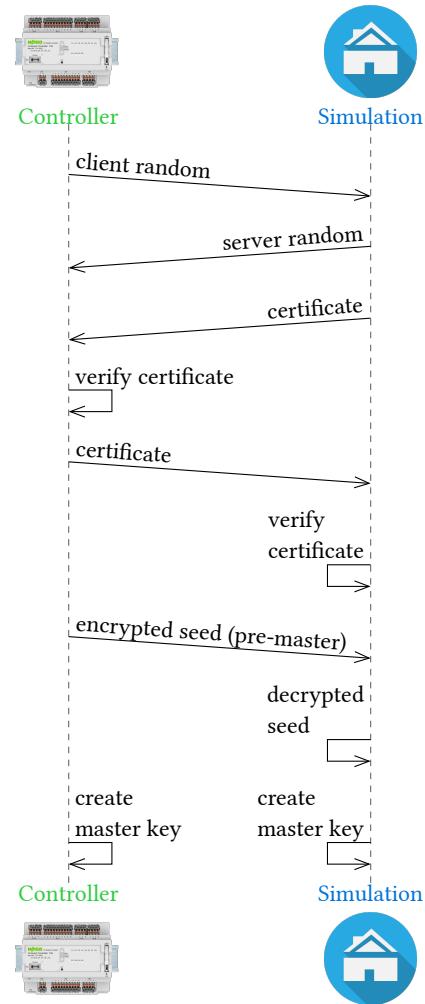


Figure 15: TLS handshake

seemingly impossible to perform a **MitM** attack to take control of the system. This is true, but only if every step of the **TLS** implementation has been executed correctly.

The thesis also reveals that control can still be compromised if certificates are not properly verified. In test or debugging environments, it's common for certificates to be unsigned by a **CA**, rendering them invalid. As a result, certificate verification is often bypassed in such environments. However, it is crucial to ensure that certificates are signed and verified in a production environment. In the **OT** world, it may be advisable for a company to maintain its own internal **CA** to sign all certificates. This makes it easier to install the **CA** on all company devices and ensure proper certificate verification.

To perform a **MitM** attack on a Modbus/**TLS** installation that does not check certificates, the attacker must first establish a **MitM** position. This can be done using the same **ARP** poisoning attack described in Section 4.2. During this thesis, considerable time was spent trying to modify random and certificates on the fly. This approach proved difficult because the **TLS** handshake (Figure 15) must be fully implemented, and there are no tools specifically designed to modify only the **TLS** layer in real-time. While many tools exist for performing **MitM** attacks in the **IT** world, such as **Burp suite**, **mitmproxy**, or **bettercap**, they are typically focused on the **Hypertext Transfer Protocol Secure (HTTPS)** protocol.

A more effective approach would be to handle the entire connection rather than attempting to modify packets on the fly. The attacker can redirect the **TLS** traffic from both targets to their own server, where the traffic can be decrypted. To redirect the traffic, **iptables** (Icon 3) can be used, as demonstrated in Listing 3.

```
iptables -t nat -A PREROUTING -p tcp --dport 5802 -j REDIRECT --to-port 5803
```

Listing 3: Redirect traffic to another port with Iptables

This command redirects all **TCP** traffic destined for port **5802** (used for **TLS** communication between the controller and Home I/O) to port **5803** (the port where the attacker's server is running).

The attacker can then set up their own Modbus/**TLS** server to decrypt the traffic and forward it to the Home I/O simulation. If desired, the attacker can modify the response before forwarding it back to the controller. It is easy to see a trace of such an attack because the attacker has to use a dummy certificate to create the symmetric encryption key. This certificate can be seen with tool like **Wireshark**

4.6 Conclusion

In summary, this chapter has outlined the simulation environment, detailed the tools required for this scenario, and demonstrated how to implement a **MitM** attack on both Modbus/**TCP** and Modbus/**TLS** communications.

The thesis focused on a simple system composed of two door sensors and a motion sensor controlling an alarm. The attacker's primary goal was to gain control over this system to open the doors without triggering the alarm. The findings illustrate how easily this can be achieved when no security measures are in place. The attacker only needs access to the local network, which could potentially be obtained by compromising an external sensor.

Additionally, this thesis has shown how implementing Modbus/TLS can secure the system and highlighted the critical importance of verifying certificates to ensure robust protection.

Finally, with this scenario, many layers of the OSI model have been tackled. Layer 2 and 3 with ARP poisoning, layer 4 with the attack on Modbus/TCP and layer 5 and 6 with the attack on Modbus/TLS.

5 | Replay Scenario

The replay attack scenario involves intercepting and resending a message on a wireless connection to trigger the same effect as the original message, like, for example, a garage door opening remote. This scenario is particularly engaging because it can be easily implemented with the [Flipper Zero](#) device, making it more interactive and enjoyable for students to witness a physical attack in action. Additionally, it highlights the significance of wireless attacks, a critical topic in the [OT](#) world. This scenario operates at the physical layer, providing a complementary perspective to the [MitM](#) scenario discussed in Section 4.

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5.1 Simulation Environnement

Orginial idea was to do a replay attack on a [wM-Bus](#) system as shown on Figure 16. Like the electrical meter where an attacker measure the power consumption of two weeks of hollidays. Then replay thoses weeks and can optionnaly add some graphical card for mining bitcoins.

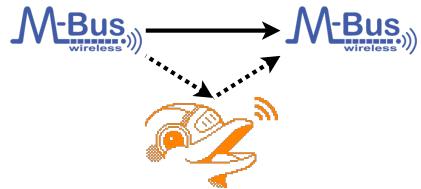


Figure 16: Replay scenario implementation

5.2 Requirements

This scenario focuses on a replay attack on a [wM-Bus](#) system, where understanding the content of the message is unnecessary. The attacker only needs to capture the physical layer of the message and retransmit it.

The [Flipper Zero](#) device (Icon 7) is used to execute this attack. The device features a “read raw” mode in the “sub-ghz” section, which allows it to listen to a specific frequency with a particular modulation and record the data at the physical layer (layer 1 of the OSI model [10]).

For transmitting messages on [wM-Bus](#), a **RC1180** transceiver from Radiocraft is employed. This device can both transmit and receive messages via a serial connection. A Go (Icon 8) program can be used to send and receive messages through the RC1180.

5.2.1 Tools

Here are all the tools that are used for this scenario :



Flipper Zero (Icon 7) is a portable multi-tool for pentesters.
Golang (Icon 8) is a statically typed, compiled programming language.

5.2.2 Closer look on RC1180

The **RC1180** is a [wM-Bus](#) transceiver interfaced via a serial connection. To function correctly, this chip must be configured to appropriate mode. In the context of this thesis, T-mode is utilized. The transceiver also needs to be set up as either a transmitter or a receiver. Configuration is achieved by sending specific serial commands to the device, which will respond with a confirmation message. The following commands are used for configuration :

- **0x00**: to enter in configuration mode
- **0x47**: to change the [wM-Bus](#) mode
- **0x01**: to configure to T-mode
- **0x46**: to change the C-field of all futur messages

- **0x44/0x04**: to set master (**0x44**) or slave (**0x04**)
- **0x00**: to exit configuration mode

After each command, a confirmation message 0x3E is expected.

Once the configuration is complete, a message can be sent to the device to initiate transmission. The message format is shown in Table 3.

L	CI	Data
---	----	------

Table 3
RC1180 uart sending message format

L: Length of the message (1 byte)

CI: Control Information (1 byte)

Data: Data to send (n bytes)

For this thesis, the **CI** is set to **0x80** to send a general message, as this is a demonstration setup rather than a real **wM-Bus** meter.

5.3 Attack on Wireless M-Bus

With the setup complete, the goal is to perform a replay attack on the **wM-Bus** system using the **Flipper Zero** device. As a reminder, the **wM-Bus** in T-Mode operates at 868.95 MHz with 2GFSK modulation and a 50 kHz deviation.

5.3.1 Flipper Zero

For this thesis, the “sub-1GHz” feature of the **Flipper Zero** is utilized. The **Flipper Zero** contains a **CC1101** chip from **Texas Instruments (TI)**, designed to operate within the 300-348 MHz, 387-464 MHz, and 779-928 MHz frequency bands. It supports various modulation schemes, including 2(G)FSK, 4(G)FSK, ASK, and OOK.

In read-raw mode, the **Flipper Zero** needs to be configured to operate at 868.95 MHz for the **wM-Bus** system. The modulation is set to **FM476**, which corresponds to frequency modulation with a 47.6 kHz deviation. Based on the documentation, the **Flipper** should ideally detect the specific type of frequency modulation used by the signal.

5.3.2 Modulation FSK vs GFSK

Initial attempts at replaying the signal were unsatisfactory. While the **Flipper Zero** successfully detected and recorded a signal, the replayed signal was received by the RC1180 but not understood. This indicated that the **Flipper Zero** was not correctly recording or replaying the signal. To diagnose the issue, the wireless signal was analysed using an Agilent spectrum analyser. Although the measurements were not conducted to obtain precise quantitative results, they provided a qualitative understanding of the signal.

A measurement of the original signal emitted by the **wM-Bus** transceiver is shown in Figure 17. The signal is centred around 868.95 MHz with a 50 kHz bandwidth and uses **2-Level Gaussian Frequency-Shift Keying (2-GFSK)** modulation.

In contrast, the signal replayed by the **Flipper Zero**, shown in Figure 18, also centres around 868.95 MHz with a 47.6 kHz bandwidth, but the modulation appears to be **2-Level Frequency-Shift Keying (2FSK)** rather than **2-GFSK**. This difference in modulation explains why the RC1180 does not recognize the replayed signal.

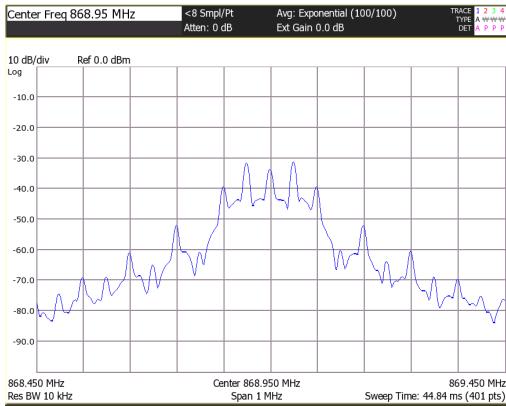


Figure 17
Spectrum analyzer of the original wM-Bus signal

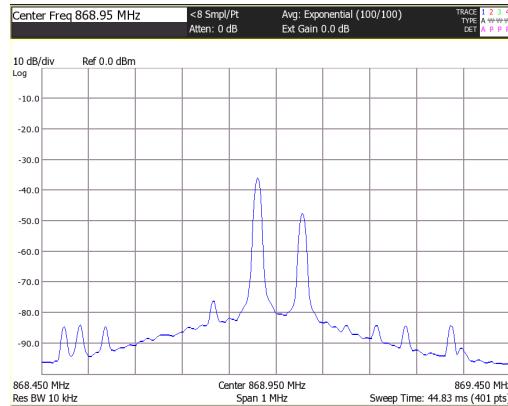


Figure 18
Spectrum analyzer of the replayed signal in FM476 modulation

The [Flipper Zero](#) seems unable to detect the correct type of frequency modulation. Upon closer examination of the firmware, it was discovered that the **FM476** preset is configured only for [2FSK](#) modulation. While a brief effort was made to add a configuration setting for [2-GFSK](#) with a 50 kHz deviation, the limited time remaining for the thesis made it impractical to proceed. Configuring this would require a detailed understanding of the CC1101 chip's register settings, a complex task requiring in-depth knowledge of the chip's datasheet.

Given these challenges, it was decided to proceed with Plan B.

5.4 Attack on basic 433 MHz transceiver

Instead of using a complete protocol like [wM-Bus](#), a basic 433 MHz transceiver can be employed for the replay attack scenario. This approach is simpler and effectively simulates a garage door and its remote control. In this thesis, a basic [OOK](#) transceiver from **M5Stack** is used. The setup consists of two chips: a transmitter (**SYN115**) and a receiver (**SYN513R**). [OOK](#) modulation, the simplest form of [ASK](#), represents digital data by the presence or absence of a carrier wave.

The transceiver emits a signal at 433.92 MHz when a signal is present on its data pin and nothing when the data pin is low. A challenge with the receiver is detecting a varying signal; if no signal is detected, it amplifies the noise until it perceives sufficient variation to consider it as a signal. Similarly, if the signal is present for too long, the receiver reduces amplification, mistaking noise variations for the signal.

To overcome this issue and maintain simplicity, the strategy involves transmitting a serial message with a long preamble to stabilize the signal's amplification, followed by start characters. This enables the receiver to correctly detect both the signal and the message.

Given the simplicity of this modulation, the [Flipper Zero](#) device has no trouble reading and replaying the signal. It has to be configurate on the right frequency and an **AM650** modulation preset. The demonstration conducted in this thesis involves a simple message sent by the transmitter and received by the receiver. The [Flipper Zero](#) is used to record the

message and replay it, allowing the receiver to detect the message and trigger the same action as the original signal.

5.5 Security in wireless broadcast isolated devices

A replay attack is always possible if two identical messages trigger the same action. To prevent such attacks, each message must be unique.

Typically, this is achieved by adding a timestamp to the message. However, in this scenario, it's not feasible due to the isolation between the receiver and transmitter, as well as the unidirectional nature of the communication. Without the ability to perform a challenge-response, alternative methods must be considered.

5.5.1 Closer look on rolling code

For this thesis, a rolling code was chosen as the security measure. Rolling code security involves appending a short, changing code to each message. This code is generated using a simple pseudo-random number generator. The receiver stores the last code received and only accepts one of the next codes in the sequence.

A pseudo-random number generator relies on a seed and a function that generates a new, seemingly random number. The seed is the last code received, and both the transmitter and receiver use the same function. The receiver must be able to compare with more than one subsequent code; otherwise, if a code is transmitted but not received, the receiver may become desynchronized and unable to decode future codes.

This method is straightforward and allows for easy addition of new remotes. To add a new remote, the receiver must enter learning mode, and the transmitter sends a code that the receiver adopts as the seed for the new remote.

This method is not perfect for security, as if the attacker knows how works the pseudo-random number generator, he can predict the next code. But it is enough for a garage door remote.

If an attacker understands how the pseudo-random number generator of this system works, they can predict future codes. While this method is not foolproof, it provides sufficient security for a garage door remote.

5.5.2 Closer look on signature

An alternative method involves signing the message with a private key, which the receiver then verifies using a public key. This approach offers greater security but requires more complex hardware and software capable of performing cryptographic operations. Additionally, adding a new remote becomes more complicated, as the receiver must be configured to recognize the new remote's public key.

To sign a message, a hash of the message is created and encrypted with the private key. The receiver decrypts the signature with the public key and compares the hash with the hash of the received message. If they match, the message is considered authentic. To prevent replay attacks, a simple counter can be included in the message, as it is also authenticated.

5.6 Conclusion

In summary, this chapter has presented the replay attack using the [Flipper Zero](#). This attack is relatively simple, as the [Flipper Zero](#) has built-in functions designed to execute such attacks on unsecured systems. Initially, the plan was to conduct this attack on a [wM-Bus](#) system, but due to the [Flipper Zero](#)'s lack of preset support for [2-GFSK](#) modulation, the attack was instead performed on a basic 433 MHz transceiver.

Since a wireless replay attack targets layer 1 of the OSI model [10], the system must implement security at a higher layer. In this thesis, a rolling code was used to secure the system. While this method is simple and effective for a garage door remote, more secure systems may benefit from a message signature approach

6 | Conclusion

TODO

- résumé
- résultats
- usage pour un labo
- difficultés

6.1 Project summary

TODO

6.2 Comparison with the initial objectives

TODO

6.3 Encountered difficulties

TODO

6.4 Future perspectives

TODO

7 | Glossary

ARP – Address Resolution Protocol: The Address Resolution Protocol (ARP) is a communication protocol used for discovering the link layer address, such as a MAC address, associated with a given internet layer address, typically an IPv4 address. [6](#), [14](#), [16](#), [18](#), [19](#), [21](#)

Flipper Zero: Flipper Zero is a portable multi-tool for pentesters and geeks in a toy-like body. [5](#), [13](#), [23](#), [24](#), [25](#), [26](#), [28](#)

HMI – Human-Machine Interface: A human-machine interface (HMI) is a user interface or dashboard that connects a person to a machine, system, or device. [13](#)

IT – Information Technology: Information Technology (IT) is the use of computers to store, retrieve, transmit, and manipulate data or information. [7](#), [9](#), [21](#)

MAC – Media Access Control: A media access control address (MAC address) is a unique identifier assigned to a network interface controller (NIC) for use as a network address in communications within a network segment. [16](#)

OT – Operational Technology: Operational Technology (OT) is hardware and software that detects or causes a change through the direct monitoring and/or control of physical devices, processes, and events in the enterprise. [6](#), [7](#), [8](#), [9](#), [13](#), [21](#), [23](#)

PLC – Programmable Logic Controller: A programmable logic controller (PLC) is an industrial digital computer that has been ruggedized and adapted for the control of manufacturing processes, such as assembly lines, robotic devices, or any activity that requires high-reliability control and ease of programming. [7](#), [11](#), [12](#), [13](#)

SDG – Sustainable Development Goal 4

7.1 Attacks

DDoS – Distributed Denial of Service: A distributed DoS is basically the same as a DoS attack, but the attack comes from multiple sources. [7](#)

DoS – Denial of Service: A denial-of-service (DoS) attack is a cyber-attack in which the perpetrator seeks to make a machine or network resource unavailable to its intended users by temporarily or indefinitely disrupting services of a host connected to the Internet. [6](#), [7](#), [11](#), [12](#), [13](#), [30](#)

MitM – Man in the Middle: A Man in the Middle (MitM) attack is a form of eavesdropping in which communication between two users is monitored and modified by an unauthorized party. [6](#), [8](#), [9](#), [11](#), [12](#), [13](#), [14](#), [15](#), [16](#), [18](#), [19](#), [21](#), [23](#)

7.2 Communications

2FSK – 2-Level Frequency-Shift Keying: 2-Level Frequency-Shift Keying (2-FSK) is a form of [Frequency-Shift Keying \(FSK\)](#) modulation that uses two levels of frequency to encode digital data. [10](#), [13](#), [25](#), [26](#)

2-GFSK – 2-Level Gaussian Frequency-Shift Keying: 2-Level Gaussian Frequency-Shift Keying (2-GFSK) is a form of [FSK](#) modulation that uses two levels of Gaussian filtering to encode digital data. [13](#), [25](#), [26](#), [28](#)

4GFSK – 4-Level Gaussian Frequency-Shift Keying: 4-Level Gaussian Frequency-Shift Keying (4-GFSK) is a form of [FSK](#) modulation that uses four levels of Gaussian filtering to encode digital data. [10](#)

ASK – Amplitude-Shift Keying: Amplitude-shift keying (ASK) is a form of modulation in which the amplitude of a carrier wave is varied proportionally to that of a modulating signal. [13](#), [26](#), [31](#)

CRC – Cyclic Redundancy Check [9](#)

FSK – Frequency-Shift Keying: Frequency-shift keying (FSK) is a frequency modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier wave. [30](#), [31](#)

HTTPS – Hypertext Transfer Protocol Secure: Hypertext Transfer Protocol Secure (HTTPS) is an extension of the Hypertext Transfer Protocol (HTTP). HTTP is an application protocol for distributed, collaborative, hypermedia information systems. HTTPS is used for secure communication over a computer network and is widely used on the Internet. [21](#)

IP – Internet Protocol [9](#), [16](#), [17](#), [18](#)

M-Bus – Meter-Bus [10](#)

OOK – On-Off Keying: On-Off Keying (OOK) denotes the simplest form of [ASK](#) modulation that represents digital data as the presence or absence of a carrier wave. [13](#), [26](#)

RTU – Remote Terminal Unit [9](#), [10](#), [17](#)

TCP – Transmission Control Protocol [9](#), [10](#), [11](#), [12](#), [13](#), [14](#), [16](#), [17](#), [18](#), [20](#), [21](#)

wM-Bus – Wireless M-Bus [5](#), [6](#), [5](#), [10](#), [13](#), [24](#), [25](#), [26](#), [28](#)

7.3 Cryptography

CA – Certificate Authority: A certificate authority (CA) is an entity that issues digital certificates. [20](#), [21](#)

Diffie-Hellman: Diffie-Hellman key exchange is a method of securely exchanging cryptographic keys over a public channel. [8](#), [13](#), [20](#)

TLS – Transport Layer Security: Transport Layer Security (TLS) is a cryptographic protocol that provides communications security over a computer network. [12](#), [20](#), [21](#), [22](#)

X.509: X.509 is a standard that defines the format of public key certificates. [9](#), [20](#)

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