Cyber-Physical Systems Security Using AI: A Comprehensive Threat Analysis and Attack Modeling

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Abstract. In the early phases of the system development life cycle, cyber threat modelling is an analytical technique that helps select security needs and detect possible risks to a system. Therefore, one of the most important tools for implementing the secure-by-design approach is threat modelling. Though widely used in software development projects, its application to cyber-physical systems still needs to be systematically developed. One of the biggest challenges facing system development teams is the intricate relationships between cyber and physical locations and how they affect the cyber threat scenario. This paper explores the intricate realm of AI-driven security for cyber-physical systems, highlighting how artificial intelligence can be utilized to safeguard these critical infrastructures against evolving threats. It will address the specific challenges of CPS security, the role AI can play in overcoming these obstacles and the practical applications of AI-enhanced security across different industries. By providing detailed analysis, case studies, and forward-thinking strategies, this piece aims to offer a thorough understanding of both the current landscape and future possibilities of AI in securing cyber-physical systems. In-depth examination of attacks using behavioural modelling is presented in this paper.

Keywords: AI-driven Security, Attack Modelling, Cyber-physical Systems, Threat Analysis.

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1 Introduction

Cyber-physical systems (CPS) integrate physical and computational components to create complex systems that use networks and embedded computers to monitor and manage physical processes [6]. Higher levels of automation, efficiency, and performance have been made possible by this integration, which has had a substantial impact on a number of industries, including healthcare, transportation, manufacturing, and smart grids [5]. By efficiently interacting with the physical world through the use of cutting-edge technology including embedded systems, sensors, actuators, and communication networks, CPS turns conventional systems into sentient and intelligent beings.

A considerable rise in the number of systems that connect digital (cyber) systems to the real world—known as the Cyber-Physical System (CPS)—has resulted from advancements in digital electronics [3].The rapid development of cyber-physical systems (CPSs) in recent years can be attributed to advancements in communication, computation, and related hardware technologies.Cyber-physical systems (CPS) are intricate systems that include network connectivity, computer methods, and physical processes [4]. These systems, which are usually found in the fields of industrial automation, healthcare, smart infrastructure, and transportation, are made to continuously monitor, control, and optimize physical processes.The substantial advancements in the fields of computer and communication have led to the growing involvement of Cyber-Physical Systems (CPSs) in a number of essential infrastructures, including energy, transportation, health, etc. When developing and validating these systems, a lot of attention has been paid to their safety; yet, human malevolence in the form of cyberthreats is sometimes overlooked.

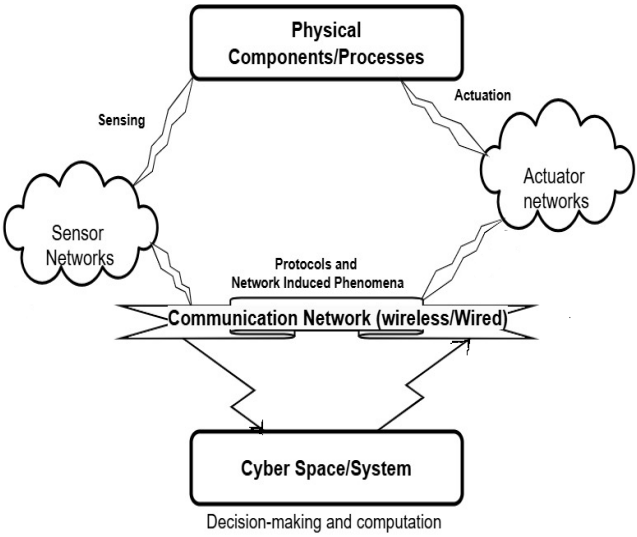

Figure 1. A CPS from a holistic perspective

Figure 1 present a CPS from a holistic perspective. In Cyber-Physical Systems (CPS), open networks provide strong productivity and cost benefits for communication. CPS must have an internet connection due of its increasing reliance on cloud computing. But this connectedness also makes them more susceptible to deliberate attacks. The reasons behind attacks might be anything from economic gain to terrorism. Modern CPSs are complex, making it difficult to build and maintain them securely, and CPS assaults are becoming more frequent.

Individuals' safety and privacy may be jeopardised by security lapses in CPS, particularly when people are involved. One of the main causes of CPS's vulnerabilities is its intrinsic complexity and diversity. Critical certified components frequently coexist with systems that were constructed with less stringent security requirements.. Additionally, the quick spread of assaults is facilitated by the extensive interdependencies across CPS components.

Security is frequently done piecemeal and as an afterthought, which is a serious risk. A comprehensive system-level security study is rarely carried out, while individual components may have particular security measures. A unified security approach is hampered by the possibility that multiple methods, even when tried, may be applied to separate areas of the system (such as databases versus wireless devices). In order to successfully reduce risks, a thorough security plan is essential to stop or at least lessen the effects of any possible attacks.

In order to successfully reduce risks, a thorough security plan is essential to stop or at least lessen the effects of any possible attacks. Attacks on CPS are categorised in Figure 2.

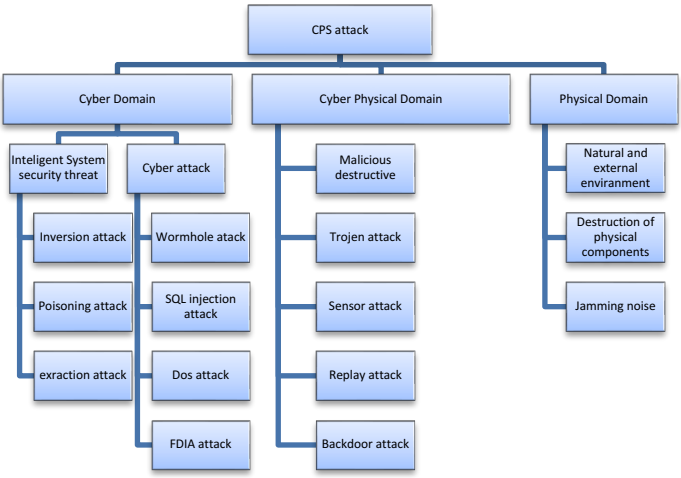

Figure 2 The classification of CPS attacks [1]

2 Threat Analysis

In today's interconnected world, organizations and individuals alike face a growing number of potential threats. These risks can take many forms, such as physical security breaches that result in damage or interruption or cyberattacks that target sensitive data. Proactive action is necessary to reduce these hazards as much as possible. As a fundamental component of this proactive approach, threat analysis recognizes, evaluates, and comprehends possible risks prior to their exploitation.

A threat is something that might occur or it might not, but it has the potential to seriously harm a network and its data. Attacks on computer systems, networks, and other systems can result from threats. An open Internet exposes data and resources to a constant threat to security and privacy. Analyzing the behavior of each and every threat type is necessary in order to design security solutions. Threat modeling is the process of identifying and mitigating potential threats to a system. It was originally developed to enhance software security during the design phase but has since been adapted for Industrial Control Systems (ICSs). ICSs are complex and interconnected systems that control critical infrastructure, such as power plants, water treatment facilities, and manufacturing plants. As such, they are major targets for cyberattacks, which may lead to human casualties, severe national security impacts, and financial instability.Cyber-physical systems (CPS) incorporate physical and computer components to create a complex environment that is susceptible to special risks. To secure these systems, a comprehensive threat analysis is required. Depending on the layer they target, CPS threats can be divided into several categories: Physical Layer: tampering with communication infrastructure, actuators, or sensors [7]. This may entail altering data or interfering with ongoing business activities. Information Layer: Focusing on the network that links the various CPS components together to transfer data. Eavesdropping, data manipulation, and denial-of-service assaults are examples of common dangers. Application Control Layer: Interrupting activities by taking advantage of flaws in software or control systems. This could entail introducing malware or changing control commands [8].

2.1 CPS Threat Examples

An actual example that targets nuclear facilities in Iran is the Stuxnet Worm. Stuxnet physically damaged centrifuges by manipulating industrial control systems [9]. Attacks on Smart Grids: By altering control systems, hackers could cause widespread blackouts by disrupting electricity grids.

3 Threads in CPS

3.1 Physical Cloning of CPS Components

Untrusted device manufacturers often develop clones of their products that have exact duplicates of the actual thing's link-layer characteristics, security settings, and unique identify. These counterfeit devices are offered at a reduced price in the market to draw in buyers. These devices provide an attacker with the ability to compromise authentic equipment or reduce their functionality. The maker of cloned items has the ability to monitor data flow over the network and may launch node replication and Sybil attacks. Every private application has the potential to have a backdoor implemented by the maker. Due to a poor authentication process, tags can be easily copied in an RFID system [10]. Cloned settings could be used by attackers to take over and obtain unauthorized access to other CPS devices on the network.

3.2 Commissioning process in CPS

When a new device or component is incorporated into the CPS system during the commissioning process, specific security vulnerabilities are introduced. Things may be open to eavesdropping attacks when they are first put into service. Wireless media can compromise configuration settings, security parameters, and keying materials most commonly. Once the attacker has access to keying material, it may be possible for them to retrieve the secret key, jeopardizing the validity and secrecy. Communication routes that are not adequately secured may be used for eavesdropping, or a prolonged period of use without key renewal or upgrades may jeopardize the session key.

A new device may be given temporary network access during commissioning for configuration reasons. It is possible for malicious actors to permanently obtain unauthorized access to the CPS by taking advantage of this transitory access. Inadequate authorization or authentication protocols during commissioning may enable unauthorized devices to pose as valid ones and obtain entry to the system.

3.3 Malicious replacement of Nodes

In the network of participating nodes, an attacker may occasionally add a new node with signed node identifying information. Malicious activity is taking place on the node that has been replaced. Lower-quality sensors may occasionally be added to the network in an effort to reduce costs and boost system revenue. The system's performance is impaired as a result of the attacker's discovery of these low-quality nodes and subsequent malicious targeting of them. In order to observe network activity, an attacker can simultaneously redirect the route of a packet toward a malicious server.

3.4 Untrustworthy communication

The question of data integrity arises when we use an untrustworthy communication link. A man-in-the-middle attack can be carried out by the attacker using this shaky communication channel as a target. The message may not be successfully delivered despite the shaky communication link. In the event that a packet is not delivered to its intended destination, it is retransmitted, which lowers system performance. The system's throughput is impacted by the length of time it takes to reach the destination as a result of repeated retransmissions. Ding et al. [2] gives a survey on security control and attack detection for industrial cyber-physical systems.

3.5 Inadequate testing and patching

The most prevalent and significant issue that the CPS faces is inadequate patching. Most of the time, the system supervisor overlooks the patching issue. The antiquated gadgets could be plagued by software problems, incompatibilities with other gadgets, outdated protocols, or vulnerabilities or flaws. As a result, attackers may utilize these vulnerabilities as a means of breaking system security.

In order to protect the system from the aforementioned vulnerabilities, patching is necessary. In order to keep the system stable, it is now crucial to watch over and test each updated path. Inadequate testing and patching also allow an attacker to gain access to a system and launch a cloning attack or viruses.

3.6 Phishing

This type of social engineering assault involves the theft of confidential user information, such as credit card numbers or login credentials. Although this kind of attack is not new, companies are still unable to fully defend against sophisticated social engineering attacks, despite increased awareness of these attacks. There are several outcomes to this attack.

4 Attack Modeling for Cyber-physical systems

Cyber-physical systems (CPS) are becoming more widespread in vital infrastructure, industrial processes, and everyday life. These sophisticated combinations of computational and physical aspects provide tremendous benefits while also posing new security challenges. Unlike standard IT systems, CPS vulnerabilities might show in both the cyber and physical worlds, potentially resulting in catastrophic outcomes. To properly safeguard these systems, a proactive strategy to recognizing and mitigating possible threats is required. Attack modeling offers a formal framework for examining system vulnerabilities and comprehending attacker motivations and capabilities. Simulating hypothetical attack scenarios can reveal security flaws before they are exploited. This proactive approach enables the creation of specific countermeasures and mitigation tactics, hence improving the CPS's overall security posture.

5 In order to create focused defenses and mitigation measures while the system is in operation, attack modeling explores specific attacker tactics, techniques, and procedures which may not be confined to cyber but may involve physical acts [11].

5.1 Sybil Attack

Every single device in a cyber-physical system has a unique identification. Malicious nodes use a separate communication route to interact with other nodes in this attack. The attacker produces a duplicate identity of the real node and hides behind it in order to establish identification. Figure 3 is present in several locations at once of the attacker. Identity spoofing is one way to accomplish this [12]. Device 1 gains access from the server upon authentication, as shown in Figure 4. Subsequently, an attacker obtains the identity verification of device 1 from the server and initiates communication with the other device by assuming the role of device 1 interacting with device 2. During this procedure, device 1's id proof is compromised, and the attacker uses it to acquire data from device 2.

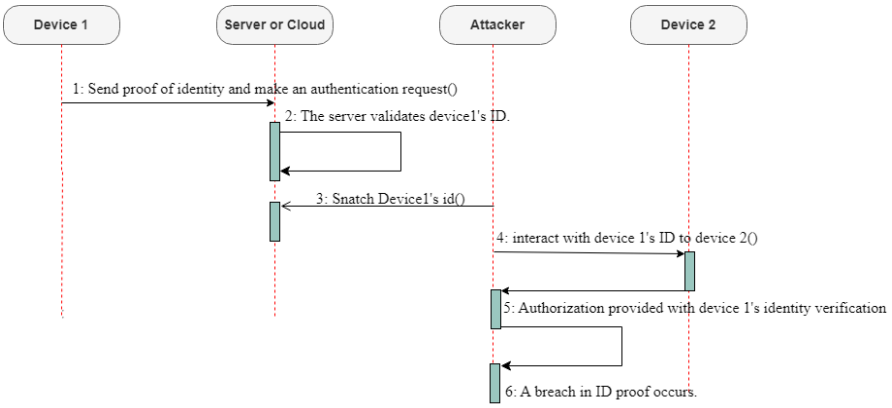

Figure 3. Sybil Attack

5.2 Deception attack

A form of cyberattack known as a deception attack involves altering the data integrity of packets transported between various cyber-parts. For example, Stuxnet worms have the ability to rewrite code in programmable logic controllers (PLCs) in SCADA systems, causing the systems to behave differently than intended.

Hackers may use remote terminal units (RTUs), such as sensors in substations, to initiate assaults in power grid transmission systems. [18]. This kind of attack involves tracking or changing data as it moves across the network. By inserting fictitious information into the data packet, the attacker modifies its contents. Through the execution of this attack, the attacker introduces more impurities into the sensor data, so impeding the victim's research. It can be categorized as a DoS attack. Decisions are made poorly by the tainted data. The perpetrator introduces within-acceptable-range contaminants into the victim's database. Therefore, the victim finds it extremely difficult to identify and distinguish between contaminants in the dataset. There are several viable options offered for preventing this attack [13]. Figure 4 illustrates the process of a data integrity attack. Any valid network node is the target of an attacker during a data integrity assault. Once within that node, the attacker inserts malicious code. This compromised node functions as a hostile node. A malicious node's code can be altered by an attacker, which modifies the data that bad node transmits.The network's other nodes will all get this flawed data.

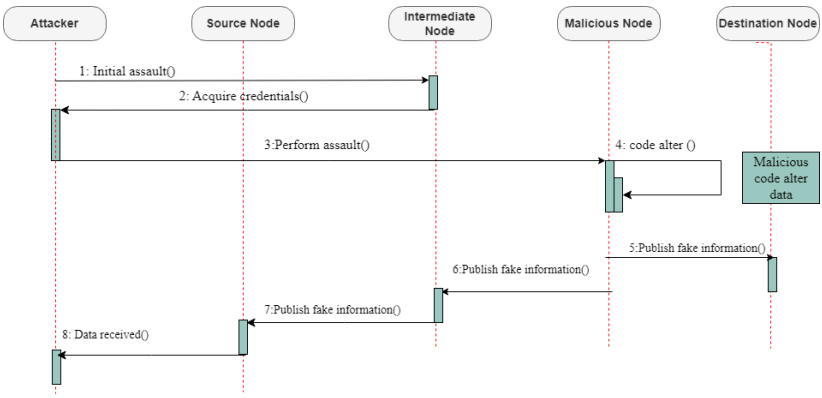

Figure 4. Deception attack

5.3 Node Replication attack

This attack is independent of application. Attackers start by seizing control of a single authentic node and collecting data such as code, secret credentials, and cryptographic material. If necessary, they can then alter the node's behavior and modify the code. The identical image is replicated by another attacker to a different node, which is then placed in the environment. Such an attack can do a great deal of damage. The general-purpose security and authentication techniques are capable of overcoming this attack [14].

Figure 5 depicts the node replication attack's behavior. This communication involves multiple entities. Any legitimate node on the network is the target of the attacker's initial attack. Attackers examine every vulnerable root that allows them to access the network prior to launching their attack. Attackers gather all of the confidential data from the node, including credentials and secret keys, as soon as they are able to control a genuine node. Once an attacker obtains this legitimate node's information, they will alter it. The attacker will require that the same data be inserted into the node's memory. Following that, these compromised nodes follow the attacker's instructions. By doing this, a hacker can cause instability in the target network.

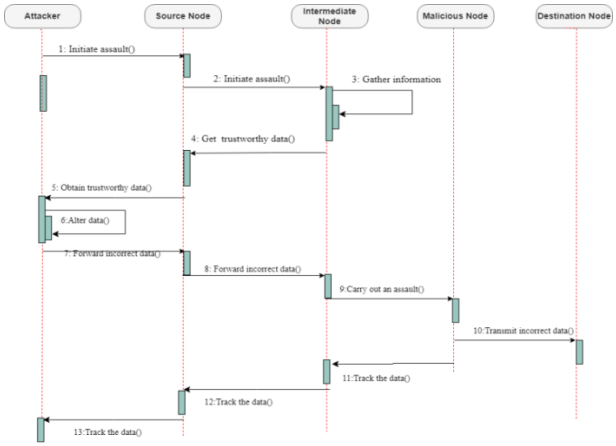

Figure 5. Node replication attack

5.4 Denial of Service (DoS) attack

In recent years, cyber-physical systems (CPSs) have drawn a lot of attention due to advancements in communication technologies and increased processing capacity. Complex cyber systems, or CPSs, integrate computation, communication, and control. They are extensively employed in a wide range of applications, including health monitoring and smart grids and intelligent transportation systems. When transmitting information, CPSs are extremely susceptible to attacks from malevolent actors. The two most popular and practical forms of attacks currently in use are denial-of-service (DoS) attacks and data deception attacks [15].

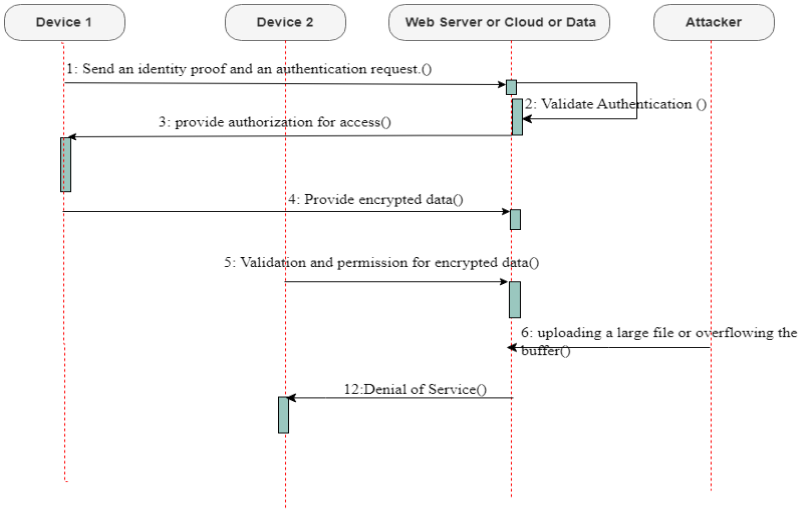

Figure 6. Denial of Service (DoS) attack

A denial-of-service attack aims to render system resources inaccessible.From a technological perspective, an attacker can alter the routing protocol, jam the shared network medium to stop devices from sending or receivingdata, or fill buffers with user or kernel domains. An attempt is made by theattacker to stop users from accessing resources or services.

Although harmful, DoS is hard to execute. Request packets are sent incessantly to the server by the attacker. There will be server downtime if the server cannot manage this volume of requests [18].After its identification is confirmed, device 1 in Figure 6 is able to access services from the server. The designated device then retrieves the encrypted data that device 1 sent to the server. After device 2 authenticates with the server, it seeks to access encrypted data that device 1 has stored there. When an attacker uploads a huge file to a server at the same time or gives it data continually, device 2 is unable to get the encrypted file it has requested from the server, which causes a buffer overflow and stops the server from serving device 2. In this manner, the attacker carries out the DoS attack.

5.5 Replay Attack

A replay attack is a tactic that naturally occurs when a legitimate data transmission is illegally or maliciously replayed or delayed. Due to the capacity to pass cryptographic key examination, such an attack is difficult to detect and ultimately breaches CPS timing limitations. Adversaries can establish a communication channel (a wormhole tunnel) between two end points in order to repeat messages seen in separate locations in wormhole assaults, which are frequently seen in wireless sensor networks (WSNs) [18]. It is a kind of network attack where data is repeatedly transferred to the destination node while data transmission on an authenticated channel is monitored using valid user credentials. The guy in the middle or the message's author can carry out this attack. It also resembles a man-in-the-middle attack [12].Figure 7 shows a representation of the replay assault sequence diagram. Attackers target reputable network nodes in this kind of assault, gathering all data from the intermediary node in the process. The hacked node is given an identity. Using malicious nodes, the attackers can direct traffic toward the hacked server or disseminate false information throughout the network. Either the source node or the malicious node repeats valid data that is relayed. Data can be intercepted and altered by malicious nodes as well.

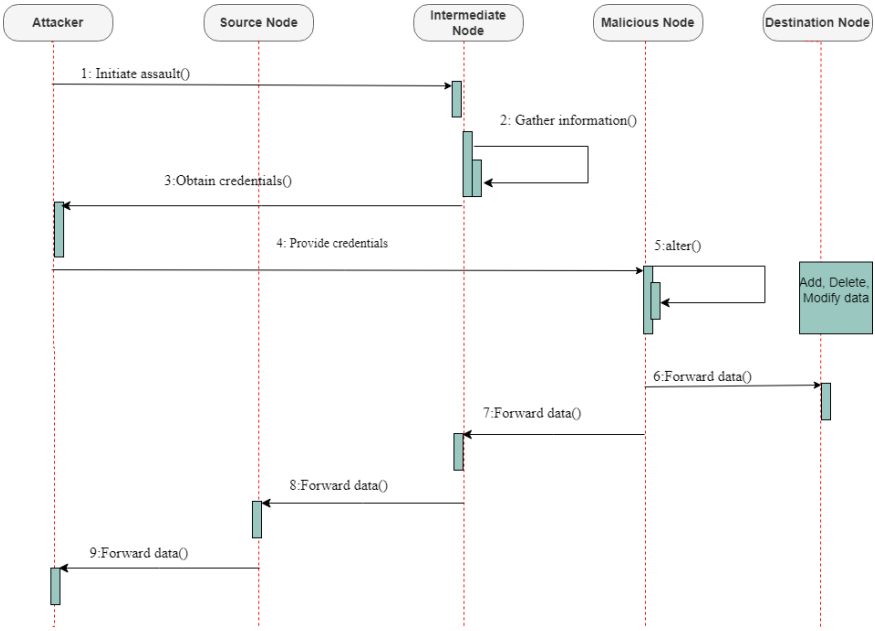

Figure 7 Replay Attack

5.6 Man in Middle attack

In Man in Middle attack, the attackers attempt to gain control of the communication link that connects the endpoints. This attack compromises the confidentiality and integrity of data. It is also known as bucket brigade or fire brigade attack. This attack has several variants. In this type of attack, the attacker can manipulate data while two parties are communicating, and we believe they are communicating directly [16]. Figure 8 demonstrates the vulnerability of a public key cryptosystem. Public key cryptosystems require key exchange for communication between two devices. When device A wants to communicate with device B, it asks device B for the public key.An attacker intercepts the request and sends their own public key to device A. So anything sent from device A to device B is intercepted and read by anattacker. To continue communication, the attacker re-encrypts this data using device B's public key before sending it to device B. The attacker also sends its public key as A's public key to device B.

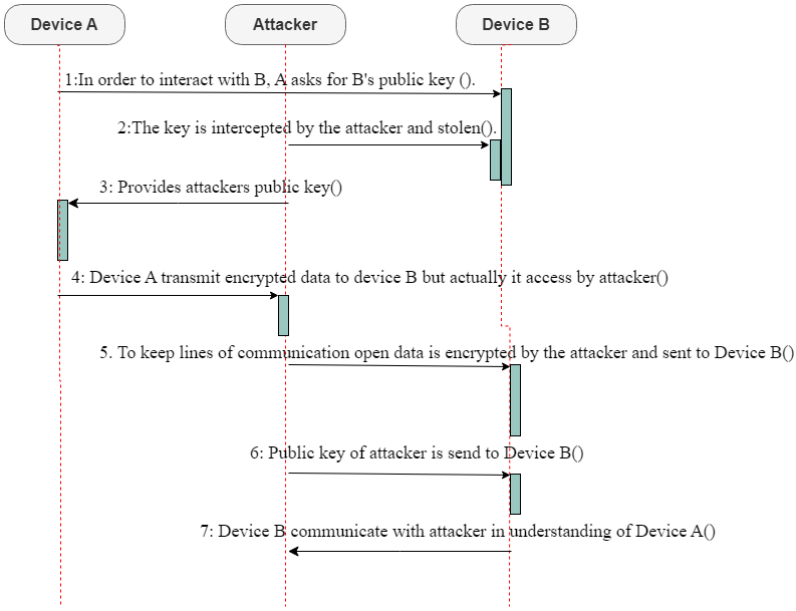

Figure 8. Man in Middle attack

5.7 Sniffing

It is an application that monitors network traffic. This sniffing is essential for both monitor authenticated networks and the theft of network information. These unauthorized sniffers are extremely dangerous since they are difficult to detect and can be placed at any node in the network. This increases the popularity of sniffing attacks throughout the attacker group [17].

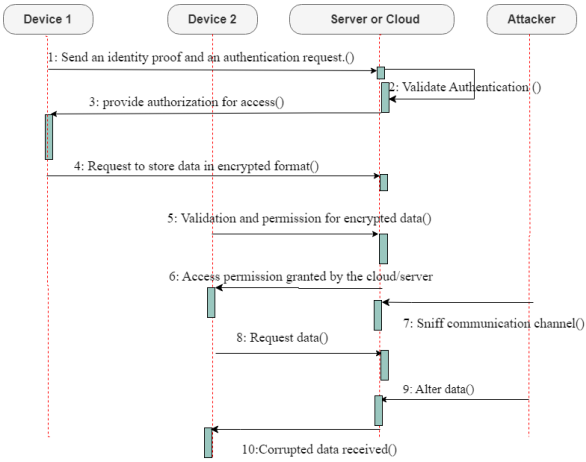

Figure 9. Sniffing attack

Figure 9 illustrates how devices 1 and 2 communicate with each other through a server. The encrypted data is stored and accessed by device 2, which the attacker monitors or sniffs. Ultimately, the attacker obtains the intended data that device 1 sniffs during the server storage process. The attacker then modifies the encrypted data, causing device 2 to receive corrupted data.

5.8 Ransomware

This type of malware prevents the victim from accessing its own resources, such as crucial computer data, and then demands payment to lift the restrictions. Phishing emails and USB sticks that carry malicious software or files are two extremely popular entry points for these Ransomwares

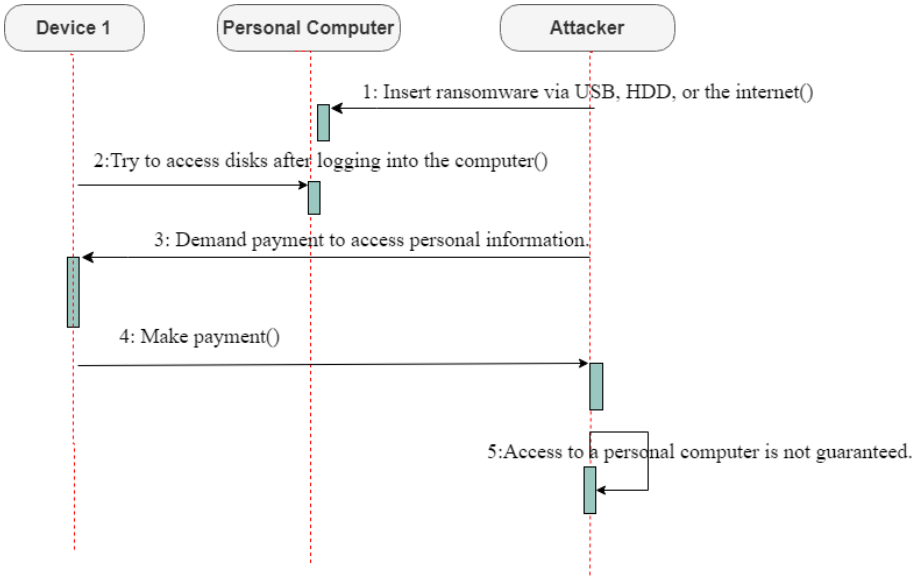

Figure 10. Ransomware Attack

Figure 10 shows how an attacker can infiltrate a system using USBs, external hard drives, or email attachments. This allows worms or viruses to enter the system and obstruct drives and personal data. An attacker requests payment to unlock personal files when the device tries to access personal data. Even if the device pays, the attacker cannot ensure that its disks or personal data will be accessible. The infection now prevents the victim from using its own resources, such as crucial computer files, and demands a ransom. Only the attacker releases the victim's resources after money has been received.

6 The Impact of AI on CPS Security

Artificial Intelligence provides a robust set of capabilities to tackle the distinct security challenges faced by cyber-physical systems. By utilizing data analysis, machine learning and autonomous decision-making, AI can strengthen CPS's security and resilience in a number of significant ways:

- Data Analytics and Predictive Maintenance: AI can anticipate any malfunctions or vulnerabilities in CPS components before they result in security problems by evaluating historical data and real-time sensor information.
- Detection of Anomaly: AI systems are able to analyse vast amounts of data from sensor devices and network traffic in order to identify anomalous patterns that might indicate a security risk. This is especially helpful in CPS, where human monitoring is impossible due to the sheer volume and complexity of data.
- Adaptive security : Unlike traditional rule-based systems, utilizes machine learning models that can adapt to evolving system conditions and emerging threats, providing flexible and dynamic security solutions.
- Autonomous Response: Without human assistance, AI-driven systems are capable of implementing security measures on their own to reduce threats in time-sensitive situations.
- Security optimization: AI algorithms can enhance the deployment of security measures within complex CPS architectures, striking a balance between security demands and performance requirements
- Threat Intelligence: By analysing global threat data, AI can produce contextual intelligence that aids organisations in setting priorities for their security resources and efforts.

6.1 To demonstrate the capabilities of AI in CPS security, let's explore a real-world application

Example: AI-Powered Security in Smart Grid Systems

Smart grids are advanced systems that manage power generation, distribution, and consumption using smart sensors and control technologies. AI plays a key role in securing these systems:

- Anomaly Detection: Machine learning models look at data such as power flow, energy use, and network traffic to spot signs of cyberattacks or physical tampering.
- Load Forecasting: AI predicts future energy demand, helping to avoid overloads that attackers might try to exploit.
- Adaptive Islanding: If an attack is detected, AI can automatically isolate the affected parts of the grid to stop problems from spreading.

- Threat Prioritization: AI systems evaluate and rank security threats, so human operators can focus on the most urgent issues.

Key metrics for this use case may include:

- False Positive Rate (FPR): The percentage of normal activities wrongly identified as threats.
- Mean Time to Detect (MTTD): The average time taken to detect an attack after it begins.
- Resilience Index: A measure of how well the grid can continue functioning during and after a security event.

AI-Enhanced Security for Smart Grids: Case study

A regional utility company adopted an AI-driven security system to protect its smart grid infrastructure. The system:

- Leverages deep learning to process large volumes of sensor data from across the grid.
- Uses reinforcement learning to create adaptive islanding strategies in response to detected attacks.
- Applies natural language processing to analyze threat intelligence feeds and operator communications for signs of potential insider threats.

Results:

- Achieved 99.999% grid uptime despite a 300% rise in cyberattack attempts.
- Reduced energy theft by 60% through better detection of meter tampering.
- Increased response speed to physical security breaches at substations by 45%.

7 Conclusion

The use of AI into cyber-physical systems security represents a fundamental leap in our approach to protecting critical infrastructure and networked devices. As we have shown throughout this article, AI provides unparalleled capabilities in threat detection, response automation, and predictive security across a wide range of industries, including manufacturing, healthcare, transportation, and energy. We can prevent potentially disastrous attacks on vital infrastructure, industrial control systems, and other CPS applications by using thread analysis and attack modeling. This ensures the seamless operation of these systems while also protecting public safety, economic well-being, and national security. However, it is critical to recognize that threat modelling is a continuous process. As CPS technology advances and new attack routes develop, security evaluations must be examined and updated on a continuous basis.As we move toward a more interconnected world, securing our cyber-physical infrastruc-

ture becomes more critical than ever. AI-driven security presents a potent solution, capable of protecting the systems that form the foundation of our modern society. By adopting these technologies in a responsible and careful manner, we can help create a safer, more secure future for cyber-physical systems across all industries.

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