Attacks and Detection in ICS - Stuxnet

CPS and IoT Security

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Vulnerabilities of ICS

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- There are many examples of things that can go wrong in an ICS
- **Computer-based accidents**
  - A whole nuclear power plant was forced into emergency shutdown for 48 hours after an operator installed a software update on the business network used to monitor chemical and diagnostic data
- **Non-targeted attacks**
  - Incidents caused by the same attacks that any other internet-connected PC may suffer, such as worms infecting computers, or controllers sending spam messages

Vulnerabilities of ICS

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- **Targeted attacks**
  - The attacker knows that the target is a control system and hence tailors the attack strategy with the aim of damaging the physical system under control
  - Although physical attacks were already famous, cyber-attacks are nowadays more and more exploited as they are cheap, they have long range, and are easy to replicate and coordinate
  - There have been many attacks, however none of them has shown the actual vulnerabilities of control systems as Stuxnet did

Stuxnet

- Stuxnet is a malicious computer worm first discovered in 2010 that targets Supervisory Control and Data Acquisition (SCADA) systems
- It is the first concrete example of a cyberweapon
- It specifically targets PLCs
- It exploited four zero-day flaws
- Targets machines using Windows OS, then Siemens Step7 Software, and finally the PLCs
- Compromised PLCs, collecting information on industrial systems and causing the fast-spinning centrifuges to tear themselves apart

Attack Scenario

- As each PLC is configured in a unique manner, the attackers would first need the ICS's schematics (stoel from an insider or retrieved by an early version)
- Once having that, the attacker can develop the latest version of Stuxnet
- In Stuxnet the attacker's malicious binaries container driver files that needed to be digitally signed. The attackers compromised two digital certificates to achieve it (stole them)

Attack Scenario

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- To infect their target, Stuxnet would need to be introduced into the target environment ➔ infect a willing or unwilling party
- The original infection may have been introduced by removable drive
- Once Stuxnet had infected a computer within the organization it began to spread in search of Field PGs, which are typical Windows computers but used to program PLCs
- Since most of these computers are non-networked, Stuxnet would first try to spread to other computers on the LAN through a zero-day vulnerability

Attack Scenario

- While attackers could control Stuxnet with a command and control server, the key computer was unlikely to have outbound internet access
- All functionalities required to sabotage a system were directly embedded in the Stuxnet executable
- Updates to the executable would be propagated throughout the facility through a peer-to-peer method established by Stuxnet
- When Stuxnet finally found a suitable computer, one that ran Step 7, it would then modify the code on the PLC.

Stuxnet Architecture

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- The heart of Stuxnet consists of a large .dll file that contains many different exports and resources
- Stuxnet also contains two encrypted configuration blocks
- The dropper component of Stuxnet is a wrapper program that contains all of the above components stored inside itself in the “stub” section
- When executed, the wrapper extracts the .dll file from the stub section, maps it into memory as a module, and calls one of the exports

Stuxnet Architecture

- During the execution, Stuxnet runs predefined actions
- The original stub section is continuously passed around between different processes and functions as a parameter to the main payload
  - A pointer to the original stub section is passed to the export as a parameter
  - This export in turn will extract the .dll file from the stub section, which was passed as a parameter, map it into memory and call another different export from inside the mapped .dll file
  - The pointer to the original stub section is again passed as a parameter

Stuxnet Architecture

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- Stuxnet also uses an alternative way to call exports besides loading the .dll file into memory and directly calling the export
- The alternative is to read an executable template from its own resources, populate the template with appropriate data, such as which .dll file to load and which export to call, and then to inject this newly populated executable into another process and execute it
- The newly populated executable template will load the original .dll file and call whatever export the template was populated with

Stuxnet Exports

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DLL Exports

Export #	Function
1	Infect connected removable drives, starts RPC server
2	Hooks APIs for Step 7 project file infections
4	Calls the removal routine (export 18)
5	Verifies if the threat is installed correctly
6	Verifies version information
7	Calls Export 6
9	Updates itself from infected Step 7 projects
10	Updates itself from infected Step 7 projects
14	Step 7 project file infection routine
15	Initial entry point
16	Main installation
17	Replaces Step 7 DLL
18	Uninstalls Stuxnet
19	Infects removable drives
22	Network propagation routines
24	Check Internet connection
27	RPC Server
28	Command and control routine
29	Command and control routine
31	Updates itself from infected Step 7 projects
32	Same as 1

Injection Technique

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- Whenever an export is called, Stuxnet typically injects the entire DLL into another process and then just calls the particular export
- When injecting into a trusted process, Stuxnet may keep the injected code in the trusted process or instruct the trusted process to inject the code into another currently running process
- The trusted process consists of a set of default Windows processes and a variety of security products (Kaspersky, McAfee, Symantec,..)

Injection Technique

- In addition, the registry is searched for indicators that the following programs are installed
  - KAV v6 or v9
  - McAfee
  - Trend PcCillin
- If one of the above security product processes are detected, version information of the main image is extracted
- Based on the version number, the target process of injection will be determined or the injection process will fail if the threat considers the security product non-bypassable

Behavior Blocking Bypass

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- Stuxnet uses a special method to load DLLs and be able to bypass behavior-blocking and host intrusion-protection that monitor LoadLibrary calls
- Stuxnet calls LoadLibrary with a specially crafted file name that does not exist on disk and normally causes LoadLibrary to fail
- The filenames used have the pattern of KERNEL32.DLL.ASLR.[HEXADECIMAL] or SHELL32.DLL.ASLR. [HEXADECIMAL], where the variable [HEXADECIMAL]is a hexadecimal value.

Distribution and Target Determination

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- Stuxnet is bigger and more complex than conventional worms
- However, the attackers relied on local distribution via USB stick and local networks
- While Stuxnet infected any Windows PC on its path, it only targeted Siemens' controllers
- The infection from PC to controller happens via Ethernet, Profibus, or Siemens' proprietary protocol
- It uses a complex process of fingerprinting to ensure that it is on target

Distribution and Target Determination

- Fingerprinting includes model number, configuration details, downloading the program code of the controller
- If match, then Stuxnet drops rogue code to the controller
- The rogue driver DLL contained three controller code sets: two (infection A and B) destined to a Siemens 315 controller, and one (infection C) to a 417 controller
- The latter is more complicated and four times the size of the former
- 417 is Siemens' top-of-the-line product

Controller Hijacking

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- The rogue code was logically structured in a set of subfunctions
- The attackers' goal was to get any of these functions called
- Stuxnet achieved this goal by injecting code into an executive loop
- Both 315 and 417 attack codes used the main cycle for this purpose, the 315 also used the 100-ms times (interrupt handler)
- Stuxnet only occasionally takes over the main code and normal behavior

Controller Hijacking

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- Whenever an export is called, Stuxnet typically injects the entire DLL into another process and then just calls the particular export
- The trusted process consists of a set of default Windows processes and a variety of security products
  - Kaspersky KAV, Mcafee, AntiVir, BitDefender, Etrust
- In addition, the registry is searched for indicators that the following programs are installed
  - KAV v6 to v9, McAfee, Trend PcCillin
- If one is detected, version information of the main image is extracted, and decision is made on whether is possible or not to infect

Removable Drive Propagation

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- One of the main propagation methods Stuxnet uses is to copy itself to inserted removable drives
- ICS are commonly programmed via Windows computers that are non-networked and operations usually exchange data using removable drives
- Stuxnet used two methods to spread to and from removable drives
  - vulnerability that allowed auto-execution when viewing the removable drive
  - using an autorun.inf file

LNK Vulnerability (CVE-2010-2568)

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- The removable-drive copying is implemented by exports 1, 19, and 32
- Export 19 must be called by other code and then it performs the copying routine immediately
- Exports 1 and 32 both register routines to wait until a removable drive is inserted
- Exports 1 and 32 both register routines to wait until a removable drive is inserted

LNK Vulnerability (CVE-2010-2568)

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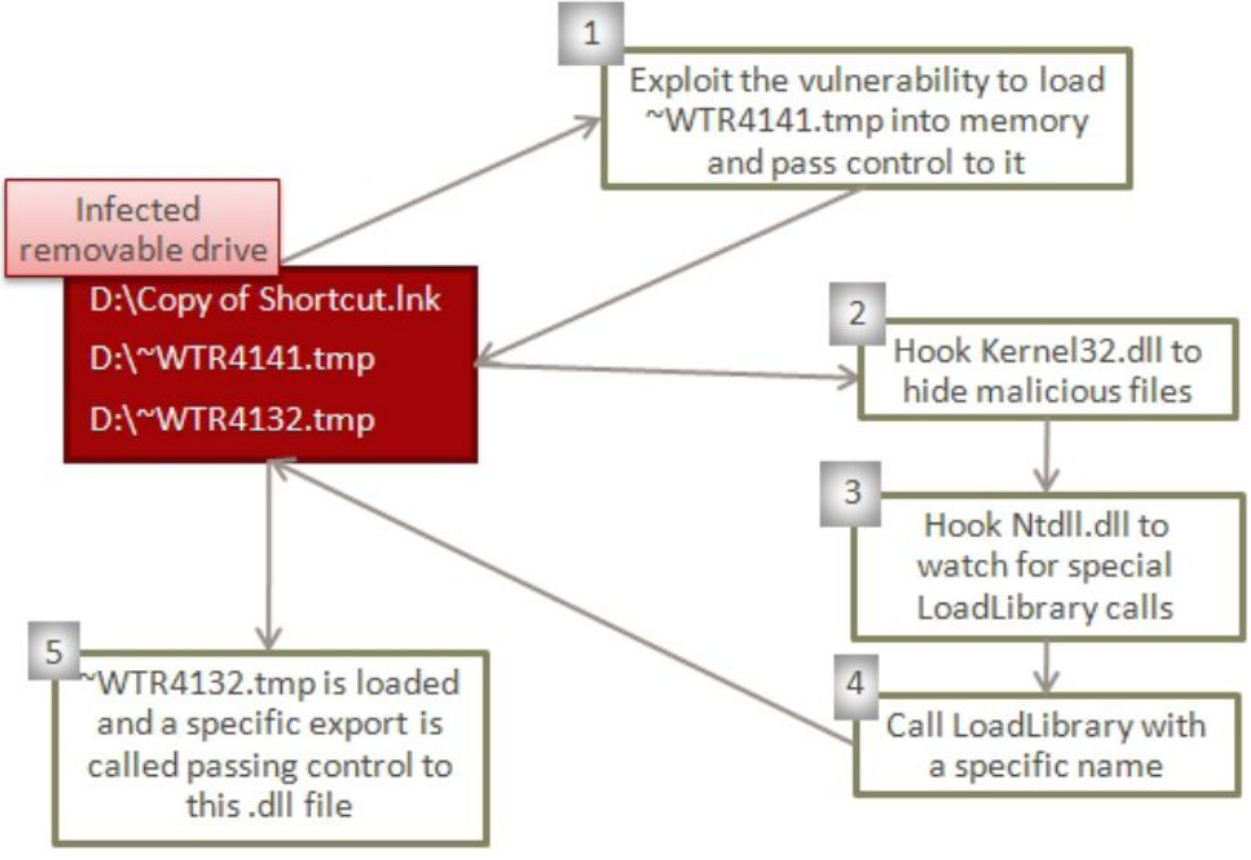
- If called from Export 1 or 32, Stuxnet will first verify it is running within services.exe, and determines which version of Windows it is running on
- It creates a new hidden window with the class name 'AFX64c313' that
  - waits for a removable drive to be inserted (via the WM_DEVICECHANGE message)
  - verifies it contains a logical volume (has a type of DBT_DEVTYP_VOLUME)
  - is a removable drive (has a drive type of DEVICE_REMOVABLE)
- It created a list of .lnk files that contain an exploit that will automatically execute a .tmp when viewing the folder and hook kernel APIs

USB Execution Flow



Modifying PLCs

- the end goal of Stuxnet is to infect specific types of Simatic programmable logic controller (PLC) devices
- PLC devices are loaded with blocks of code and data written using a variety of languages, such as STL or SCL
- The compiled code is an assembly called MC7
- To access a PLC, one needs a specific software (e.g., WinCC/Step 7)
- With this software installed, the programmer can connect to the PLC with a data cable and access the memory contents, reconfigure it, download a program onto it, or debug previously loaded code

Modifying PLCs

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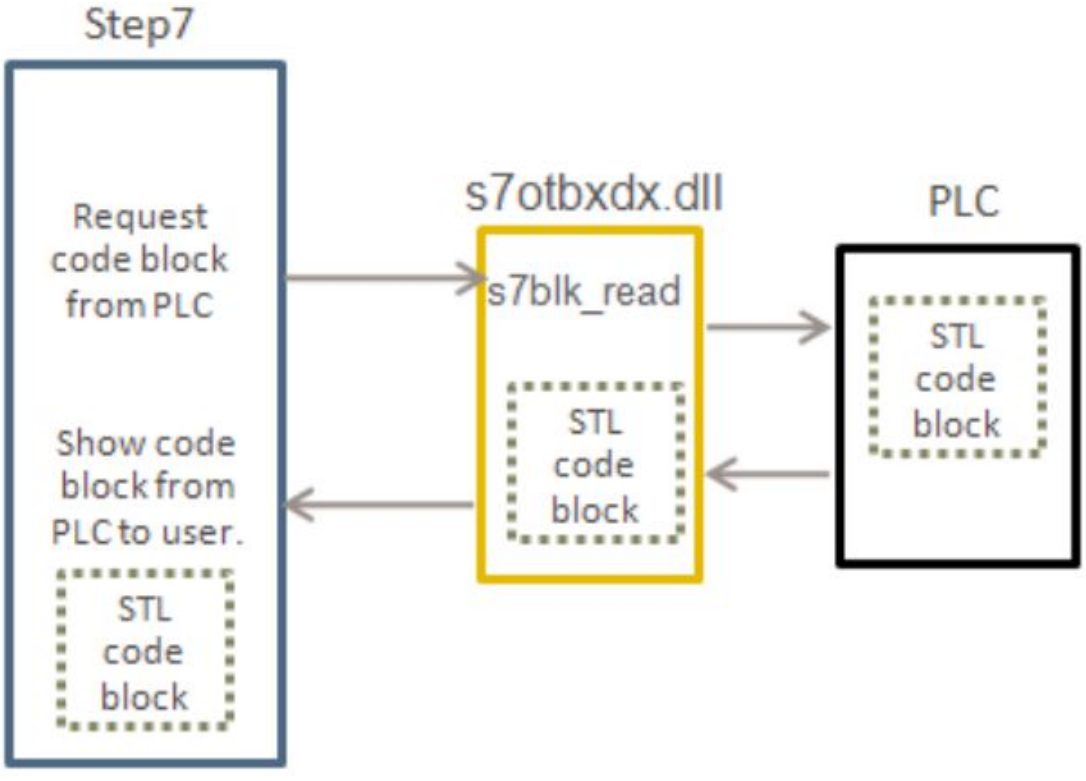
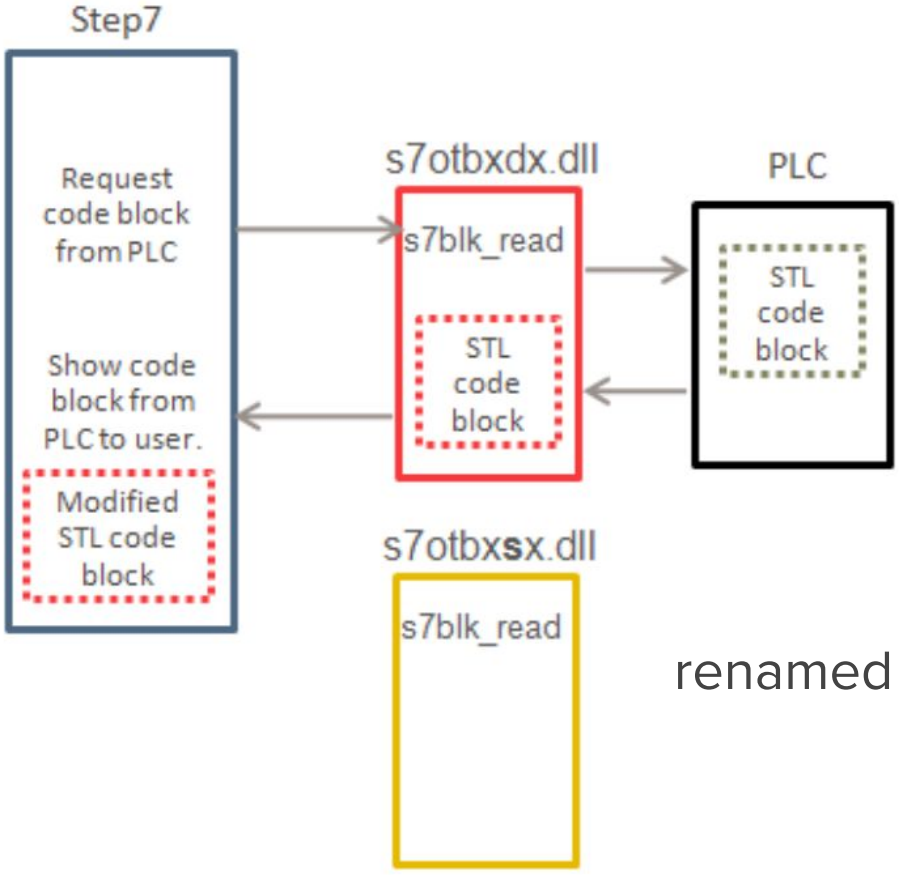
- Step 7 uses a library file called s7otbxdx.dll to perform the actual communication with the PLC (block exchange)
- Stuxnet aims at replacing the s7otbxdx.dll file responsible of handling PLC block exchange between a programming device and the PLC
- By replacing this file, Stuxnet can
  - Monitor PLC blocks being written to and read from the PLC
  - Infect a PLC by inserting its own blocks and replacing or infecting existing blocks
  - Mask the fact that a PLC is infected

Modifying PLCs



Modifying PLCs



Modifying PLCs

- Stuxnet renames the original s7otbxdx.dll file to s7otbxsx.dll
- It then replaces the original .dll file with its own version
- It can now intercept any call that is made to access the PLC from any software package
- Stuxnet's s7otbxdx.dll file contains all potential exports of the original .dll file
- The majority of these exports are simply forwarded to the real .dll file
- The trick is in 16 non-forwarded but intercepted exports, where intercepted exports are the routines to read, write, and enumerate code blocks on the PLC, among others

Modifying PLCs

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- By intercepting these requests, Stuxnet can modify the data sent to or returned from the PLC without the operator of the PLC realizing it
- Thanks to these routines, Stuxnet is able to hide the malicious code on the PLC
- Types of blocks:
  - Data blocks contain program-specific data, such as numbers, structures
  - System Data Blocks (SDB) contain information about how the PLC is configured
  - Organization blocks are the entry point of programs cyclically executed by the CPU

Attack Behavior

- The attacks were triggered by complex timer and process conditions
- Initial state: attack code just stays put and let the legitimate controller code do its thing
- Strike time: take over control without the legitimate controller noticing
- For the 315 attack, execution of legitimate code simply halted during the strike condition
- 417 attack implemented a man-in-the-middle attack on the controller, intercepting the interaction between the legitimate control program and physical I/O

Attack Behavior

- Similar to a computer application that does not directly access any physical interface registers of an I/O chip (such as Ethernet, USB, or serial), but would use data from the driver's buffer
- Providing the legitimate program code with a fake process image
- The fake data that the 417 attack code fed to the legitimate controller program was recorded from real, unsuspicious inputs
- Stuxnet replayed prerecorded input to the legitimate code during the attack

Infection Thread A and B

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- This thread runs the infection routine every 15 minutes
- Check if PLC type is 6ES7-315-2 via API call
- The SDB blocks are checked to determine whether the PLC should be infected (check whether it is using Profibus identification numbers 7050h and 9500h, i.e., frequency converters)
- The DP_RECV block (used to receive Profibus frames) is copied to FC1869, and then replaced by a malicious block embedded in Stuxnet
- The malicious blocks of the selected infection sequence are written to the PLC

Infection Thread A and B

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- Organization Block (OB) 1 is infected so that the malicious code sequence is executed at the start of a cycle
  - Increase the size of the original block
  - Write malicious code to the beginning of the block
  - Insert the original OB1 code after the malicious code

- OB35 is also infected. It acts as a watchdog, and on certain conditions, it can stop the execution of OB1

Behavior of Infected PLC by A/B

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- DP_RECV is the name of a standard function block used by network coprocessors, used to receive Porfibus network frames
- The infection of a 315-2 is organized as follows
- The replaced DP_RECV block (referred to as DP_RECV monitor) is meant to monitor data sent by the frequency converter drives to the 315-2 CPU via Profibus
- Up to 6 CP 342-5 Profibus communication modules are supported
- The addresses of the CP 342-5 modules are recorded

Behavior of Infected PLC by A/B

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- Frames sent over Profibus are inspected. They are expected to have a specific format.
- Each frame should
- have 31 records—one for each slave—of either 28 or 32 bytes as the format differs slightly for the two different frequency converter drives.
- Some fields are stored.

Behavior of Infected PLC by A/B

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- The other blocks implement a finite state machine
- In state 1 fields recorded by the DP_RECV monitor are examined to determine if the target system is in a particular state of operation. When enough fields match simple criteria, a transition to state 2 occurs.
- In state 2 a timer is started. Transitioning to state 3 occurs after two hours have elapsed.

Behavior of Infected PLC by A/B

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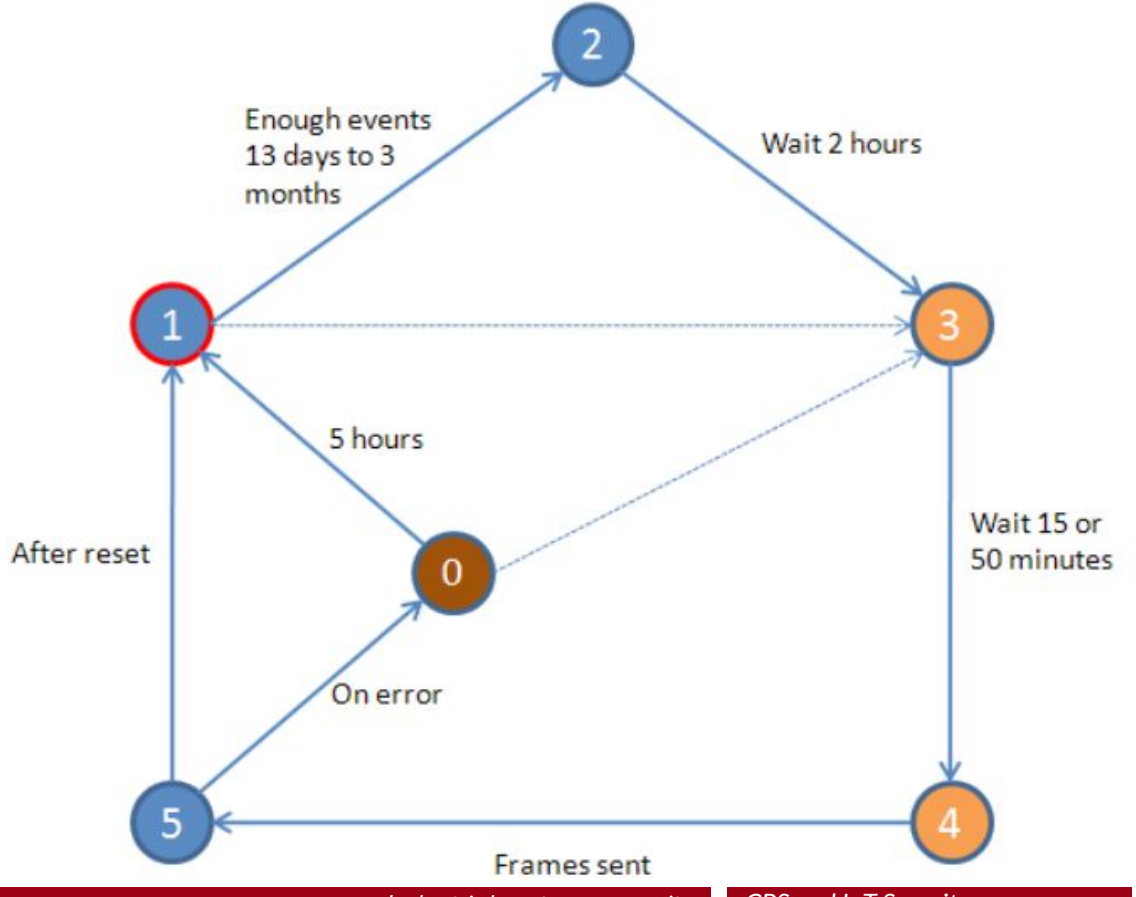
- In states 3 and 4, semi-fixed network frames are generated and sent on the Profibus to DP slaves
- The content partially depends on what DP_REECV monitor has recorded
- State 5 initiates a reset of various variables used by the infection sequence before transitioning to state 1. Transitioning to state 0 may also occur in case of errors.
- In state 0, a 5-hour timer is started

Behavior of Infected PLC by A/B



Behavior of Infected PLC by A/B

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- The initial state is 1 and transitioning to state 2 can take a fair amount of time
- The code specifically monitors for records within the frames sent from the frequency converter drives that contain the current operating frequency (speed of device being controlled) ➔ referred to as PD1
- Frequency values can be represented in Hz or deciHz, and are in the range 807-1210 Hz
- If value(PD1) > 1210, the code assumes is represented in deciHz and adjusts all frequency values by a factor of 10

Behavior of Infected PLC by A/B

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- The data in the frames are instructions for the frequency converter drives
- E.g., one of the frames contains records that change the maximum frequency (the speed at which the motor will operate)
- The frequency converter drives consist of parameters, which can be remotely configured via Profibus
- Thus, one can write new values to these parameters changing the behavior of the device

Behavior of Infected PLC by A/B

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- For sequence A, the maximum frequency is set to 1410 Hz in sequence 1a, then set to 2 Hz in sequence 2a, and then set to 1064 Hz in sequence 2b
- The normal operating frequency at this time is supposed to be between 807 Hz and 1210 Hz
- Thus, Stuxnet sabotages the system by slowing down or speeding up the motor to different rates at different times
- When a network send (done through the DP_SEND primitive) error occurs, up to two more attempts to resend the frame will be made

Behavior of Infected PLC by A/B

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- During states 3 and 4, the execution of the original code in OB1 and OB35 is temporarily halted by Stuxnet
- Likely used to prevent interference from the normal mode of operation while Stuxnet sends its own frames
- short-circuits, used to transition directly through states 0 and 1 to state 3, were planned and implemented
- However, they appear to be disabled, which means the wait period for the transition from 1 to 2 cannot be avoided

Behavior of Infected PLC by A/B

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- When reaching states 3 and 4, the original PLC code is halted and the malicious PLC code begins sending frames of data based on the recorded values during the DP_RECV monitor phase
- The purpose of sending the frames is to change the behavior of the frequency converter drives
- Each record sent changes a configuration, such as the maximum frequency on the frequency converter drive

Summary

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- The PLC is infected
- Frequency converter slaves send records to their CP342-5 master, building a frame of 31 records The CPU records the CP-342-5 addresses
- The frames are examined and the fields are recorded
- After approximately 13 days, enough events have been recorded, showing the system has been operating between 807 Hz and 1210 Hz
- The infected PLC generates and sends sequence 1 to its frequency converter drives, setting the frequency to 1410Hz

Summary

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- Normal operation resumes
- After approximately 27 days, enough events have been recorded
- The infected PLC generates and sends sequence 1 to its frequency converter drives, setting the frequency to 1410Hz
- Normal operation resumes
- After approximately 27 days, enough events have been recorded
- The infected PLC generates and sends sequence 2 to its frequency converter drives, setting the frequency initially to 2Hz and then 1064Hz
- .....