

ENHANCED NETWORK SECURITY USING ZERO TRUST IN SMART HOME NETWORKS AGAINST MAN-IN-THE-MIDDLE ATTACKS

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Abstract

The rapid adoption of Internet of Things (IoT) devices in Smart Home environments has increased network vulnerability to internal threats, such as Man-in-the-Middle (MitM) attacks, which traditional security models often fail to address. This study aims to design, simulate, and comparatively analyze the effectiveness of a Zero Trust architecture against a traditional security model in protecting a smart home network from MitM attacks. A comparative experiment was conducted in a GNS3 simulation environment featuring two topologies: a conventional flat network using HTTP and a Zero Trust network implementing microsegmentation via VLANs, Access Control Lists (ACLs), and encrypted HTTPS communication. MitM attacks, specifically ARP Spoofing and packet sniffing, were launched against both scenarios. The results unequivocally show that the traditional network was highly vulnerable, allowing attackers to successfully intercept user credentials in plaintext. In contrast, the Zero Trust architecture completely thwarted the attack; its layered defenses blocked unauthorized traffic and encrypted sensitive data, preventing any credential theft. This research concludes that the Zero Trust model is a significantly more effective and robust security strategy for IoT-based smart homes, providing superior protection against internal threats with minimal performance trade-offs compared to conventional approaches.

Keywords: *Internet Of Things, Man-in-the-Middle, Smart Home, Zero Trust, Network Security*

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1. INTRODUCTION

The advancement of Internet of Things (IoT) technology has brought significant transformations in various aspects of human life[1]. One of the most prominent applications is in Smart Home systems, where devices such as security cameras, smart thermostats, digital door locks, and automatic lights are interconnected via the internet and can be controlled remotely[2]. With the increasing adoption of this technology, network security has become an increasingly important and complex issue[3].

Smart Home networks generally still rely on traditional security approaches, such as the use of firewalls, Network Address Translation (NAT) systems, and basic authentication[4], [5]. Although these approaches are effective in certain conditions, they have fundamental weaknesses in dealing with internal network threats, such as Man-in-the-Middle (MitM) attacks[6][7]. In such attacks, perpetrators can infiltrate the local network and monitor or even modify communication between devices without being detected[8], [9]. This threat is exacerbated by the open

nature of household networks, where connected devices often have weak security, lack network segmentation, and minimal control over who can access these devices. Therefore, a new approach is needed that can provide more comprehensive and adaptive protection[10].

The Zero Trust architecture emerges as an innovative solution that no longer relies on implicit trust in entities within the network. Its main principle is "never trust, always verify," meaning that every access request must be strictly verified, regardless of the origin of the request[11], [12]. With this approach, the network is built on the assumption that every connection is a potential threat, and access is granted based on strict policies and multi-layered authentication[13], [14]. In the context of Smart Homes, the implementation of Zero Trust offers great potential for strengthening security, but it also presents its own challenges, such as limited device resources, complexity in identity management, and the need for systems that can operate efficiently with low overhead[15].

Although numerous studies have explored the theoretical concepts and benefits of the Zero Trust architecture, there remains a gap in literature demonstrating a practical, head-to-head comparison within the specific context of Smart Home networks[16]. Many existing works discuss Zero Trust broadly, without providing a replicable simulation blueprint or empirical data on its effectiveness against specific internal threats like Man-in-the-Middle attacks. This study aims to fill this gap by not only implementing but also quantitatively assessing a Zero Trust topology against a traditional one. Our unique contribution lies in providing a clear, evidence-based demonstration of Zero Trust's superiority in a simulated, yet realistic, Smart Home environment, complete with performance metrics such as network latency[17][18].

By conducting simulations in a virtual environment, this research is expected to provide empirical evidence regarding the benefits and challenges of each approach, as well as offer more targeted implementation recommendations. This research aims to:

1. Design and simulate Smart Home network topologies with traditional and Zero Trust security approaches;
2. Test and compare the vulnerability levels of both approaches to MitM attacks;
3. Analyze the test results to provide recommendations for more adaptive and effective security implementations.

2. RESEARCH METHOD

This research article adopts a comparative experimental approach, utilizing a virtual network simulation environment to compare the effectiveness of two security strategies: conventional and Zero Trust. The simulation environment is realized through the integration of GNS3 software for network orchestration and Oracle VirtualBox for virtual machine hosts, which collectively replicate realistic household network conditions. The research process is structured into a series of methodical steps, as illustrated in Figure 1.

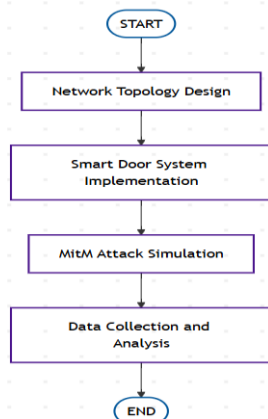


Figure 1. Research Methodology Flowchart

2.1 Network Topology Design

Two distinct network configurations were meticulously designed to represent different security scenarios: traditional and Zero Trust. The choice of these designs is based on common characteristics of home networks and the security principles of each model.

Traditional Network Topology: This topology was designed to mirror a common and conventional household network architecture, where implicit internal trust still prevails. This configuration consists of a router (simulating a generic home router), a switch, and three main entities: a user device (represented by a Ubuntu virtual machine), an IoT device (represented by an Ubuntu Server running the Smart Door application), and an attacker device (represented by a Kali Linux virtual machine). All these devices are placed within a single, flat network segment without significant segmentation or isolation, using the 192.168.10.0/24 subnet. This design reflects the inherent vulnerabilities in traditional networks, where once an attacker successfully breaches the perimeter (through physical access or compromise of a weak device), they have implicit access to all devices within the network. This openness significantly increases the attack surface for lateral movement and MitM attacks. This topology is illustrated in detail in Figure 2.

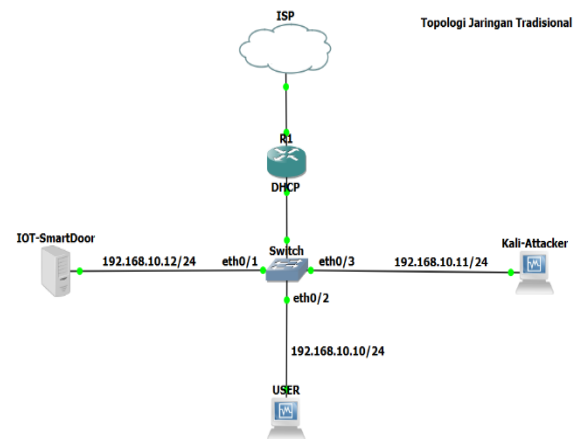


Figure 2. Traditional Network Topology

Zero Trust Network Topology: In contrast to the traditional approach, the Zero Trust topology is built upon the principles of "never trust, always verify" and "least privilege access"[19][20]. This architecture leverages a multilayer router configured to provide strict network segmentation through the use of Virtual LANs (VLANs). Each device is placed within a separate and logically isolated subnet: the IoT device (Smart Door) is on 192.168.10.0/24, the user device (Ubuntu) on 192.168.20.0/24, and the attacker device (Kali Linux) on 192.168.30.0/24. Communication between subnets is strictly controlled using Access Control Lists (ACLs) applied to the multilayer router. These ACLs function as microsegmentation policies, explicitly defining allowed traffic and implicitly

denying all other traffic by default. For example, only specific traffic from the user's subnet to certain ports on the IoT device is permitted. This drastically reduces the attack surface and prevents lateral movement by attackers. The architectural details can be seen in Figure 3.

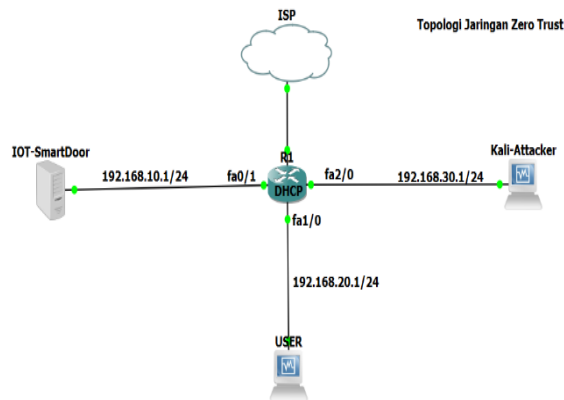


Figure 3. Zero Trust Network Topology

2.2 Smart Door System Implementation

To replicate a realistic Smart Home interaction scenario, a Smart Door application was developed on the IoT device (Ubuntu Server) using the Python-based Flask framework. Flask was chosen for its lightweight and flexible nature, suitable for simulating resource-constrained IoT devices. This application simulates the function of a smart door lock that can be operated via a web interface, allowing users to virtually "lock" or "unlock" the door. The application interface was designed to be simple and intuitive, as shown in Figure 4.

In the traditional network scenario, interaction between the user device and the Smart Door application occurred via the standard HTTP (Hypertext Transfer Protocol) protocol, running on port 8080. The choice of HTTP is based on the fact that many IoT devices, especially older or less secure models, still use unencrypted communication, which is inherently vulnerable to eavesdropping. Conversely, in the Zero Trust topology, communication between the user and the Smart Door was encrypted using HTTPS (Hypertext Transfer Protocol Secure), running on port 8443. The implementation of HTTPS involved configuring SSL/TLS (Secure Sockets Layer/Transport Layer Security) certificates on the Flask server, ensuring the confidentiality, integrity, and authentication of transmitted data. This fundamental difference in communication protocols serves as a key variable in evaluating the effectiveness of both security approaches.

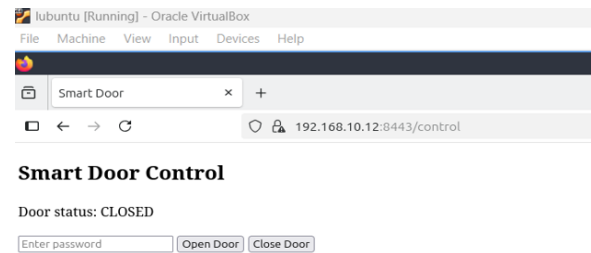


Figure 4. Illustration of Smart Door Application Interface

2.3 MitM Attack Simulation

Man-in-the-Middle (MitM) attack simulation phase is the core of this comparative testing. The Kali Linux device was utilized as a comprehensive primary platform for launching various types of cyberattacks, thanks to its extensive collection of security tools. The main focus of this simulation was on exploiting network protocol vulnerabilities through ARP Spoofing[21][22]. ARP Spoofing is a technique where an attacker sends forged ARP (Address Resolution Protocol) messages to a local network, manipulating the ARP tables on target devices (user and Smart Door). Consequently, network traffic that should flow directly between the user and the Smart Door is redirected through the attacker's device, placing the attacker in the "middle" of the communication. The arpspoof tool was used to execute this attack, continuously sending fake ARP packets.

During this ARP Spoofing attack, packet sniffing tools like Wireshark were simultaneously implemented on the attacker device. Wireshark functions to intercept, capture, and then thoroughly analyze all data traffic transmitted between the user device (Lubuntu) and the Smart Door IoT device. This analysis is crucial for identifying whether sensitive credentials (username and password) or other important information were successfully intercepted and read by the attacker in plaintext format. Additionally, the nmap tool was used to perform port scanning from the attacker's device to the target devices (Smart Door and Lubuntu). Port scanning aims to map open ports and running services on target devices, providing an overview of the exploitable attack surface. The results of packet sniffing and port scanning will then be used to verify the effectiveness of the implemented security measures in both network topologies.

2.4 Data Collection and Analysis

Primary data collection was performed by capturing network traffic using Wireshark software on the attacker device during the MitM attack simulations. The main focus of quantitative data

analysis was to assess the attacker's success in stealing user credentials (username and password) in each network topology. Credentials were considered successfully stolen if they were visible in plaintext format in the Wireshark capture results. Furthermore, several additional quantitative metrics were also measured and evaluated to understand the impact of the security architecture on network performance and security more comprehensively:

1. **Credential Interception Success:** Judged as binary (successful/failed) based on the visibility of credentials in Wireshark.
2. **Network Latency:** Measured using the ping command between the user device and the Smart Door, both under normal conditions and during an attack, to monitor the potential performance impact of security implementation.
3. **Data Packet Volume:** Observed from Wireshark to note differences in the number and types of packets transmitted and intercepted in both topologies.
4. **Port Scanning Results:** Recorded from nmap output to identify open/closed/filtered ports, indicating the level of access restriction.
5. **Packet Loss (%):** This metric was measured during ping to indicate whether there was effective traffic blocking by ACLs.

Specific details regarding the parameters and configurations used in this simulation, including IP addresses, subnets, communication protocols, and ACL configurations, can be found in Table 1, providing a complete overview of the experimental environment and enabling replication.

Table 1. Simulation Parameters and Configuration

Parameters	Traditional Topology	Zero Trust Topology
Main Network Devices	IoT Device (Ubuntu Flask Smart Door), User (Lubuntu), Attacker (Kali Linux)	IoT Device (Ubuntu Flask Smart Door), User (Lubuntu), Attacker (Kali Linux)
Network Segmentation	None, all in subnet 192.168.10.0/24	IoT:192.168.10.0/24 User:192.168.20.0/24 Attacker:192.168.30.0/24
Communication Protocol	HTTP (Port 8080)	HTTPS (Port 8443)
Router Specific Configuration	Basic routing configuration	DHCP: Three pools for each subnet ACL: • access-list 100 permit tcp 192.168.20.0 0.0.0.255 host 192.168.10.10 eq 8080 • access-list 100 permit udp any any eq bootps • access-list 100 permit udp any any eq bootpc • access-list 100 permit ip 192.168.10.0 0.0.0.255 any • access-list 100 deny ip any

host 192.168.10.10
Implementation of ACL: ip access-group 100 in on interface fa0/1

Attack Tools Used	arpspoof, wireshark, nmap	arpspoof, wireshark, nmap
Attack Objective	Getting credentials, port mapping	Getting credentials, port mapping
Credential Interception	Success (Credentials read in plaintext 12 ms)	Failed (Data encrypted / Traffic blocked)
Average Latency (ms)	12 ms	17 ms
Package Lost (%)	0%	100% (Due to ACL blocking)
Port Scanning	Port 8080 is open	Port 8443 (HTTPS) is filtered/restricted access

3. RESULT AND DISCUSSION

This section presents the detailed results of the simulations performed on both network topologies (traditional and Zero Trust) against Man-in-the-Middle (MitM) attacks, followed by an in-depth discussion regarding the effectiveness of each approach in the context of IoT-based Smart Home security. The discussion will integrate the findings with relevant cybersecurity principles, highlighting the practical and theoretical implications of the obtained results

3.1 Comparison of Network Vulnerability to ARP Spoofing and Packet Sniffing Attacks

The simulation of Man-in-the-Middle (MitM) attacks through ARP Spoofing and Packet Sniffing techniques forms the core of the comparative vulnerability assessment of the two topologies. The results obtained from these tests reveal significant differences in the security posture between traditional and Zero Trust networks.

Vulnerability in Traditional Network Topology In the traditional network topology, the ARP Spoofing attack simulation, conducted using the arpspoof tool on the Kali Linux device, successfully manipulated the ARP tables on both the user device (Lubuntu) and the IoT device (Ubuntu Server Smart Door). This success strategically positioned the attacker's device in the communication path between the two devices, effectively creating a "man-in-the-middle" scenario. The implications were severe: when the user accessed the Smart Door application via the HTTP protocol, all data traffic, including highly sensitive authentication credentials (username and password), was transmitted in plaintext.

Packet capture using Wireshark on the attacker's device clearly and unambiguously revealed that these credentials could be intercepted and read without encryption. This indicates a serious vulnerability to sensitive data interception, which can lead to account compromise, unauthorized access to IoT devices, and

severe privacy breaches. This vulnerability is exacerbated by the inherent characteristics of household networks: frequent use of devices with weak default security (e.g., Wi-Fi with weak or widely shared passwords), insufficient network segmentation (allowing an attacker already on the local network to easily move laterally), and weak inherent security in many IoT devices manufactured with a focus on functionality over security. Figure 5 displays an example Wireshark screenshot illustrating the credentials successfully intercepted in the traditional topology, confirming the real threat of MitM attacks on network architectures relying on implicit trust.

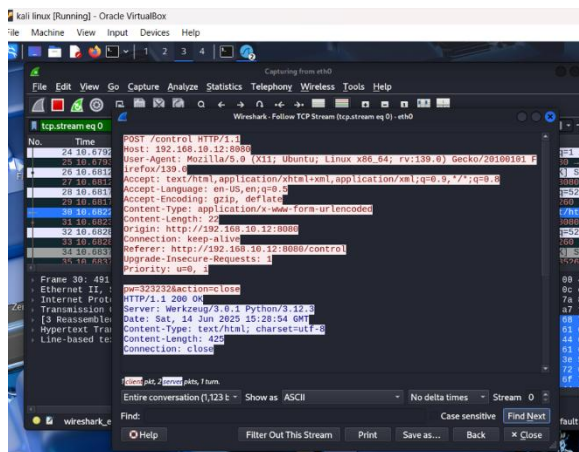


Figure 5. Credential Interception Results in Traditional Network Topology

Strict Subnet Segmentation and Microsegmentation via ACLs implementation of strict subnet segmentation, where the IoT device (192.168.10.0/24), the user device (192.168.20.0/24), and the attacker device (192.168.30.0/24) reside in separate, logically isolated subnets, fundamentally alters the attack landscape. Communication between these subnets is rigorously controlled by Access Control Lists (ACLs) applied to the multilayer router. Specifically, ACL rules such as access-list 100 deny ip any host 192.168.10.10 applied to interface fa0/1 of the router (the interface connected to the Smart Door's subnet) effectively blocked unauthorized access from the attacker's subnet to the Smart Door device (192.168.10.10). This is a manifestation of the "least privilege" and "explicit verify" principles of Zero Trust, where only traffic explicitly permitted by strict policies is allowed. Consequently, even if the attacker attempted to redirect traffic, the ACLs would deny those packets before they reached their intended destination.

Encrypted Communication using HTTPS Furthermore, communication between the user and the Smart Door application was encrypted end-to-end using HTTPS (running on https://192.168.10.10:8443/). This constitutes a crucial defense layer at the application level. Even if traffic was successfully intercepted by the attacker (e.g., if the attacker managed to bypass other security layers or if there was a misconfiguration), its content would be

ciphertext that could not be read or understood without the appropriate decryption key. Thus, attempts to intercept credentials by Wireshark on the attacker's device would only display encrypted data containing no informative value, as shown in Figure 6. These results empirically prove the Zero Trust principle of rejecting implicit trust and verifying every access at every layer (network and application), significantly reducing the risk of sensitive data interception.

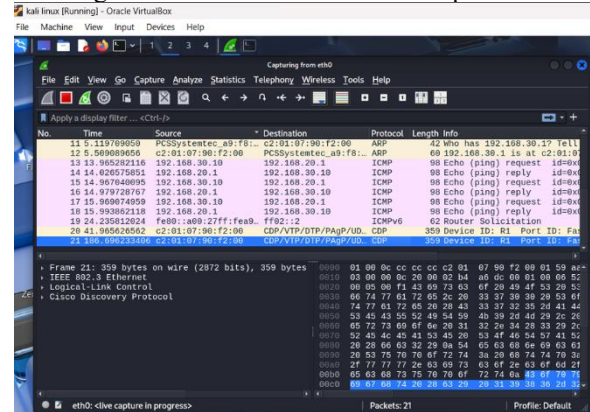


Figure 6. Encrypted Traffic Display Zero Trust

3.2 Analysis of Port Security and Access

Beyond credential interception, port scanning is a common method used by attackers to identify potential vulnerabilities within a network. The analysis of port scanning results reveals a striking difference between the two topologies.

Open Vulnerabilities in Traditional Topology In the traditional topology, port scanning tests using the nmap tool from the attacker's device (Kali Linux) clearly showed that various ports on both the IoT device (Smart Door) and the user device were open and identifiable. These ports included, but were not limited to, those used for the Smart Door application services (HTTP port 8080) as well as potential other services that might be running by default on the operating system (e.g., SSH, FTP, or other network services). The absence of specific filters or access restrictions configured on the traditional network allowed the attacker to easily map running services and discover potential security loopholes. The attacker's ability to access services like curl or obtain credentials unhindered, as demonstrated in the previous section, provides evidence that this network is vulnerable to further exploitation and possesses a broad attack surface. Every open port represents a potential entry point for attackers. Figure 7 presents an example of nmap output showing the open ports detected in the traditional topology.

```

kali linux [Running] - Oracle VirtualBox
File Machine View Input Devices Help

(bewit@Bewit)-[~]
$ nmap -sS -p- 192.168.10.12

Starting Nmap 7.95 ( https://nmap.org ) at 2025-06-14 12:43 EDT
Nmap scan report for 192.168.10.12
Host is up (0.00088s latency).
Not shown: 65534 closed tcp ports (reset)
PORT      STATE SERVICE
8080/tcp   open  http-proxy
MAC Address: 08:00:27:BB:D3:B1 (PCS Systemtechnik/Oracle VirtualBox virtual NIC)

Nmap done: 1 IP address (1 host up) scanned in 5.04 seconds

(bewit@Bewit)-[~]
$ nmap -sS -p- 192.168.10.10

Starting Nmap 7.95 ( https://nmap.org ) at 2025-06-14 12:49 EDT
Nmap scan report for 192.168.10.10
Host is up (0.0013s latency).
All 65535 scanned ports on 192.168.10.10 are in ignored states.
Not shown: 65535 closed tcp ports (reset)
MAC Address: 08:00:27:BB:7A:4D (PCS Systemtechnik/Oracle VirtualBox virtual NIC)

Nmap done: 1 IP address (1 host up) scanned in 5.76 seconds

```

Figure 7. Nmap Port Scanning Output On Traditional Topology

Effective Access Restriction in Zero Trust Topology On the other hand, the Zero Trust topology demonstrated a significant improvement in security regarding access restriction and port protection. With network segmentation via VLANs and strict ACL implementation, port scanning from the attacker's subnet to the Smart Door IoT device (192.168.10.10) largely failed or showed irrelevant/filtered ports. The ACL rule access-list 100 permit tcp 192.168.20.0 0.0.0.255 host 192.168.10.10 eq 8443 selectively permitted only TCP traffic from the user's subnet (192.168.20.0/24) to the Smart Door device on port 8443 (HTTPS). Other traffic from the attacker's subnet was implicitly denied by the ACL (implicit deny), or explicitly denied by a more specific rule access-list 100 deny ip any host 192.168.10.10.

```

kali linux [Running] - Oracle VirtualBox
File Machine View Input Devices Help

(bewit@Bewit)-[~]
$ nmap -sS -p- 192.168.10.12

Starting Nmap 7.95 ( https://nmap.org ) at 2025-06-14 13:26 EDT
Note: Host seems down. If it is really up, but blocking our ping probes, try -Pn
Nmap done: 1 IP address (0 hosts up) scanned in 3.07 seconds

(bewit@Bewit)-[~]
$ nmap -sS -p- 192.168.20.10

Starting Nmap 7.95 ( https://nmap.org ) at 2025-06-14 13:27 EDT
RTTVAR has grown to over 2.3 seconds, decreasing to 2.0
RTTVAR has grown to over 2.3 seconds, decreasing to 2.0
RTTVAR has grown to over 2.3 seconds, decreasing to 2.0
RTTVAR has grown to over 2.3 seconds, decreasing to 2.0
RTTVAR has grown to over 2.3 seconds, decreasing to 2.0

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Figure 8. Nmap Port Scanning Output on Zero Trust Topology

This ensures that only authorized and verified traffic can reach the IoT device, significantly minimizing the attack surface and preventing attackers from freely exploring ports. When an attacker attempts port scanning, they will find that most ports are closed or filtered, providing very limited information about the target network's configuration. This is a direct demonstration of the principles of least privilege and

microsegmentation within the Zero Trust architecture, where every connection and access must be explicitly authorized. Figure 8 displays the nmap output indicating closed or inaccessible ports in the Zero Trust topology, proving the effectiveness of this approach in reducing the exploitable footprint for attackers.

3.3 Implications of HTTPS Encryption in the Context of Zero Trust and Smart Home

The implementation of the Hypertext Transfer Protocol Secure (HTTPS) protocol for the Smart Door application in the Zero Trust topology is a crucial factor that directly contributes to the overall enhancement of the security posture. Unlike Hypertext Transfer Protocol (HTTP) communication in the traditional topology, which is inherently vulnerable to plaintext interception, HTTPS ensures that all communication between the user and the Smart Door, including requests, data responses, and highly sensitive authentication credentials, is encrypted end-to-end.

This encryption process fundamentally alters the nature of data traffic; it transforms information that was previously easily readable into ciphertext that cannot be deciphered without the appropriate decryption key. Thus, packet sniffing attempts by attackers become ineffective for obtaining meaningful information, as intercepted data remains protected in encrypted form. HTTPS utilizes the SSL/TLS protocol, which provides three core security services: encryption (protecting data confidentiality), data integrity (ensuring data is not modified in transit), and authentication (verifying the identity of the server, and optionally the client, to prevent impersonation). The effectiveness of HTTPS in protecting data privacy and integrity is a fundamental difference that separates the security of the Zero Trust topology from the weaknesses of conventional topologies.

Although strict network segmentation and the implementation of Access Control Lists (ACLs) have provided strong layers of isolation and access control at the network level (OSI Layer 3 and 4), HTTPS encryption acts as a vital additional defense layer at the application level (OSI Layer 7). The presence of this encryption layer effectively addresses potential weaknesses that might arise if an attacker somehow manages to breach network defenses (e.g., through zero-day vulnerabilities or undetected misconfigurations) or if they are already within a "permitted" network segment but not the direct target (lateral movement). In such scenarios, even if an attacker manages to intercept packets, they still cannot extract useful data due to the encryption protection applied by HTTPS. This is a perfect illustration of the "Assume Breach" principle in Zero Trust, where every layer must be secured as if a breach has already occurred at another layer.

In the context of Smart Home environments, where Internet of Things (IoT) devices often have

limited computational resources, slow patching cycles, and potential inherent vulnerabilities in firmware or hardware, the use of HTTPS becomes a critically important last-line defense mechanism to protect user privacy and security. Resource limitations on IoT devices can complicate the implementation of complex security controls at the device level itself, such as advanced Intrusion Prevention Systems (IPS) or endpoint security solutions. Therefore, ensuring that core data communication is encrypted becomes paramount as a primary line of defense. This evidence significantly strengthens the argument that the Zero Trust architecture, with its emphasis on "always verifying" every access and securing communication individually without assuming trust, is highly suitable for inherently vulnerable and often targeted IoT environments. HTTPS encryption not only fulfills the "explicit verification" principle of Zero Trust but also strengthens the overall security posture, even in the face of internal or lateral threats within segmented networks.

3.4 Comparison with Existing Research

To more deeply contextualize the unique contribution of this study, it is essential to compare its approach with the existing literature in this field.

On one hand, there are comprehensive survey studies, such as that by Syed et al., which effectively map the theoretical pillars of Zero Trust Architecture (ZTA), including the importance of micro-segmentation and strict access control. While such research provides a strong conceptual foundation, it does not present a practical implementation. Our study addresses this by not only discussing these concepts but also demonstrating them directly through a head-to-head simulation, presenting empirical data on their effectiveness against a specific attack.

On the other hand, there are studies proposing innovative new architectures, such as 'OUTSIDE' by Zhang et al.,[6] which introduces a per-packet authorization mechanism using cryptographic tokens. This approach offers security at a highly granular level but potentially requires more significant changes to the network stack. In contrast, our research demonstrates significant security enhancements by applying well-established and widely available ZT principles, such as network isolation using VLANs and traffic filtering via standard ACLs.

Thus, our approach offers a more pragmatic and immediately applicable path for typical Smart Home configurations. This positions our research as an important bridge connecting high-level theoretical discussions, as reviewed by Syed et al.,[21] with the development of complex new architectures, like that of Zhang et al., by providing a practical and replicable validation case study.

4. CONCLUSION

This study has successfully demonstrated the comparative effectiveness of the Zero Trust

architecture in enhancing Smart Home network security against Man-in-the-Middle (MitM) attacks compared to traditional security approaches. Through virtual environment simulations, it was found that traditional topologies, which rely on perimeter-based security and HTTP communication, are highly vulnerable to attacks such as ARP Spoofing and Packet Sniffing, allowing for unrestricted credential interception and port mapping. This vulnerability is exacerbated by the lack of adequate segmentation and access restrictions.

Conversely, the implementation of Zero Trust, involving strict network segmentation, selective Access Control List (ACL) enforcement, and the use of HTTPS encryption, significantly reduces the attack surface and mitigates the risk of data interception. Testing results show that credential interception attempts on the Zero Trust topology failed due to encrypted data and unauthorized traffic being blocked by ACLs. Port access restrictions also proved effective, limiting attackers from performing network exploration. The advantage of Zero Trust lies in its rejection of implicit trust assumptions and its reinforcement of the "never trust, always verify" and least privilege principles, which are realized through communication segmentation and encryption.

The implications of this research highlight that the application of the Zero Trust architecture, supported by encryption at the application layer, is an adaptive and effective strategy for securing IoT devices in increasingly complex and vulnerable Smart Home environments. Although implementation challenges such as limited device resources and identity management complexity may exist, the security benefits offered by Zero Trust far outweigh these risks.

This study recommends the adoption of Zero Trust principles as a security foundation for future Smart Home systems, aiming to create a more resilient and protected environment against evolving cyber threats. For future research, it is suggested to explore Zero Trust implementation on physical IoT hardware to validate findings in real-world scenarios, as well as to investigate the impact of Zero Trust on the performance of larger and more diverse Smart Home networks. Furthermore, the development of lighter and more automated identity and authentication mechanisms for low-power IoT devices within a Zero Trust framework also represents a promising area for future research.

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